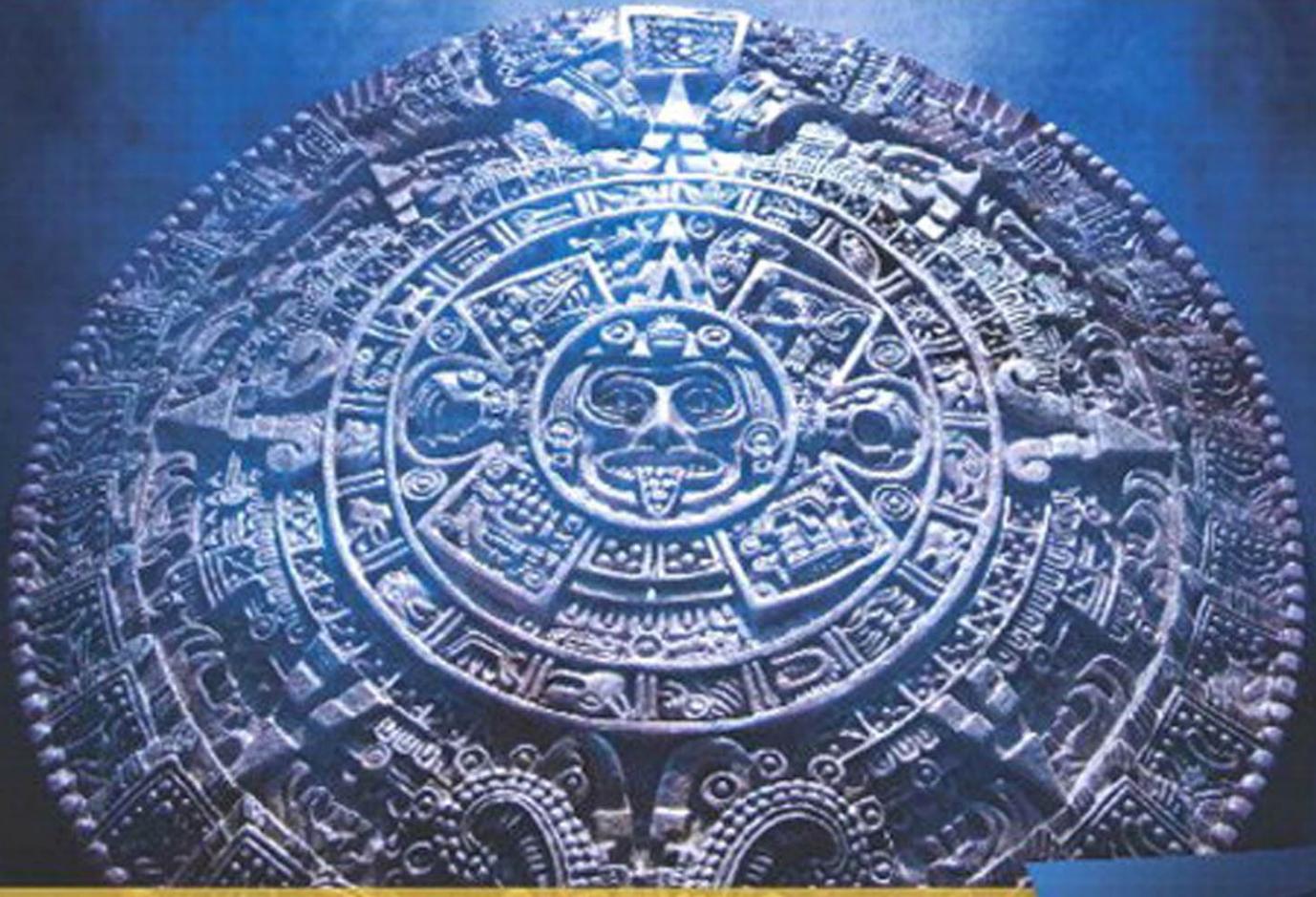


INTRODUCTION TO
JAVATM
PROGRAMMING
COMPREHENSIVE VERSION
10TH EDITION



Y. Daniel Liang

Covers
JAVA™ 7
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INTRODUCTION TO

JAVA[®]

PROGRAMMING

COMPREHENSIVE VERSION

Tenth Edition

Y. Daniel Liang

Armstrong Atlantic State University

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PREFACE

Dear Reader,

Many of you have provided feedback on earlier editions of this book, and your comments and suggestions have greatly improved the book. This edition has been substantially enhanced in presentation, organization, examples, exercises, and supplements. The new edition:

- Replaces Swing with JavaFX. JavaFX is a new framework for developing Java GUI programs. JavaFX greatly simplifies GUI programming and is easier to learn than Swing. what is new?
- Introduces exception handling, abstract classes, and interfaces before GUI programming to enable the GUI chapters to be skipped completely if the instructor chooses not to cover GUI.
- Covers introductions to objects and strings earlier in Chapter 4 to enable students to use objects and strings to develop interesting programs early.
- Includes many new interesting examples and exercises to stimulate student interests. More than 100 additional programming exercises are provided to instructors only on the Companion Website.

Please visit www.pearsonhighered.com/liang for a complete list of new features as well as correlations to the previous edition.

The book is fundamentals first by introducing basic programming concepts and techniques before designing custom classes. The fundamental concepts and techniques of selection statements, loops, methods, and arrays are the foundation for programming. Building this strong foundation prepares students to learn object-oriented programming and advanced Java programming.

This book teaches programming in a problem-driven way that focuses on problem solving rather than syntax. We make introductory programming interesting by using thought-provoking problems in a broad context. The central thread of early chapters is on problem solving. Appropriate syntax and library are introduced to enable readers to write programs for solving the problems. To support the teaching of programming in a problem-driven way, the book provides a wide variety of problems at various levels of difficulty to motivate students. To appeal to students in all majors, the problems cover many application areas, including math, science, business, financial, gaming, animation, and multimedia.

The book seamlessly integrates programming, data structures, and algorithms into one text. It employs a practical approach to teach data structures. We first introduce how to use various data structures to develop efficient algorithms, and then show how to implement these data structures. Through implementation, students gain a deep understanding on the efficiency of data structures and on how and when to use certain data structures. Finally we design and implement custom data structures for trees and graphs.

The book is widely used in the introductory programming, data structures, and algorithms courses in the universities around the world. This *comprehensive version* covers fundamentals of programming, object-oriented programming, GUI programming, data structures, algorithms, concurrency, networking, database, and Web programming. It is designed to prepare students to become proficient Java programmers. A *brief version* (*Introduction to Java Programming, Brief Version, Tenth Edition*) is available for a first course on programming, commonly known as CS1. The brief version contains the first 18 chapters of the comprehensive version. The first 13 chapters are appropriate for preparing the AP Computer Science exam.

The best way to teach programming is *by example*, and the only way to learn programming is *by doing*. Basic concepts are explained by example and a large number of exercises

fundamentals-first

problem-driven

data structures

comprehensive version

brief version
AP Computer Science

examples and exercises

with various levels of difficulty are provided for students to practice. For our programming courses, we assign programming exercises after each lecture.

Our goal is to produce a text that teaches problem solving and programming in a broad context using a wide variety of interesting examples. If you have any comments on and suggestions for improving the book, please email me.

Sincerely,

Y. Daniel Liang
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www.pearsonhighered.com/liang

ACM/IEEE Curricular 2013 and ABET Course Assessment

The new ACM/IEEE Computer Science Curricular 2013 defines the Body of Knowledge organized into 18 Knowledge Areas. To help instructors design the courses based on this book, we provide sample syllabi to identify the Knowledge Areas and Knowledge Units. The sample syllabi are for a three semester course sequence and serve as an example for institutional customization. The sample syllabi are available to instructors at www.pearsonhighered.com/liang.

Many of our users are from the ABET-accredited programs. A key component of the ABET accreditation is to identify the weakness through continuous course assessment against the course outcomes. We provide sample course outcomes for the courses and sample exams for measuring course outcomes on the instructor Website accessible from www.pearsonhighered.com/liang.

What's New in This Edition?

This edition is completely revised in every detail to enhance clarity, presentation, content, examples, and exercises. The major improvements are as follows:

- Updated to Java 8.
- Since Swing is replaced by JavaFX, all GUI examples and exercises are revised using JavaFX.
- Lambda expressions are used to simplify coding in JavaFX and threads.
- More than 100 additional programming exercises with solutions are provided to the instructor on the Companion Website. These exercises are not printed in the text.
- Math methods are introduced earlier in Chapter 4 to enable students to write code using math functions.
- Strings are introduced earlier in Chapter 4 to enable students to use objects and strings to develop interesting programs early.
- The GUI chapters are moved to after abstract classes and interfaces so that these chapters can be easily skipped if the instructor chooses not to cover GUI.
- Chapters 4, 14, 15, and 16 are brand new chapters.
- Chapters 28 and 29 have been substantially revised with simpler implementations for minimum spanning trees and shortest paths.

Pedagogical Features

The book uses the following elements to help students get the most from the material:

- The **Objectives** at the beginning of each chapter list what students should learn from the chapter. This will help them determine whether they have met the objectives after completing the chapter.
- The **Introduction** opens the discussion with representative problems to give the reader an overview of what to expect from the chapter.
- **Key Points** highlight the important concepts covered in each section.
- **Check Points** provide review questions to help students track their progress as they read through the chapter and evaluate their learning.
- **Problems and Case Studies**, carefully chosen and presented in an easy-to-follow style, teach problem solving and programming concepts. The book uses many small, simple, and stimulating examples to demonstrate important ideas.
- The **Chapter Summary** reviews the important subjects that students should understand and remember. It helps them reinforce the key concepts they have learned in the chapter.
- **Quizzes** are accessible online, grouped by sections, for students to do self-test on programming concepts and techniques.
- **Programming Exercises** are grouped by sections to provide students with opportunities to apply the new skills they have learned on their own. The level of difficulty is rated as easy (no asterisk), moderate (*), hard (**), or challenging (***) . The trick of learning programming is practice, practice, and practice. To that end, the book provides a great many exercises. Additionally, more than 100 programming exercises with solutions are provided to the instructors on the Companion Website. These exercises are not printed in the text.
- **Notes, Tips, Cautions, and Design Guides** are inserted throughout the text to offer valuable advice and insight on important aspects of program development.



Note

Provides additional information on the subject and reinforces important concepts.



Tip

Teaches good programming style and practice.



Caution

Helps students steer away from the pitfalls of programming errors.

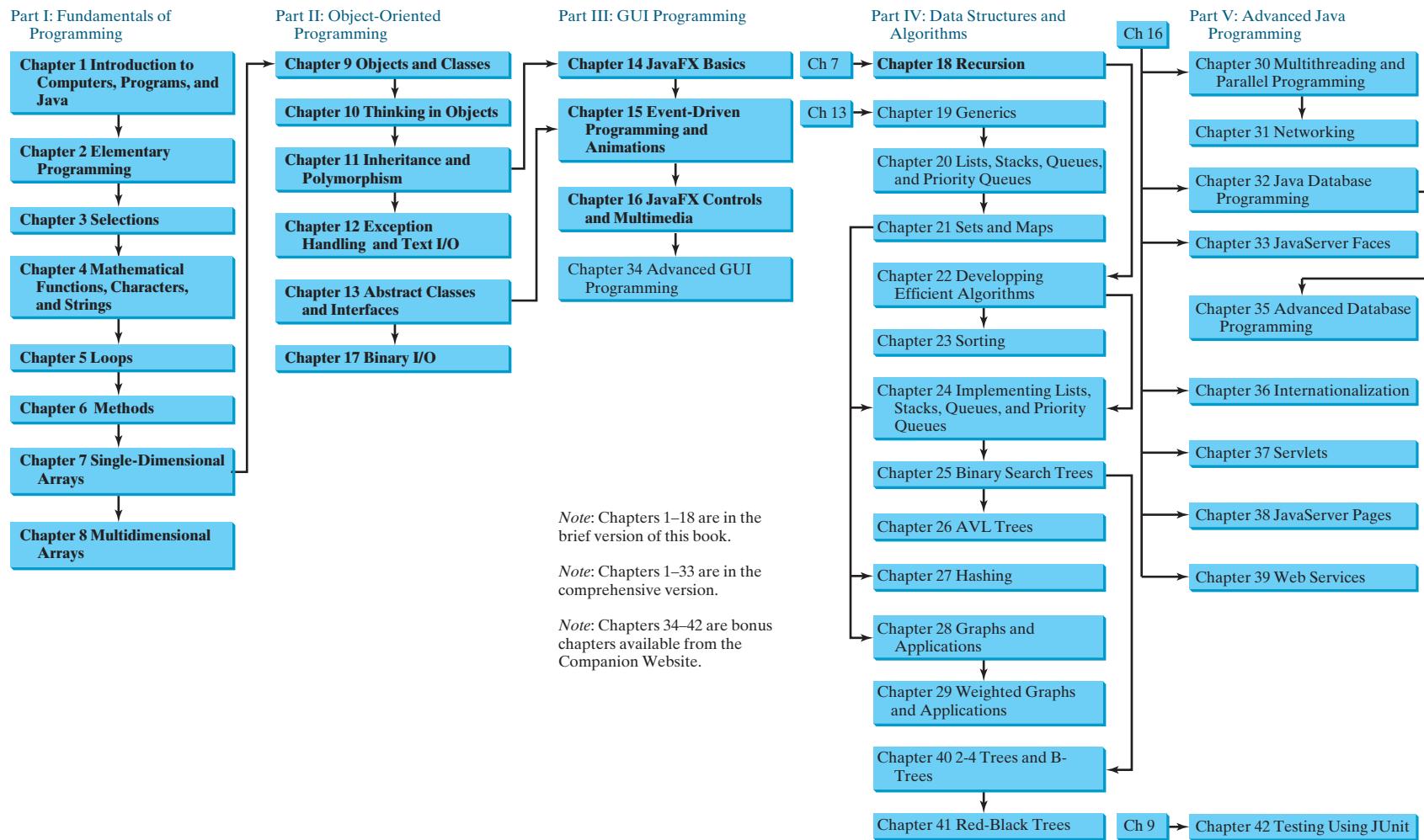


Design Guide

Provides guidelines for designing programs.

Flexible Chapter Orderings

The book is designed to provide flexible chapter orderings to enable GUI, exception handling, recursion, generics, and the Java Collections Framework to be covered earlier or later. The diagram on the next page shows the chapter dependencies.



Organization of the Book

The chapters can be grouped into five parts that, taken together, form a comprehensive introduction to Java programming, data structures and algorithms, and database and Web programming. Because knowledge is cumulative, the early chapters provide the conceptual basis for understanding programming and guide students through simple examples and exercises; subsequent chapters progressively present Java programming in detail, culminating with the development of comprehensive Java applications. The appendixes contain a mixed bag of topics, including an introduction to number systems, bitwise operations, regular expressions, and enumerated types.

Part I: Fundamentals of Programming (Chapters 1–8)

The first part of the book is a stepping stone, preparing you to embark on the journey of learning Java. You will begin to learn about Java (Chapter 1) and fundamental programming techniques with primitive data types, variables, constants, assignments, expressions, and operators (Chapter 2), selection statements (Chapter 3), mathematical functions, characters, and strings (Chapter 4), loops (Chapter 5), methods (Chapter 6), and arrays (Chapters 7–8). After Chapter 7, you can jump to Chapter 18 to learn how to write recursive methods for solving inherently recursive problems.

Part II: Object-Oriented Programming (Chapters 9–13, and 17)

This part introduces object-oriented programming. Java is an object-oriented programming language that uses abstraction, encapsulation, inheritance, and polymorphism to provide great flexibility, modularity, and reusability in developing software. You will learn programming with objects and classes (Chapters 9–10), class inheritance (Chapter 11), polymorphism (Chapter 11), exception handling (Chapter 12), abstract classes (Chapter 13), and interfaces (Chapter 13). Text I/O is introduced in Chapter 12 and binary I/O is discussed in Chapter 17.

Part III: GUI Programming (Chapters 14–16 and Bonus Chapter 34)

JavaFX is a new framework for developing Java GUI programs. It is not only useful for developing GUI programs, but also an excellent pedagogical tool for learning object-oriented programming. This part introduces Java GUI programming using JavaFX in Chapters 14–16. Major topics include GUI basics (Chapter 14), container panes (Chapter 14), drawing shapes (Chapter 14), event-driven programming (Chapter 15), animations (Chapter 15), and GUI controls (Chapter 16), and playing audio and video (Chapter 16). You will learn the architecture of JavaFX GUI programming and use the controls, shapes, panes, image, and video to develop useful applications. Chapter 34 covers advanced features in JavaFX.

Part IV: Data Structures and Algorithms (Chapters 18–29 and Bonus Chapters 40–41)

This part covers the main subjects in a typical data structures and algorithms course. Chapter 18 introduces recursion to write methods for solving inherently recursive problems. Chapter 19 presents how generics can improve software reliability. Chapters 20 and 21 introduce the Java Collection Framework, which defines a set of useful API for data structures. Chapter 22 discusses measuring algorithm efficiency in order to choose an appropriate algorithm for applications. Chapter 23 describes classic sorting algorithms. You will learn how to implement several classic data structures lists, queues, and priority queues in Chapter 24. Chapters 25 and 26 introduce binary search trees and AVL trees. Chapter 27 presents hashing and implementing maps and sets using hashing. Chapters 28 and 29 introduce graph applications. The 2-4 trees, B-trees, and red-black trees are covered in Bonus Chapters 40–41.

Part V: Advanced Java Programming (Chapters 30–33 and Bonus Chapters 35–39, 42)

This part of the book is devoted to advanced Java programming. Chapter 30 treats the use of multithreading to make programs more responsive and interactive and introduces parallel programming. Chapter 31 discusses how to write programs that talk with each other from different hosts over the Internet. Chapter 32 introduces the use of Java to develop database

projects. Chapter 33 introduces modern Web application development using JavaServer Faces. Chapter 35 delves into advanced Java database programming. Chapter 36 covers the use of internationalization support to develop projects for international audiences. Chapters 37 and 38 introduce how to use Java servlets and JavaServer Pages to generate dynamic content from Web servers. Chapter 39 discusses Web services. Chapter 42 introduces testing Java programs using JUnit.

Appendices

This part of the book covers a mixed bag of topics. Appendix A lists Java keywords. Appendix B gives tables of ASCII characters and their associated codes in decimal and in hex. Appendix C shows the operator precedence. Appendix D summarizes Java modifiers and their usage. Appendix E discusses special floating-point values. Appendix F introduces number systems and conversions among binary, decimal, and hex numbers. Finally, Appendix G introduces bitwise operations. Appendix H introduces regular expressions. Appendix I covers enumerated types.

Java Development Tools

IDE tutorials

You can use a text editor, such as the Windows Notepad or WordPad, to create Java programs and to compile and run the programs from the command window. You can also use a Java development tool, such as NetBeans or Eclipse. These tools support an integrated development environment (IDE) for developing Java programs quickly. Editing, compiling, building, executing, and debugging programs are integrated in one graphical user interface. Using these tools effectively can greatly increase your programming productivity. NetBeans and Eclipse are easy to use if you follow the tutorials. Tutorials on NetBeans and Eclipse can be found under Tutorials on the Student Companion Website at www.pearsonhighered.com/liang.

Student Resource Website

The Student Resource Website www.pearsonhighered.com/liang provides access to some of the following resources. Other resources are available using the student access code printed on the inside front cover of this book. (For students with a used copy of this book, you can purchase access to the premium student resources through www.pearsonhighered.com/liang.)

- Answers to review questions
- Solutions to even-numbered programming exercises
- Source code for the examples in the book
- Interactive quiz (organized by sections for each chapter)
- Supplements
- Debugging tips
- Algorithm animations
- Errata

Instructor Resource Website

The Instructor Resource Website, accessible from www.pearsonhighered.com/liang, provides access to the following resources:

- Microsoft PowerPoint slides with interactive buttons to view full-color, syntax-highlighted source code and to run programs without leaving the slides.
- Solutions to all programming exercises. Students will have access to the solutions of even-numbered programming exercises.

- More than 100 additional programming exercises organized by chapters. These exercises are available only to the instructors. Solutions to these exercises are provided.
- Web-based quiz generator. (Instructors can choose chapters to generate quizzes from a large database of more than two thousand questions.)
- Sample exams. Most exams have four parts:
 - Multiple-choice questions or short-answer questions
 - Correct programming errors
 - Trace programs
 - Write programs
- ACM/IEEE Curricula 2013. The new ACM/IEEE Computer Science Curricula 2013 defines the Body of Knowledge organized into 18 Knowledge Areas. To help instructors design the courses based on this book, we provide sample syllabi to identify the Knowledge Areas and Knowledge Units. The sample syllabi are for a three semester course sequence and serve as an example for institutional customization. Instructors can access the syllabi at www.pearsonhighered.com/liang.
- Sample exams with ABET course assessment.
- Projects. In general, each project gives a description and asks students to analyze, design, and implement the project.

Some readers have requested the materials from the Instructor Resource Website. Please understand that these are for instructors only. Such requests will not be answered.

Online Practice and Assessment with MyProgrammingLab

MyProgrammingLab™

MyProgrammingLab helps students fully grasp the logic, semantics, and syntax of programming. Through practice exercises and immediate, personalized feedback, MyProgrammingLab improves the programming competence of beginning students who often struggle with the basic concepts and paradigms of popular high-level programming languages.

A self-study and homework tool, a MyProgrammingLab course consists of hundreds of small practice problems organized around the structure of this textbook. For students, the system automatically detects errors in the logic and syntax of their code submissions and offers targeted hints that enable students to figure out what went wrong—and why. For instructors, a comprehensive gradebook tracks correct and incorrect answers and stores the code inputted by students for review.

MyProgrammingLab is offered to users of this book in partnership with Turing's Craft, the makers of the CodeLab interactive programming exercise system. For a full demonstration, to see feedback from instructors and students, or to get started using MyProgrammingLab in your course, visit www.myprogramminglab.com.

VideoNotes

We are excited about the new VideoNotes feature that is found in this new edition. These videos provide additional help by presenting examples of key topics and showing how to solve problems completely, from design through coding. VideoNotes are available from www.pearsonhighered.com/liang.



VideoNote



Algorithm Animations

We have provided numerous animations for algorithms. These are valuable pedagogical tools to demonstrate how algorithms work. Algorithm animations can be accessed from the Companion Website.

Acknowledgments

I would like to thank Armstrong Atlantic State University for enabling me to teach what I write and for supporting me in writing what I teach. Teaching is the source of inspiration for continuing to improve the book. I am grateful to the instructors and students who have offered comments, suggestions, bug reports, and praise.

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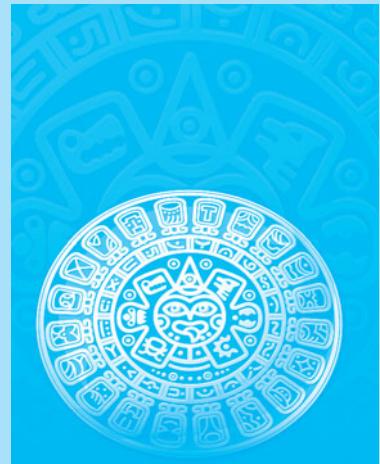
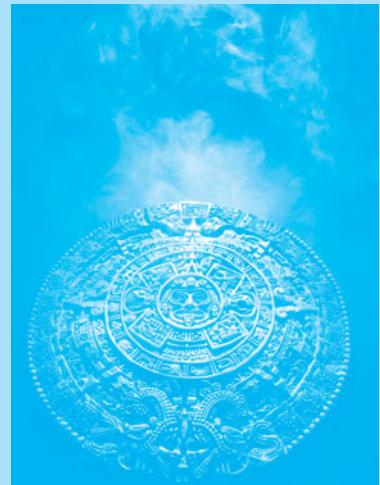
CHAPTER

1

INTRODUCTION TO COMPUTERS, PROGRAMS, AND JAVA

Objectives

- To understand computer basics, programs, and operating systems (§§1.2–1.4).
- To describe the relationship between Java and the World Wide Web (§1.5).
- To understand the meaning of Java language specification, API, JDK, and IDE (§1.6).
- To write a simple Java program (§1.7).
- To display output on the console (§1.7).
- To explain the basic syntax of a Java program (§1.7).
- To create, compile, and run Java programs (§1.8).
- To use sound Java programming style and document programs properly (§1.9).
- To explain the differences between syntax errors, runtime errors, and logic errors (§1.10).
- To develop Java programs using NetBeans (§1.11).
- To develop Java programs using Eclipse (§1.12).



1.1 Introduction



what is programming?
programming
program

The central theme of this book is to learn how to solve problems by writing a program.

This book is about programming. So, what is programming? The term *programming* means to create (or develop) software, which is also called a *program*. In basic terms, software contains the instructions that tell a computer—or a computerized device—what to do.

Software is all around you, even in devices that you might not think would need it. Of course, you expect to find and use software on a personal computer, but software also plays a role in running airplanes, cars, cell phones, and even toasters. On a personal computer, you use word processors to write documents, Web browsers to explore the Internet, and e-mail programs to send and receive messages. These programs are all examples of software. Software developers create software with the help of powerful tools called *programming languages*.

This book teaches you how to create programs by using the Java programming language. There are many programming languages, some of which are decades old. Each language was invented for a specific purpose—to build on the strengths of a previous language, for example, or to give the programmer a new and unique set of tools. Knowing that there are so many programming languages available, it would be natural for you to wonder which one is best. But, in truth, there is no “best” language. Each one has its own strengths and weaknesses. Experienced programmers know that one language might work well in some situations, whereas a different language may be more appropriate in other situations. For this reason, seasoned programmers try to master as many different programming languages as they can, giving them access to a vast arsenal of software-development tools.

If you learn to program using one language, you should find it easy to pick up other languages. The key is to learn how to solve problems using a programming approach. That is the main theme of this book.

You are about to begin an exciting journey: learning how to program. At the outset, it is helpful to review computer basics, programs, and operating systems. If you are already familiar with such terms as CPU, memory, disks, operating systems, and programming languages, you may skip Sections 1.2–1.4.

1.2 What Is a Computer?



hardware
software

A computer is an electronic device that stores and processes data.

A computer includes both *hardware* and *software*. In general, *hardware* comprises the visible, physical elements of the computer, and *software* provides the invisible instructions that control the hardware and make it perform specific tasks. Knowing computer hardware isn’t essential to learning a programming language, but it can help you better understand the effects that a program’s instructions have on the computer and its components. This section introduces computer hardware components and their functions.

A computer consists of the following major hardware components (Figure 1.1):

- A central processing unit (CPU)
- Memory (main memory)
- Storage devices (such as disks and CDs)
- Input devices (such as the mouse and keyboard)
- Output devices (such as monitors and printers)
- Communication devices (such as modems and network interface cards)

bus

A computer’s components are interconnected by a subsystem called a *bus*. You can think of a bus as a sort of system of roads running among the computer’s components; data and power travel along the bus from one part of the computer to another. In personal computers,

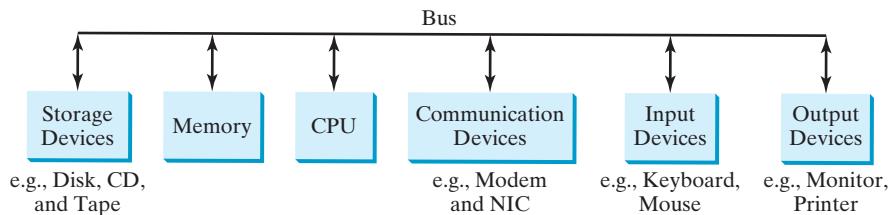


FIGURE 1.1 A computer consists of a CPU, memory, storage devices, input devices, output devices, and communication devices.

the **bus** is built into the computer's **motherboard**, which is a circuit board that connects all of the parts of a computer together. **motherboard**

1.2.1 Central Processing Unit

The **central processing unit (CPU)** is the computer's brain. It retrieves instructions from memory and executes them. The CPU usually has two components: a **control unit** and an **arithmetic/logic unit**. The control unit controls and coordinates the actions of the other components. The arithmetic/logic unit performs numeric operations (addition, subtraction, multiplication, division) and logical operations (comparisons).

Today's CPUs are built on small silicon semiconductor chips that contain millions of tiny electric switches, called **transistors**, for processing information.

Every computer has an **internal clock**, which emits electronic pulses at a constant rate. These pulses are used to control and synchronize the pace of operations. A higher **clock speed** enables more instructions to be executed in a given period of time. The unit of measurement of clock speed is the **hertz (Hz)**, with 1 hertz equaling 1 pulse per second. In the 1990s, computers measured clocked speed in **megahertz (MHz)**, but CPU speed has been improving continuously; the clock speed of a computer is now usually stated in **gigahertz (GHz)**. Intel's newest processors run at about 3 GHz.

CPUs were originally developed with only one core. The **core** is the part of the processor that performs the reading and executing of instructions. In order to increase **CPU processing power**, chip manufacturers are now producing CPUs that contain multiple cores. A **multicore CPU** is a single component with two or more independent cores. Today's consumer computers typically have two, three, and even four separate cores. Soon, CPUs with dozens or even hundreds of cores will be affordable.

1.2.2 Bits and Bytes

Before we discuss memory, let's look at how information (data and programs) are stored in a computer.

A computer is really nothing more than a series of switches. Each switch exists in two states: on or off. Storing information in a computer is simply a matter of setting a sequence of switches on or off. If the switch is on, its value is 1. If the switch is off, its value is 0. These 0s and 1s are interpreted as **digits in the binary number system and are called bits** (binary digits).

The minimum storage unit in a computer is a **byte**. A byte is composed of eight bits. A small number such as 3 can be stored as a single byte. To store a number that cannot fit into a single byte, the computer uses several bytes.

Data of various kinds, such as numbers and characters, are encoded as a series of bytes. As a programmer, you don't need to worry about the encoding and decoding of data, which the computer system performs automatically, based on the encoding scheme. An **encoding scheme** is a set of rules that govern how a computer translates characters, numbers, and symbols into data the computer can actually work with. Most schemes translate each character

CPU

speed

hertz

megahertz

gigahertz

core

bits

byte

encoding scheme

4 Chapter I Introduction to Computers, Programs, and Java

into a predetermined string of bits. In the popular ASCII encoding scheme, for example, the character **C** is represented as **01000011** in one byte.

A computer's storage capacity is measured in bytes and multiples of the byte, as follows:

- kilobyte (KB) ■ A *kilobyte (KB)* is about 1,000 bytes.
- megabyte (MB) ■ A *megabyte (MB)* is about 1 million bytes.
- gigabyte (GB) ■ A *gigabyte (GB)* is about 1 billion bytes.
- terabyte (TB) ■ A *terabyte (TB)* is about 1 trillion bytes.

A typical one-page word document might take 20 KB. Therefore, 1 MB can store 50 pages of documents and 1 GB can store 50,000 pages of documents. A typical two-hour high-resolution movie might take 8 GB, so it would require 160 GB to store 20 movies.

1.2.3 Memory

memory

A computer's *memory* consists of an ordered sequence of bytes for storing programs as well as data that the program is working with. You can think of memory as the computer's work area for executing a program. A program and its data must be moved into the computer's memory before they can be executed by the CPU.

unique address

Every byte in the memory has a *unique address*, as shown in Figure 1.2. The address is used to locate the byte for storing and retrieving the data. Since the bytes in the memory can be accessed in any order, the memory is also referred to as *random-access memory (RAM)*.

RAM

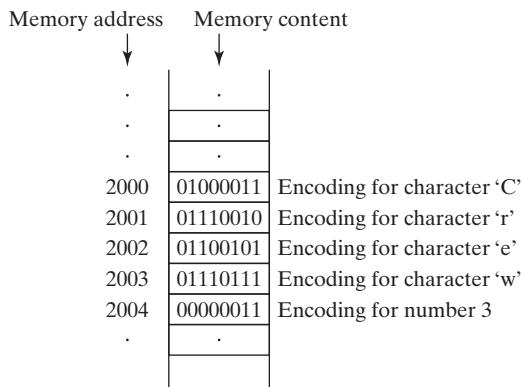


FIGURE 1.2 Memory stores data and program instructions in uniquely addressed memory locations.

Today's personal computers usually have at least 4 gigabyte of RAM, but they more commonly have 6 to 8 GB installed. Generally speaking, the more *RAM* a computer has, the faster it can operate, but there are limits to this simple rule of thumb.

A memory byte is never empty, but its initial content may be meaningless to your program. The current content of a memory byte is lost whenever new information is placed in it.

Like the CPU, memory is built on silicon semiconductor chips that have millions of transistors embedded on their surface. Compared to CPU chips, memory chips are less complicated, slower, and less expensive.

1.2.4 Storage Devices

storage devices

A computer's memory (RAM) is a volatile form of data storage: any information that has been stored in memory (i.e., saved) is lost when the system's power is turned off. Programs and data are permanently stored on *storage devices* and are moved, when the computer

actually uses them, to memory, which operates at much faster speeds than permanent storage devices can.

There are three main types of storage devices:

- Magnetic disk drives
- Optical disc drives (CD and DVD)
- USB flash drives

Drives are devices for operating a medium, such as disks and CDs. A storage medium physically stores data and program instructions. The drive reads data from the medium and writes data onto the medium.

Disks

A computer usually has at least one hard disk drive. *Hard disks* are used for permanently storing data and programs. Newer computers have hard disks that can store from 500 gigabytes to 1 terabyte of data. Hard disk drives are usually encased inside the computer, but removable hard disks are also available.

hard disk

CDs and DVDs

CD stands for compact disc. There are two types of CD drives: CD-R and CD-RW. A *CD-R* is for read-only permanent storage; the user cannot modify its contents once they are recorded. A *CD-RW* can be used like a hard disk; that is, you can write data onto the disc, and then overwrite that data with new data. A single CD can hold up to 700 MB. Most new PCs are equipped with a CD-RW drive that can work with both CD-R and CD-RW discs.

CD-R

CD-RW

DVD stands for digital versatile disc or digital video disc. DVDs and CDs look alike, and you can use either to store data. A DVD can hold more information than a CD; a standard DVD's storage capacity is 4.7 GB. Like CDs, there are two types of DVDs: DVD-R (read-only) and DVD-RW (rewritable).

DVD

USB Flash Drives

Universal serial bus (USB) connectors allow the user to attach many kinds of peripheral devices to the computer. You can use a USB to connect a printer, digital camera, mouse, external hard disk drive, and other devices to the computer.

A *USB flash drive* is a device for storing and transporting data. A flash drive is small—about the size of a pack of gum. It acts like a portable hard drive that can be plugged into your computer's USB port. USB flash drives are currently available with up to 256 GB storage capacity.

1.2.5 Input and Output Devices

Input and output devices let the user communicate with the computer. The most common input devices are *keyboards* and *mice*. The most common output devices are *monitors* and *printers*.

The Keyboard

A keyboard is a device for entering input. Compact keyboards are available without a numeric keypad.

Function keys are located across the top of the keyboard and are prefaced with the letter *F*. Their functions depend on the software currently being used.

function key

A *modifier key* is a special key (such as the *Shift*, *Alt*, and *Ctrl* keys) that modifies the normal action of another key when the two are pressed simultaneously.

modifier key

The *numeric keypad*, located on the right side of most keyboards, is a separate set of keys styled like a calculator to use for entering numbers quickly.

numeric keypad

Arrow keys, located between the main keypad and the numeric keypad, are used to move the mouse pointer up, down, left, and right on the screen in many kinds of programs.

arrow keys

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Insert key

Delete key

Page Up key

Page Down key

The *Insert*, *Delete*, *Page Up*, and *Page Down* keys are used in word processing and other programs for inserting text and objects, deleting text and objects, and moving up or down through a document one screen at a time.

The Mouse

A *mouse* is a pointing device. It is used to move a graphical pointer (usually in the shape of an arrow) called a *cursor* around the screen or to click on-screen objects (such as a button) to trigger them to perform an action.

The Monitor

The *monitor* displays information (text and graphics). The screen resolution and dot pitch determine the quality of the display.

screen resolution
pixels

The *screen resolution* specifies the number of pixels in horizontal and vertical dimensions of the display device. *Pixels* (short for “picture elements”) are tiny dots that form an image on the screen. A common resolution for a 17-inch screen, for example, is 1,024 pixels wide and 768 pixels high. The resolution can be set manually. The higher the resolution, the sharper and clearer the image is.

dot pitch

The *dot pitch* is the amount of space between pixels, measured in millimeters. The smaller the dot pitch, the sharper the display.

1.2.6 Communication Devices

Computers can be networked through communication devices, such as a dial-up modem (*modulator/demodulator*), a DSL or cable modem, a wired network interface card, or a wireless adapter.

dial-up modem

■ A *dial-up modem* uses a phone line and can transfer data at a speed up to 56,000 bps (bits per second).

digital subscriber line (DSL)

■ A *digital subscriber line (DSL)* connection also uses a standard phone line, but it can transfer data 20 times faster than a standard dial-up modem.

cable modem

■ A *cable modem* uses the cable TV line maintained by the cable company and is generally faster than DSL.

network interface card (NIC)

■ A *network interface card (NIC)* is a device that connects a computer to a *local area network (LAN)*. LANs are commonly used in universities, businesses, and government agencies. A high-speed NIC called *1000BaseT* can transfer data at 1,000 million bits per second (mbps).

local area network (LAN)

million bits per second

(mbps)

■ Wireless networking is now extremely popular in homes, businesses, and schools. Every laptop computer sold today is equipped with a wireless adapter that enables the computer to connect to a local area network and the Internet.



Note

Answers to checkpoint questions are on the Companion Website.



1.1 What are hardware and software?

1.2 List five major hardware components of a computer.

1.3 What does the acronym “CPU” stand for?

1.4 What unit is used to measure CPU speed?

1.5 What is a bit? What is a byte?

1.6 What is memory for? What does RAM stand for? Why is memory called RAM?

1.7 What unit is used to measure memory size?

- 1.8** What unit is used to measure disk size?
1.9 What is the primary difference between memory and a storage device?

1.3 Programming Languages

Computer programs, known as software, are instructions that tell a computer what to do.



Computers do not understand human languages, so programs must be written in a language a computer can use. There are hundreds of programming languages, and they were developed to make the programming process easier for people. However, all programs must be converted into the instructions the computer can execute.

1.3.1 Machine Language

A computer's native language, which differs among different types of computers, is its **machine language**—a set of built-in primitive instructions. These instructions are in the form of binary code, so if you want to give a computer an instruction in its native language, you have to enter the instruction as binary code. For example, to add two numbers, you might have to write an instruction in binary code, like this:

1101101010011010

machine language

1.3.2 Assembly Language

Programming in machine language is a tedious process. Moreover, programs written in machine language are very difficult to read and modify. For this reason, **assembly language** was created in the early days of computing as an alternative to machine languages. Assembly language uses a short descriptive word, known as a **mnemonic**, to represent each of the machine-language instructions. For example, the mnemonic **add** typically means to add numbers and **sub** means to subtract numbers. To add the numbers **2** and **3** and get the result, you might write an instruction in assembly code like this:

assembly language

add 2, 3, result

Assembly languages were developed to make programming easier. However, because the computer cannot execute assembly language, another program—called an **assembler**—is used to translate assembly-language programs into machine code, as shown in Figure 1.3.

assembler

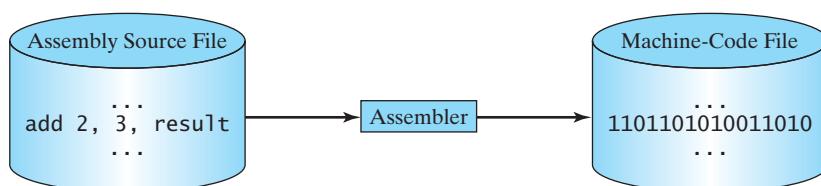


FIGURE 1.3 An assembler translates assembly-language instructions into machine code.

Writing code in assembly language is easier than in machine language. However, it is still tedious to write code in assembly language. An instruction in assembly language essentially corresponds to an instruction in machine code. Writing in assembly requires that you know how the CPU works. Assembly language is referred to as a *low-level language*, because assembly language is close in nature to machine language and is machine dependent.

low-level language

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1.3.3 High-Level Language

high-level language

statement

In the 1950s, a new generation of programming languages known as *high-level languages* emerged. They are platform independent, which means that you can write a program in a high-level language and run it in different types of machines. High-level languages are English-like and easy to learn and use. The instructions in a high-level programming language are called *statements*. Here, for example, is a high-level language statement that computes the area of a circle with a radius of 5:

```
area = 5 * 5 * 3.14159;
```

There are many high-level programming languages, and each was designed for a specific purpose. Table 1.1 lists some popular ones.

TABLE 1.1 Popular High-Level Programming Languages

Language	Description
Ada	Named for Ada Lovelace, who worked on mechanical general-purpose computers. The Ada language was developed for the Department of Defense and is used mainly in defense projects.
BASIC	Beginner's All-purpose Symbolic Instruction Code. It was designed to be learned and used easily by beginners.
C	Developed at Bell Laboratories. C combines the power of an assembly language with the ease of use and portability of a high-level language.
C++	C++ is an object-oriented language, based on C.
C#	Pronounced "C Sharp." It is a hybrid of Java and C++ and was developed by Microsoft.
COBOL	COmmon Business Oriented Language. Used for business applications.
FORTRAN	FORmula TRANslation. Popular for scientific and mathematical applications.
Java	Developed by Sun Microsystems, now part of Oracle. It is widely used for developing platform-independent Internet applications.
Pascal	Named for Blaise Pascal, who pioneered calculating machines in the seventeenth century. It is a simple, structured, general-purpose language primarily for teaching programming.
Python	A simple general-purpose scripting language good for writing short programs.
Visual Basic	Visual Basic was developed by Microsoft and it enables the programmers to rapidly develop graphical user interfaces.

source program
source code
interpreter
compiler

A program written in a high-level language is called a *source program* or *source code*. Because a computer cannot execute a source program, a source program must be translated into machine code for execution. The translation can be done using another programming tool called an *interpreter* or a *compiler*.

- An interpreter reads one statement from the source code, translates it to the machine code or virtual machine code, and then executes it right away, as shown in Figure 1.4a. Note that a statement from the source code may be translated into several machine instructions.
- A compiler translates the entire source code into a machine-code file, and the machine-code file is then executed, as shown in Figure 1.4b.



- 1.10** What language does the CPU understand?
- 1.11** What is an assembly language?
- 1.12** What is an assembler?
- 1.13** What is a high-level programming language?
- 1.14** What is a source program?

- 1.15** What is an interpreter?
1.16 What is a compiler?
1.17 What is the difference between an interpreted language and a compiled language?

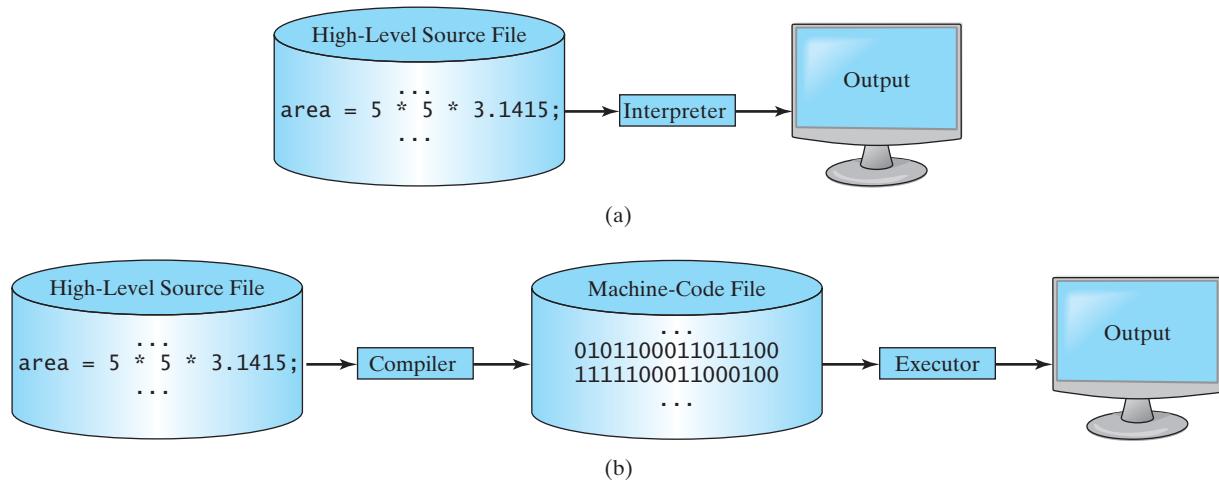


FIGURE 1.4 (a) An interpreter translates and executes a program one statement at a time. (b) A compiler translates the entire source program into a machine-language file for execution.

1.4 Operating Systems

*The operating system (OS) is the most important program that runs on a computer.
The OS manages and controls a computer's activities.*



operating system (OS)

The popular *operating systems* for general-purpose computers are Microsoft Windows, Mac OS, and Linux. Application programs, such as a Web browser or a word processor, cannot run unless an operating system is installed and running on the computer. Figure 1.5 shows the interrelationship of hardware, operating system, application software, and the user.



FIGURE 1.5 Users and applications access the computer's hardware via the operating system.

The major tasks of an operating system are as follows:

- Controlling and monitoring system activities
- Allocating and assigning system resources
- Scheduling operations

1.4.1 Controlling and Monitoring System Activities

Operating systems perform basic tasks, such as recognizing input from the keyboard, sending output to the monitor, keeping track of files and folders on storage devices, and controlling peripheral devices, such as disk drives and printers. An operating system must also ensure that different programs and users working at the same time do not interfere with each other. In addition, the OS is responsible for security, ensuring that unauthorized users and programs are not allowed to access the system.

1.4.2 Allocating and Assigning System Resources

The operating system is responsible for determining what computer resources a program needs (such as CPU time, memory space, disks, input and output devices) and for allocating and assigning them to run the program.

1.4.3 Scheduling Operations

The OS is responsible for scheduling programs' activities to make efficient use of system resources. Many of today's operating systems support techniques such as *multiprogramming*, *multithreading*, and *multiprocessing* to increase system performance.

multiprogramming

Multiprogramming allows multiple programs to run simultaneously by sharing the same CPU. The CPU is much faster than the computer's other components. As a result, it is idle most of the time—for example, while waiting for data to be transferred from a disk or waiting for other system resources to respond. A multiprogramming OS takes advantage of this situation by allowing multiple programs to use the CPU when it would otherwise be idle. For example, multiprogramming enables you to use a word processor to edit a file at the same time as your Web browser is downloading a file.

multithreading

Multithreading allows a single program to execute multiple tasks at the same time. For instance, a word-processing program allows users to simultaneously edit text and save it to a disk. In this example, editing and saving are two tasks within the same application. These two tasks may run concurrently.

multiprocessing

Multiprocessing, or *parallel processing*, uses two or more processors together to perform subtasks concurrently and then combine solutions of the subtasks to obtain a solution for the entire task. It is like a surgical operation where several doctors work together on one patient.



1.18 What is an operating system? List some popular operating systems.

1.19 What are the major responsibilities of an operating system?

1.20 What are multiprogramming, multithreading, and multiprocessing?

1.5 Java, the World Wide Web, and Beyond



Java is a powerful and versatile programming language for developing software running on mobile devices, desktop computers, and servers.

This book introduces Java programming. Java was developed by a team led by James Gosling at Sun Microsystems. Sun Microsystems was purchased by Oracle in 2010. Originally called *Oak*, Java was designed in 1991 for use in embedded chips in consumer electronic appliances. In 1995, renamed *Java*, it was redesigned for developing Web applications. For the history of Java, see www.java.com/en/javahistory/index.jsp.

Java has become enormously popular. Its rapid rise and wide acceptance can be traced to its design characteristics, particularly its promise that you can write a program once and run it anywhere. As stated by its designer, Java is *simple, object oriented, distributed,*

interpreted, robust, secure, architecture neutral, portable, high performance, multi-threaded, and dynamic. For the anatomy of Java characteristics, see www.cs.armstrong.edu/liang/JavaCharacteristics.pdf.

Java is a full-featured, general-purpose programming language that can be used to develop robust mission-critical applications. Today, it is employed not only for Web programming but also for developing standalone applications across platforms on servers, desktop computers, and mobile devices. It was used to develop the code to communicate with and control the robotic rover on Mars. Many companies that once considered Java to be more hype than substance are now using it to create distributed applications accessed by customers and partners across the Internet. For every new project being developed today, companies are asking how they can use Java to make their work easier.

The World Wide Web is an electronic information repository that can be accessed on the Internet from anywhere in the world. The Internet, the Web's infrastructure, has been around for more than forty years. The colorful World Wide Web and sophisticated Web browsers are the major reason for the Internet's popularity.

Java initially became attractive because Java programs can be run from a Web browser. Such programs are called *applets*. Applets employ a modern graphical interface with buttons, text fields, text areas, radio buttons, and so on, to interact with users on the Web and process their requests. Applets make the Web responsive, interactive, and fun to use. Applets are embedded in an HTML file. *HTML (Hypertext Markup Language)* is a simple scripting language for laying out documents, linking documents on the Internet, and bringing images, sound, and video alive on the Web. Today, you can use Java to develop rich Internet applications. A rich Internet application (RIA) is a Web application designed to deliver the same features and functions normally associated with desktop applications.

Java is now very popular for developing applications on Web servers. These applications process data, perform computations, and generate dynamic Web pages. Many commercial Websites are developed using Java on the backend.

Java is a versatile programming language: you can use it to develop applications for desktop computers, servers, and small handheld devices. The software for Android cell phones is developed using Java.

- 1.21** Who invented Java? Which company owns Java now?
- 1.22** What is a Java applet?
- 1.23** What programming language does Android use?



1.6 The Java Language Specification, API, JDK, and IDE

Java syntax is defined in the Java language specification, and the Java library is defined in the Java API. The JDK is the software for developing and running Java programs. An IDE is an integrated development environment for rapidly developing programs.



Computer languages have strict rules of usage. If you do not follow the rules when writing a program, the computer will not be able to understand it. The Java language specification and the Java API define the Java standards.

The *Java language specification* is a technical definition of the Java programming language's syntax and semantics. You can find the complete Java language specification at <http://docs.oracle.com/javase/specs/>.

Java language specification

The *application program interface (API)*, also known as *library*, contains predefined classes and interfaces for developing Java programs. The API is still expanding. You can view and download the latest version of the Java API at <http://download.java.net/jdk8/docs/api/>.

API
library

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Java is a full-fledged and powerful language that can be used in many ways. It comes in three editions:

Java SE, EE, and ME

- Java *Standard Edition* (*Java SE*) to develop client-side applications. The applications can run standalone or as applets running from a Web browser.
- Java *Enterprise Edition* (*Java EE*) to develop server-side applications, such as Java servlets, JavaServer Pages (JSP), and JavaServer Faces (JSF).
- Java *Micro Edition* (*Java ME*) to develop applications for mobile devices, such as cell phones.

Java Development Toolkit (JDK)
JDK 1.8 = JDK 8

Integrated development environment

This book uses Java SE to introduce Java programming. Java SE is the foundation upon which all other Java technology is based. There are many versions of Java SE. The latest, Java SE 8, is used in this book. Oracle releases each version with a *Java Development Toolkit (JDK)*. For Java SE 8, the Java Development Toolkit is called *JDK 1.8* (also known as *Java 8* or *JDK 8*).

The JDK consists of a set of separate programs, each invoked from a command line, for developing and testing Java programs. Instead of using the JDK, you can use a Java development tool (e.g., NetBeans, Eclipse, and TextPad)—software that provides an *integrated development environment (IDE)* for developing Java programs quickly. Editing, compiling, building, debugging, and online help are integrated in one graphical user interface. You simply enter source code in one window or open an existing file in a window, and then click a button or menu item or press a function key to compile and run the program.



- 1.24** What is the Java language specification?
- 1.25** What does JDK stand for?
- 1.26** What does IDE stand for?
- 1.27** Are tools like NetBeans and Eclipse different languages from Java, or are they dialects or extensions of Java?



what is a console?
console input
console output

1.7 A Simple Java Program

A Java program is executed from the `main` method in the class.

Let's begin with a simple Java program that displays the message **Welcome to Java!** on the console. (The word *console* is an old computer term that refers to the text entry and display device of a computer. *Console input* means to receive input from the keyboard, and *console output* means to display output on the monitor.) The program is shown in Listing 1.1.

LISTING 1.1 Welcome.java

```
1 public class Welcome {  
2     public static void main(String[] args) {  
3         // Display message Welcome to Java! on the console  
4         System.out.println("Welcome to Java!");  
5     }  
6 }
```

class
main method
display message

VideoNote
Your first Java program

Welcome to Java!

line numbers

Note that the line numbers are for reference purposes only; they are not part of the program. So, don't type line numbers in your program.

Line 1 defines a class. Every Java program must have at least one class. Each class has a name. By convention, class names start with an uppercase letter. In this example, the class name is `Welcome`.

Line 2 defines the `main` method. The program is executed from the `main` method. A class may contain several methods. The `main` method is the entry point where the program begins execution.

A method is a construct that contains statements. The `main` method in this program contains the `System.out.println` statement. This statement displays the string `Welcome to Java!` on the console (line 4). `String` is a programming term meaning a sequence of characters. A string must be enclosed in double quotation marks. Every statement in Java ends with a semicolon (`;`), known as the *statement terminator*.

Reserved words, or *keywords*, have a specific meaning to the compiler and cannot be used for other purposes in the program. For example, when the compiler sees the word `class`, it understands that the word after `class` is the name for the class. Other reserved words in this program are `public`, `static`, and `void`.

Line 3 is a *comment* that documents what the program is and how it is constructed. Comments help programmers to communicate and understand the program. They are not programming statements and thus are ignored by the compiler. In Java, comments are preceded by two slashes (`//`) on a line, called a *line comment*, or enclosed between `/*` and `*/` on one or several lines, called a *block comment* or *paragraph comment*. When the compiler sees `//`, it ignores all text after `//` on the same line. When it sees `/*`, it scans for the next `*/` and ignores any text between `/*` and `*/`. Here are examples of comments:

```
// This application program displays Welcome to Java!
/* This application program displays Welcome to Java! */
/* This application program
   displays Welcome to Java! */
```

A pair of curly braces in a program forms a *block* that groups the program's components. In Java, each block begins with an opening brace (`{`) and ends with a closing brace (`}`). Every class has a *class block* that groups the data and methods of the class. Similarly, every method has a *method block* that groups the statements in the method. Blocks can be *nested*, meaning that one block can be placed within another, as shown in the following code.

```
public class Welcome {
    public static void main(String[] args) {
        System.out.println("Welcome to Java!");
    }
}
```



Tip

An opening brace must be matched by a closing brace. Whenever you type an opening brace, immediately type a closing brace to prevent the missing-brace error. Most Java IDEs automatically insert the closing brace for each opening brace.

class name

main method

string

statement terminator

reserved word

keyword

comment

line comment

block comment

block

match braces



Caution

Java source programs are case sensitive. It would be wrong, for example, to replace `main` in the program with `Main`.

case sensitive

You have seen several special characters (e.g., `{`, `}`, `//`, `;`) in the program. They are used in almost every program. Table 1.2 summarizes their uses.

special characters

The most common errors you will make as you learn to program will be syntax errors. Like any programming language, Java has its own syntax, and you need to write code that

common errors

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TABLE 1.2 Special Characters

Character	Name	Description
{}	Opening and closing braces	Denote a block to enclose statements.
()	Opening and closing parentheses	Used with methods.
[]	Opening and closing brackets	Denote an array.
//	Double slashes	Precede a comment line.
""	Opening and closing quotation marks	Enclose a string (i.e., sequence of characters).
;	Semicolon	Mark the end of a statement.

syntax rules

conforms to the *syntax rules*. If your program violates a rule—for example, if the semicolon is missing, a brace is missing, a quotation mark is missing, or a word is misspelled—the Java compiler will report syntax errors. Try to compile the program with these errors and see what the compiler reports.



Note

You are probably wondering why the `main` method is defined this way and why `System.out.println(...)` is used to display a message on the console. For the time being, simply accept that this is how things are done. Your questions will be fully answered in subsequent chapters.

The program in Listing 1.1 displays one message. Once you understand the program, it is easy to extend it to display more messages. For example, you can rewrite the program to display three messages, as shown in Listing 1.2.

LISTING 1.2 WelcomeWithThreeMessages.java

```
1 public class WelcomeWithThreeMessages {  
2     public static void main(String[] args) {  
3         System.out.println("Programming is fun!");  
4         System.out.println("Fundamentals First");  
5         System.out.println("Problem Driven");  
6     }  
7 }
```



```
Programming is fun!  
Fundamentals First  
Problem Driven
```

class
main method
display message

Further, you can perform mathematical computations and display the result on the console.

Listing 1.3 gives an example of evaluating $\frac{10.5 + 2 \times 3}{45 - 3.5}$.

LISTING 1.3 ComputeExpression.java

```
1 public class ComputeExpression {  
2     public static void main(String[] args) {  
3         System.out.println((10.5 + 2 * 3) / (45 - 3.5));  
4     }  
5 }
```



```
0.39759036144578314
```

The multiplication operator in Java is `*`. As you can see, it is a straightforward process to translate an arithmetic expression to a Java expression. We will discuss Java expressions further in Chapter 2.

- I.28** What is a keyword? List some Java keywords.
- I.29** Is Java case sensitive? What is the case for Java keywords?
- I.30** What is a comment? Is the comment ignored by the compiler? How do you denote a comment line and a comment paragraph?
- I.31** What is the statement to display a string on the console?
- I.32** Show the output of the following code:



```
public class Test {
    public static void main(String[] args) {
        System.out.println("3.5 * 4 / 2 - 2.5 is ");
        System.out.println(3.5 * 4 / 2 - 2.5);
    }
}
```

I.8 Creating, Compiling, and Executing a Java Program

You save a Java program in a `.java` file and compile it into a `.class` file. The `.class` file is executed by the Java Virtual Machine.



You have to create your program and compile it before it can be executed. This process is repetitive, as shown in Figure 1.6. If your program has compile errors, you have to modify the program to fix them, and then recompile it. If your program has runtime errors or does not produce the correct result, you have to modify the program, recompile it, and execute it again.

You can use any text editor or IDE to create and edit a Java source-code file. This section demonstrates how to create, compile, and run Java programs from a command window. Sections 1.10 and 1.11 will introduce developing Java programs using NetBeans and Eclipse. From the command window, you can use a text editor such as Notepad to create the Java source-code file, as shown in Figure 1.7.

command window



Note

The source file must end with the extension `.java` and must have the same exact name as the public class name. For example, the file for the source code in Listing I.1 should be named **Welcome.java**, since the public class name is **Welcome**.

file name Welcome.java,

compile

A Java compiler translates a Java source file into a Java bytecode file. The following command compiles **Welcome.java**:

```
javac Welcome.java
```



Note

You must first install and configure the JDK before you can compile and run programs. See Supplement I.B, Installing and Configuring JDK 8, for how to install the JDK and set up the environment to compile and run Java programs. If you have trouble compiling and running programs, see Supplement I.C, Compiling and Running Java from the Command Window. This supplement also explains how to use basic DOS commands and how to use Windows Notepad to create and edit files. All the supplements are accessible from the Companion Website at www.cs.armstrong.edu/liang/intro10e/supplement.html.

Supplement I.B

Supplement I.C

If there aren't any syntax errors, the *compiler* generates a bytecode file with a `.class` extension. Thus, the preceding command generates a file named **Welcome.class**, as shown

.class bytecode file

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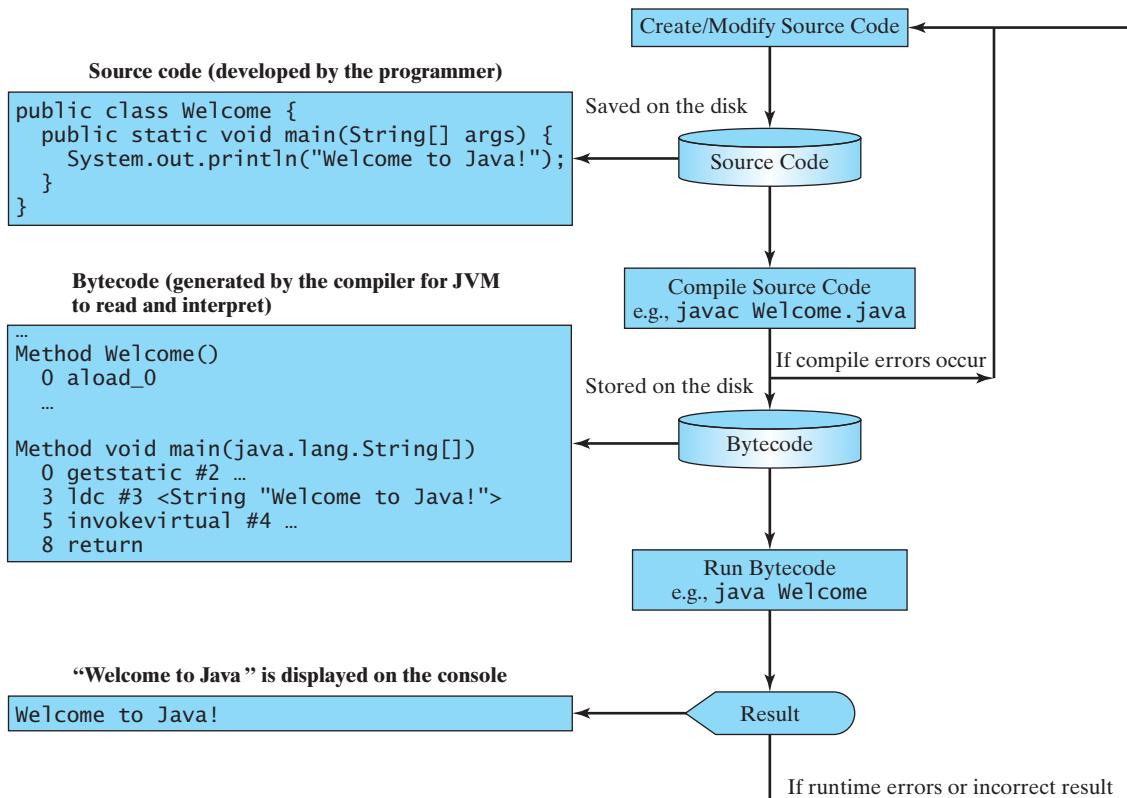


FIGURE 1.6 The Java program-development process consists of repeatedly creating/modifying source code, compiling, and executing programs.

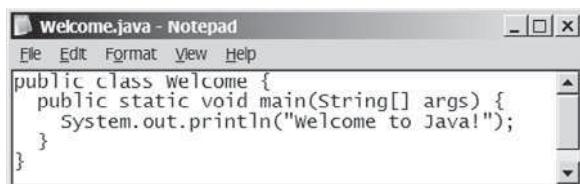


FIGURE 1.7 You can create a Java source file using Windows Notepad.

bytecode
Java Virtual Machine (JVM)

interpret bytecode

run

in Figure 1.8a. The Java language is a high-level language, but Java bytecode is a low-level language. The *bytecode* is similar to machine instructions but is architecture neutral and can run on any platform that has a *Java Virtual Machine (JVM)*, as shown in Figure 1.8b. Rather than a physical machine, the virtual machine is a program that interprets Java bytecode. This is one of Java's primary advantages: *Java bytecode can run on a variety of hardware platforms and operating systems*. Java source code is compiled into Java bytecode and Java bytecode is interpreted by the JVM. Your Java code may use the code in the Java library. The JVM executes your code along with the code in the library.

To execute a Java program is to run the program's bytecode. You can execute the bytecode on any platform with a JVM, which is an interpreter. It translates the individual instructions in the bytecode into the target machine language code one at a time rather than the whole program as a single unit. Each step is executed immediately after it is translated.

The following command runs the bytecode for Listing 1.1:

```
java Welcome
```

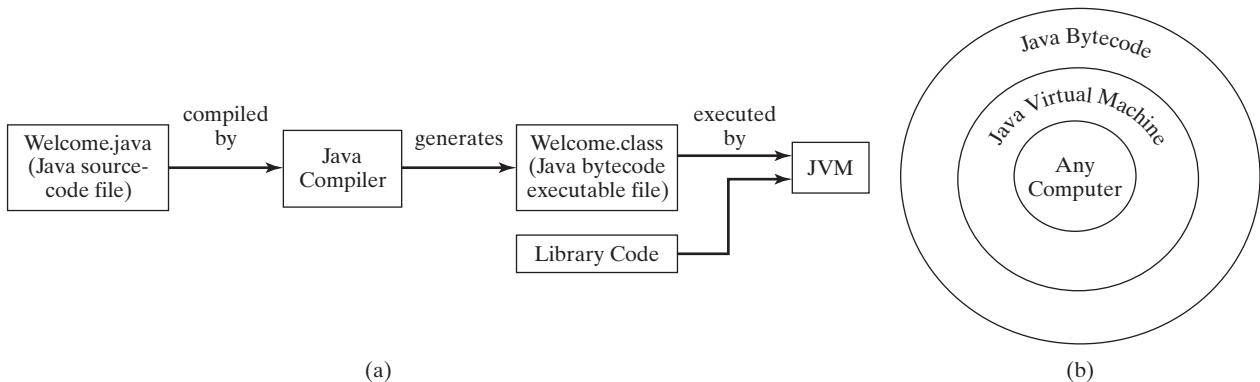


FIGURE 1.8 (a) Java source code is translated into bytecode. (b) Java bytecode can be executed on any computer with a Java Virtual Machine.

Figure 1.9 shows the **javac** command for compiling **Welcome.java**. The compiler generates the **Welcome.class** file, and this file is executed using the **java** command.

javac command
java command



Note

For simplicity and consistency, all source-code and class files used in this book are placed under **c:\book** unless specified otherwise.

c:\book

The screenshot shows a Windows Command Prompt window titled 'Command Prompt'. The user has typed the following commands:

- 'javac Welcome.java' (Compile)
- 'dir Welcome.*' (Show files)
- 'java Welcome' (Run)

The output shows the creation of the 'Welcome.class' file and its execution, displaying the message 'Welcome to Java!'.



VideoNote

Compile and run a Java program

FIGURE 1.9 The output of Listing 1.1 displays the message “Welcome to Java!”



Caution

Do not use the extension **.class** in the command line when executing the program. Use **java ClassName** to run the program. If you use **java ClassName.class** in the command line, the system will attempt to fetch **ClassName.class.class**.

java ClassName



Tip

If you execute a class file that does not exist, a **NoClassDefFoundError** will occur. If you execute a class file that does not have a **main** method or you mistype the **main** method (e.g., by typing **Main** instead of **main**), a **NoSuchMethodError** will occur.

NoClassDefFoundError

NoSuchMethodError



Note

When executing a Java program, the JVM first loads the bytecode of the class to memory using a program called the *class loader*. If your program uses other classes, the class loader dynamically loads them just before they are needed. After a class is loaded, the JVM uses a program called the *bytecode verifier* to check the validity of the bytecode and

class loader
bytecode verifier

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to ensure that the bytecode does not violate Java's security restrictions. Java enforces strict security to make sure that Java class files are not tampered with and do not harm your computer.

use package



Pedagogical Note

Your instructor may require you to use packages for organizing programs. For example, you may place all programs in this chapter in a package named *chapterI*. For instructions on how to use packages, see Supplement I.F, Using Packages to Organize the Classes in the Text.



- I.33** What is the Java source filename extension, and what is the Java bytecode filename extension?
- I.34** What are the input and output of a Java compiler?
- I.35** What is the command to compile a Java program?
- I.36** What is the command to run a Java program?
- I.37** What is the JVM?
- I.38** Can Java run on any machine? What is needed to run Java on a computer?
- I.39** If a **NoClassDefFoundError** occurs when you run a program, what is the cause of the error?
- I.40** If a **NoSuchMethodError** occurs when you run a program, what is the cause of the error?



1.9 Programming Style and Documentation

Good programming style and proper documentation make a program easy to read and help programmers prevent errors.

programming style

Programming style deals with what programs look like. A program can compile and run properly even if written on only one line, but writing it all on one line would be bad programming style because it would be hard to read. *Documentation* is the body of explanatory remarks and comments pertaining to a program. Programming style and documentation are as important as coding. Good programming style and appropriate documentation reduce the chance of errors and make programs easy to read. This section gives several guidelines. For more detailed guidelines, see Supplement I.D, Java Coding Style Guidelines, on the Companion Website.

documentation

1.9.1 Appropriate Comments and Comment Styles

Include a summary at the beginning of the program that explains what the program does, its key features, and any unique techniques it uses. In a long program, you should also include comments that introduce each major step and explain anything that is difficult to read. It is important to make comments concise so that they do not crowd the program or make it difficult to read.

javadoc comment

In addition to line comments (beginning with `//`) and block comments (beginning with `/*`), Java supports comments of a special type, referred to as *javadoc comments*. javadoc comments begin with `/**` and end with `*/`. They can be extracted into an HTML file using the JDK's **javadoc** command. For more information, see Supplement III.Y, javadoc Comments, on the companion Website.

Use javadoc comments (`/** ... */`) for commenting on an entire class or an entire method. These comments must precede the class or the method header in order to be extracted into a javadoc HTML file. For commenting on steps inside a method, use line comments (`//`).

To see an example of a javadoc HTML file, check out www.cs.armstrong.edu/liang/javadoc/Exercise1.html. Its corresponding Java code is shown in www.cs.armstrong.edu/liang/javadoc/Exercise1.java.

1.9.2 Proper Indentation and Spacing

A consistent indentation style makes programs clear and easy to read, debug, and maintain. *Indentation* is used to illustrate the structural relationships between a program's components or statements. Java can read the program even if all of the statements are on the same long line, but humans find it easier to read and maintain code that is aligned properly. Indent each subcomponent or statement at least *two* spaces more than the construct within which it is nested.

A single space should be added on both sides of a binary operator, as shown in the following statement:

<code>System.out.println(3+4*4);</code>	Bad style
<code>System.out.println(3 + 4 * 4);</code>	Good style

1.9.3 Block Styles

A *block* is a group of statements surrounded by braces. There are two popular styles, *next-line* style and *end-of-line* style, as shown below.

```
public class Test {
    public static void main(String[] args)
    {
        System.out.println("Block Styles");
    }
}
```

Next-line style

```
public class Test {
    public static void main(String[] args) {
        System.out.println("Block Styles");
    }
}
```

End-of-line style

The next-line style aligns braces vertically and makes programs easy to read, whereas the end-of-line style saves space and may help avoid some subtle programming errors. Both are acceptable block styles. The choice depends on personal or organizational preference. You should use a block style consistently—mixing styles is not recommended. This book uses the *end-of-line* style to be consistent with the Java API source code.

- 1.41** Reformat the following program according to the programming style and documentation guidelines. Use the end-of-line brace style.



```
public class Test
{
    // Main method
    public static void main(String[] args) {
        /** Display output */
        System.out.println("Welcome to Java");
    }
}
```

1.10 Programming Errors



Programming errors can be categorized into three types: syntax errors, runtime errors, and logic errors.

1.10.1 Syntax Errors

syntax errors
compile errors

Errors that are detected by the compiler are called *syntax errors* or *compile errors*. Syntax errors result from errors in code construction, such as mistyping a keyword, omitting some necessary punctuation, or using an opening brace without a corresponding closing brace. These errors are usually easy to detect because the compiler tells you where they are and what caused them. For example, the program in Listing 1.4 has a syntax error, as shown in Figure 1.10.

LISTING 1.4 ShowSyntaxErrors.java

```
1 public class ShowSyntaxErrors {
2     public static main(String[] args) {
3         System.out.println("Welcome to Java");
4     }
5 }
```

Four errors are reported, but the program actually has two errors:

- The keyword **void** is missing before **main** in line 2.
- The string **Welcome to Java** should be closed with a closing quotation mark in line 3.

Since a single error will often display many lines of compile errors, it is a good practice to fix errors from the top line and work downward. Fixing errors that occur earlier in the program may also fix additional errors that occur later.

Compile →

```
c:\book>javac ShowSyntaxErrors.java
ShowSyntaxErrors.java:2: error: invalid method declaration; return type required
    public static ^main(String[] args) {
                                         ^
ShowSyntaxErrors.java:3: error: unclosed string literal
    System.out.println('Welcome to Java');
                                         ^
ShowSyntaxErrors.java:3: error: ';' expected
    System.out.println('Welcome to Java');^
ShowSyntaxErrors.java:5: error: reached end of file while parsing
> ^
4 errors
c:\book>
```

FIGURE 1.10 The compiler reports syntax errors.

fix syntax errors



Tip

If you don't know how to correct it, compare your program closely, character by character, with similar examples in the text. In the first few weeks of this course, you will probably spend a lot of time fixing syntax errors. Soon you will be familiar with Java syntax and can quickly fix syntax errors.

1.10.2 Runtime Errors

runtime errors

Runtime errors are errors that cause a program to terminate abnormally. They occur while a program is running if the environment detects an operation that is impossible to carry out. Input mistakes typically cause runtime errors. An *input error* occurs when the program is

waiting for the user to enter a value, but the user enters a value that the program cannot handle. For instance, if the program expects to read in a number, but instead the user enters a string, this causes data-type errors to occur in the program.

Another example of runtime errors is division by zero. This happens when the divisor is zero for integer divisions. For instance, the program in Listing 1.5 would cause a runtime error, as shown in Figure 1.11.

LISTING 1.5 ShowRuntimeErrors.java

```
1 public class ShowRuntimeErrors {
2     public static void main(String[] args) {
3         System.out.println(1 / 0);           runtime error
4     }
5 }
```

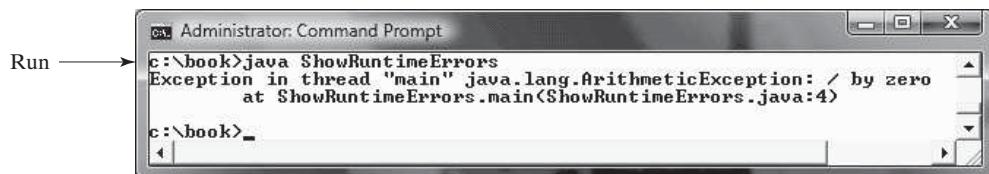


FIGURE 1.11 The runtime error causes the program to terminate abnormally.

1.10.3 Logic Errors

Logic errors occur when a program does not perform the way it was intended to. Errors of this kind occur for many different reasons. For example, suppose you wrote the program in Listing 1.6 to convert Celsius 35 degrees to a Fahrenheit degree:

logic errors

LISTING 1.6 ShowLogicErrors.java

```
1 public class ShowLogicErrors {
2     public static void main(String[] args) {
3         System.out.println("Celsius 35 is Fahrenheit degree ");
4         System.out.println((9 / 5) * 35 + 32);
5     }
6 }
```

Celsius 35 is Fahrenheit degree
67



You will get Fahrenheit 67 degrees, which is wrong. It should be 95.0. In Java, the division for integers is the quotient—the fractional part is truncated—so in Java $9 / 5$ is 1. To get the correct result, you need to use $9.0 / 5$, which results in 1.8.

In general, syntax errors are easy to find and easy to correct because the compiler gives indications as to where the errors came from and why they are wrong. Runtime errors are not difficult to find, either, since the reasons and locations for the errors are displayed on the console when the program aborts. Finding logic errors, on the other hand, can be very challenging. In the upcoming chapters, you will learn the techniques of tracing programs and finding logic errors.

1.10.4 Common Errors

Missing a closing brace, missing a semicolon, missing quotation marks for strings, and misspelling names are common errors for new programmers.

Common Error 1: Missing Braces

The braces are used to denote a block in the program. Each opening brace must be matched by a closing brace. A common error is missing the closing brace. To avoid this error, type a closing brace whenever an opening brace is typed, as shown in the following example.

```
public class Welcome {
```

} ←—Type this closing brace right away to match the opening brace

If you use an IDE such as NetBeans and Eclipse, the IDE automatically inserts a closing brace for each opening brace typed.

Common Error 2: Missing Semicolons

Each statement ends with a statement terminator (;). Often, a new programmer forgets to place a statement terminator for the last statement in a block, as shown in the following example.

```
public static void main(String[] args) {
    System.out.println("Programming is fun!");
    System.out.println("Fundamentals First");
    System.out.println("Problem Driven")
}
```

↑
Missing a semicolon

Common Error 3: Missing Quotation Marks

A string must be placed inside the quotation marks. Often, a new programmer forgets to place a quotation mark at the end of a string, as shown in the following example.

```
System.out.println("Problem Driven");
```

↑
Missing a quotation mark

If you use an IDE such as NetBeans and Eclipse, the IDE automatically inserts a closing quotation mark for each opening quotation mark typed.

Common Error 4: Misspelling Names

Java is case sensitive. Misspelling names is a common error for new programmers. For example, the word **main** is misspelled as **Main** and **String** is misspelled as **string** in the following code.

```
1 public class Test {
2     public static void Main(string[] args) {
3         System.out.println((10.5 + 2 * 3) / (45 - 3.5));
4     }
5 }
```



- 1.42** What are syntax errors (compile errors), runtime errors, and logic errors?
- 1.43** Give examples of syntax errors, runtime errors, and logic errors.
- 1.44** If you forget to put a closing quotation mark on a string, what kind error will be raised?
- 1.45** If your program needs to read integers, but the user entered strings, an error would occur when running this program. What kind of error is this?
- 1.46** Suppose you write a program for computing the perimeter of a rectangle and you mistakenly write your program so that it computes the area of a rectangle. What kind of error is this?

- I.47** Identify and fix the errors in the following code:

```

1 public class Welcome {
2     public void Main(String[] args) {
3         System.out.println('Welcome to Java!');
4     }
5 }
```

I.II Developing Java Programs Using NetBeans

You can edit, compile, run, and debug Java Programs using NetBeans.

NetBeans and Eclipse are two free popular integrated development environments for developing Java programs. They are easy to learn if you follow simple instructions. We recommend that you use either one for developing Java programs. This section gives the essential instructions to guide new users to create a project, create a class, compile, and run a class in NetBeans. The use of Eclipse will be introduced in the next section. For instructions on downloading and installing latest version of NetBeans, see Supplement II.B.



VideoNote

NetBeans brief tutorial

I.II.1 Creating a Java Project

Before you can create Java programs, you need to first create a project. A project is like a folder to hold Java programs and all supporting files. You need to create a project only once. Here are the steps to create a Java project:

1. Choose *File, New Project* to display the New Project dialog box, as shown in Figure 1.12.
2. Select Java in the Categories section and Java Application in the Projects section and click *Next* to display the New Java Application dialog box, as shown in Figure 1.13.
3. Type **demo** in the Project Name field and **c:\michael** in Project Location field. Uncheck *Use Dedicated Folder for Storing Libraries* and uncheck *Create Main Class*.
4. Click *Finish* to create the project, as shown in Figure 1.14.

I.II.2 Creating a Java Class

After a project is created, you can create Java programs in the project using the following steps:

1. Right-click the demo node in the project pane to display a context menu. Choose *New, Java Class* to display the New Java Class dialog box, as shown in Figure 1.15.

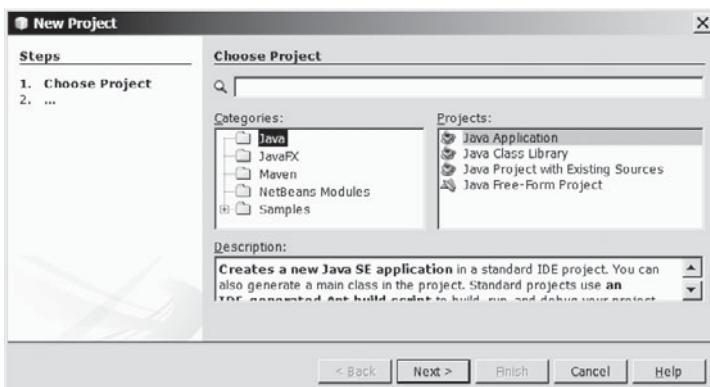


FIGURE I.12 The New Project dialog is used to create a new project and specify a project type.

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FIGURE 1.13 The New Java Application dialog is for specifying a project name and location.

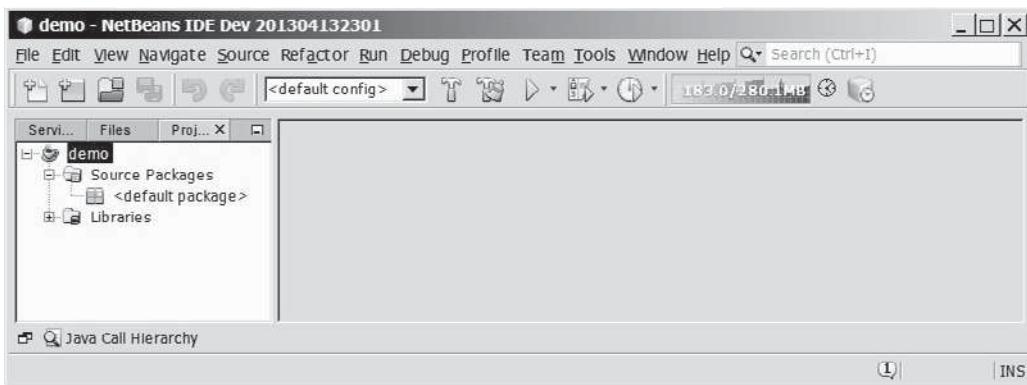


FIGURE 1.14 A New Java project named demo is created.

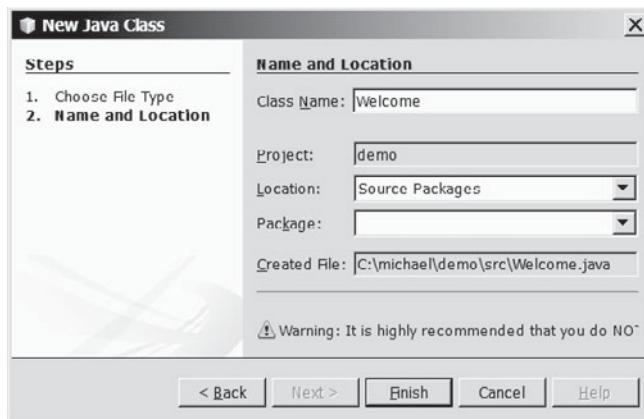


FIGURE 1.15 The New Java Class dialog box is used to create a new Java class.

2. Type **Welcome** in the Class Name field and select the Source Packages in the Location field. Leave the Package field blank. This will create a class in the default package.
3. Click *Finish* to create the Welcome class. The source code file Welcome.java is placed under the <default package> node.
4. Modify the code in the Welcome class to match Listing 1.1 in the text, as shown in Figure 1.16.

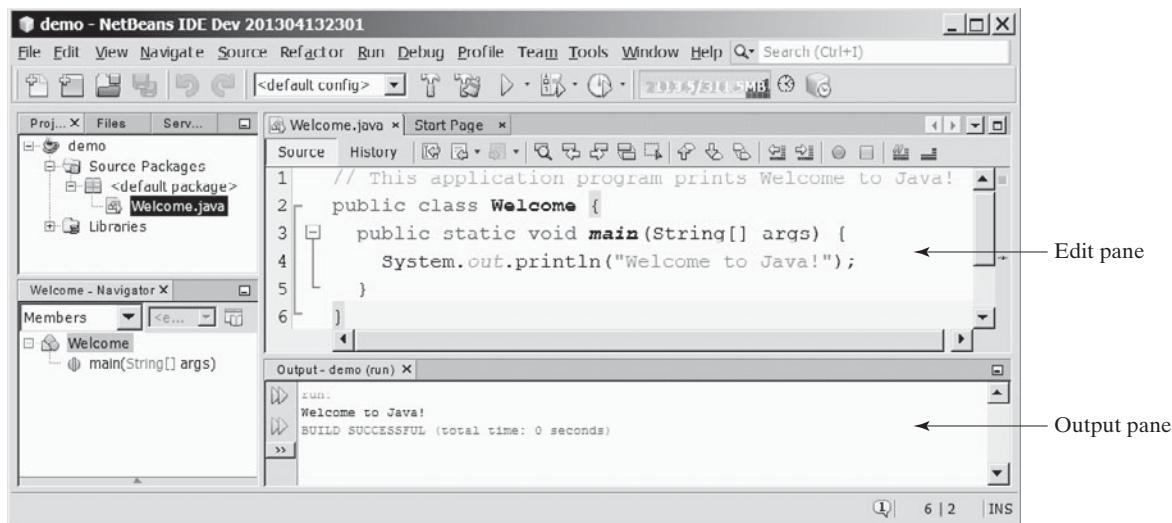


FIGURE 1.16 You can edit a program and run it in NetBeans.

1.11.3 Compiling and Running a Class

To run **Welcome.java**, right-click **Welcome.java** to display a context menu and choose *Run File*, or simply press Shift + F6. The output is displayed in the Output pane, as shown in Figure 1.16. The *Run File* command automatically compiles the program if the program has been changed.

1.12 Developing Java Programs Using Eclipse

You can edit, compile, run, and debug Java Programs using Eclipse.

The preceding section introduced developing Java programs using NetBeans. You can also use Eclipse to develop Java programs. This section gives the essential instructions to guide new users to create a project, create a class, and compile/run a class in Eclipse. For instructions on downloading and installing latest version of Eclipse, see Supplement II.D.



1.12.1 Creating a Java Project

Before creating Java programs in Eclipse, you need to first create a project to hold all files.

Here are the steps to create a Java project in Eclipse:



VideoNote

Eclipse brief tutorial

1. Choose *File, New, Java Project* to display the New Project wizard, as shown in Figure 1.17.
2. Type **demo** in the Project name field. As you type, the Location field is automatically set by default. You may customize the location for your project.
3. Make sure that you selected the options *Use project folder as root for sources and class files* so that the .java and .class files are in the same folder for easy access.
4. Click *Finish* to create the project, as shown in Figure 1.18.

1.12.2 Creating a Java Class

After a project is created, you can create Java programs in the project using the following steps:

1. Choose *File, New, Class* to display the New Java Class wizard.
2. Type **Welcome** in the Name field.

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FIGURE 1.17 The New Java Project dialog is for specifying a project name and properties.

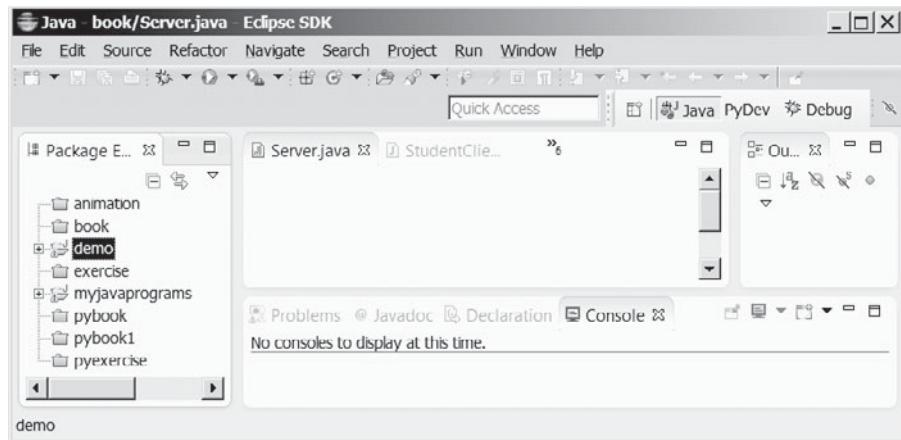


FIGURE 1.18 A New Java project named demo is created.

3. Check the option `public static void main(String[] args)`.
4. Click *Finish* to generate the template for the source code `Welcome.java`, as shown in Figure 1.19.

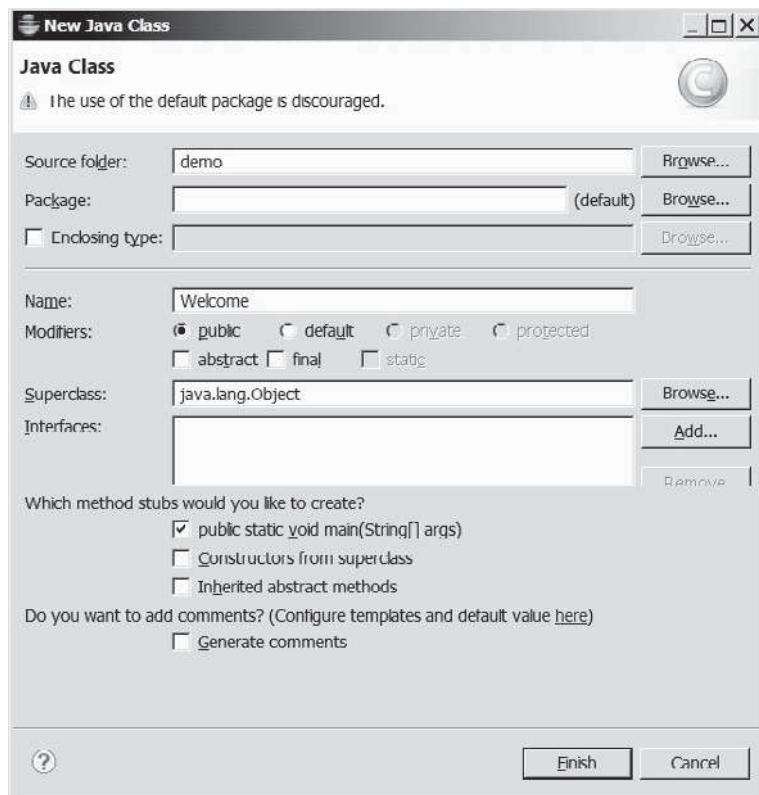


FIGURE I.19 The New Java Class dialog box is used to create a new Java class.

1.12.3 Compiling and Running a Class

To run the program, right-click the class in the project to display a context menu. Choose *Run*, *Java Application* in the context menu to run the class. The output is displayed in the Console pane, as shown in Figure 1.20.

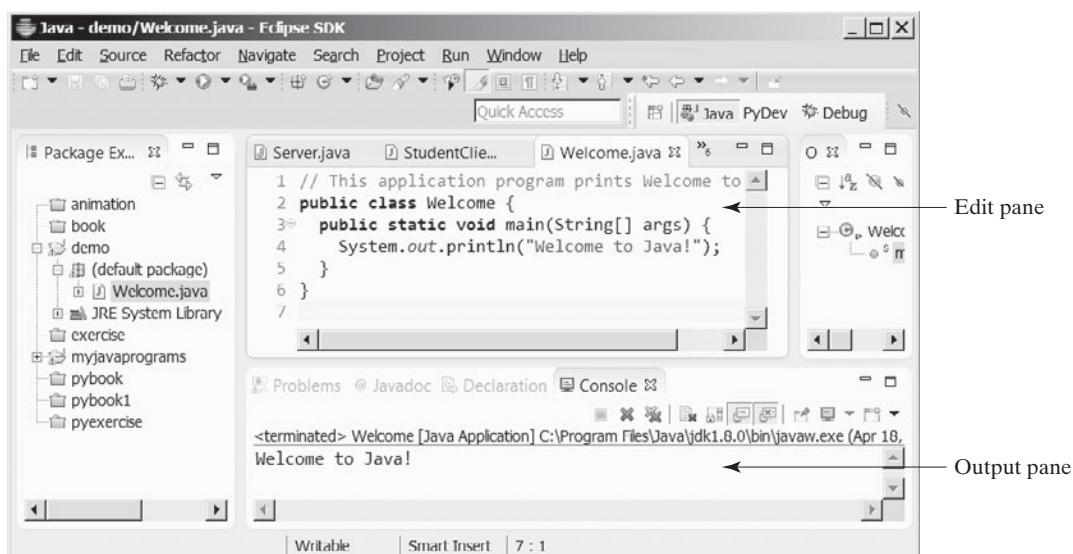


FIGURE I.20 You can edit a program and run it in Eclipse.

KEY TERMS

Application Program Interface (API)	11	Java Virtual Machine (JVM)	16
assembler	7	javac command	17
assembly language	7	keyword (or reserved word)	13
bit	3	library	11
block	13	line comment	13
block comment	13	logic error	21
bus	2	low-level language	7
byte	3	machine language	7
bytecode	16	main method	13
bytecode verifier	17	memory	4
cable modem	6	modem	00
central processing unit (CPU)	3	motherboard	3
class loader	17	network interface card (NIC)	6
comment	13	operating system (OS)	9
compiler	8	pixel	6
console	12	program	2
dot pitch	6	programming	2
DSL (digital subscriber line)	6	runtime error	20
encoding scheme	3	screen resolution	6
hardware	2	software	2
high-level language	8	source code	8
integrated development environment (IDE)	12	source program	8
interpreter	8	statement	8
java command	17	statement terminator	13
Java Development Toolkit (JDK)	12	storage devices	4
Java language specification	11	syntax error	20

Supplement I.A



Note

The above terms are defined in this chapter. Supplement I.A, Glossary, lists all the key terms and descriptions in the book, organized by chapters.

CHAPTER SUMMARY

1. A computer is an electronic device that stores and processes data.
2. A computer includes both *hardware* and *software*.
3. Hardware is the physical aspect of the computer that can be touched.
4. Computer *programs*, known as *software*, are the invisible instructions that control the hardware and make it perform tasks.
5. Computer *programming* is the writing of instructions (i.e., code) for computers to perform.
6. The *central processing unit (CPU)* is a computer's brain. It retrieves instructions from *memory* and executes them.
7. Computers use zeros and ones because digital devices have two stable states, referred to by convention as zero and one.

8. A *bit* is a binary digit 0 or 1.
9. A *byte* is a sequence of 8 bits.
10. A kilobyte is about 1,000 bytes, a megabyte about 1 million bytes, a gigabyte about 1 billion bytes, and a terabyte about 1,000 gigabytes.
11. Memory stores data and program instructions for the CPU to execute.
12. A memory unit is an ordered sequence of bytes.
13. Memory is volatile, because information is lost when the power is turned off.
14. Programs and data are permanently stored on *storage devices* and are moved to memory when the computer actually uses them.
15. The *machine language* is a set of primitive instructions built into every computer.
16. *Assembly language* is a *low-level programming language* in which a mnemonic is used to represent each machine-language instruction.
17. *High-level languages* are English-like and easy to learn and program.
18. A program written in a high-level language is called a *source program*.
19. A *compiler* is a software program that translates the source program into a *machine-language program*.
20. The *operating system (OS)* is a program that manages and controls a computer's activities.
21. Java is platform independent, meaning that you can write a program once and run it on any computer.
22. Java programs can be embedded in HTML pages and downloaded by Web browsers to bring live animation and interaction to Web clients.
23. The Java source file name must match the public class name in the program. Java source code files must end with the `.java` extension.
24. Every class is compiled into a separate bytecode file that has the same name as the class and ends with the `.class` extension.
25. To compile a Java source-code file from the command line, use the **javac** command.
26. To run a Java class from the command line, use the **java** command.
27. Every Java program is a set of class definitions. The keyword `class` introduces a class definition. The contents of the class are included in a *block*.
28. A block begins with an opening brace (`{`) and ends with a closing brace (`}`).
29. Methods are contained in a class. To run a Java program, the program must have a `main` method. The `main` method is the entry point where the program starts when it is executed.

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30. Every *statement* in Java ends with a semicolon (;), known as the *statement terminator*.
31. Reserved words, or *keywords*, have a specific meaning to the compiler and cannot be used for other purposes in the program.
32. In Java, comments are preceded by two slashes (//) on a line, called a *line comment*, or enclosed between /* and */ on one or several lines, called a *block comment* or *paragraph comment*. Comments are ignored by the compiler.
33. Java source programs are case sensitive.
34. Programming errors can be categorized into three types: *syntax errors*, *runtime errors*, and *logic errors*. Errors reported by a compiler are called syntax errors or *compile errors*. Runtime errors are errors that cause a program to terminate abnormally. Logic errors occur when a program does not perform the way it was intended to.

Quiz

Answer the quiz for this chapter online at www.cs.armstrong.edu/liang/intro10e/quiz.html.

MyProgrammingLab™

PROGRAMMING EXERCISES



Note

Solutions to even-numbered programming exercises are on the Companion Website. Solutions to all programming exercises are on the Instructor Resource Website. Additional programming exercises with solutions are provided to the instructors on the Instructor Resource Website. The level of difficulty is rated easy (no star), moderate (*), hard (**), or challenging (***)�.

level of difficulty

- 1.1 (Display three messages) Write a program that displays **Welcome to Java**, **Welcome to Computer Science**, and **Programming is fun**.
- 1.2 (Display five messages) Write a program that displays **Welcome to Java** five times.
- *1.3 (Display a pattern) Write a program that displays the following pattern:

J	A	V	V	A
J	A A	V	V	A A
J	J	AAAAA	V V	AAAAA
J	J	A	V	A

- 1.4 (Print a table) Write a program that displays the following table:

a	a^2	a^3
1	1	1
2	4	8
3	9	27
4	16	64

- 1.5 (Compute expressions) Write a program that displays the result of

$$\frac{9.5 \times 4.5 - 2.5 \times 3}{45.5 - 3.5}.$$

- 1.6 (Summation of a series) Write a program that displays the result of

$$1 + 2 + 3 + 4 + 5 + 6 + 7 + 8 + 9.$$

- 1.7** (*Approximate π*) π can be computed using the following formula:

$$\pi = 4 \times \left(1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \frac{1}{9} - \frac{1}{11} + \dots \right)$$

Write a program that displays the result of $4 \times \left(1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \frac{1}{9} - \frac{1}{11} \right)$ and $4 \times \left(1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \frac{1}{9} - \frac{1}{11} + \frac{1}{13} \right)$. Use **1.0** instead of **1** in your program.

- 1.8** (*Area and perimeter of a circle*) Write a program that displays the area and perimeter of a circle that has a radius of **5.5** using the following formula:

$$\text{perimeter} = 2 \times \text{radius} \times \pi$$

$$\text{area} = \text{radius} \times \text{radius} \times \pi$$

- 1.9** (*Area and perimeter of a rectangle*) Write a program that displays the area and perimeter of a rectangle with the width of **4.5** and height of **7.9** using the following formula:

$$\text{area} = \text{width} \times \text{height}$$

- 1.10** (*Average speed in miles*) Assume a runner runs **14** kilometers in **45** minutes and **30** seconds. Write a program that displays the average speed in miles per hour. (Note that **1** mile is **1.6** kilometers.)

- ***1.11** (*Population projection*) The U.S. Census Bureau projects population based on the following assumptions:

- One birth every 7 seconds
- One death every 13 seconds
- One new immigrant every 45 seconds

Write a program to display the population for each of the next five years. Assume the current population is 312,032,486 and one year has 365 days. Hint: In Java, if two integers perform division, the result is an integer. The fractional part is truncated. For example, **5 / 4** is **1** (not **1.25**) and **10 / 4** is **2** (not **2.5**). To get an accurate result with the fractional part, one of the values involved in the division must be a number with a decimal point. For example, **5.0 / 4** is **1.25** and **10 / 4.0** is **2.5**.

- 1.12** (*Average speed in kilometers*) Assume a runner runs **24** miles in **1** hour, **40** minutes, and **35** seconds. Write a program that displays the average speed in kilometers per hour. (Note that **1** mile is **1.6** kilometers.)

- ***1.13** (*Algebra: solve 2×2 linear equations*) You can use Cramer's rule to solve the following 2×2 system of linear equation:

$$\begin{aligned} ax + by &= e \\ cx + dy &= f \end{aligned} \quad x = \frac{ed - bf}{ad - bc} \quad y = \frac{af - ec}{ad - bc}$$

Write a program that solves the following equation and displays the value for x and y :

$$3.4x + 50.2y = 44.5$$

$$2.1x + .55y = 5.9$$

This page intentionally left blank

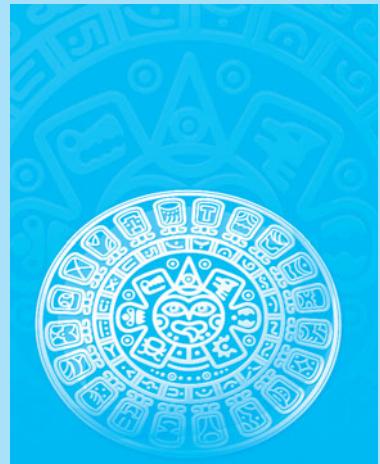
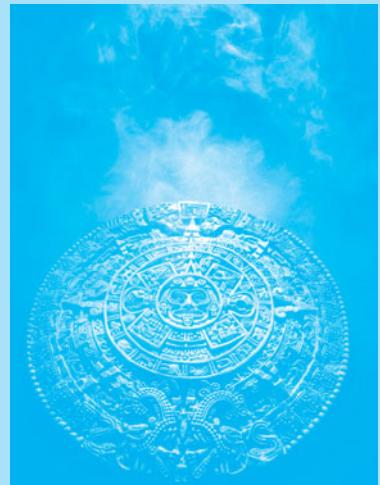
CHAPTER

2

ELEMENTARY PROGRAMMING

Objectives

- To write Java programs to perform simple computations (§2.2).
- To obtain input from the console using the `Scanner` class (§2.3).
- To use identifiers to name variables, constants, methods, and classes (§2.4).
- To use variables to store data (§§2.5–2.6).
- To program with assignment statements and assignment expressions (§2.6).
- To use constants to store permanent data (§2.7).
- To name classes, methods, variables, and constants by following their naming conventions (§2.8).
- To explore Java numeric primitive data types: `byte`, `short`, `int`, `long`, `float`, and `double` (§2.9.1).
- To read a `byte`, `short`, `int`, `long`, `float`, or `double` value from the keyboard (§2.9.2).
- To perform operations using operators `+`, `-`, `*`, `/`, and `%` (§2.9.3).
- To perform exponent operations using `Math.pow(a, b)` (§2.9.4).
- To write integer literals, floating-point literals, and literals in scientific notation (§2.10).
- To write and evaluate numeric expressions (§2.11).
- To obtain the current system time using `System.currentTimeMillis()` (§2.12).
- To use augmented assignment operators (§2.13).
- To distinguish between postincrement and preincrement and between postdecrement and predecrement (§2.14).
- To cast the value of one type to another type (§2.15).
- To describe the software development process and apply it to develop the loan payment program (§2.16).
- To write a program that converts a large amount of money into smaller units (§2.17).
- To avoid common errors and pitfalls in elementary programming (§2.18).



2.1 Introduction



The focus of this chapter is on learning elementary programming techniques to solve problems.

In Chapter 1 you learned how to create, compile, and run very basic Java programs. Now you will learn how to solve problems by writing programs. Through these problems, you will learn elementary programming using primitive data types, variables, constants, operators, expressions, and input and output.

Suppose, for example, that you need to take out a student loan. Given the loan amount, loan term, and annual interest rate, can you write a program to compute the monthly payment and total payment? This chapter shows you how to write programs like this. Along the way, you learn the basic steps that go into analyzing a problem, designing a solution, and implementing the solution by creating a program.

2.2 Writing a Simple Program



Writing a program involves designing a strategy for solving the problem and then using a programming language to implement that strategy.

problem

algorithm

pseudocode

Let's first consider the simple problem of computing the area of a circle. How do we write a program for solving this problem?

Writing a program involves designing algorithms and translating algorithms into programming instructions, or code. An *algorithm* describes how a problem is solved by listing the actions that need to be taken and the order of their execution. Algorithms can help the programmer plan a program before writing it in a programming language. Algorithms can be described in natural languages or in *pseudocode* (natural language mixed with some programming code). The algorithm for calculating the area of a circle can be described as follows:

1. Read in the circle's radius.
2. Compute the area using the following formula:

$$\text{area} = \text{radius} \times \text{radius} \times \pi$$

3. Display the result.



Tip

It's always good practice to outline your program (or its underlying problem) in the form of an algorithm before you begin coding.

When you *code*—that is, when you write a program—you translate an algorithm into a program. You already know that every Java program begins with a class definition in which the keyword **class** is followed by the class name. Assume that you have chosen **ComputeArea** as the class name. The outline of the program would look like this:

```
public class ComputeArea {
    // Details to be given later
}
```

As you know, every Java program must have a **main** method where program execution begins. The program is then expanded as follows:

```
public class ComputeArea {
    public static void main(String[] args) {
        // Step 1: Read in radius
        // Step 2: Compute area
```

```
// Step 3: Display the area
}
}
```

The program needs to read the radius entered by the user from the keyboard. This raises two important issues:

- Reading the radius.
- Storing the radius in the program.

Let's address the second issue first. In order to store the radius, the program needs to declare a symbol called a *variable*. A variable represents a value stored in the computer's memory.

Rather than using **x** and **y** as variable names, choose descriptive names: in this case, **radius** for radius, and **area** for area. To let the compiler know what **radius** and **area** are, specify their data types. That is the kind of data stored in a variable, whether integer, real number, or something else. This is known as *declaring variables*. Java provides simple data types for representing integers, real numbers, characters, and Boolean types. These types are known as *primitive data types* or *fundamental types*.

Real numbers (i.e., numbers with a decimal point) are represented using a method known as *floating-point* in computers. So, the real numbers are also called *floating-point numbers*. In Java, you can use the keyword **double** to declare a floating-point variable. Declare **radius** and **area** as **double**. The program can be expanded as follows:

```
public class ComputeArea {
    public static void main(String[] args) {
        double radius;
        double area;

        // Step 1: Read in radius
        // Step 2: Compute area
        // Step 3: Display the area
    }
}
```

The program declares **radius** and **area** as variables. The reserved word **double** indicates that **radius** and **area** are floating-point values stored in the computer.

The first step is to prompt the user to designate the circle's **radius**. You will soon learn how to prompt the user for information. For now, to learn how variables work, you can assign a fixed value to **radius** in the program as you write the code; later, you'll modify the program to prompt the user for this value.

The second step is to compute **area** by assigning the result of the expression **radius * radius * 3.14159** to **area**.

In the final step, the program will display the value of **area** on the console by using the **System.out.println** method.

Listing 2.1 shows the complete program, and a sample run of the program is shown in Figure 2.1.

LISTING 2.1 ComputeArea.java

```
1  public class ComputeArea {
2      public static void main(String[] args) {
3          double radius; // Declare radius
4          double area; // Declare area
5
6          // Assign a radius
```

variable
descriptive names

data type
declare variables
primitive data types

floating-point number

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```
7     radius = 20; // radius is now 20
8
9     // Compute area
10    area = radius * radius * 3.14159;
11
12    // Display results
13    System.out.println("The area for the circle of radius " +
14        " is " + area);
15 }
16 }
```

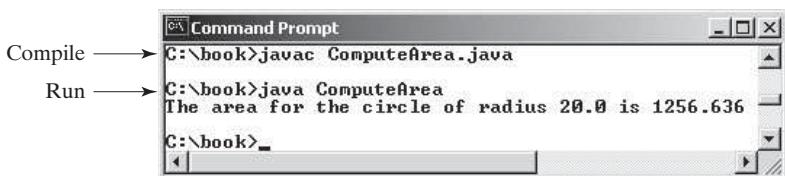


FIGURE 2.1 The program displays the area of a circle.

declare variable
assign value

tracing program

Variables such as `radius` and `area` correspond to memory locations. Every variable has a name, a type, a size, and a value. Line 3 declares that `radius` can store a `double` value. The value is not defined until you assign a value. Line 7 assigns `20` into variable `radius`. Similarly, line 4 declares variable `area`, and line 10 assigns a value into `area`. The following table shows the value in the memory for `area` and `radius` as the program is executed. Each row in the table shows the values of variables after the statement in the corresponding line in the program is executed. This method of reviewing how a program works is called *tracing a program*. Tracing programs are helpful for understanding how programs work, and they are useful tools for finding errors in programs.



line#	radius	area
3	no value	
4		no value
7	20	
10		1256.636

concatenate strings

concatenate strings with
numbers

The plus sign (+) has two meanings: one for addition and the other for concatenating (combining) strings. The plus sign (+) in lines 13–14 is called a *string concatenation operator*. It combines two strings into one. If a string is combined with a number, the number is converted into a string and concatenated with the other string. Therefore, the plus signs (+) in lines 13–14 concatenate strings into a longer string, which is then displayed in the output. Strings and string concatenation will be discussed further in Chapter 4.



Caution

A string cannot cross lines in the source code. Thus, the following statement would result in a compile error:

```
System.out.println("Introduction to Java Programming,
by Y. Daniel Liang");
```

break a long string

To fix the error, break the string into separate substrings, and use the concatenation operator (+) to combine them:

```
System.out.println("Introduction to Java Programming, " +
"by Y. Daniel Liang");
```

2.1 Identify and fix the errors in the following code:

```

1 public class Test {
2     public void main(string[] args) {
3         double i = 50.0;
4         double k = i + 50.0;
5         double j = k + 1;
6
7         System.out.println("j is " + j + " and
8             k is " + k);
9     }
10 }
```



2.3 Reading Input from the Console

Reading input from the console enables the program to accept input from the user.

In Listing 2.1, the radius is fixed in the source code. To use a different radius, you have to modify the source code and recompile it. Obviously, this is not convenient, so instead you can use the **Scanner** class for console input.

Java uses **System.out** to refer to the standard output device and **System.in** to the standard input device. By default, the output device is the display monitor and the input device is the keyboard. To perform console output, you simply use the **println** method to display a primitive value or a string to the console. Console input is not directly supported in Java, but you can use the **Scanner** class to create an object to read input from **System.in**, as follows:

```
Scanner input = new Scanner(System.in);
```

The syntax **new Scanner(System.in)** creates an object of the **Scanner** type. The syntax **Scanner input** declares that **input** is a variable whose type is **Scanner**. The whole line **Scanner input = new Scanner(System.in)** creates a **Scanner** object and assigns its reference to the variable **input**. An object may invoke its methods. To invoke a method on an object is to ask the object to perform a task. You can invoke the **nextDouble()** method to read a **double** value as follows:

```
double radius = input.nextDouble();
```

This statement reads a number from the keyboard and assigns the number to **radius**.

Listing 2.2 rewrites Listing 2.1 to prompt the user to enter a radius.

LISTING 2.2 ComputeAreaWithConsoleInput.java

```

1 import java.util.Scanner; // Scanner is in the java.util package           import class
2
3 public class ComputeAreaWithConsoleInput {
4     public static void main(String[] args) {
5         // Create a Scanner object
6         Scanner input = new Scanner(System.in);                                create a Scanner
7
8         // Prompt the user to enter a radius
9         System.out.print("Enter a number for radius: ");
10        double radius = input.nextDouble();                                    read a double
11
12        // Compute area
13        double area = radius * radius * 3.14159;
14
15        // Display results
```



VideoNote

Obtain input

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```
16     System.out.println("The area for the circle of radius " +
17         "radius + " + " is " + area);
18 }
19 }
```



```
Enter a number for radius: 2.5 ↵Enter
The area for the circle of radius 2.5 is 19.6349375
```



```
Enter a number for radius: 23 ↵Enter
The area for the circle of radius 23.0 is 1661.90111
```

prompt

Line 9 displays a string "**Enter a number for radius:**" to the console. This is known as a *prompt*, because it directs the user to enter an input. Your program should always tell the user what to enter when expecting input from the keyboard.

The **print** method in line 9

```
System.out.print("Enter a number for radius: ");
```

print vs. println

is identical to the **println** method except that **println** moves to the beginning of the next line after displaying the string, but **print** does not advance to the next line when completed.

Line 6 creates a **Scanner** object. The statement in line 10 reads input from the keyboard.

```
double radius = input.nextDouble();
```

After the user enters a number and presses the *Enter* key, the program reads the number and assigns it to **radius**.

More details on objects will be introduced in Chapter 9. For the time being, simply accept that this is how to obtain input from the console.

specific import

The **Scanner** class is in the **java.util** package. It is imported in line 1. There are two types of **import** statements: *specific import* and *wildcard import*. The *specific import* specifies a single class in the import statement. For example, the following statement imports **Scanner** from the package **java.util**.

```
import java.util.Scanner;
```

wildcard import

The *wildcard import* imports all the classes in a package by using the asterisk as the wildcard. For example, the following statement imports all the classes from the package **java.util**.

```
import java.util.*;
```

no performance difference

The information for the classes in an imported package is not read in at compile time or runtime unless the class is used in the program. The import statement simply tells the compiler where to locate the classes. There is no performance difference between a specific import and a wildcard import declaration.

Listing 2.3 gives an example of reading multiple input from the keyboard. The program reads three numbers and displays their average.

LISTING 2.3 ComputeAverage.java

import class

```
1 import java.util.Scanner; // Scanner is in the java.util package
2
3 public class ComputeAverage {
4     public static void main(String[] args) {
5         // Create a Scanner object
6         Scanner input = new Scanner(System.in);
7 }
```

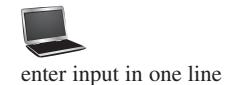
create a Scanner

```

8 // Prompt the user to enter three numbers
9 System.out.print("Enter three numbers: ");
10 double number1 = input.nextDouble();
11 double number2 = input.nextDouble();
12 double number3 = input.nextDouble();
13
14 // Compute average
15 double average = (number1 + number2 + number3) / 3;
16
17 // Display results
18 System.out.println("The average of " + number1 + " " + number2
19     + " " + number3 + " is " + average);
20 }
21 }
```

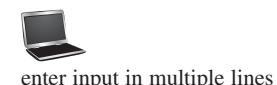
Enter three numbers: 1 2 3 ↵Enter
The average of 1.0 2.0 3.0 is 2.0

read a double



enter input in one line

Enter three numbers: 10.5 ↵Enter
11 ↵Enter
11.5 ↵Enter
The average of 10.5 11.0 11.5 is 11.0



enter input in multiple lines

The code for importing the **Scanner** class (line 1) and creating a **Scanner** object (line 6) are the same as in the preceding example as well as in all new programs you will write for reading input from the keyboard.

Line 9 prompts the user to enter three numbers. The numbers are read in lines 10–12. You may enter three numbers separated by spaces, then press the *Enter* key, or enter each number followed by a press of the *Enter* key, as shown in the sample runs of this program.

If you entered an input other than a numeric value, a runtime error would occur. In Chapter 12, you will learn how to handle the exception so that the program can continue to run.

runtime error



Note

Most of the programs in the early chapters of this book perform three steps—input, process, and output—called *IPO*. Input is receiving input from the user; process is producing results using the input; and output is displaying the results.

IPO

2.2 How do you write a statement to let the user enter a double value from the keyboard? What happens if you entered **5a** when executing the following code?



double radius = input.nextDouble();

2.3 Are there any performance differences between the following two **import** statements?

import java.util.Scanner;
import java.util.*;

2.4 Identifiers

Identifiers are the names that identify the elements such as classes, methods, and variables in a program.



As you see in Listing 2.3, **ComputeAverage**, **main**, **input**, **number1**, **number2**, **number3**, and so on are the names of things that appear in the program. In programming terminology, such names are called *identifiers*. All identifiers must obey the following rules:

identifiers
identifier naming rules

- An identifier is a sequence of characters that consists of letters, digits, underscores (_), and dollar signs (\$).

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- An identifier must start with a letter, an underscore (_), or a dollar sign (\$). It cannot start with a digit.
- An identifier cannot be a reserved word. (See Appendix A for a list of reserved words.)
- An identifier cannot be `true`, `false`, or `null`.
- An identifier can be of any length.

For example, `$2`, `ComputeArea`, `area`, `radius`, and `print` are legal identifiers, whereas `2A` and `d+4` are not because they do not follow the rules. The Java compiler detects illegal identifiers and reports syntax errors.

case sensitive



Note

Since Java is case sensitive, `area`, `Area`, and `AREA` are all different identifiers.

descriptive names



Tip

Identifiers are for naming variables, methods, classes, and other items in a program. Descriptive identifiers make programs easy to read. Avoid using abbreviations for identifiers. Using complete words is more descriptive. For example, `numberOfStudents` is better than `numStuds`, `numOfStuds`, or `numOfStudents`. We use descriptive names for complete programs in the text. However, we will occasionally use variable names such as `i`, `j`, `k`, `x`, and `y` in the code snippets for brevity. These names also provide a generic tone to the code snippets.

the \$ character



Tip

Do not name identifiers with the \$ character. By convention, the \$ character should be used only in mechanically generated source code.



2.4 Which of the following identifiers are valid? Which are Java keywords?

`miles`, `Test`, `a++`, `--a`, `4#R`, `$4`, `#44`, `apps`
`class`, `public`, `int`, `x`, `y`, `radius`

2.5 Variables



Variables are used to represent values that may be changed in the program.

why called variables?

As you see from the programs in the preceding sections, variables are used to store values to be used later in a program. They are called variables because their values can be changed. In the program in Listing 2.2, `radius` and `area` are variables of the `double` type. You can assign any numerical value to `radius` and `area`, and the values of `radius` and `area` can be reassigned. For example, in the following code, `radius` is initially `1.0` (line 2) and then changed to `2.0` (line 7), and `area` is set to `3.14159` (line 3) and then reset to `12.56636` (line 8).

```
1 // Compute the first area
2 radius = 1.0;                                radius: 1.0
3 area = radius * radius * 3.14159;            area: 3.14159
4 System.out.println("The area is " + area + " for radius " + radius);
5
6 // Compute the second area
7 radius = 2.0;                                radius: 2.0
8 area = radius * radius * 3.14159;            area: 12.56636
9 System.out.println("The area is " + area + " for radius " + radius);
```

Variables are for representing data of a certain type. To use a variable, you declare it by telling the compiler its name as well as what type of data it can store. The *variable declaration*

tells the compiler to allocate appropriate memory space for the variable based on its data type.
The syntax for declaring a variable is

```
datatype variableName;
```

Here are some examples of variable declarations:

declare variable

```
int count;           // Declare count to be an integer variable
double radius;     // Declare radius to be a double variable
double interestRate; // Declare interestRate to be a double variable
```

These examples use the data types **int** and **double**. Later you will be introduced to additional data types, such as **byte**, **short**, **long**, **float**, **char**, and **boolean**.

If variables are of the same type, they can be declared together, as follows:

```
datatype variable1, variable2, ..., variablen;
```

The variables are separated by commas. For example,

```
int i, j, k; // Declare i, j, and k as int variables
```

Variables often have initial values. You can declare a variable and initialize it in one step. initialize variables
Consider, for instance, the following code:

```
int count = 1;
```

This is equivalent to the next two statements:

```
int count;
count = 1;
```

You can also use a shorthand form to declare and initialize variables of the same type together. For example,

```
int i = 1, j = 2;
```



Tip

A variable must be declared before it can be assigned a value. A variable declared in a method must be assigned a value before it can be used.

Whenever possible, declare a variable and assign its initial value in one step. This will make the program easy to read and avoid programming errors.

Every variable has a scope. The *scope of a variable* is the part of the program where the variable can be referenced. The rules that define the scope of a variable will be introduced gradually later in the book. For now, all you need to know is that a variable must be declared and initialized before it can be used.

2.5 Identify and fix the errors in the following code:

```
1 public class Test {
2     public static void main(String[] args) {
3         int i = k + 2;
4         System.out.println(i);
5     }
6 }
```



2.6 Assignment Statements and Assignment Expressions

An assignment statement designates a value for a variable. An assignment statement can be used as an expression in Java.



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assignment statement
assignment operator

After a variable is declared, you can assign a value to it by using an *assignment statement*. In Java, the equal sign (`=`) is used as the *assignment operator*. The syntax for assignment statements is as follows:

```
variable = expression;
```

expression

An *expression* represents a computation involving values, variables, and operators that, taking them together, evaluates to a value. For example, consider the following code:

```
int y = 1;           // Assign 1 to variable y
double radius = 1.0; // Assign 1.0 to variable radius
int x = 5 * (3 / 2); // Assign the value of the expression to x
x = y + 1;          // Assign the addition of y and 1 to x
double area = radius * radius * 3.14159; // Compute area
```

You can use a variable in an expression. A variable can also be used in both sides of the `=` operator. For example,

```
x = x + 1;
```

In this assignment statement, the result of `x + 1` is assigned to `x`. If `x` is `1` before the statement is executed, then it becomes `2` after the statement is executed.

To assign a value to a variable, you must place the variable name to the left of the assignment operator. Thus, the following statement is wrong:

```
1 = x; // Wrong
```



Note

In mathematics, `x = 2 * x + 1` denotes an equation. However, in Java, `x = 2 * x + 1` is an assignment statement that evaluates the expression `2 * x + 1` and assigns the result to `x`.

assignment expression

In Java, an assignment statement is essentially an expression that evaluates to the value to be assigned to the variable on the left side of the assignment operator. For this reason, an assignment statement is also known as an *assignment expression*. For example, the following statement is correct:

```
System.out.println(x = 1);
```

which is equivalent to

```
x = 1;
System.out.println(x);
```

If a value is assigned to multiple variables, you can use this syntax:

```
i = j = k = 1;
```

which is equivalent to

```
k = 1;
j = k;
i = j;
```



Note

In an assignment statement, the data type of the variable on the left must be compatible with the data type of the value on the right. For example, `int x = 1.0` would be

illegal, because the data type of `x` is `int`. You cannot assign a `double` value (`1.0`) to an `int` variable without using type casting. Type casting is introduced in Section 2.15.

2.6 Identify and fix the errors in the following code:

```
1 public class Test {
2     public static void main(String[] args) {
3         int i = j = k = 2;
4         System.out.println(i + " " + j + " " + k);
5     }
6 }
```



2.7 Named Constants

A *named constant* is an identifier that represents a permanent value.

The value of a variable may change during the execution of a program, but a *named constant*, or simply *constant*, represents permanent data that never changes. In our `ComputeArea` program, π is a constant. If you use it frequently, you don't want to keep typing `3.14159`; instead, you can declare a constant for π . Here is the syntax for declaring a constant:

```
final datatype CONSTANTNAME = value;
```

A constant must be declared and initialized in the same statement. The word `final` is a Java keyword for declaring a constant. For example, you can declare π as a constant and rewrite Listing 2.1 as in Listing 2.4.



constant

LISTING 2.4 ComputeAreaWithConstant.java

```
1 import java.util.Scanner; // Scanner is in the java.util package
2
3 public class ComputeAreaWithConstant {
4     public static void main(String[] args) {
5         final double PI = 3.14159; // Declare a constant
6
7         // Create a Scanner object
8         Scanner input = new Scanner(System.in);
9
10        // Prompt the user to enter a radius
11        System.out.print("Enter a number for radius: ");
12        double radius = input.nextDouble();
13
14        // Compute area
15        double area = radius * radius * PI;
16
17        // Display result
18        System.out.println("The area for the circle of radius " +
19                      radius + " is " + area);
20    }
21 }
```

There are three benefits of using constants: (1) you don't have to repeatedly type the same value if it is used multiple times; (2) if you have to change the constant value (e.g., from `3.14` to `3.14159` for `PI`), you need to change it only in a single location in the source code; and (3) a descriptive name for a constant makes the program easy to read.

benefits of constants

2.8 Naming Conventions



Sticking with the Java naming conventions makes your programs easy to read and avoids errors.

Make sure that you choose descriptive names with straightforward meanings for the variables, constants, classes, and methods in your program. As mentioned earlier, names are case sensitive. Listed below are the conventions for naming variables, methods, and classes.

name variables and methods

- Use lowercase for variables and methods. If a name consists of several words, concatenate them into one, making the first word lowercase and capitalizing the first letter of each subsequent word—for example, the variables `radius` and `area` and the method `print`.

name classes

- Capitalize the first letter of each word in a class name—for example, the class names `ComputeArea` and `System`.

name constants

- Capitalize every letter in a constant, and use underscores between words—for example, the constants `PI` and `MAX_VALUE`.

It is important to follow the naming conventions to make your programs easy to read.

name classes



Caution

Do not choose class names that are already used in the Java library. For example, since the `System` class is defined in Java, you should not name your class `System`.



- 2.7** What are the benefits of using constants? Declare an `int` constant `SIZE` with value `20`.
- 2.8** What are the naming conventions for class names, method names, constants, and variables? Which of the following items can be a constant, a method, a variable, or a class according to the Java naming conventions?
`MAX_VALUE`, `Test`, `read`, `readDouble`
- 2.9** Translate the following algorithm into Java code:
 - Step 1: Declare a `double` variable named `miles` with initial value `100`.
 - Step 2: Declare a `double` constant named `KILOMETERS_PER_MILE` with value `1.609`.
 - Step 3: Declare a `double` variable named `kilometers`, multiply `miles` and `KILOMETERS_PER_MILE`, and assign the result to `kilometers`.
 - Step 4: Display `kilometers` to the console.

What is `kilometers` after Step 4?

2.9 Numeric Data Types and Operations



*Java has six numeric types for integers and floating-point numbers with operators +, -, *, /, and %.*

2.9.1 Numeric Types

Every data type has a range of values. The compiler allocates memory space for each variable or constant according to its data type. Java provides eight primitive data types for numeric values, characters, and Boolean values. This section introduces numeric data types and operators.

Table 2.1 lists the six numeric data types, their ranges, and their storage sizes.

TABLE 2.1 Numeric Data Types

Name	Range	Storage Size	
byte	-2^7 to $2^7 - 1$ (-128 to 127)	8-bit signed	byte type
short	-2^{15} to $2^{15} - 1$ (-32768 to 32767)	16-bit signed	short type
int	-2^{31} to $2^{31} - 1$ (-2147483648 to 2147483647)	32-bit signed	int type
long	-2^{63} to $2^{63} - 1$ (i.e., -9223372036854775808 to 9223372036854775807)	64-bit signed	long type
float	Negative range: $-3.4028235E + 38$ to $-1.4E - 45$ Positive range: $1.4E - 45$ to $3.4028235E + 38$	32-bit IEEE 754	float type
double	Negative range: $-1.7976931348623157E + 308$ to $-4.9E - 324$ Positive range: $4.9E - 324$ to $1.7976931348623157E + 308$	64-bit IEEE 754	double type

**Note**

IEEE 754 is a standard approved by the Institute of Electrical and Electronics Engineers for representing floating-point numbers on computers. The standard has been widely adopted. Java uses the 32-bit **IEEE 754** for the **float** type and the 64-bit **IEEE 754** for the **double** type. The **IEEE 754** standard also defines special floating-point values, which are listed in Appendix E.

Java uses four types for integers: **byte**, **short**, **int**, and **long**. Choose the type that is most appropriate for your variable. For example, if you know an integer stored in a variable is within a range of a byte, declare the variable as a **byte**. For simplicity and consistency, we will use **int** for integers most of the time in this book.

Java uses two types for floating-point numbers: **float** and **double**. The **double** type is twice as big as **float**, so the **double** is known as *double precision* and **float** as *single precision*. Normally, you should use the **double** type, because it is more accurate than the **float** type.

2.9.2 Reading Numbers from the Keyboard

You know how to use the `nextDouble()` method in the `Scanner` class to read a double value from the keyboard. You can also use the methods listed in Table 2.2 to read a number of the **byte**, **short**, **int**, **long**, and **float** type.

TABLE 2.2 Methods for `Scanner` Objects

Method	Description
<code>nextByte()</code>	reads an integer of the byte type.
<code>nextShort()</code>	reads an integer of the short type.
<code>nextInt()</code>	reads an integer of the int type.
<code>nextLong()</code>	reads an integer of the long type.
<code>nextFloat()</code>	reads a number of the float type.
<code>nextDouble()</code>	reads a number of the double type.

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Here are examples for reading values of various types from the keyboard:

```
1 Scanner input = new Scanner(System.in);
2 System.out.print("Enter a byte value: ");
3 byte byteValue = input.nextByte();
4
5 System.out.print("Enter a short value: ");
6 short shortValue = input.nextShort();
7
8 System.out.print("Enter an int value: ");
9 int intValue = input.nextInt();
10
11 System.out.print("Enter a long value: ");
12 long longValue = input.nextLong();
13
14 System.out.print("Enter a float value: ");
15 float floatValue = input.nextFloat();
```

If you enter a value with an incorrect range or format, a runtime error would occur. For example, you enter a value **128** for line 3, an error would occur because **128** is out of range for a **byte** type integer.

2.9.3 Numeric Operators

operators +, -, *, /, %

operands

The operators for numeric data types include the standard arithmetic operators: addition (+), subtraction (-), multiplication (*), division (/), and remainder (%), as shown in Table 2.3. The *operands* are the values operated by an operator.

TABLE 2.3 Numeric Operators

Name	Meaning	Example	Result
+	Addition	34 + 1	35
-	Subtraction	34.0 - 0.1	33.9
*	Multiplication	300 * 30	9000
/	Division	1.0 / 2.0	0.5
%	Remainder	20 % 3	2

integer division

When both operands of a division are integers, the result of the division is the quotient and the fractional part is truncated. For example, **5 / 2** yields **2**, not **2.5**, and **-5 / 2** yields **-2**, not **-2.5**. To perform a float-point division, one of the operands must be a floating-point number. For example, **5.0 / 2** yields **2.5**.

The % operator, known as *remainder* or *modulo* operator, yields the remainder after division. The operand on the left is the dividend and the operand on the right is the divisor. Therefore, **7 % 3** yields **1**, **3 % 7** yields **3**, **12 % 4** yields **0**, **26 % 8** yields **2**, and **20 % 13** yields **7**.

$$\begin{array}{ccccccc} & 2 & & 0 & & 3 & \\ 3 \sqrt{7} & & 7 \sqrt{3} & & 4 \sqrt{12} & & 8 \sqrt{26} \\ & 6 & & 0 & & 12 & & 24 \\ \hline & 1 & & 3 & & 0 & & 2 \\ & & & & & & & \\ & & & & & & & \\ \text{Divisor} & \longrightarrow & & & & & \longrightarrow & \begin{array}{l} 1 \leftarrow \text{Quotient} \\ \text{Dividend} \\ \hline 7 \leftarrow \text{Remainder} \end{array} \\ & & & & & & & \end{array}$$

The % operator is often used for positive integers, but it can also be used with negative integers and floating-point values. The remainder is negative only if the dividend is negative. For example, **-7 % 3** yields **-1**, **-12 % 4** yields **0**, **-26 % -8** yields **-2**, and **20 % -13** yields **7**.

Remainder is very useful in programming. For example, an even number $\% 2$ is always **0** and an odd number $\% 2$ is always **1**. Thus, you can use this property to determine whether a number is even or odd. If today is Saturday, it will be Saturday again in 7 days. Suppose you and your friends are going to meet in 10 days. What day is in 10 days? You can find that the day is Tuesday using the following expression:



The program in Listing 2.5 obtains minutes and remaining seconds from an amount of time in seconds. For example, **500** seconds contains **8** minutes and **20** seconds.

LISTING 2.5 DisplayTime.java

```

1 import java.util.Scanner;
2
3 public class DisplayTime {
4     public static void main(String[] args) {
5         Scanner input = new Scanner(System.in);
6         // Prompt the user for input
7         System.out.print("Enter an integer for seconds: ");
8         int seconds = input.nextInt();
9
10        int minutes = seconds / 60; // Find minutes in seconds
11        int remainingSeconds = seconds % 60; // Seconds remaining
12        System.out.println(seconds + " seconds is " + minutes +
13            " minutes and " + remainingSeconds + " seconds");
14    }
15 }
```

import Scanner
create a Scanner
read an integer
divide
remainder

Enter an integer for seconds: 500 ↵Enter
500 seconds is 8 minutes and 20 seconds



line#	seconds	minutes	remainingSeconds
8	500		
10		8	
11			20



The `nextInt()` method (line 8) reads an integer for `seconds`. Line 10 obtains the minutes using `seconds / 60`. Line 11 (`seconds % 60`) obtains the remaining seconds after taking away the minutes.

The `+` and `-` operators can be both unary and binary. A *unary* operator has only one operand; a *binary* operator has two. For example, the `-` operator in `-5` is a unary operator to negate number **5**, whereas the `-` operator in **4 - 5** is a binary operator for subtracting **5** from **4**.

unary operator
binary operator

2.9.4 Exponent Operations

`Math.pow(a, b)` method

The `Math.pow(a, b)` method can be used to compute a^b . The `pow` method is defined in the `Math` class in the Java API. You invoke the method using the syntax `Math.pow(a, b)` (e.g., `Math.pow(2, 3)`), which returns the result of a^b (2^3). Here, `a` and `b` are parameters for the `pow` method and the numbers `2` and `3` are actual values used to invoke the method. For example,

```
System.out.println(Math.pow(2, 3)); // Displays 8.0
System.out.println(Math.pow(4, 0.5)); // Displays 2.0
System.out.println(Math.pow(2.5, 2)); // Displays 6.25
System.out.println(Math.pow(2.5, -2)); // Displays 0.16
```

Chapter 5 introduces more details on methods. For now, all you need to know is how to invoke the `pow` method to perform the exponent operation.



2.10 Find the largest and smallest `byte`, `short`, `int`, `long`, `float`, and `double`. Which of these data types requires the least amount of memory?

2.11 Show the result of the following remainders.

```
56 % 6
78 % -4
-34 % 5
-34 % -5
5 % 1
1 % 5
```

2.12 If today is Tuesday, what will be the day in 100 days?

2.13 What is the result of `25 / 4`? How would you rewrite the expression if you wished the result to be a floating-point number?

2.14 Show the result of the following code:

```
System.out.println(2 * (5 / 2 + 5 / 2));
System.out.println(2 * 5 / 2 + 2 * 5 / 2);
System.out.println(2 * (5 / 2));
System.out.println(2 * 5 / 2);
```

2.15 Are the following statements correct? If so, show the output.

```
System.out.println("25 / 4 is " + 25 / 4);
System.out.println("25 / 4.0 is " + 25 / 4.0);
System.out.println("3 * 2 / 4 is " + 3 * 2 / 4);
System.out.println("3.0 * 2 / 4 is " + 3.0 * 2 / 4);
```

2.16 Write a statement to display the result of $2^{3.5}$.

2.17 Suppose `m` and `r` are integers. Write a Java expression for mr^2 to obtain a floating-point result.

2.10 Numeric Literals



A literal is a constant value that appears directly in a program.

For example, `34` and `0.305` are literals in the following statements:

```
int numberOfYears = 34;
double weight = 0.305;
```

2.10.1 Integer Literals

An integer literal can be assigned to an integer variable as long as it can fit into the variable. A compile error will occur if the literal is too large for the variable to hold. The statement `byte b = 128`, for example, will cause a compile error, because `128` cannot be stored in a variable of the `byte` type. (Note that the range for a byte value is from `-128` to `127`.)

An integer literal is assumed to be of the `int` type, whose value is between -2^{31} (`-2147483648`) and $2^{31} - 1$ (`2147483647`). To denote an integer literal of the `long` type, append the letter `L` or `l` to it. For example, to write integer `2147483648` in a Java program, you have to write it as `2147483648L` or `2147483648l`, because `2147483648` exceeds the range for the `int` value. `L` is preferred because `l` (lowercase `L`) can easily be confused with `1` (the digit one).



Note

By default, an integer literal is a decimal integer number. To denote a binary integer literal, use a leading `0b` or `0B` (zero B), to denote an octal integer literal, use a leading `0` (zero), and to denote a hexadecimal integer literal, use a leading `0x` or `0X` (zero X). For example,

```
System.out.println(0B1111); // Displays 15
System.out.println(07777); // Displays 4095
System.out.println(0xFFFF); // Displays 65535
```

binary, octal, and hex literals

Hexadecimal numbers, binary numbers, and octal numbers are introduced in Appendix F.

2.10.2 Floating-Point Literals

Floating-point literals are written with a decimal point. By default, a floating-point literal is treated as a `double` type value. For example, `5.0` is considered a `double` value, not a `float` value. You can make a number a `float` by appending the letter `f` or `F`, and you can make a number a `double` by appending the letter `d` or `D`. For example, you can use `100.2f` or `100.2F` for a `float` number, and `100.2d` or `100.2D` for a `double` number.

suffix f or F
suffix d or D



Note

The `double` type values are more accurate than the `float` type values. For example,

```
System.out.println("1.0 / 3.0 is " + 1.0 / 3.0);
displays 1.0 / 3.0 is 0.3333333333333333
                                         16 digits

System.out.println("1.0F / 3.0F is " + 1.0F / 3.0F);
displays 1.0F / 3.0F is 0.33333334
                                         8 digits
```

double vs. float

A float value has `7` to `8` number of significant digits and a double value has `15` to `17` number of significant digits.

2.10.3 Scientific Notation

Floating-point literals can be written in scientific notation in the form of $a \times 10^b$. For example, the scientific notation for `123.456` is `1.23456 × 102` and for `0.0123456` is `1.23456 × 10-2`. A special syntax is used to write scientific notation numbers. For example, `1.23456 × 102` is written as `1.23456E2` or `1.23456E+2` and `1.23456 × 10-2` as `1.23456E-2`. `E` (or `e`) represents an exponent and can be in either lowercase or uppercase.

why called floating-point?



Note

The `float` and `double` types are used to represent numbers with a decimal point. Why are they called *floating-point numbers*? These numbers are stored in scientific notation internally. When a number such as `50.534` is converted into scientific notation, such as `5.0534E+1`, its decimal point is moved (i.e., floated) to a new position.



Note

To improve readability, Java allows you to use underscores between two digits in a number literal. For example, the following literals are correct.

```
long ssn = 232_45_4519;
long creditCardNumber = 2324_4545_4519_3415L;
```

underscores in numbers

However, `45_` or `_45` is incorrect. The underscore must be placed between two digits.



2.18 How many accurate digits are stored in a `float` or `double` type variable?

2.19 Which of the following are correct literals for floating-point numbers?

`12.3`, `12.3e+2`, `23.4e-2`, `-334.4`, `20.5`, `39F`, `40D`

2.20 Which of the following are the same as `52.534`?

`5.2534e+1`, `0.52534e+2`, `525.34e-1`, `5.2534e+0`

2.21 Which of the following are correct literals?

`5_2534e+1`, `_2534`, `5_2`, `5_`



2.11 Evaluating Expressions and Operator Precedence

Java expressions are evaluated in the same way as arithmetic expressions.

Writing a numeric expression in Java involves a straightforward translation of an arithmetic expression using Java operators. For example, the arithmetic expression

$$\frac{3 + 4x}{5} - \frac{10(y - 5)(a + b + c)}{x} + 9\left(\frac{4}{x} + \frac{9 + x}{y}\right)$$

can be translated into a Java expression as:

```
(3 + 4 * x) / 5 - 10 * (y - 5) * (a + b + c) / x +
9 * (4 / x + (9 + x) / y)
```

evaluating an expression

Though Java has its own way to evaluate an expression behind the scene, the result of a Java expression and its corresponding arithmetic expression is the same. Therefore, you can safely apply the arithmetic rule for evaluating a Java expression. Operators contained within pairs of parentheses are evaluated first. Parentheses can be nested, in which case the expression in the inner parentheses is evaluated first. When more than one operator is used in an expression, the following operator precedence rule is used to determine the order of evaluation.

- Multiplication, division, and remainder operators are applied first. If an expression contains several multiplication, division, and remainder operators, they are applied from left to right.
- Addition and subtraction operators are applied last. If an expression contains several addition and subtraction operators, they are applied from left to right.

operator precedence rule

Here is an example of how an expression is evaluated:

$$\begin{aligned}
 & 3 + 4 * 4 + 5 * (4 + 3) - 1 \\
 & \quad \uparrow \qquad \qquad \qquad \text{(1) inside parentheses first} \\
 & 3 + 4 * 4 + 5 * 7 - 1 \\
 & \quad \uparrow \qquad \qquad \qquad \text{(2) multiplication} \\
 & 3 + 16 + 5 * 7 - 1 \\
 & \quad \uparrow \qquad \qquad \qquad \text{(3) multiplication} \\
 & 3 + 16 + 35 - 1 \\
 & \uparrow \qquad \qquad \qquad \text{(4) addition} \\
 & 19 + 35 - 1 \\
 & \uparrow \qquad \qquad \qquad \text{(5) addition} \\
 & 54 - 1 \\
 & \uparrow \qquad \qquad \qquad \text{(6) subtraction} \\
 & 53
 \end{aligned}$$

Listing 2.6 gives a program that converts a Fahrenheit degree to Celsius using the formula $celsius = (\frac{5}{9})(fahrenheit - 32)$.

LISTING 2.6 FahrenheitToCelsius.java

```

1 import java.util.Scanner;
2
3 public class FahrenheitToCelsius {
4     public static void main(String[] args) {
5         Scanner input = new Scanner(System.in);
6
7         System.out.print("Enter a degree in Fahrenheit: ");
8         double fahrenheit = input.nextDouble();
9
10        // Convert Fahrenheit to Celsius
11        double celsius = (5.0 / 9) * (fahrenheit - 32);           divide
12        System.out.println("Fahrenheit " + fahrenheit + " is " +
13            celsius + " in Celsius");
14    }
15 }
```

Enter a degree in Fahrenheit: 100 ↵Enter
Fahrenheit 100.0 is 37.7777777777778 in Celsius



line#	fahrenheit	celsius
8	100	
11		37.7777777777778



Be careful when applying division. Division of two integers yields an integer in Java. $\frac{5}{9}$ is translated to $5.0 / 9$ instead of $5 / 9$ in line 11, because $5 / 9$ yields 0 in Java.

integer vs. floating-point division

2.22 How would you write the following arithmetic expression in Java?

- $\frac{4}{3(r + 34)} - 9(a + bc) + \frac{3 + d(2 + a)}{a + bd}$
- $5.5 \times (r + 2.5)^{2.5+t}$





2.12 Case Study: Displaying the Current Time

You can invoke `System.currentTimeMillis()` to return the current time.



VideoNote

Use operators / and %

`currentTimeMillis`

UNIX epoch

The problem is to develop a program that displays the current time in GMT (Greenwich Mean Time) in the format hour:minute:second, such as 13:19:8.

The `currentTimeMillis` method in the `System` class returns the current time in milliseconds elapsed since midnight, January 1, 1970 GMT, as shown in Figure 2.2. This time is known as the *UNIX epoch*. The epoch is the point when time starts, and 1970 was the year when the UNIX operating system was formally introduced.



FIGURE 2.2 The `System.currentTimeMillis()` returns the number of milliseconds since the UNIX epoch.

You can use this method to obtain the current time, and then compute the current second, minute, and hour as follows.

1. Obtain the total milliseconds since midnight, January 1, 1970, in `totalMilliseconds` by invoking `System.currentTimeMillis()` (e.g., `1203183068328` milliseconds).
2. Obtain the total seconds `totalSeconds` by dividing `totalMilliseconds` by `1000` (e.g., `1203183068328` milliseconds / `1000` = `1203183068` seconds).
3. Compute the current second from `totalSeconds % 60` (e.g., `1203183068` seconds % `60` = `8`, which is the current second).
4. Obtain the total minutes `totalMinutes` by dividing `totalSeconds` by `60` (e.g., `1203183068` seconds / `60` = `20053051` minutes).
5. Compute the current minute from `totalMinutes % 60` (e.g., `20053051` minutes % `60` = `31`, which is the current minute).
6. Obtain the total hours `totalHours` by dividing `totalMinutes` by `60` (e.g., `20053051` minutes / `60` = `334217` hours).
7. Compute the current hour from `totalHours % 24` (e.g., `334217` hours % `24` = `17`, which is the current hour).

Listing 2.7 gives the complete program.

LISTING 2.7 ShowCurrentTime.java

`totalMilliseconds`

`totalSeconds`

`currentSecond`

```

1  public class ShowCurrentTime {
2      public static void main(String[] args) {
3          // Obtain the total milliseconds since midnight, Jan 1, 1970
4          long totalMilliseconds = System.currentTimeMillis();
5
6          // Obtain the total seconds since midnight, Jan 1, 1970
7          long totalSeconds = totalMilliseconds / 1000;
8
9          // Compute the current second in the minute in the hour
10         long currentSecond = totalSeconds % 60;

```

```

11 // Obtain the total minutes
12 long totalMinutes = totalSeconds / 60;           totalMinutes
13
14 // Compute the current minute in the hour
15 long currentMinute = totalMinutes % 60;          currentMinute
16
17 // Obtain the total hours
18 long totalHours = totalMinutes / 60;            totalHours
19
20 // Compute the current hour
21 long currentHour = totalHours % 24;           currentHour
22
23 // Display results
24 System.out.println("Current time is " + currentHour + ":"+
25   + currentMinute + ":" + currentSecond + " GMT"); preparing output
26
27 }
28 }
```

Current time is 17:31:8 GMT



Line 4 invokes `System.currentTimeMillis()` to obtain the current time in milliseconds as a `long` value. Thus, all the variables are declared as the long type in this program. The seconds, minutes, and hours are extracted from the current time using the `/` and `%` operators (lines 6–22).

variables	line#	4	7	10	13	16	19	22
<code>totalMilliseconds</code>								
<code>totalSeconds</code>								
<code>currentSecond</code>								
<code>totalMinutes</code>								
<code>currentMinute</code>								
<code>totalHours</code>								
<code>currentHour</code>								



In the sample run, a single digit `8` is displayed for the second. The desirable output would be `08`. This can be fixed by using a method that formats a single digit with a prefix `0` (see Exercise 6.37).

2.23 How do you obtain the current second, minute, and hour?



2.13 Augmented Assignment Operators



The operators `+`, `-`, `*`, `/`, and `%` can be combined with the assignment operator to form augmented operators.

Very often the current value of a variable is used, modified, and then reassigned back to the same variable. For example, the following statement increases the variable `count` by 1:

```
count = count + 1;
```

Java allows you to combine assignment and addition operators using an augmented (or compound) assignment operator. For example, the preceding statement can be written as

```
count += 1;
```

addition assignment operator

The `+=` is called the *addition assignment operator*. Table 2.4 shows other augmented assignment operators.

TABLE 2.4 Augmented Assignment Operators

Operator	Name	Example	Equivalent
<code>+=</code>	Addition assignment	<code>i += 8</code>	<code>i = i + 8</code>
<code>-=</code>	Subtraction assignment	<code>i -= 8</code>	<code>i = i - 8</code>
<code>*=</code>	Multiplication assignment	<code>i *= 8</code>	<code>i = i * 8</code>
<code>/=</code>	Division assignment	<code>i /= 8</code>	<code>i = i / 8</code>
<code>%=</code>	Remainder assignment	<code>i %= 8</code>	<code>i = i % 8</code>

The augmented assignment operator is performed last after all the other operators in the expression are evaluated. For example,

```
x /= 4 + 5.5 * 1.5;
```

is same as

```
x = x / (4 + 5.5 * 1.5);
```



Caution

There are no spaces in the augmented assignment operators. For example, `+=` should be `+=`.



Note

Like the assignment operator (`=`), the operators (`+=`, `-=`, `*=`, `/=`, `%=`) can be used to form an assignment statement as well as an expression. For example, in the following code, `x += 2` is a statement in the first line and an expression in the second line.

```
x += 2; // Statement
System.out.println(x += 2); // Expression
```



2.24 Show the output of the following code:

```
double a = 6.5;
a += a + 1;
```

```
System.out.println(a);
a = 6;
a /= 2;
System.out.println(a);
```

2.14 Increment and Decrement Operators

The `++` and `--` are two shorthand operators for incrementing and decrementing a variable by 1. These are handy because that's often how much the value needs to be changed in many programming tasks. For example, the following code increments `i` by 1 and decrements `j` by 1.



increment operator (`++`)
decrement operator (`--`)

```
int i = 3, j = 3;
i++; // i becomes 4
j--; // j becomes 2
```

`i++` is pronounced as `i` plus plus and `i--` as `i` minus minus. These operators are known as *postfix increment* (or postincrement) and *postfix decrement* (or postdecrement), because the operators `++` and `--` are placed after the variable. These operators can also be placed before the variable. For example,

postincrement
postdecrement

```
int i = 3, j = 3;
++i; // i becomes 4
--j; // j becomes 2
```

preincrement
predecrement

`++i` increments `i` by 1 and `--j` decrements `j` by 1. These operators are known as *prefix increment* (or preincrement) and *prefix decrement* (or predecrement).

As you see, the effect of `i++` and `++i` or `i--` and `--i` are the same in the preceding examples. However, their effects are different when they are used in statements that do more than just increment and decrement. Table 2.5 describes their differences and gives examples.

TABLE 2.5 Increment and Decrement Operators

Operator	Name	Description	Example (assume <code>i = 1</code>)
<code>++var</code>	preincrement	Increment <code>var</code> by 1, and use the new <code>var</code> value in the statement	<code>int j = ++i;</code> <code>// j is 2, i is 2</code>
<code>var++</code>	postincrement	Increment <code>var</code> by 1, but use the original <code>var</code> value in the statement	<code>int j = i++;</code> <code>// j is 1, i is 2</code>
<code>--var</code>	predecrement	Decrement <code>var</code> by 1, and use the new <code>var</code> value in the statement	<code>int j = --i;</code> <code>// j is 0, i is 0</code>
<code>var--</code>	postdecrement	Decrement <code>var</code> by 1, and use the original <code>var</code> value in the statement	<code>int j = i--;</code> <code>// j is 1, i is 0</code>

Here are additional examples to illustrate the differences between the prefix form of `++` (or `--`) and the postfix form of `++` (or `--`). Consider the following code:

```
int i = 10;
int newNum = 10 * i++;
System.out.print("i is " + i
+ ", newNum is " + newNum);
```

Same effect as

```
int newNum = 10 * i;
i = i + 1;
```

i is 11, newNum is 100



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In this case, `i` is incremented by `1`, then the *old* value of `i` is used in the multiplication. So `newNum` becomes `100`. If `i++` is replaced by `++i` as follows,

```
int i = 10;
int newNum = 10 * (++i);    Same effect as
System.out.print("i is " + i
                  + ", newNum is " + newNum);
```

`i = i + 1;
int newNum = 10 * i;`



`i` is `11`, `newNum` is `110`

`i` is incremented by `1`, and the new value of `i` is used in the multiplication. Thus `newNum` becomes `110`.

Here is another example:

```
double x = 1.0;
double y = 5.0;
double z = x-- + (++y);
```

After all three lines are executed, `y` becomes `6.0`, `z` becomes `7.0`, and `x` becomes `0.0`.



Tip

Using increment and decrement operators makes expressions short, but it also makes them complex and difficult to read. Avoid using these operators in expressions that modify multiple variables or the same variable multiple times, such as this one: `int k = ++i + i`.



2.25 Which of these statements are true?

- a. Any expression can be used as a statement.
- b. The expression `x++` can be used as a statement.
- c. The statement `x = x + 5` is also an expression.
- d. The statement `x = y = x = 0` is illegal.

2.26 Show the output of the following code:

```
int a = 6;
int b = a++;
System.out.println(a);
System.out.println(b);
a = 6;
b = ++a;
System.out.println(a);
System.out.println(b);
```



2.15 Numeric Type Conversions

Floating-point numbers can be converted into integers using explicit casting.

Can you perform binary operations with two operands of different types? Yes. If an integer and a floating-point number are involved in a binary operation, Java automatically converts the integer to a floating-point value. So, `3 * 4.5` is same as `3.0 * 4.5`.

You can always assign a value to a numeric variable whose type supports a larger range of values; thus, for instance, you can assign a **long** value to a **float** variable. You cannot, however, assign a value to a variable of a type with a smaller range unless you use *type casting*. *Casting* is an operation that converts a value of one data type into a value of another data type. Casting a type with a small range to a type with a larger range is known as *widening a type*. Casting a type with a large range to a type with a smaller range is known as *narrowing a type*. Java will automatically widen a type, but you must narrow a type explicitly.

The syntax for casting a type is to specify the target type in parentheses, followed by the variable's name or the value to be cast. For example, the following statement

```
System.out.println((int)1.7);
```

displays 1. When a **double** value is cast into an **int** value, **the fractional part is truncated**.

The following statement

```
System.out.println((double)1 / 2);
```

displays 0.5, because 1 is cast to 1.0 first, then 1.0 is divided by 2. However, the statement

```
System.out.println(1 / 2);
```

displays 0, because 1 and 2 are both integers and the resulting value should also be an integer.



Caution

Casting is necessary if you are assigning a value to a variable of a smaller type range, such as assigning a **double** value to an **int** variable. A compile error will occur if casting is not used in situations of this kind. However, be careful when using casting, as loss of information might lead to inaccurate results.

possible loss of precision



Note

Casting does not change the variable being cast. For example, d is not changed after casting in the following code:

```
double d = 4.5;
int i = (int)d; // i becomes 4, but d is still 4.5
```



Note

In Java, an augmented expression of the form **x1 op= x2** is implemented as **x1 = (T)(x1 op x2)**, where T is the type for x1. Therefore, the following code is correct.

casting in an augmented expression

```
int sum = 0;
sum += 4.5; // sum becomes 4 after this statement
sum += 4.5 is equivalent to sum = (int)(sum + 4.5).
```



Note

To assign a variable of the **int** type to a variable of the **short** or **byte** type, explicit casting must be used. For example, the following statements have a compile error:

```
int i = 1;
byte b = i; // Error because explicit casting is required
```

However, so long as the integer literal is within the permissible range of the target variable, explicit casting is not needed to assign an integer literal to a variable of the **short** or **byte** type (see Section 2.10, Numeric Literals).

The program in Listing 2.8 displays the sales tax with two digits after the decimal point.

LISTING 2.8 SalesTax.java

```

1 import java.util.Scanner;
2
3 public class SalesTax {
4     public static void main(String[] args) {
5         Scanner input = new Scanner(System.in);
6
7         System.out.print("Enter purchase amount: ");
8         double purchaseAmount = input.nextDouble();
9
10        double tax = purchaseAmount * 0.06;
11        System.out.println("Sales tax is $" + (int)(tax * 100) / 100.0);
12    }
13 }
```

casting



Enter purchase amount: 197.55

Sales tax is \$11.85



line#	purchaseAmount	tax	output
8	197.55		
10		11.853	
11			11.85

formatting numbers

The variable **purchaseAmount** is **197.55** (line 8). The sales tax is **6%** of the purchase, so the **tax** is evaluated as **11.853** (line 10). Note that

tax * 100 is **1185.3**
(int)(tax * 100) is **1185**
(int)(tax * 100) / 100.0 is **11.85**

So, the statement in line 11 displays the tax **11.85** with two digits after the decimal point.



- 2.27** Can different types of numeric values be used together in a computation?
2.28 What does an explicit casting from a **double** to an **int** do with the fractional part of the **double** value? Does casting change the variable being cast?
2.29 Show the following output:

```

float f = 12.5F;
int i = (int)f;
System.out.println("f is " + f);
System.out.println("i is " + i);
```

- 2.30** If you change **(int)(tax * 100) / 100.0** to **(int)(tax * 100) / 100** in line 11 in Listing 2.8, what will be the output for the input purchase amount of **197.55**?
2.31 Show the output of the following code:

```

double amount = 5;
System.out.println(amount / 2);
System.out.println(5 / 2);
```

2.16 Software Development Process

The software development life cycle is a multistage process that includes requirements specification, analysis, design, implementation, testing, deployment, and maintenance.



Software development process

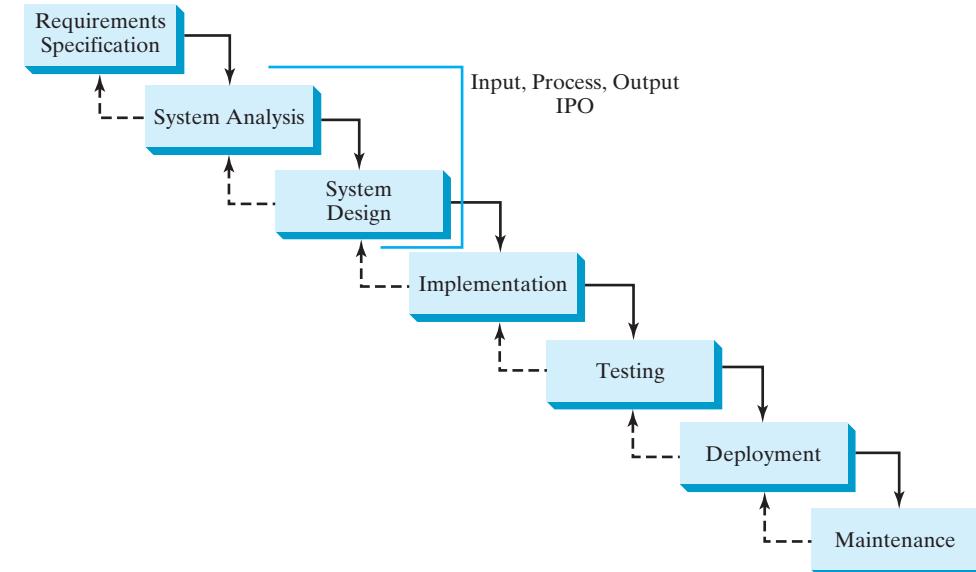


FIGURE 2.3 At any stage of the software development life cycle, it may be necessary to go back to a previous stage to correct errors or deal with other issues that might prevent the software from functioning as expected.

Requirements specification is a formal process that seeks to understand the problem that the software will address and to document in detail what the software system needs to do. This phase involves close interaction between users and developers. Most of the examples in this book are simple, and their requirements are clearly stated. In the real world, however, problems are not always well defined. Developers need to work closely with their customers (the individuals or organizations that will use the software) and study the problem carefully to identify what the software needs to do.

requirements specification

System analysis seeks to analyze the data flow and to identify the system's input and output. When you do analysis, it helps to identify what the output is first, and then figure out what input data you need in order to produce the output.

system analysis

System design is to design a process for obtaining the output from the input. This phase involves the use of many levels of abstraction to break down the problem into manageable components and design strategies for implementing each component. You can view each component as a subsystem that performs a specific function of the system. The essence of system analysis and design is input, process, and output (IPO).

system design

Implementation involves translating the system design into programs. Separate programs are written for each component and then integrated to work together. This phase requires the use of a programming language such as Java. The implementation involves coding, self-testing, and debugging (that is, finding errors, called *bugs*, in the code).

IPO

implementation

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testing

Testing ensures that the code meets the requirements specification and weeds out bugs. An independent team of software engineers not involved in the design and implementation of the product usually conducts such testing.

deployment

Deployment makes the software available for use. Depending on the type of software, it may be installed on each user's machine or installed on a server accessible on the Internet.

maintenance

Maintenance is concerned with updating and improving the product. A software product must continue to perform and improve in an ever-evolving environment. This requires periodic upgrades of the product to fix newly discovered bugs and incorporate changes.



VideoNote

Compute loan payments

To see the software development process in action, we will now create a program that computes loan payments. The loan can be a car loan, a student loan, or a home mortgage loan. For an introductory programming course, we focus on requirements specification, analysis, design, implementation, and testing.

Stage 1: Requirements Specification

The program must satisfy the following requirements:

- It must let the user enter the interest rate, the loan amount, and the number of years for which payments will be made.
- It must compute and display the monthly payment and total payment amounts.

Stage 2: System Analysis

The output is the monthly payment and total payment, which can be obtained using the following formulas:

$$monthlyPayment = \frac{loanAmount \times monthlyInterestRate}{1 - \frac{1}{(1 + monthlyInterestRate)^{numberOfYears \times 12}}}$$

$$totalPayment = monthlyPayment \times numberOfYears \times 12$$

So, the input needed for the program is the monthly interest rate, the length of the loan in years, and the loan amount.



Note

The requirements specification says that the user must enter the annual interest rate, the loan amount, and the number of years for which payments will be made. During analysis, however, it is possible that you may discover that input is not sufficient or that some values are unnecessary for the output. If this happens, you can go back and modify the requirements specification.



Note

In the real world, you will work with customers from all walks of life. You may develop software for chemists, physicists, engineers, economists, and psychologists, and of course you will not have (or need) complete knowledge of all these fields. Therefore, you don't have to know how formulas are derived, but given the monthly interest rate, the number of years, and the loan amount, you can compute the monthly payment in this program. You will, however, need to communicate with customers and understand how a mathematical model works for the system.

Stage 3: System Design

During system design, you identify the steps in the program.

- Step 1. Prompt the user to enter the annual interest rate, the number of years, and the loan amount.

(The interest rate is commonly expressed as a percentage of the principal for a period of one year. This is known as the *annual interest rate*.)

- Step 2. The input for the annual interest rate is a number in percent format, such as 4.5%. The program needs to convert it into a decimal by dividing it by 100. To obtain the monthly interest rate from the annual interest rate, divide it by 12, since a year has 12 months. So, to obtain the monthly interest rate in decimal format, you need to divide the annual interest rate in percentage by 1200. For example, if the annual interest rate is 4.5%, then the monthly interest rate is $4.5/1200 = 0.00375$.

- Step 3. Compute the monthly payment using the preceding formula.
- Step 4. Compute the total payment, which is the monthly payment multiplied by 12 and multiplied by the number of years.

- Step 5. Display the monthly payment and total payment.

Stage 4: Implementation

Implementation is also known as *coding* (writing the code). In the formula, you have to compute $(1 + monthlyInterestRate)^{numberOfYears \times 12}$, which can be obtained using `Math.pow(1 + monthlyInterestRate, numberOfYears * 12)`.

`Math.pow(a, b)` method

Listing 2.9 gives the complete program.

LISTING 2.9 ComputeLoan.java

```

1 import java.util.Scanner;                                import class
2
3 public class ComputeLoan {                            create a Scanner
4     public static void main(String[] args) {
5         // Create a Scanner
6         Scanner input = new Scanner(System.in);
7
8         // Enter annual interest rate in percentage, e.g., 7.25%
9         System.out.print("Enter annual interest rate, e.g., 7.25%: ");
10        double annualInterestRate = input.nextDouble();      enter interest rate
11
12        // Obtain monthly interest rate
13        double monthlyInterestRate = annualInterestRate / 1200;
14
15        // Enter number of years
16        System.out.print(
17            "Enter number of years as an integer, e.g., 5: ");
18        int numberOfYears = input.nextInt();                  enter years
19
20        // Enter loan amount
21        System.out.print("Enter loan amount, e.g., 120000.95: ");
22        double loanAmount = input.nextDouble();              enter loan amount
23
24        // Calculate payment
25        double monthlyPayment = loanAmount * monthlyInterestRate / (1
26            - 1 / Math.pow(1 + monthlyInterestRate, numberOfYears * 12));    monthlyPayment

```

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```
totalPayment          27      double totalPayment = monthlyPayment * numberOfYears * 12;
                           28
                           29      // Display results
                           30      System.out.println("The monthly payment is $" +
                           31                  (int)(monthlyPayment * 100) / 100.0);
                           32      System.out.println("The total payment is $" +
                           33                  (int)(totalPayment * 100) / 100.0);
                           34  }
                           35 }
```



```
Enter annual interest rate, e.g., 5.75%: 5.75 ↵ Enter
Enter number of years as an integer, e.g., 5: 15 ↵ Enter
Enter loan amount, e.g., 120000.95: 250000 ↵ Enter
The monthly payment is $2076.02
The total payment is $373684.53
```



variables	line#	10	13	18	22	25	27
annualInterestRate			5.75				
monthlyInterestRate				0.004791666666			
numberOfYears					15		
loanAmount						250000	
monthlyPayment							2076.0252175
totalPayment							373684.539

Line 10 reads the annual interest rate, which is converted into the monthly interest rate in line 13.

Choose the most appropriate data type for the variable. For example, `numberOfYears` is best declared as an `int` (line 18), although it could be declared as a `long`, `float`, or `double`. Note that `byte` might be the most appropriate for `numberOfYears`. For simplicity, however, the examples in this book will use `int` for integer and `double` for floating-point values.

The formula for computing the monthly payment is translated into Java code in lines 25–27.

Casting is used in lines 31 and 33 to obtain a new `monthlyPayment` and `totalPayment` with two digits after the decimal points.

java.lang package

The program uses the `Scanner` class, imported in line 1. The program also uses the `Math` class, and you might be wondering why that class isn't imported into the program. The `Math` class is in the `java.lang` package, and all classes in the `java.lang` package are implicitly imported. Therefore, you don't need to explicitly import the `Math` class.

Stage 5: Testing

After the program is implemented, test it with some sample input data and verify whether the output is correct. Some of the problems may involve many cases, as you will see in later chapters. For these types of problems, you need to design test data that cover all cases.

incremental code and test



Tip

The system design phase in this example identified several steps. It is a good approach to code and test these steps incrementally by adding them one at a time. This approach makes it much easier to pinpoint problems and debug the program.

2.32 How would you write the following arithmetic expression?

$$\frac{-b + \sqrt{b^2 - 4ac}}{2a}$$



2.17 Case Study: Counting Monetary Units

This section presents a program that breaks a large amount of money into smaller units.



Suppose you want to develop a program that changes a given amount of money into smaller monetary units. The program lets the user enter an amount as a **double** value representing a total in dollars and cents, and outputs a report listing the monetary equivalent in the maximum number of dollars, quarters, dimes, nickels, and pennies, in this order, to result in the minimum number of coins.

Here are the steps in developing the program:

1. Prompt the user to enter the amount as a decimal number, such as **11.56**.
2. Convert the amount (e.g., **11.56**) into cents (**1156**).
3. Divide the cents by **100** to find the number of dollars. Obtain the remaining cents using the cents remainder **100**.
4. Divide the remaining cents by **25** to find the number of quarters. Obtain the remaining cents using the remaining cents remainder **25**.
5. Divide the remaining cents by **10** to find the number of dimes. Obtain the remaining cents using the remaining cents remainder **10**.
6. Divide the remaining cents by **5** to find the number of nickels. Obtain the remaining cents using the remaining cents remainder **5**.
7. The remaining cents are the pennies.
8. Display the result.

The complete program is given in Listing 2.10.

LISTING 2.10 ComputeChange.java

```

1 import java.util.Scanner;                                import class
2
3 public class ComputeChange {                           enter input
4     public static void main(String[] args) {
5         // Create a Scanner
6         Scanner input = new Scanner(System.in);
7
8         // Receive the amount
9         System.out.print(
10            "Enter an amount in double, for example 11.56: ");
11        double amount = input.nextDouble();
12
13        int remainingAmount = (int)(amount * 100);           dollars
14
15        // Find the number of one dollars
16        int numberOneDollars = remainingAmount / 100;
17        remainingAmount = remainingAmount % 100;
18
19        // Find the number of quarters in the remaining amount
20        int numberQuarters = remainingAmount / 25;           quarters

```

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```
21     remainingAmount = remainingAmount % 25;
22
23     // Find the number of dimes in the remaining amount
24     int numberOfDimes = remainingAmount / 10;
25     remainingAmount = remainingAmount % 10;
26
27     // Find the number of nickels in the remaining amount
28     int numberOfNickels = remainingAmount / 5;
29     remainingAmount = remainingAmount % 5;
30
31     // Find the number of pennies in the remaining amount
32     int numberOfPennies = remainingAmount;
33
34     // Display results
35     System.out.println("Your amount " + amount + " consists of");
36     System.out.println("    " + numberOfOneDollars + " dollars");
37     System.out.println("    " + numberOfQuarters + " quarters ");
38     System.out.println("    " + numberOfDimes + " dimes");
39     System.out.println("    " + numberOfNickels + " nickels");
40     System.out.println("    " + numberOfPennies + " pennies");
41 }
42 }
```



Enter an amount, for example, 11.56: 11.56 ↵ Enter

Your amount 11.56 consists of

11 dollars
2 quarters
0 dimes
1 nickels
1 pennies



variables	line#	11	13	16	17	20	21	24	25	28	29	32
amount				11.56								
remainingAmount					1156	56	6	6	6			1
numberOfOneDollars						11						
numberOfQuarters							2					
numberOfDimes								0				
numberOfNickels									1			
numberOfPennies												1

The variable `amount` stores the amount entered from the console (line 11). This variable is not changed, because the amount has to be used at the end of the program to display the results. The program introduces the variable `remainingAmount` (line 13) to store the changing remaining amount.

The variable `amount` is a `double` decimal representing dollars and cents. It is converted to an `int` variable `remainingAmount`, which represents all the cents. For instance, if `amount`

is **11.56**, then the initial **remainingAmount** is **1156**. The division operator yields the integer part of the division, so **1156 / 100** is **11**. The remainder operator obtains the remainder of the division, so **1156 % 100** is **56**.

The program extracts the maximum number of singles from the remaining amount and obtains a new remaining amount in the variable **remainingAmount** (lines 16–17). It then extracts the maximum number of quarters from **remainingAmount** and obtains a new **remainingAmount** (lines 20–21). Continuing the same process, the program finds the maximum number of dimes, nickels, and pennies in the remaining amount.

One serious problem with this example is the possible loss of precision when casting a **double** amount to an **int remainingAmount**. This could lead to an inaccurate result. If you try to enter the amount **10.03**, **10.03 * 100** becomes **1002.9999999999999**. You will find that the program displays **10** dollars and **2** pennies. To fix the problem, enter the amount as an integer value representing cents (see Programming Exercise 2.22).

loss of precision

2.33 Show the output with the input value **1.99**.



2.18 Common Errors and Pitfalls

Common elementary programming errors often involve undeclared variables, uninitialized variables, integer overflow, unintended integer division, and round-off errors.



Common Error 1: Undeclared/Uninitialized Variables and Unused Variables

A variable must be declared with a type and assigned a value before using it. A common error is not declaring a variable or initializing a variable. Consider the following code:

```
double interestRate = 0.05;
double interest = interestrte * 45;
```

This code is wrong, because **interestRate** is assigned a value **0.05**; but **interestrte** has not been declared and initialized. Java is case sensitive, so it considers **interestRate** and **interestrte** to be two different variables.

If a variable is declared, but not used in the program, it might be a potential programming error. So, you should remove the unused variable from your program. For example, in the following code, **taxRate** is never used. It should be removed from the code.

```
double interestRate = 0.05;
double taxRate = 0.05;
double interest = interestRate * 45;
System.out.println("Interest is " + interest);
```

If you use an IDE such as Eclipse and NetBeans, you will receive a warning on unused variables.

Common Error 2: Integer Overflow

Numbers are stored with a limited numbers of digits. When a variable is assigned a value that is too large (*in size*) to be stored, it causes *overflow*. For example, executing the following statement causes overflow, because the largest value that can be stored in a variable of the **int** type is **2147483647**. **2147483648** will be too large for an **int** value.

what is overflow?

```
int value = 2147483647 + 1;
// value will actually be -2147483648
```

Likewise, executing the following statement causes overflow, because the smallest value that can be stored in a variable of the **int** type is **-2147483648**. **-2147483649** is too large in size to be stored in an **int** variable.

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```
int value = -2147483648 - 1;  
// value will actually be 2147483647
```

Java does not report warnings or errors on overflow, so be careful when working with numbers close to the maximum or minimum range of a given type.

what is underflow?

When a floating-point number is too small (i.e., too close to zero) to be stored, it causes *underflow*. Java approximates it to zero, so normally you don't need to be concerned about underflow.

floating-point approximation

Common Error 3: Round-off Errors

A *round-off error*, also called a *rounding error*, is the difference between the calculated approximation of a number and its exact mathematical value. For example, $1/3$ is approximately 0.333 if you keep three decimal places, and is 0.333333 if you keep seven decimal places. Since the number of digits that can be stored in a variable is limited, round-off errors are inevitable. Calculations involving floating-point numbers are approximated because these numbers are not stored with complete accuracy. For example,

```
System.out.println(1.0 - 0.1 - 0.1 - 0.1 - 0.1 - 0.1);
```

displays **0.5000000000000001**, not **0.5**, and

```
System.out.println(1.0 - 0.9);
```

displays **0.0999999999999998**, not **0.1**. Integers are stored precisely. Therefore, calculations with integers yield a precise integer result.

Common Error 4: Unintended Integer Division

Java uses the same divide operator, namely `/`, to perform both integer and floating-point division. When two operands are integers, the `/` operator performs an integer division. The result of the operation is an integer. The fractional part is truncated. To force two integers to perform a floating-point division, make one of the integers into a floating-point number. For example, the code in (a) displays that average is **1** and the code in (b) displays that average is **1.5**.

```
int number1 = 1;  
int number2 = 2;  
double average = (number1 + number2) / 2;  
System.out.println(average);
```

(a)

```
int number1 = 1;  
int number2 = 2;  
double average = (number1 + number2) / 2.0;  
System.out.println(average);
```

(b)

Common Pitfall 1: Redundant Input Objects

New programmers often write the code to create multiple input objects for each input. For example, the following code reads an integer and a double value.

```
Scanner input = new Scanner(System.in);  
System.out.print("Enter an integer: ");  
int v1 = input.nextInt();  
  
Scanner input1 = new Scanner(System.in);  
System.out.print("Enter a double value: ");  
double v2 = input1.nextDouble();
```

BAD CODE

The code is not wrong, but inefficient. It creates two input objects unnecessarily and may lead to some subtle errors. You should rewrite the code as follows:

```
Scanner input = new Scanner(System.in);    GOOD CODE
System.out.print("Enter an integer: ");
int v1 = input.nextInt();
System.out.print("Enter a double value: ");
double v2 = input.nextDouble();
```

- 2.34** Can you declare a variable as `int` and later redeclare it as `double`?
- 2.35** What is an integer overflow? Can floating-point operations cause overflow?
- 2.36** Will overflow cause a runtime error?
- 2.37** What is a round-off error? Can integer operations cause round-off errors? Can floating-point operations cause round-off errors?



Key Terms

algorithm 34	narrowing (of types) 57
assignment operator (=) 42	operands 46
assignment statement 42	operator 46
<code>byte</code> type 45	overflow 65
casting 57	postdecrement 55
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CHAPTER SUMMARY

- 1.** *Identifiers* are names for naming elements such as variables, constants, methods, classes, packages in a program.
- 2.** An identifier is a sequence of characters that consists of letters, digits, underscores (_), and dollar signs (\$). An identifier must start with a letter or an underscore. It cannot start with a digit. An identifier cannot be a reserved word. An identifier can be of any length.
- 3.** *Variables* are used to store data in a program. To declare a variable is to tell the compiler what type of data a variable can hold.

4. There are two types of **import** statements: *specific import* and *wildcard import*. The specific import specifies a single class in the import statement; the wildcard import imports all the classes in a package.
5. In Java, the equal sign (**=**) is used as the *assignment operator*.
6. A variable declared in a method must be assigned a value before it can be used.
7. A *named constant* (or simply a *constant*) represents permanent data that never changes.
8. A named constant is declared by using the keyword **final**.
9. Java provides four integer types (**byte**, **short**, **int**, and **long**) that represent integers of four different sizes.
10. Java provides two *floating-point types* (**Float** and **double**) that represent floating-point numbers of two different precisions.
11. Java provides *operators* that perform numeric operations: **+** (addition), **-** (subtraction), ***** (multiplication), **/** (division), and **%** (remainder).
12. Integer arithmetic (**/**) yields an integer result.
13. The numeric operators in a Java expression are applied the same way as in an arithmetic expression.
14. Java provides the augmented assignment operators **+=** (addition assignment), **-=** (subtraction assignment), ***=** (multiplication assignment), **/=** (division assignment), and **%=** (remainder assignment).
15. The *increment operator* (**++**) and the *decrement operator* (**--**) increment or decrement a variable by **1**.
16. When evaluating an expression with values of mixed types, Java automatically converts the operands to appropriate types.
17. You can explicitly convert a value from one type to another using the **(type)value** notation.
18. *Casting* a variable of a type with a small range to a variable of a type with a larger range is known as *widening a type*.
19. Casting a variable of a type with a large range to a variable of a type with a smaller range is known as *narrowing a type*.
20. Widening a type can be performed automatically without explicit casting. Narrowing a type must be performed explicitly.
21. In computer science, midnight of January 1, 1970, is known as the *UNIX epoch*.

Quiz

Answer the quiz for this chapter online at www.cs.armstrong.edu/liang/intro10e/quiz.html.

PROGRAMMING EXERCISES

MyProgrammingLab™



Debugging TIP

The compiler usually gives a reason for a syntax error. If you don't know how to correct it, compare your program closely, character by character, with similar examples in the text.

learn from examples



Pedagogical Note

Instructors may ask you to document your analysis and design for selected exercises. Use your own words to analyze the problem, including the input, output, and what needs to be computed, and describe how to solve the problem in pseudocode.

document analysis and design

Sections 2.2–2.12

- 2.1** (*Convert Celsius to Fahrenheit*) Write a program that reads a Celsius degree in a **double** value from the console, then converts it to Fahrenheit and displays the result. The formula for the conversion is as follows:

```
fahrenheit = (9 / 5) * celsius + 32
```

Hint: In Java, **9 / 5** is **1**, but **9.0 / 5** is **1.8**.

Here is a sample run:

```
Enter a degree in Celsius: 43 ↵ Enter
43 Celsius is 109.4 Fahrenheit
```



- 2.2** (*Compute the volume of a cylinder*) Write a program that reads in the radius and length of a cylinder and computes the area and volume using the following formulas:

```
area = radius * radius * π
volume = area * length
```

Here is a sample run:

```
Enter the radius and length of a cylinder: 5.5 12 ↵ Enter
The area is 95.0331
The volume is 1140.4
```



- 2.3** (*Convert feet into meters*) Write a program that reads a number in feet, converts it to meters, and displays the result. One foot is **0.305** meter. Here is a sample run:

```
Enter a value for feet: 16.5 ↵ Enter
16.5 feet is 5.0325 meters
```



- 2.4** (*Convert pounds into kilograms*) Write a program that converts pounds into kilograms. The program prompts the user to enter a number in pounds, converts it to kilograms, and displays the result. One pound is **0.454** kilograms. Here is a sample run:



```
Enter a number in pounds: 55.5 ↵Enter
55.5 pounds is 25.197 kilograms
```

- *2.5** (*Financial application: calculate tips*) Write a program that reads the subtotal and the gratuity rate, then computes the gratuity and total. For example, if the user enters **10** for subtotal and **15%** for gratuity rate, the program displays **\$1.5** as gratuity and **\$11.5** as total. Here is a sample run:



```
Enter the subtotal and a gratuity rate: 10 15 ↵Enter
The gratuity is $1.5 and total is $11.5
```

- **2.6** (*Sum the digits in an integer*) Write a program that reads an integer between **0** and **1000** and adds all the digits in the integer. For example, if an integer is **932**, the sum of all its digits is **14**.

Hint: Use the **%** operator to extract digits, and use the **/** operator to remove the extracted digit. For instance, **932 % 10 = 2** and **932 / 10 = 93**.

Here is a sample run:



```
Enter a number between 0 and 1000: 999 ↵Enter
The sum of the digits is 27
```

- *2.7** (*Find the number of years*) Write a program that prompts the user to enter the minutes (e.g., 1 billion), and displays the number of years and days for the minutes. For simplicity, assume a year has **365** days. Here is a sample run:



```
Enter the number of minutes: 10000000000 ↵Enter
10000000000 minutes is approximately 1902 years and 214 days
```

- *2.8** (*Current time*) Listing 2.7, ShowCurrentTime.java, gives a program that displays the current time in GMT. Revise the program so that it prompts the user to enter the time zone offset to GMT and displays the time in the specified time zone. Here is a sample run:



```
Enter the time zone offset to GMT: -5 ↵Enter
The current time is 4:50:34
```

- 2.9** (*Physics: acceleration*) Average acceleration is defined as the change of velocity divided by the time taken to make the change, as shown in the following formula:

$$a = \frac{v_1 - v_0}{t}$$

Write a program that prompts the user to enter the starting velocity v_0 in meters/second, the ending velocity v_1 in meters/second, and the time span t in seconds, and displays the average acceleration. Here is a sample run:

```
Enter v0, v1, and t: 5.5 50.9 4.5 ↵Enter
The average acceleration is 10.0889
```



- 2.10** (*Science: calculating energy*) Write a program that calculates the energy needed to heat water from an initial temperature to a final temperature. Your program should prompt the user to enter the amount of water in kilograms and the initial and final temperatures of the water. The formula to compute the energy is

$$Q = M * (\text{finalTemperature} - \text{initialTemperature}) * 4184$$

where **M** is the weight of water in kilograms, temperatures are in degrees Celsius, and energy **Q** is measured in joules. Here is a sample run:

```
Enter the amount of water in kilograms: 55.5 ↵Enter
Enter the initial temperature: 3.5 ↵Enter
Enter the final temperature: 10.5 ↵Enter
The energy needed is 1625484.0
```



- 2.11** (*Population projection*) Rewrite Programming Exercise 1.11 to prompt the user to enter the number of years and displays the population after the number of years. Use the hint in Programming Exercise 1.11 for this program. The population should be cast into an integer. Here is a sample run of the program:

```
Enter the number of years: 5 ↵Enter
The population in 5 years is 325932970
```



- 2.12** (*Physics: finding runway length*) Given an airplane's acceleration a and take-off speed v , you can compute the minimum runway length needed for an airplane to take off using the following formula:

$$\text{length} = \frac{v^2}{2a}$$

Write a program that prompts the user to enter v in meters/second (m/s) and the acceleration a in meters/second squared (m/s²), and displays the minimum runway length. Here is a sample run:

```
Enter speed and acceleration: 60 3.5 ↵Enter
The minimum runway length for this airplane is 514.286
```



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- **2.13** (*Financial application: compound value*) Suppose you save \$100 each month into a savings account with the annual interest rate 5%. Thus, the monthly interest rate is $0.05/12 = 0.00417$. After the first month, the value in the account becomes

$$100 * (1 + 0.00417) = 100.417$$

After the second month, the value in the account becomes

$$(100 + 100.417) * (1 + 0.00417) = 201.252$$

After the third month, the value in the account becomes

$$(100 + 201.252) * (1 + 0.00417) = 302.507$$

and so on.

Write a program that prompts the user to enter a monthly saving amount and displays the account value after the sixth month. (In Exercise 5.30, you will use a loop to simplify the code and display the account value for any month.)



Enter the monthly saving amount: 100 ↵ Enter
After the sixth month, the account value is \$608.81



- *2.14** (*Health application: computing BMI*) Body Mass Index (BMI) is a measure of health on weight. It can be calculated by taking your weight in kilograms and dividing by the square of your height in meters. Write a program that prompts the user to enter a weight in pounds and height in inches and displays the BMI. Note that one pound is **0.45359237** kilograms and one inch is **0.0254** meters. Here is a sample run:



Enter weight in pounds: 95.5 ↵ Enter
Enter height in inches: 50 ↵ Enter
BMI is 26.8573

- 2.15** (*Geometry: distance of two points*) Write a program that prompts the user to enter two points **(x₁, y₁)** and **(x₂, y₂)** and displays their distance between them. The formula for computing the distance is $\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$. Note that you can use **Math.pow(a, 0.5)** to compute \sqrt{a} . Here is a sample run:



Enter x1 and y1: 1.5 -3.4 ↵ Enter
Enter x2 and y2: 4 5 ↵ Enter
The distance between the two points is 8.764131445842194

- 2.16** (*Geometry: area of a hexagon*) Write a program that prompts the user to enter the side of a hexagon and displays its area. The formula for computing the area of a hexagon is

$$\text{Area} = \frac{3\sqrt{3}}{2}s^2,$$

where s is the length of a side. Here is a sample run:

```
Enter the side: 5.5 ↵Enter
The area of the hexagon is 78.5895
```



- *2.17** (*Science: wind-chill temperature*) How cold is it outside? The temperature alone is not enough to provide the answer. Other factors including wind speed, relative humidity, and sunshine play important roles in determining coldness outside. In 2001, the National Weather Service (NWS) implemented the new wind-chill temperature to measure the coldness using temperature and wind speed. The formula is

$$t_{wc} = 35.74 + 0.6215t_a - 35.75v^{0.16} + 0.4275t_av^{0.16}$$

where t_a is the outside temperature measured in degrees Fahrenheit and v is the speed measured in miles per hour. t_{wc} is the wind-chill temperature. The formula cannot be used for wind speeds below 2 mph or temperatures below -58°F or above 41°F .

Write a program that prompts the user to enter a temperature between -58°F and 41°F and a wind speed greater than or equal to 2 and displays the wind-chill temperature. Use `Math.pow(a, b)` to compute $v^{0.16}$. Here is a sample run:

```
Enter the temperature in Fahrenheit between -58°F and 41°F:
5.3 ↵Enter
Enter the wind speed (>=2) in miles per hour: 6 ↵Enter
The wind chill index is -5.56707
```



- 2.18** (*Print a table*) Write a program that displays the following table. Cast floating-point numbers into integers.

a	b	pow(a, b)
1	2	1
2	3	8
3	4	81
4	5	1024
5	6	15625

- *2.19** (*Geometry: area of a triangle*) Write a program that prompts the user to enter three points `(x1, y1)`, `(x2, y2)`, `(x3, y3)` of a triangle and displays its area. The formula for computing the area of a triangle is

$$s = (\text{side1} + \text{side2} + \text{side3})/2;$$

$$\text{area} = \sqrt{s(s - \text{side1})(s - \text{side2})(s - \text{side3})}$$

Here is a sample run:

```
Enter three points for a triangle: 1.5 -3.4 4.6 5 9.5 -3.4 ↵Enter
The area of the triangle is 33.6
```



Sections 2.13–2.17

- *2.20** (*Financial application: calculate interest*) If you know the balance and the annual percentage interest rate, you can compute the interest on the next monthly payment using the following formula:

$$\text{interest} = \text{balance} \times (\text{annualInterestRate}/1200)$$

Write a program that reads the balance and the annual percentage interest rate and displays the interest for the next month. Here is a sample run:



```
Enter balance and interest rate (e.g., 3 for 3%): 1000 3.5 ↵Enter
The interest is 2.91667
```

- *2.21** (*Financial application: calculate future investment value*) Write a program that reads in investment amount, annual interest rate, and number of years, and displays the future investment value using the following formula:

$$\text{futureInvestmentValue} =$$

$$\text{investmentAmount} \times (1 + \text{monthlyInterestRate})^{\text{numberOfYears} * 12}$$

For example, if you enter amount **1000**, annual interest rate **3.25%**, and number of years **1**, the future investment value is **1032.98**.

Here is a sample run:



```
Enter investment amount: 1000.56 ↵Enter
Enter annual interest rate in percentage: 4.25 ↵Enter
Enter number of years: 1 ↵Enter
Accumulated value is $1043.92
```

- *2.22** (*Financial application: monetary units*) Rewrite Listing 2.10, ComputeChange.java, to fix the possible loss of accuracy when converting a **double** value to an **int** value. Enter the input as an integer whose last two digits represent the cents. For example, the input **1156** represents **11** dollars and **56** cents.

- *2.23** (*Cost of driving*) Write a program that prompts the user to enter the distance to drive, the fuel efficiency of the car in miles per gallon, and the price per gallon, and displays the cost of the trip. Here is a sample run:



```
Enter the driving distance: 900.5 ↵Enter
Enter miles per gallon: 25.5 ↵Enter
Enter price per gallon: 3.55 ↵Enter
The cost of driving is $125.36
```

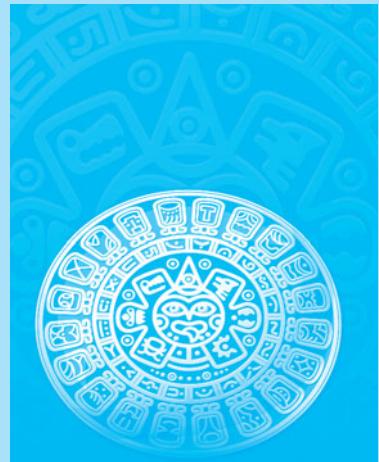
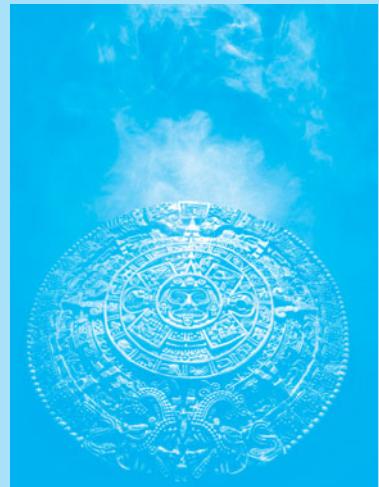
CHAPTER

3

SELECTIONS

Objectives

- To declare `boolean` variables and write Boolean expressions using relational operators (§3.2).
- To implement selection control using one-way `if` statements (§3.3).
- To implement selection control using two-way `if-else` statements (§3.4).
- To implement selection control using nested `if` and multi-way `if` statements (§3.5).
- To avoid common errors and pitfalls in `if` statements (§3.6).
- To generate random numbers using the `Math.random()` method (§3.7).
- To program using selection statements for a variety of examples ([SubtractionQuiz](#), [BMI](#), [ComputeTax](#)) (§§3.7–3.9).
- To combine conditions using logical operators (`!`, `&&`, `||`, and `^`) (§3.10).
- To program using selection statements with combined conditions ([LeapYear](#), [Lottery](#)) (§§3.11–3.12).
- To implement selection control using `switch` statements (§3.13).
- To write expressions using the conditional expression (§3.14).
- To examine the rules governing operator precedence and associativity (§3.15).
- To apply common techniques to debug errors (§3.16).



problem



selection statements

Boolean expression
Boolean valueboolean data type
relational operators

3.1 Introduction

The program can decide which statements to execute based on a condition.

If you enter a negative value for `radius` in Listing 2.2, `ComputeAreaWithConsoleInput.java`, the program displays an invalid result. If the radius is negative, you don't want the program to compute the area. How can you deal with this situation?

Like all high-level programming languages, Java provides *selection statements*: statements that let you choose actions with alternative courses. You can use the following selection statement to replace lines 12–17 in Listing 2.2:

```
if (radius < 0) {
    System.out.println("Incorrect input");
}
else {
    area = radius * radius * 3.14159;
    System.out.println("Area is " + area);
}
```

Selection statements use conditions that are Boolean expressions. A *Boolean expression* is an expression that evaluates to a *Boolean value*: `true` or `false`. We now introduce Boolean types and relational operators.

3.2 boolean Data Type

The `boolean` data type declares a variable with the value either `true` or `false`.

How do you compare two values, such as whether a radius is greater than `0`, equal to `0`, or less than `0`? Java provides six *relational operators* (also known as *comparison operators*), shown in Table 3.1, which can be used to compare two values (assume radius is `5` in the table).

TABLE 3.1 Relational Operators

Java Operator	Mathematics Symbol	Name	Example (radius is 5)	Result
<code><</code>	<code><</code>	less than	<code>radius < 0</code>	<code>false</code>
<code><=</code>	<code>≤</code>	less than or equal to	<code>radius <= 0</code>	<code>false</code>
<code>></code>	<code>></code>	greater than	<code>radius > 0</code>	<code>true</code>
<code>>=</code>	<code>≥</code>	greater than or equal to	<code>radius >= 0</code>	<code>true</code>
<code>==</code>	<code>=</code>	equal to	<code>radius == 0</code>	<code>false</code>
<code>!=</code>	<code>≠</code>	not equal to	<code>radius != 0</code>	<code>true</code>

`==` vs. `=`

Caution

The equality testing operator is two equal signs (`==`), not a single equal sign (`=`). The latter symbol is for assignment.

The result of the comparison is a Boolean value: `true` or `false`. For example, the following statement displays `true`:

```
double radius = 1;
System.out.println(radius > 0);
```

Boolean variable

A variable that holds a Boolean value is known as a *Boolean variable*. The `boolean` data type is used to declare Boolean variables. A `boolean` variable can hold one of the

two values: `true` or `false`. For example, the following statement assigns `true` to the variable `lightsOn`:

```
boolean lightsOn = true;
```

`true` and `false` are literals, just like a number such as `10`. They are treated as reserved words and cannot be used as identifiers in the program.

Suppose you want to develop a program to let a first-grader practice addition. The program randomly generates two single-digit integers, `number1` and `number2`, and displays to the student a question such as “What is $1 + 7$?” as shown in the sample run in Listing 3.1. After the student types the answer, the program displays a message to indicate whether it is true or false.

There are several ways to generate random numbers. For now, generate the first integer using `System.currentTimeMillis() % 10` and the second using `System.currentTimeMillis() / 7 % 10`. Listing 3.1 gives the program. Lines 5–6 generate two numbers, `number1` and `number2`. Line 14 obtains an answer from the user. The answer is graded in line 18 using a Boolean expression `number1 + number2 == answer`.

LISTING 3.1 AdditionQuiz.java

```

1 import java.util.Scanner;
2
3 public class AdditionQuiz {
4     public static void main(String[] args) {
5         int number1 = (int)(System.currentTimeMillis() % 10);
6         int number2 = (int)(System.currentTimeMillis() / 7 % 10);
7
8         // Create a Scanner
9         Scanner input = new Scanner(System.in);
10
11        System.out.print(
12            "What is " + number1 + " + " + number2 + "? ");
13
14        int number = input.nextInt();
15
16        System.out.println(
17            number1 + " + " + number2 + " = " + answer + " is " +
18            (number1 + number2 == answer));
19    }
20 }
```

Boolean literals



VideoNote

Program addition quiz

generate number1
generate number2

show question

display result



What is $1 + 7$? 8 ↵Enter
 $1 + 7 = 8$ is true



What is $4 + 8$? 9 ↵Enter
 $4 + 8 = 9$ is false



line#	number1	number2	answer	output
5	4			
6		8		
14			9	
16				$4 + 8 = 9$ is false



- 3.1** List six relational operators.
3.2 Assuming that `x` is 1, show the result of the following Boolean expressions:

`(x > 0)`
`(x < 0)`
`(x != 0)`
`(x >= 0)`
`(x != 1)`

- 3.3** Can the following conversions involving casting be allowed? Write a test program to verify your answer.

```
boolean b = true;
i = (int)b;

int i = 1;
boolean b = (boolean)i;
```

3.3 if Statements



why `if` statement?

An `if` statement is a construct that enables a program to specify alternative paths of execution.

The preceding program displays a message such as “6 + 2 = 7 is false.” If you wish the message to be “6 + 2 = 7 is incorrect,” you have to use a selection statement to make this minor change.

Java has several types of selection statements: one-way `if` statements, two-way `if-else` statements, nested `if` statements, multi-way `if-else` statements, `switch` statements, and conditional expressions.

A one-way `if` statement executes an action if and only if the condition is `true`. The syntax for a one-way `if` statement is:

`if` statement

```
if (boolean-expression) {
    statement(s);
}
```

flowchart

The flowchart in Figure 3.1a illustrates how Java executes the syntax of an `if` statement. A *flowchart* is a diagram that describes an algorithm or process, showing the steps as boxes of various kinds, and their order by connecting these with arrows. Process operations are represented in these boxes, and arrows connecting them represent the flow of control. A diamond box denotes a Boolean condition and a rectangle box represents statements.

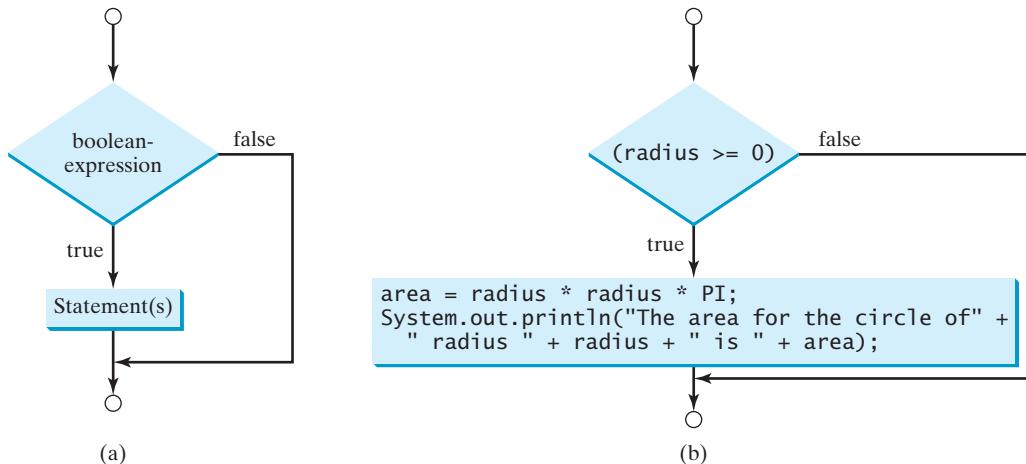


FIGURE 3.1 An `if` statement executes statements if the `boolean-expression` evaluates to `true`.

If the **boolean-expression** evaluates to **true**, the statements in the block are executed. As an example, see the following code:

```
if (radius >= 0) {
    area = radius * radius * PI;
    System.out.println("The area for the circle of radius " +
        radius + " is " + area);
}
```

The flowchart of the preceding statement is shown in Figure 3.1b. If the value of **radius** is greater than or equal to **0**, then the **area** is computed and the result is displayed; otherwise, the two statements in the block will not be executed.

The **boolean-expression** is enclosed in parentheses. For example, the code in (a) is wrong. It should be corrected, as shown in (b).

```
if i > 0 {
    System.out.println("i is positive");
}
```

(a) Wrong

```
if (i > 0) {
    System.out.println("i is positive");
}
```

(b) Correct

The block braces can be omitted if they enclose a single statement. For example, the following statements are equivalent.

```
if (i > 0) {
    System.out.println("i is positive");
}
```

(a)

Equivalent

```
if (i > 0)
    System.out.println("i is positive");
```

(b)



Note

Omitting braces makes the code shorter, but it is prone to errors. It is a common mistake to forget the braces when you go back to modify the code that omits the braces.

Omitting braces or not

Listing 3.2 gives a program that prompts the user to enter an integer. If the number is a multiple of **5**, the program displays **HiFive**. If the number is divisible by **2**, it displays **HiEven**.

LISTING 3.2 SimpleIfDemo.java

```
1 import java.util.Scanner;
2
3 public class SimpleIfDemo {
4     public static void main(String[] args) {
5         Scanner input = new Scanner(System.in);
6         System.out.println("Enter an integer: ");
7         int number = input.nextInt();                                enter input
8
9         if (number % 5 == 0)                                         check 5
10            System.out.println("HiFive");
11
12         if (number % 2 == 0)                                         check even
13            System.out.println("HiEven");
14     }
15 }
```



Enter an integer: 4 ↵ Enter
HiEven



Enter an integer: 30 ↵ Enter
HiFive
HiEven

The program prompts the user to enter an integer (lines 6–7) and displays **HiFive** if it is divisible by **5** (lines 9–10) and **HiEven** if it is divisible by **2** (lines 12–13).

Check Point

3.4 Write an **if** statement that assigns **1** to **x** if **y** is greater than **0**.

3.5 Write an **if** statement that increases pay by **3%** if **score** is greater than **90**.

Key Point

3.4 Two-Way **if-else** Statements

An **if-else** statement decides the execution path based on whether the condition is **true** or **false**.

A one-way **if** statement performs an action if the specified condition is **true**. If the condition is **false**, nothing is done. But what if you want to take alternative actions when the condition is **false**? You can use a two-way **if-else** statement. The actions that a two-way **if-else** statement specifies differ based on whether the condition is **true** or **false**.

Here is the syntax for a two-way **if-else** statement:

```
if (boolean-expression) {
    statement(s)-for-the-true-case;
}
else {
    statement(s)-for-the-false-case;
}
```

The flowchart of the statement is shown in Figure 3.2.

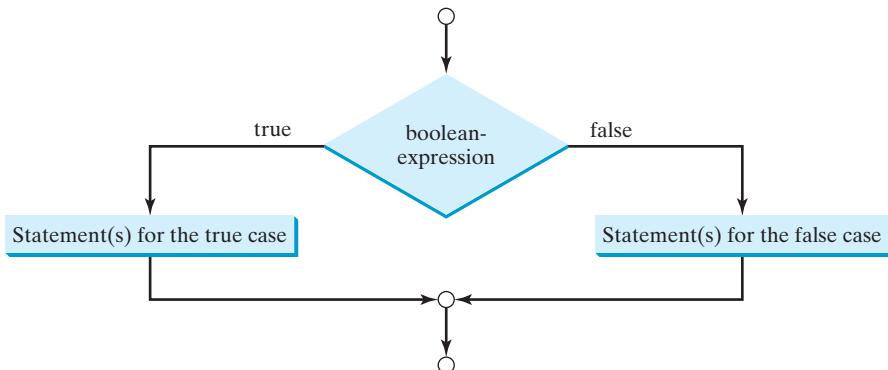


FIGURE 3.2 An **if-else** statement executes statements for the true case if the **Boolean-expression** evaluates to **true**; otherwise, statements for the false case are executed.

If the **boolean-expression** evaluates to **true**, the statement(s) for the true case are executed; otherwise, the statement(s) for the false case are executed. For example, consider the following code:

```
if (radius >= 0) {  
    area = radius * radius * PI;  
    System.out.println("The area for the circle of radius " +  
        radius + " is " + area);  
}  
else {  
    System.out.println("Negative input");  
}
```

two-way **if-else** statement

If **radius >= 0** is **true**, **area** is computed and displayed; if it is **false**, the message "**Negative input**" is displayed.

As usual, the braces can be omitted if there is only one statement within them. The braces enclosing the **System.out.println("Negative input")** statement can therefore be omitted in the preceding example.

Here is another example of using the **if-else** statement. The example checks whether a number is even or odd, as follows:

```
if (number % 2 == 0)  
    System.out.println(number + " is even.");  
else  
    System.out.println(number + " is odd.");
```

- 3.6** Write an **if** statement that increases **pay** by 3% if **score** is greater than **90**, otherwise increases **pay** by 1%.
- 3.7** What is the output of the code in (a) and (b) if **number** is **30**? What if **number** is **35**?



```
if (number % 2 == 0)  
    System.out.println(number + " is even.");  
  
System.out.println(number + " is odd.");
```

(a)

```
if (number % 2 == 0)  
    System.out.println(number + " is even.");  
else  
    System.out.println(number + " is odd.");
```

(b)



nested **if** statement

3.5 Nested **if** and Multi-Way **if-else** Statements

An **if** statement can be inside another **if** statement to form a nested **if** statement.

The statement in an **if** or **if-else** statement can be any legal Java statement, including another **if** or **if-else** statement. The inner **if** statement is said to be *nested* inside the outer **if** statement. The inner **if** statement can contain another **if** statement; in fact, there is no limit to the depth of the nesting. For example, the following is a nested **if** statement:

```
if (i > k) {  
    if (j > k)  
        System.out.println("i and j are greater than k");  
    }  
else  
    System.out.println("i is less than or equal to k");
```

The **if (j > k)** statement is nested inside the **if (i > k)** statement.

The nested **if** statement can be used to implement multiple alternatives. The statement given in Figure 3.3a, for instance, prints a letter grade according to the score, with multiple alternatives.

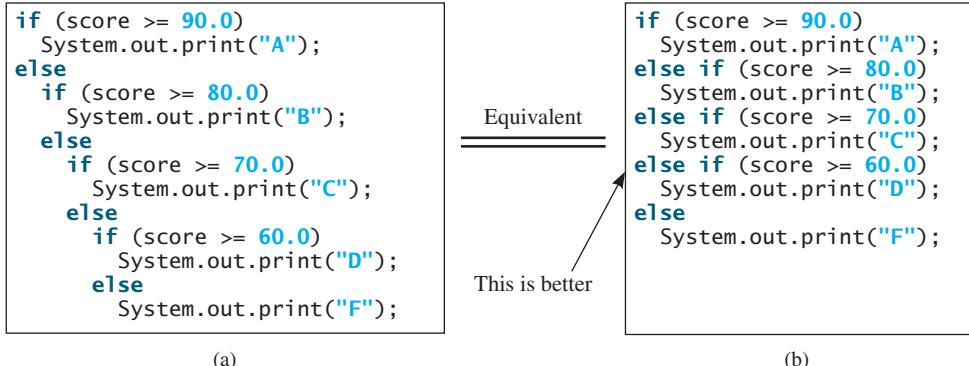


FIGURE 3.3 A preferred format for multiple alternatives is shown in (b) using a multi-way **if-else** statement.

The execution of this **if** statement proceeds as shown in Figure 3.4. The first condition (`score >= 90.0`) is tested. If it is **true**, the grade is **A**. If it is **false**, the second condition (`score >= 80.0`) is tested. If the second condition is **true**, the grade is **B**. If that condition is **false**, the third condition and the rest of the conditions (if necessary) are tested until a condition is met or all of the conditions prove to be **false**. If all of the conditions are **false**, the grade is **F**. Note that a condition is tested only when all of the conditions that come before it are **false**.

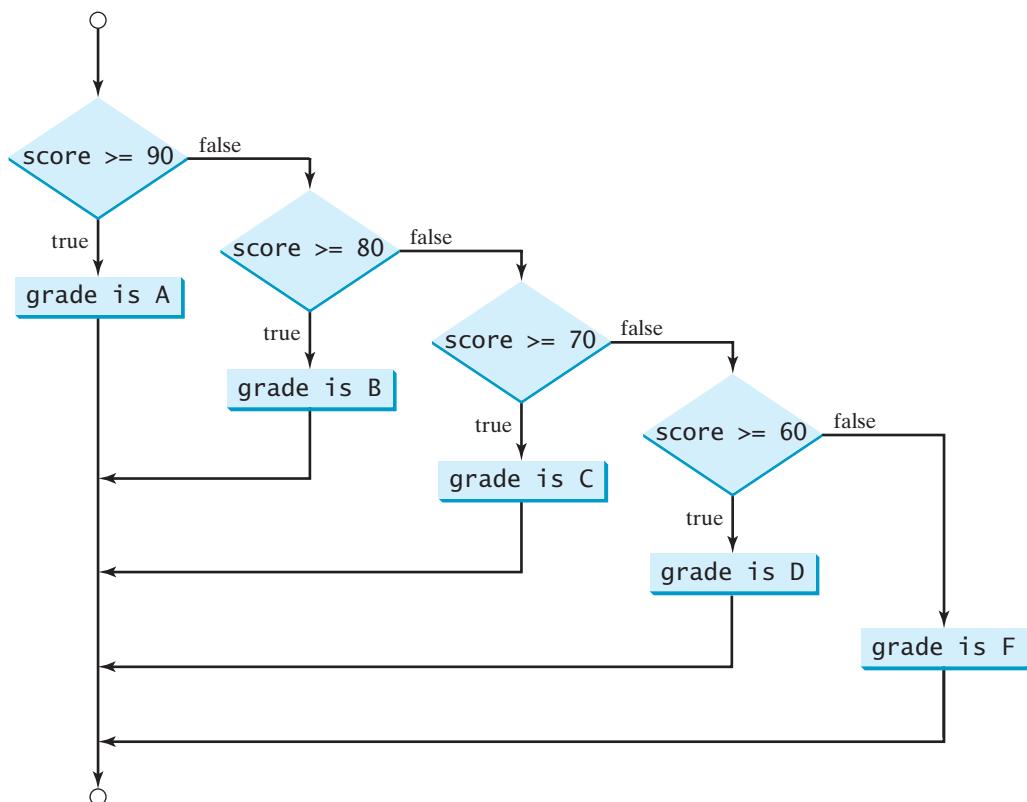


FIGURE 3.4 You can use a multi-way **if-else** statement to assign a grade.

The **if** statement in Figure 3.3a is equivalent to the **if** statement in Figure 3.3b. In fact, Figure 3.3b is the preferred coding style for multiple alternative **if** statements. This style, called *multi-way if-else statements*, avoids deep indentation and makes the program easy to read.

multi-way if statement

- 3.8** Suppose **x = 3** and **y = 2**; show the output, if any, of the following code. What is the output if **x = 3** and **y = 4**? What is the output if **x = 2** and **y = 2**? Draw a flowchart of the code.



```
if (x > 2) {
    if (y > 2) {
        z = x + y;
        System.out.println("z is " + z);
    }
}
else
    System.out.println("x is " + x);
```

- 3.9** Suppose **x = 2** and **y = 3**. Show the output, if any, of the following code. What is the output if **x = 3** and **y = 2**? What is the output if **x = 3** and **y = 3**?

```
if (x > 2)
    if (y > 2) {
        int z = x + y;
        System.out.println("z is " + z);
    }
else
    System.out.println("x is " + x);
```

- 3.10** What is wrong in the following code?

```
if (score >= 60.0)
    System.out.println("D");
else if (score >= 70.0)
    System.out.println("C");
else if (score >= 80.0)
    System.out.println("B");
else if (score >= 90.0)
    System.out.println("A");
else
    System.out.println("F");
```

3.6 Common Errors and Pitfalls

Forgetting necessary braces, ending an if statement in the wrong place, mistaking == for =, and dangling else clauses are common errors in selection statements.



Duplicated statements in if-else statements and testing equality of double values are common pitfalls.

The following errors are common among new programmers.

Common Error 1: Forgetting Necessary Braces

The braces can be omitted if the block contains a single statement. However, forgetting the braces when they are needed for grouping multiple statements is a common programming error. If you modify the code by adding new statements in an **if** statement without braces, you will have to insert the braces. For example, the following code in (a) is wrong. It should be written with braces to group multiple statements, as shown in (b).

```
if (radius >= 0)
    area = radius * radius * PI;
    System.out.println("The area "
        + " is " + area);
```

(a) Wrong

```
if (radius >= 0) {
    area = radius * radius * PI;
    System.out.println("The area "
        + " is " + area);
}
```

(b) Correct

Common Error 2: Wrong Semicolon at the `if` Line

Adding a semicolon at the end of an `if` line, as shown in (a) below, is a common mistake.

Logic error

```
if (radius >= 0); {
    area = radius * radius * PI;
    System.out.println("The area "
        + " is " + area);
}
```

(a)

Equivalent

Empty block

```
if (radius >= 0) {};
{
    area = radius * radius * PI;
    System.out.println("The area "
        + " is " + area);
}
```

(b)

This mistake is hard to find, because it is neither a compile error nor a runtime error; it is a logic error. The code in (a) is equivalent to that in (b) with an empty block.

This error often occurs when you use the next-line block style. Using the end-of-line block style can help prevent this error.

Common Error 3: Redundant Testing of Boolean Values

To test whether a `boolean` variable is `true` or `false` in a test condition, it is redundant to use the equality testing operator like the code in (a):

```
if (even == true)
    System.out.println(
        "It is even.");
```

(a)

Equivalent

```
if (even)
    System.out.println(
        "It is even.");
```

(b)

This is better

Instead, it is better to test the `boolean` variable directly, as shown in (b). Another good reason for doing this is to avoid errors that are difficult to detect. Using the `=` operator instead of the `==` operator to compare the equality of two items in a test condition is a common error. It could lead to the following erroneous statement:

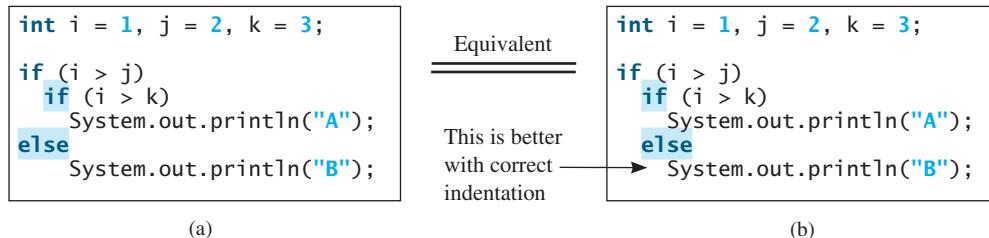
```
if (even = true)
    System.out.println("It is even.");
```

This statement does not have compile errors. It assigns `true` to `even`, so that `even` is always `true`.

Common Error 4: Dangling `else` Ambiguity

The code in (a) below has two `if` clauses and one `else` clause. Which `if` clause is matched by the `else` clause? The indentation indicates that the `else` clause matches the first `if` clause.

However, the `else` clause actually matches the second `if` clause. This situation is known as *dangling else ambiguity*. The `else` clause always matches the most recent unmatched `if` clause in the same block. So, the statement in (a) is equivalent to the code in (b).



Since `(i > j)` is false, nothing is displayed from the statements in (a) and (b). To force the `else` clause to match the first `if` clause, you must add a pair of braces:

```
int i = 1, j = 2, k = 3;  
  
if (i > j) {  
    if (i > k)  
        System.out.println("A");  
}  
else  
    System.out.println("B");
```

This statement displays **B**.

Common Error 5: Equality Test of Two Floating-Point Values

As discussed in Common Error 3 in Section 2.18, floating-point numbers have a limited precision and calculations; involving floating-point numbers can introduce round-off errors. So, equality test of two floating-point values is not reliable. For example, you expect the following code to display `true`, but surprisingly it displays `false`.

```
double x = 1.0 - 0.1 - 0.1 - 0.1 - 0.1 - 0.1 - 0.1;  
System.out.println(x == 0.5);
```

Here, `x` is not exactly **0.5**, but is **0.5000000000000001**. You cannot reliably test equality of two floating-point values. However, you can compare whether they are close enough by testing whether the difference of the two numbers is less than some threshold. That is, two numbers x and y are very close if $|x - y| < \varepsilon$ for a very small value, ε . ε , a Greek letter pronounced epsilon, is commonly used to denote a very small value. Normally, you set ε to 10^{-14} for comparing two values of the **double** type and to 10^{-7} for comparing two values of the **float** type. For example, the following code

```
final double EPSILON = 1E-14;
double x = 1.0 - 0.1 - 0.1 - 0.1 - 0.1 - 0.1;
if (Math.abs(x - 0.5) < EPSILON)
    System.out.println(x + " is approximately 0.5");
```

will display that

0.5000000000000001 is approximately 0.5

The `Math.abs(a)` method can be used to return the absolute value of `a`.

Common Pitfall 1: Simplifying Boolean Variable Assignment

Often, new programmers write the code that assigns a test condition to a **boolean** variable like the code in (a):

```
if (number % 2 == 0)
even = true;
else
even = false;
```

(a)

Equivalent
This is shorter

```
boolean even
= number % 2 == 0;
```

(b)

This is not an error, but it should be better written as shown in (b).

Common Pitfall 2: Avoiding Duplicate Code in Different Cases

Often, new programmers write the duplicate code in different cases that should be combined in one place. For example, the highlighted code in the following statement is duplicated.

```
if (inState) {
tuition = 5000;
System.out.println("The tuition is " + tuition);
}
else {
tuition = 15000;
System.out.println("The tuition is " + tuition);
}
```

This is not an error, but it should be better written as follows:

```
if (inState) {
tuition = 5000;
}
else {
tuition = 15000;
}
System.out.println("The tuition is " + tuition);
```

The new code removes the duplication and makes the code easy to maintain, because you only need to change in one place if the print statement is modified.



3.11 Which of the following statements are equivalent? Which ones are correctly indented?

```
if (i > 0) if
(j > 0)
x = 0; else
if (k > 0) y = 0;
else z = 0;
```

(a)

```
if (i > 0) {
if (j > 0)
x = 0;
else if (k > 0)
y = 0;
}
else
z = 0;
```

(b)

```
if (i > 0)
if (j > 0)
x = 0;
else if (k > 0)
y = 0;
else
z = 0;
```

(c)

```
if (i > 0)
if (j > 0)
x = 0;
else if (k > 0)
y = 0;
else
z = 0;
```

(d)

3.12 Rewrite the following statement using a Boolean expression:

```
if (count % 10 == 0)
newLine = true;
else
newLine = false;
```

3.13 Are the following statements correct? Which one is better?

```
if (age < 16)
    System.out.println
        ("Cannot get a driver's license");
if (age >= 16)
    System.out.println
        ("Can get a driver's license");
```

(a)

```
if (age < 16)
    System.out.println
        ("Cannot get a driver's license");
else
    System.out.println
        ("Can get a driver's license");
```

(b)

3.14 What is the output of the following code if **number** is 14, 15, or 30?

```
if (number % 2 == 0)
    System.out.println
        (number + " is even");
if (number % 5 == 0)
    System.out.println
        (number + " is multiple of 5");
```

(a)

```
if (number % 2 == 0)
    System.out.println
        (number + " is even");
else if (number % 5 == 0)
    System.out.println
        (number + " is multiple of 5");
```

(b)

3.7 Generating Random Numbers

You can use **Math.random()** to obtain a random double value between 0.0 and 1.0, excluding 1.0.

Suppose you want to develop a program for a first-grader to practice subtraction. The program randomly generates two single-digit integers, **number1** and **number2**, with **number1 >= number2**, and it displays to the student a question such as “What is $9 - 2$?”. After the student enters the answer, the program displays a message indicating whether it is correct.

The previous programs generate random numbers using **System.currentTimeMillis()**. A better approach is to use the **random()** method in the **Math** class. Invoking this method returns a random double value **d** such that $0.0 \leq d < 1.0$. Thus, **(int)(Math.random() * 10)** returns a random single-digit integer (i.e., a number between 0 and 9).

The program can work as follows:

1. Generate two single-digit integers into **number1** and **number2**.
2. If **number1 < number2**, swap **number1** with **number2**.
3. Prompt the student to answer, “**What is number1 - number2?**”
4. Check the student’s answer and display whether the answer is correct.

The complete program is shown in Listing 3.3.

LISTING 3.3 SubtractionQuiz.java

```
1 import java.util.Scanner;
2
3 public class SubtractionQuiz {
4     public static void main(String[] args) {
5         // 1. Generate two random single-digit integers
6         int number1 = (int)(Math.random() * 10);
7         int number2 = (int)(Math.random() * 10);
8
9         // 2. If number1 < number2, swap number1 with number2
10        if (number1 < number2) {
11            int temp = number1;
```



Key Point
Program subtraction quiz

random() method

```

12     number1 = number2;
13     number2 = temp;
14 }
15
16 // 3. Prompt the student to answer "What is number1 - number2?"
17 System.out.print
18   ("What is " + number1 + " - " + number2 + "? ");
19 Scanner input = new Scanner(System.in);
20 int answer = input.nextInt();
21
22 // 4. Grade the answer and display the result
23 if (number1 - number2 == answer)
24   System.out.println("You are correct!");
25 else {
26   System.out.println("Your answer is wrong.");
27   System.out.println(number1 + " - " + number2 +
28     " should be " + (number1 - number2));
29 }
30 }
31 }
```



What is 6 - 6? 0 ↵Enter
You are correct!



What is 9 - 2? 5 ↵Enter
Your answer is wrong
9 - 2 is 7



line#	number1	number2	temp	answer	output
6	2				
7		9			
11			2		
12	9				
13		2			
20				5	
26					Your answer is wrong 9 - 2 should be 7

To swap two variables `number1` and `number2`, a temporary variable `temp` (line 11) is used to first hold the value in `number1`. The value in `number2` is assigned to `number1` (line 12), and the value in `temp` is assigned to `number2` (line 13).



3.15 Which of the following is a possible output from invoking `Math.random()`?

`323.4, 0.5, 34, 1.0, 0.0, 0.234`

3.16 a. How do you generate a random integer `i` such that $0 \leq i < 20$?

b. How do you generate a random integer `i` such that $10 \leq i < 20$?

c. How do you generate a random integer `i` such that $10 \leq i \leq 50$?

d. Write an expression that returns `0` or `1` randomly.

3.8 Case Study: Computing Body Mass Index

You can use nested `if` statements to write a program that interprets body mass index.



Body Mass Index (BMI) is a measure of health based on height and weight. It can be calculated by taking your weight in kilograms and dividing it by the square of your height in meters. The interpretation of BMI for people 20 years or older is as follows:

BMI	Interpretation
$\text{BMI} < 18.5$	Underweight
$18.5 \leq \text{BMI} < 25.0$	Normal
$25.0 \leq \text{BMI} < 30.0$	Overweight
$30.0 \leq \text{BMI}$	Obese

Write a program that prompts the user to enter a weight in pounds and height in inches and displays the BMI. Note that one pound is **0.45359237** kilograms and one inch is **0.0254** meters. Listing 3.4 gives the program.

LISTING 3.4 ComputeAndInterpretBMI.java

```

1 import java.util.Scanner;
2
3 public class ComputeAndInterpretBMI {
4     public static void main(String[] args) {
5         Scanner input = new Scanner(System.in);
6
7         // Prompt the user to enter weight in pounds
8         System.out.print("Enter weight in pounds: ");
9         double weight = input.nextDouble();           input weight
10
11        // Prompt the user to enter height in inches
12        System.out.print("Enter height in inches: ");
13        double height = input.nextDouble();          input height
14
15        final double KILOGRAMS_PER_POUND = 0.45359237; // Constant
16        final double METERS_PER_INCH = 0.0254; // Constant
17
18        // Compute BMI
19        double weightInKilograms = weight * KILOGRAMS_PER_POUND;
20        double heightInMeters = height * METERS_PER_INCH;      compute bmi
21        double bmi = weightInKilograms /
22            (heightInMeters * heightInMeters);
23
24        // Display result
25        System.out.println("BMI is " + bmi);                  display output
26        if (bmi < 18.5)
27            System.out.println("Underweight");
28        else if (bmi < 25)
29            System.out.println("Normal");
30        else if (bmi < 30)
31            System.out.println("Overweight");
32        else
33            System.out.println("Obese");
34    }
35 }
```



Enter weight in pounds: 146

Enter height in inches: 70

BMI is 20.948603801493316

Normal



line#	weight	height	weightInKilograms	heightInMeters	bmi	output
9	146					
13		70				
19			66.22448602			
20				1.778		
21					20.9486	
25						BMI is 20.95
31						Normal

The constants `KILOGRAMS_PER_POUND` and `METERS_PER_INCH` are defined in lines 15–16. Using constants here makes programs easy to read.

test all cases

You should test the input that covers all possible cases for BMI to ensure that the program works for all cases.

3.9 Case Study: Computing Taxes



You can use nested if statements to write a program for computing taxes.



VideoNote

Use multi-way if-else statements

The United States federal personal income tax is calculated based on filing status and taxable income. There are four filing statuses: single filers, married filing jointly or qualified widow(er), married filing separately, and head of household. The tax rates vary every year. Table 3.2 shows the rates for 2009. If you are, say, single with a taxable income of \$10,000, the first \$8,350 is taxed at 10% and the other \$1,650 is taxed at 15%, so, your total tax is \$1,082.50.

TABLE 3.2 2009 U.S. Federal Personal Tax Rates

Marginal Tax Rate	Single	Married Filing Jointly or Qualifying Widow(er)	Married Filing Separately	Head of Household
10%	\$0 – \$8,350	\$0 – \$16,700	\$0 – \$8,350	\$0 – \$11,950
15%	\$8,351 – \$33,950	\$16,701 – \$67,900	\$8,351 – \$33,950	\$11,951 – \$45,500
25%	\$33,951 – \$82,250	\$67,901 – \$137,050	\$33,951 – \$68,525	\$45,501 – \$117,450
28%	\$82,251 – \$171,550	\$137,051 – \$208,850	\$68,526 – \$104,425	\$117,451 – \$190,200
33%	\$171,551 – \$372,950	\$208,851 – \$372,950	\$104,426 – \$186,475	\$190,201 – \$372,950
35%	\$372,951+	\$372,951+	\$186,476+	\$372,951+

You are to write a program to compute personal income tax. Your program should prompt the user to enter the filing status and taxable income and compute the tax. Enter **0** for single filers, **1** for married filing jointly or qualified widow(er), **2** for married filing separately, and **3** for head of household.

Your program computes the tax for the taxable income based on the filing status. The filing status can be determined using `if` statements outlined as follows:

```

if (status == 0) {
    // Compute tax for single filers
}
else if (status == 1) {
    // Compute tax for married filing jointly or qualifying widow(er)
}
else if (status == 2) {
    // Compute tax for married filing separately
}
else if (status == 3) {
    // Compute tax for head of household
}
else {
    // Display wrong status
}

```

For each filing status there are six tax rates. Each rate is applied to a certain amount of taxable income. For example, of a taxable income of \$400,000 for single filers, \$8,350 is taxed at 10%, $(33,950 - 8,350)$ at 15%, $(82,250 - 33,950)$ at 25%, $(171,550 - 82,250)$ at 28%, $(372,950 - 171,550)$ at 33%, and $(400,000 - 372,950)$ at 35%.

Listing 3.5 gives the solution for computing taxes for single filers. The complete solution is left as an exercise.

LISTING 3.5 ComputeTax.java

```

1 import java.util.Scanner;
2
3 public class ComputeTax {
4     public static void main(String[] args) {
5         // Create a Scanner
6         Scanner input = new Scanner(System.in);
7
8         // Prompt the user to enter filing status
9         System.out.print("(0-single filer, 1-married jointly or " +
10             "qualifying widow(er), 2-married separately, 3-head of " +
11             "household) Enter the filing status: ");
12
13     int status = input.nextInt();                                input status
14
15     // Prompt the user to enter taxable income
16     System.out.print("Enter the taxable income: ");
17     double income = input.nextDouble();                         input income
18
19     // Compute tax
20     double tax = 0;                                            compute tax
21
22     if (status == 0) { // Compute tax for single filers
23         if (income <= 8350)
24             tax = income * 0.10;
25         else if (income <= 33950)
26             tax = 8350 * 0.10 + (income - 8350) * 0.15;
27         else if (income <= 82250)
28             tax = 8350 * 0.10 + (33950 - 8350) * 0.15 +
29                 (income - 33950) * 0.25;
30         else if (income <= 171550)
31             tax = 8350 * 0.10 + (33950 - 8350) * 0.15 +
32                 (82250 - 33950) * 0.25 + (income - 82250) * 0.28;

```

```

33     else if (income <= 372950)
34         tax = 8350 * 0.10 + (33950 - 8350) * 0.15 +
35             (82250 - 33950) * 0.25 + (171550 - 82250) * 0.28 +
36             (income - 171550) * 0.33;
37     else
38         tax = 8350 * 0.10 + (33950 - 8350) * 0.15 +
39             (82250 - 33950) * 0.25 + (171550 - 82250) * 0.28 +
40             (372950 - 171550) * 0.33 + (income - 372950) * 0.35;
41 }
42 else if (status == 1) { // Left as an exercise
43     // Compute tax for married file jointly or qualifying widow(er)
44 }
45 else if (status == 2) { // Compute tax for married separately
46     // Left as an exercise
47 }
48 else if (status == 3) { // Compute tax for head of household
49     // Left as an exercise
50 }
51 else {
52     System.out.println("Error: invalid status");
53     System.exit(1);
54 }
55
56 // Display the result
57 System.out.println("Tax is " + (int)(tax * 100) / 100.0);
58 }
59 }
```

exit program

display output



(0-single filer, 1-married jointly or qualifying widow(er),
2-married separately, 3-head of household)
Enter the filing status: 0 ↵ Enter
Enter the taxable income: 400000 ↵ Enter
Tax is 117683.5



line#	status	income	tax	output
13	0			
17		400000		
20			0	
38			117683.5	
57				Tax is 117683.5

The program receives the filing status and taxable income. The multi-way **if-else** statements (lines 22, 42, 45, 48, 51) check the filing status and compute the tax based on the filing status.

System.exit(status) (line 53) is defined in the **System** class. Invoking this method terminates the program. The status **0** indicates that the program is terminated normally. A nonzero status code indicates abnormal termination.

An initial value of **0** is assigned to **tax** (line 20). A compile error would occur if it had no initial value, because all of the other statements that assign values to **tax** are within the **if** statement. The compiler thinks that these statements may not be executed and therefore reports a compile error.

System.exit(status)

To test a program, you should provide the input that covers all cases. For this program, your input should cover all statuses (0, 1, 2, 3). For each status, test the tax for each of the six brackets. So, there are a total of 24 cases.

**Tip**

For all programs, you should write a small amount of code and test it before moving on to add more code. This is called *incremental development and testing*. This approach makes testing easier, because the errors are likely in the new code you just added.

test all cases

incremental development and testing

3.17 Are the following two statements equivalent?



```
if (income <= 10000)
    tax = income * 0.1;
else if (income <= 20000)
    tax = 1000 +
        (income - 10000) * 0.15;
```

```
if (income <= 10000)
    tax = income * 0.1;
else if (income > 10000 &&
         income <= 20000)
    tax = 1000 +
        (income - 10000) * 0.15;
```

3.10 Logical Operators

The logical operators !, &&, ||, and ^ can be used to create a compound Boolean expression.



Sometimes, whether a statement is executed is determined by a combination of several conditions. You can use logical operators to combine these conditions to form a compound Boolean expression. *Logical operators*, also known as *Boolean operators*, operate on Boolean values to create a new Boolean value. Table 3.3 lists the Boolean operators. Table 3.4 defines the not (!) operator, which negates true to false and false to true. Table 3.5 defines the and (&&) operator. The and (&&) of two Boolean operands is true if and only if both operands are true. Table 3.6 defines the or (||) operator. The or (||) of two Boolean operands is true if at least one of the operands is true. Table 3.7 defines the exclusive or (^) operator. The exclusive or (^) of two Boolean operands is true if and only if the two operands have different Boolean values. Note that p1 ^ p2 is the same as p1 != p2.

TABLE 3.3 Boolean Operators

Operator	Name	Description
!	not	logical negation
&&	and	logical conjunction
	or	logical disjunction
^	exclusive or	logical exclusion

TABLE 3.4 Truth Table for Operator !

p	!p	Example (assume age = 24, weight = 140)
true	false	!(age > 18) is false, because (age > 18) is true.
false	true	!(weight == 150) is true, because (weight == 150) is false.

TABLE 3.5 Truth Table for Operator **&&**

p₁	p₂	p₁ && p₂	<i>Example (assume age = 24, weight = 140)</i>
false	false	false	
false	true	false	<code>(age > 28) && (weight <= 140)</code> is false , because <code>(age > 28)</code> is false .
true	false	false	
true	true	true	<code>(age > 18) && (weight >= 140)</code> is true , because <code>(age > 18)</code> and <code>(weight >= 140)</code> are both true .

TABLE 3.6 Truth Table for Operator **||**

p₁	p₂	p₁ p₂	<i>Example (assume age = 24, weight = 140)</i>
false	false	false	<code>(age > 34) (weight >= 150)</code> is false , because <code>(age > 34)</code> and <code>(weight >= 150)</code> are both false .
false	true	true	
true	false	true	<code>(age > 18) (weight < 140)</code> is true , because <code>(age > 18)</code> is true .
true	true	true	

TABLE 3.7 Truth Table for Operator **^**

p₁	p₂	p₁ ^ p₂	<i>Example (assume age = 24, weight = 140)</i>
false	false	false	<code>(age > 34) ^ (weight > 140)</code> is false , because <code>(age > 34)</code> and <code>(weight > 140)</code> are both false .
false	true	true	<code>(age > 34) ^ (weight >= 140)</code> is true , because <code>(age > 34)</code> is false but <code>(weight >= 140)</code> is true .
true	false	true	
true	true	false	

Listing 3.6 gives a program that checks whether a number is divisible by 2 and 3, by 2 or 3, and by 2 or 3 but not both:

LISTING 3.6 TestBooleanOperators.java

```

import class
1 import java.util.Scanner;
2
3 public class TestBooleanOperators {
4     public static void main(String[] args) {
5         // Create a Scanner
6         Scanner input = new Scanner(System.in);
7
8         // Receive an input
9         System.out.print("Enter an integer: ");
10        int number = input.nextInt();
11
12        if (number % 2 == 0 && number % 3 == 0)
13            System.out.println(number + " is divisible by 2 and 3.");
14

```

input
and

```

15  if (number % 2 == 0 || number % 3 == 0)
16      System.out.println(number + " is divisible by 2 or 3.");
17
18  if (number % 2 == 0 ^ number % 3 == 0)
19      System.out.println(number +
20          " is divisible by 2 or 3, but not both.");
21 }
22 }
```

or

exclusive or

Enter an integer: 4 
4 is divisible by 2 or 3.
4 is divisible by 2 or 3, but not both.



Enter an integer: 18 
18 is divisible by 2 and 3.
18 is divisible by 2 or 3.



`(number % 2 == 0 && number % 3 == 0)` (line 12) checks whether the number is divisible by both 2 and 3. `(number % 2 == 0 || number % 3 == 0)` (line 15) checks whether the number is divisible by 2 or by 3. `(number % 2 == 0 ^ number % 3 == 0)` (line 18) checks whether the number is divisible by 2 or 3, but not both.



Caution

In mathematics, the expression

`1 <= numberOfDaysInAMonth <= 31`

is correct. However, it is incorrect in Java, because `1 <= numberOfDaysInAMonth` is evaluated to a `boolean` value, which cannot be compared with `31`. Here, two operands (a `boolean` value and a numeric value) are *incompatible*. The correct expression in Java is

`(1 <= numberOfDaysInAMonth) && (numberOfDaysInAMonth <= 31)`

incompatible operands



Note

De Morgan's law, named after Indian-born British mathematician and logician Augustus De Morgan (1806–1871), can be used to simplify Boolean expressions. The law states:

`!(condition1 && condition2)` is the same as
`!condition1 || !condition2`
`!(condition1 || condition2)` is the same as
`!condition1 && !condition2`

For example,

`!(number % 2 == 0 && number % 3 == 0)`

De Morgan's law

can be simplified using an equivalent expression:

`(number % 2 != 0 || number % 3 != 0)`

As another example,

`!(number == 2 || number == 3)`

is better written as

`number != 2 && number != 3`

short-circuit operator
lazy operator

If one of the operands of an `&&` operator is `false`, the expression is `false`; if one of the operands of an `||` operator is `true`, the expression is `true`. Java uses these properties to improve the performance of these operators. When evaluating `p1 && p2`, Java first evaluates `p1` and then, if `p1` is `true`, evaluates `p2`; if `p1` is `false`, it does not evaluate `p2`. When evaluating `p1 || p2`, Java first evaluates `p1` and then, if `p1` is `false`, evaluates `p2`; if `p1` is `true`, it does not evaluate `p2`. In programming language terminology, `&&` and `||` are known as the *short-circuit* or *lazy* operators. Java also provides the unconditional AND (`&`) and OR (`|`) operators, which are covered in Supplement III.C for advanced readers.



- 3.18** Assuming that `x` is `1`, show the result of the following Boolean expressions.

```
(true) && (3 > 4)
!(x > 0) && (x > 0)
(x > 0) || (x < 0)

(x != 0) || (x == 0)
(x >= 0) || (x < 0)
(x != 1) == !(x == 1)
```

- 3.19** (a) Write a Boolean expression that evaluates to `true` if a number stored in variable `num` is between `1` and `100`. (b) Write a Boolean expression that evaluates to `true` if a number stored in variable `num` is between `1` and `100` or the number is negative.
- 3.20** (a) Write a Boolean expression for $|x - 5| < 4.5$. (b) Write a Boolean expression for $|x - 5| > 4.5$.
- 3.21** Assume that `x` and `y` are `int` type. Which of the following are legal Java expressions?

```
x > y > 0
x = y && y
x /= y
x or y
x and y
(x != 0) || (x = 0)
```

- 3.22** Are the following two expressions the same?

a. `x % 2 == 0 && x % 3 == 0`
 b. `x % 6 == 0`

- 3.23** What is the value of the expression `x >= 50 && x <= 100` if `x` is `45`, `67`, or `101`?
3.24 Suppose, when you run the following program, you enter the input `2 3 6` from the console. What is the output?

```
public class Test {
    public static void main(String[] args) {
        java.util.Scanner input = new java.util.Scanner(System.in);
        double x = input.nextDouble();
        double y = input.nextDouble();
        double z = input.nextDouble();

        System.out.println("(x < y && y < z) is " + (x < y && y < z));
        System.out.println("(x < y || y < z) is " + (x < y || y < z));
        System.out.println("!(x < y) is " + !(x < y));
        System.out.println("(x + y < z) is " + (x + y < z));
        System.out.println("(x + y > z) is " + (x + y > z));
    }
}
```

- 3.25** Write a Boolean expression that evaluates to `true` if `age` is greater than `13` and less than `18`.

- 3.26** Write a Boolean expression that evaluates to **true** if **weight** is greater than **50** pounds or height is greater than **60** inches.
- 3.27** Write a Boolean expression that evaluates to **true** if **weight** is greater than **50** pounds and height is greater than **60** inches.
- 3.28** Write a Boolean expression that evaluates to **true** if either **weight** is greater than **50** pounds or height is greater than **60** inches, but not both.

3.11 Case Study: Determining Leap Year

A year is a leap year if it is divisible by 4 but not by 100, or if it is divisible by 400.

You can use the following Boolean expressions to check whether a year is a leap year:



```
// A leap year is divisible by 4
boolean isLeapYear = (year % 4 == 0);

// A leap year is divisible by 4 but not by 100
isLeapYear = isLeapYear && (year % 100 != 0);

// A leap year is divisible by 4 but not by 100 or divisible by 400
isLeapYear = isLeapYear || (year % 400 == 0);
```

Or you can combine all these expressions into one like this:

```
isLeapYear = (year % 4 == 0 && year % 100 != 0) || (year % 400 == 0);
```

Listing 3.7 gives the program that lets the user enter a year and checks whether it is a leap year.

LISTING 3.7 LeapYear.java

```
1 import java.util.Scanner;
2
3 public class LeapYear {
4     public static void main(String[] args) {
5         // Create a Scanner
6         Scanner input = new Scanner(System.in);
7         System.out.print("Enter a year: ");
8         int year = input.nextInt();                                input
9
10        // Check if the year is a leap year
11        boolean isLeapYear =                                         leap year?
12            (year % 4 == 0 && year % 100 != 0) || (year % 400 == 0);
13
14        // Display the result
15        System.out.println(year + " is a leap year? " + isLeapYear);    display result
16    }
17 }
```

Enter a year: 2008 ↵Enter
2008 is a leap year? true



Enter a year: 1900 ↵Enter
1900 is a leap year? false





Enter a year: 2002

2002 is a leap year? false



3.12 Case Study: Lottery

The lottery program involves generating random numbers, comparing digits, and using Boolean operators.

Suppose you want to develop a program to play lottery. The program randomly generates a lottery of a two-digit number, prompts the user to enter a two-digit number, and determines whether the user wins according to the following rules:

1. If the user input matches the lottery number in the exact order, the award is \$10,000.
2. If all digits in the user input match all digits in the lottery number, the award is \$3,000.
3. If one digit in the user input matches a digit in the lottery number, the award is \$1,000.

Note that the digits of a two-digit number may be **0**. If a number is less than **10**, we assume the number is preceded by a **0** to form a two-digit number. For example, number **8** is treated as **08** and number **0** is treated as **00** in the program. Listing 3.8 gives the complete program.

LISTING 3.8 Lottery.java

generate a lottery number

enter a guess

exact match?

match all digits?

match one digit?

```

1 import java.util.Scanner;
2
3 public class Lottery {
4     public static void main(String[] args) {
5         // Generate a lottery number
6         int lottery = (int)(Math.random() * 100);
7
8         // Prompt the user to enter a guess
9         Scanner input = new Scanner(System.in);
10        System.out.print("Enter your lottery pick (two digits): ");
11        int guess = input.nextInt();
12
13        // Get digits from lottery
14        int lotteryDigit1 = lottery / 10;
15        int lotteryDigit2 = lottery % 10;
16
17        // Get digits from guess
18        int guessDigit1 = guess / 10;
19        int guessDigit2 = guess % 10;
20
21        System.out.println("The lottery number is " + lottery);
22
23        // Check the guess
24        if (guess == lottery)
25            System.out.println("Exact match: you win $10,000");
26        else if (guessDigit2 == lotteryDigit1
27                  && guessDigit1 == lotteryDigit2)
28            System.out.println("Match all digits: you win $3,000");
29        else if (guessDigit1 == lotteryDigit1
30                  || guessDigit1 == lotteryDigit2
31                  || guessDigit2 == lotteryDigit1
32                  || guessDigit2 == lotteryDigit2)
33            System.out.println("Match one digit: you win $1,000");

```

```

34     else
35         System.out.println("Sorry, no match");
36     }
37 }
```

Enter your lottery pick (two digits): 15

The lottery number is 15

Exact match: you win \$10,000



Enter your lottery pick (two digits): 45

The lottery number is 54

Match all digits: you win \$3,000



Enter your lottery pick: 23

The lottery number is 34

Match one digit: you win \$1,000



Enter your lottery pick: 23

The lottery number is 14

Sorry: no match



variable	line#	6	11	14	15	18	19	33
lottery		34						
guess			23					
lotteryDigit1				3				
lotteryDigit2					4			
guessDigit1						2		
guessDigit2							3	
Output								Match one digit: you win \$1,000



The program generates a lottery using the `random()` method (line 6) and prompts the user to enter a guess (line 11). Note that `guess % 10` obtains the last digit from `guess` and `guess / 10` obtains the first digit from `guess`, since `guess` is a two-digit number (lines 18–19).

The program checks the guess against the lottery number in this order:

1. First, check whether the guess matches the lottery exactly (line 24).
2. If not, check whether the reversal of the guess matches the lottery (lines 26–27).
3. If not, check whether one digit is in the lottery (lines 29–32).
4. If not, nothing matches and display "Sorry, no match" (lines 34–35).

3.13 switch Statements



A **switch** statement executes statements based on the value of a variable or an expression.

The **if** statement in Listing 3.5, ComputeTax.java, makes selections based on a single **true** or **false** condition. There are four cases for computing taxes, which depend on the value of **status**. To fully account for all the cases, nested **if** statements were used. Overuse of nested **if** statements makes a program difficult to read. Java provides a **switch** statement to simplify coding for multiple conditions. You can write the following **switch** statement to replace the nested **if** statement in Listing 3.5:

```
switch (status) {
    case 0: compute tax for single filers;
    break;
    case 1: compute tax for married jointly or qualifying widow(er);
    break;
    case 2: compute tax for married filing separately;
    break;
    case 3: compute tax for head of household;
    break;
    default: System.out.println("Error: invalid status");
        System.exit(1);
}
```

The flowchart of the preceding **switch** statement is shown in Figure 3.5.

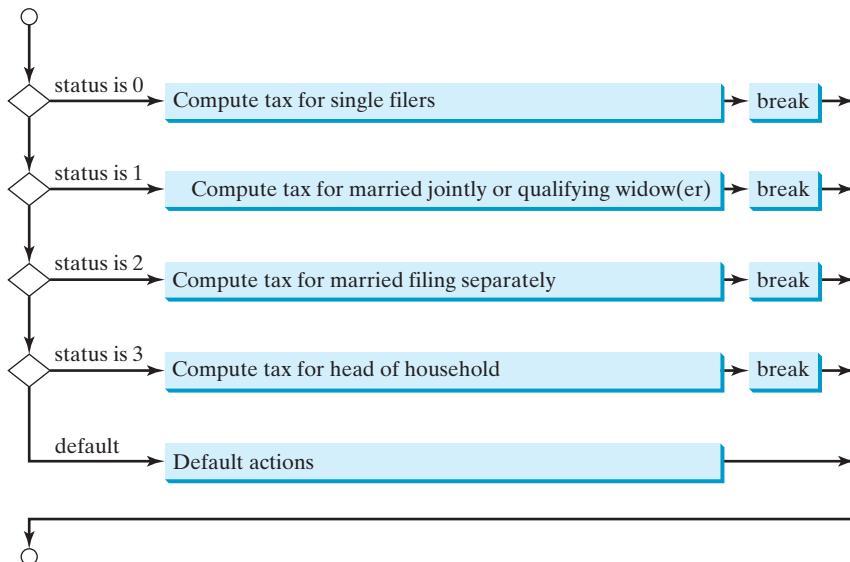


FIGURE 3.5 The **switch** statement checks all cases and executes the statements in the matched case.

This statement checks to see whether the status matches the value **0**, **1**, **2**, or **3**, in that order. If matched, the corresponding tax is computed; if not matched, a message is displayed. Here is the full syntax for the **switch** statement:

```
switch (switch-expression) {
    case value1: statement(s)1;
    break;
```

```

case value2: statement(s)2;
    break;
...
case valueN: statement(s)N;
    break;
default:     statement(s)-for-default;
}

```

The **switch** statement observes the following rules:

- The **switch-expression** must yield a value of **char**, **byte**, **short**, **int**, or **String** type and must always be enclosed in parentheses. (The **char** and **String** types will be introduced in the next chapter.)
- The **value1**, . . . , and **valueN** must have the same data type as the value of the **switch-expression**. Note that **value1**, . . . , and **valueN** are constant expressions, meaning that they cannot contain variables, such as **1 + x**.
- When the value in a **case** statement matches the value of the **switch-expression**, the statements *starting from this case* are executed until either a **break** statement or the end of the **switch** statement is reached.
- The **default** case, which is optional, can be used to perform actions when none of the specified cases matches the **switch-expression**.
- The keyword **break** is optional. The **break** statement immediately ends the **switch** statement.



Caution

Do not forget to use a **break** statement when one is needed. Once a case is matched, the statements starting from the matched case are executed until a **break** statement or the end of the **switch** statement is reached. This is referred to as *fall-through* behavior. For example, the following code displays **Weekdays** for day of **1** to **5** and **Weekends** for day **0** and **6**.

without break

fall-through behavior

```

switch (day) {
    case 1:
    case 2:
    case 3:
    case 4:
    case 5: System.out.println("Weekday"); break;
    case 0:
    case 6: System.out.println("Weekend");
}

```



Tip

To avoid programming errors and improve code maintainability, it is a good idea to put a comment in a case clause if **break** is purposely omitted.

Now let us write a program to find out the Chinese Zodiac sign for a given year. The Chinese Zodiac is based on a twelve-year cycle, with each year represented by an animal—monkey, rooster, dog, pig, rat, ox, tiger, rabbit, dragon, snake, horse, or sheep—in this cycle, as shown in Figure 3.6.

Note that **year % 12** determines the Zodiac sign. 1900 is the year of the rat because **1900 % 12** is **4**. Listing 3.9 gives a program that prompts the user to enter a year and displays the animal for the year.

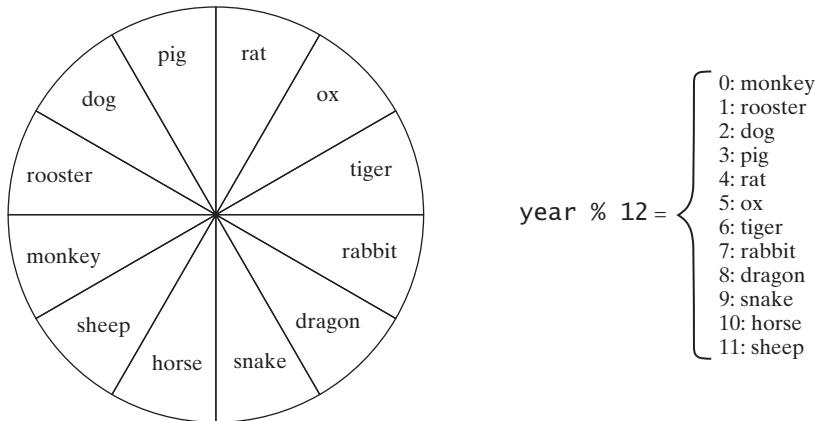


FIGURE 3.6 The Chinese Zodiac is based on a twelve-year cycle.

LISTING 3.9 ChineseZodiac.java

```

1 import java.util.Scanner;
2
3 public class ChineseZodiac {
4     public static void main(String[] args) {
5         Scanner input = new Scanner(System.in);
6
7         System.out.print("Enter a year: ");
8         int year = input.nextInt();
9
10        switch (year % 12) {
11            case 0: System.out.println("monkey"); break;
12            case 1: System.out.println("rooster"); break;
13            case 2: System.out.println("dog"); break;
14            case 3: System.out.println("pig"); break;
15            case 4: System.out.println("rat"); break;
16            case 5: System.out.println("ox"); break;
17            case 6: System.out.println("tiger"); break;
18            case 7: System.out.println("rabbit"); break;
19            case 8: System.out.println("dragon"); break;
20            case 9: System.out.println("snake"); break;
21            case 10: System.out.println("horse"); break;
22            case 11: System.out.println("sheep");
23        }
24    }
25 }
```



Enter a year: 1963 ↵Enter
rabbit



Enter a year: 1877 ↵Enter
ox



- 3.29** What data types are required for a **switch** variable? If the keyword **break** is not used after a case is processed, what is the next statement to be executed? Can you convert a **switch** statement to an equivalent **if** statement, or vice versa? What are the advantages of using a **switch** statement?

- 3.30** What is `y` after the following `switch` statement is executed? Rewrite the code using an `if-else` statement.

```
x = 3; y = 3;
switch (x + 3) {
    case 6: y = 1;
    default: y += 1;
}
```

- 3.31** What is `x` after the following `if-else` statement is executed? Use a `switch` statement to rewrite it and draw the flowchart for the new `switch` statement.

```
int x = 1, a = 3;
if (a == 1)
    x += 5;
else if (a == 2)
    x += 10;
else if (a == 3)
    x += 16;
else if (a == 4)
    x += 34;
```

- 3.32** Write a `switch` statement that displays Sunday, Monday, Tuesday, Wednesday, Thursday, Friday, Saturday, if `day` is `0, 1, 2, 3, 4, 5, 6`, accordingly.

3.14 Conditional Expressions

A conditional expression evaluates an expression based on a condition.

You might want to assign a value to a variable that is restricted by certain conditions. For example, the following statement assigns `1` to `y` if `x` is greater than `0`, and `-1` to `y` if `x` is less than or equal to `0`.



```
if (x > 0)
    y = 1;
else
    y = -1;
```

Alternatively, as in the following example, you can use a conditional expression to achieve the same result.

```
y = (x > 0) ? 1 : -1;
```

Conditional expressions are in a completely different style, with no explicit `if` in the statement. The syntax is:

```
boolean-expression ? expression1 : expression2;
```

The result of this conditional expression is `expression1` if `boolean-expression` is true; otherwise the result is `expression2`.

Suppose you want to assign the larger number of variable `num1` and `num2` to `max`. You can simply write a statement using the conditional expression:

```
max = (num1 > num2) ? num1 : num2;
```

For another example, the following statement displays the message “`num` is even” if `num` is even, and otherwise displays “`num` is odd.”

```
System.out.println((num % 2 == 0) ? "num is even" : "num is odd");
```

As you can see from these examples, conditional expressions enable you to write short and concise code.

conditional operator
ternary operator



Note

The symbols `?` and `:` appear together in a conditional expression. They form a *conditional operator* and also called a *ternary operator* because it uses three operands. It is the only ternary operator in Java.

- 3.33** Suppose that, when you run the following program, you enter the input `2 3 6` from the console. What is the output?

```
public class Test {
    public static void main(String[] args) {
        java.util.Scanner input = new java.util.Scanner(System.in);
        double x = input.nextDouble();
        double y = input.nextDouble();
        double z = input.nextDouble();

        System.out.println((x < y && y < z) ? "sorted" : "not sorted");
    }
}
```

- 3.34** Rewrite the following `if` statements using the conditional operator.

```
if (ages >= 16)
    ticketPrice = 20;
else
    ticketPrice = 10;
```

- 3.35** Rewrite the following conditional expressions using `if-else` statements.

- `score = (x > 10) ? 3 * scale : 4 * scale;`
- `tax = (income > 10000) ? income * 0.2 : income * 0.17 + 1000;`
- `System.out.println((number % 3 == 0) ? i : j);`

- 3.36** Write conditional expression that returns `-1` or `1` randomly.



3.15 Operator Precedence and Associativity

Operator precedence and associativity determine the order in which operators are evaluated.

Section 2.11 introduced operator precedence involving arithmetic operators. This section discusses operator precedence in more detail. Suppose that you have this expression:

`3 + 4 * 4 > 5 * (4 + 3) - 1 && (4 - 3 > 5)`

What is its value? What is the execution order of the operators?

The expression within parentheses is evaluated first. (Parentheses can be nested, in which case the expression within the inner parentheses is executed first.) When evaluating an expression without parentheses, the operators are applied according to the precedence rule and the associativity rule.

The precedence rule defines precedence for operators, as shown in Table 3.8, which contains the operators you have learned so far. Operators are listed in decreasing order of precedence from top to bottom. The logical operators have lower precedence than the relational operators and the relational operators have lower precedence than the arithmetic operators. Operators with the same precedence appear in the same group. (See Appendix C, *Operator Precedence Chart*, for a complete list of Java operators and their precedence.)

operator precedence

TABLE 3.8 Operator Precedence Chart

Precedence	Operator
	<code>var++</code> and <code>var--</code> (Postfix)
	<code>+, -</code> (Unary plus and minus), <code>++var</code> and <code>--var</code> (Prefix)
	(type) (Casting)
	<code>!</code> (Not)
	<code>*, /, %</code> (Multiplication, division, and remainder)
	<code>+, -</code> (Binary addition and subtraction)
	<code><, <=, >, >=</code> (Relational)
	<code>==, !=</code> (Equality)
	<code>^</code> (Exclusive OR)
	<code>&&</code> (AND)
	<code> </code> (OR)
	<code>=, +=, -=, *=, /=, %=</code> (Assignment operator)

If operators with the same precedence are next to each other, their *associativity* determines the order of evaluation. All binary operators except assignment operators are *left associative*. For example, since `+` and `-` are of the same precedence and are left associative, the expression

$$a - b + c - d \quad \text{is equivalent to} \quad ((a - b) + c) - d$$

Assignment operators are *right associative*. Therefore, the expression

$$a = b += c = 5 \quad \text{is equivalent to} \quad a = (b += (c = 5))$$

Suppose `a`, `b`, and `c` are `1` before the assignment; after the whole expression is evaluated, `a` becomes `6`, `b` becomes `6`, and `c` becomes `5`. Note that left associativity for the assignment operator would not make sense.



Note

Java has its own way to evaluate an expression internally. The result of a Java evaluation is the same as that of its corresponding arithmetic evaluation. Advanced readers may refer to Supplement III.B for more discussions on how an expression is evaluated in Java *behind the scenes*.

behind the scenes

- 3.37** List the precedence order of the Boolean operators. Evaluate the following expressions:

`true || true && false`
`true && true || false`



Check Point

- 3.38** True or false? All the binary operators except `=` are left associative.

- 3.39** Evaluate the following expressions:

`2 * 2 - 3 > 2 && 4 - 2 > 5`
`2 * 2 - 3 > 2 || 4 - 2 > 5`

- 3.40** Is `(x > 0 && x < 10)` the same as `((x > 0) && (x < 10))`? Is `(x > 0 || x < 10)` the same as `((x > 0) || (x < 10))`? Is `(x > 0 || x < 10 && y < 0)` the same as `(x > 0 || (x < 10 && y < 0))`?

3.16 Debugging



Debugging is the process of finding and fixing errors in a program.

bugs
debugging
hand-traces

As mentioned in Section 1.10.1, syntax errors are easy to find and easy to correct because the compiler gives indications as to where the errors came from and why they are there. Runtime errors are not difficult to find either, because the Java interpreter displays them on the console when the program aborts. Finding logic errors, on the other hand, can be very challenging.

Logic errors are called *bugs*. The process of finding and correcting errors is called *debugging*. A common approach to debugging is to use a combination of methods to help pinpoint the part of the program where the bug is located. You can *hand-trace* the program (i.e., catch errors by reading the program), or you can insert print statements in order to show the values of the variables or the execution flow of the program. These approaches might work for debugging a short, simple program, but for a large, complex program, the most effective approach is to use a debugger utility.

JDK includes a command-line debugger, `jdb`, which is invoked with a class name. `jdb` is itself a Java program, running its own copy of Java interpreter. All the Java IDE tools, such as Eclipse and NetBeans, include integrated debuggers. The debugger utilities let you follow the execution of a program. They vary from one system to another, but they all support most of the following helpful features.

- **Executing a single statement at a time:** The debugger allows you to execute one statement at a time so that you can see the effect of each statement.
- **Tracing into or stepping over a method:** If a method is being executed, you can ask the debugger to enter the method and execute one statement at a time in the method, or you can ask it to step over the entire method. You should step over the entire method if you know that the method works. For example, always step over system-supplied methods, such as `System.out.println`.
- **Setting breakpoints:** You can also set a breakpoint at a specific statement. Your program pauses when it reaches a breakpoint. You can set as many breakpoints as you want. Breakpoints are particularly useful when you know where your programming error starts. You can set a breakpoint at that statement and have the program execute until it reaches the breakpoint.
- **Displaying variables:** The debugger lets you select several variables and display their values. As you trace through a program, the content of a variable is continuously updated.
- **Displaying call stacks:** The debugger lets you trace all of the method calls. This feature is helpful when you need to see a large picture of the program-execution flow.
- **Modifying variables:** Some debuggers enable you to modify the value of a variable when debugging. This is convenient when you want to test a program with different samples but do not want to leave the debugger.



Tip

If you use an IDE such as Eclipse or NetBeans, please refer to *Learning Java Effectively with Eclipse/NetBeans* in Supplements II.C and II.E on the Companion Website. The supplement shows you how to use a debugger to trace programs and how debugging can help in learning Java effectively.

debugging in IDE

KEY TERMS

Boolean expression 76	flowchart 78
boolean data type 76	lazy operator 96
Boolean value 76	operator associativity 105
conditional operator 104	operator precedence 104
dangling else ambiguity 85	selection statement 76
debugging 106	short-circuit operator 96
fall-through behavior 101	

CHAPTER SUMMARY

1. A **boolean** type variable can store a **true** or **false** value.
2. The relational operators (**<**, **<=**, **==**, **!=**, **>**, **>=**) yield a Boolean value.
3. *Selection statements* are used for programming with alternative courses of actions. There are several types of selection statements: one-way **if** statements, two-way **if-else** statements, nested **if** statements, multi-way **if-else** statements, **switch** statements, and conditional expressions.
4. The various **if** statements all make control decisions based on a *Boolean expression*. Based on the **true** or **false** evaluation of the expression, these statements take one of two possible courses.
5. The Boolean operators **&&**, **||**, **!**, and **^** operate with Boolean values and variables.
6. When evaluating **p1 && p2**, Java first evaluates **p1** and then evaluates **p2** if **p1** is **true**; if **p1** is **false**, it does not evaluate **p2**. When evaluating **p1 || p2**, Java first evaluates **p1** and then evaluates **p2** if **p1** is **false**; if **p1** is **true**, it does not evaluate **p2**. Therefore, **&&** is referred to as the *conditional* or *short-circuit AND operator*, and **||** is referred to as the *conditional* or *short-circuit OR operator*.
7. The **switch** statement makes control decisions based on a switch expression of type **char**, **byte**, **short**, **int**, or **String**.
8. The keyword **break** is optional in a **switch** statement, but it is normally used at the end of each case in order to skip the remainder of the **switch** statement. If the **break** statement is not present, the next **case** statement will be executed.
9. The operators in expressions are evaluated in the order determined by the rules of parentheses, *operator precedence*, and *operator associativity*.
10. Parentheses can be used to force the order of evaluation to occur in any sequence.
11. Operators with higher precedence are evaluated earlier. For operators of the same precedence, their associativity determines the order of evaluation.
12. All binary operators except assignment operators are left-associative; assignment operators are right-associative.

TEST QUESTIONS

Answer the quiz for this chapter online at www.cs.armstrong.edu/liang/intro10e/quiz.html.

MyProgrammingLab™

PROGRAMMING EXERCISES

think before coding

**Pedagogical Note**

For each exercise, carefully analyze the problem requirements and design strategies for solving the problem before coding.

learn from mistakes

**Debugging Tip**

Before you ask for help, read and explain the program to yourself, and trace it using several representative inputs by hand or using an IDE debugger. You learn how to program by debugging your own mistakes.

Section 3.2

- *3.1** (*Algebra: solve quadratic equations*) The two roots of a quadratic equation $ax^2 + bx + c = 0$ can be obtained using the following formula:

$$r_1 = \frac{-b + \sqrt{b^2 - 4ac}}{2a} \quad \text{and} \quad r_2 = \frac{-b - \sqrt{b^2 - 4ac}}{2a}$$

$b^2 - 4ac$ is called the discriminant of the quadratic equation. If it is positive, the equation has two real roots. If it is zero, the equation has one root. If it is negative, the equation has no real roots.

Write a program that prompts the user to enter values for a , b , and c and displays the result based on the discriminant. If the discriminant is positive, display two roots. If the discriminant is 0, display one root. Otherwise, display “The equation has no real roots”.

Note that you can use `Math.pow(x, 0.5)` to compute \sqrt{x} . Here are some sample runs.



Enter a, b, c: 1.0 3 1 ↵Enter

The equation has two roots -0.381966 and -2.61803



Enter a, b, c: 1 2.0 1 ↵Enter

The equation has one root -1



Enter a, b, c: 1 2 3 ↵Enter

The equation has no real roots

- 3.2** (*Game: add three numbers*) The program in Listing 3.1, `AdditionQuiz.java`, generates two integers and prompts the user to enter the sum of these two integers. Revise the program to generate three single-digit integers and prompt the user to enter the sum of these three integers.

Sections 3.3–3.7

- *3.3** (*Algebra: solve 2×2 linear equations*) A linear equation can be solved using Cramer's rule given in Programming Exercise 1.13. Write a program that prompts the user to enter a , b , c , d , e , and f and displays the result. If $ad - bc$ is 0, report that “The equation has no solution.”

```
Enter a, b, c, d, e, f: 9.0 4.0 3.0 -5.0 -6.0 -21.0 ↵Enter
x is -2.0 and y is 3.0
```



```
Enter a, b, c, d, e, f: 1.0 2.0 2.0 4.0 4.0 5.0 ↵Enter
The equation has no solution
```



- **3.4** (*Random month*) Write a program that randomly generates an integer between 1 and 12 and displays the English month name January, February, ..., December for the number 1, 2, ..., 12, accordingly.

- *3.5** (*Find future dates*) Write a program that prompts the user to enter an integer for today's day of the week (Sunday is 0, Monday is 1, ..., and Saturday is 6). Also prompt the user to enter the number of days after today for a future day and display the future day of the week. Here is a sample run:

```
Enter today's day: 1 ↵Enter
Enter the number of days elapsed since today: 3 ↵Enter
Today is Monday and the future day is Thursday
```



```
Enter today's day: 0 ↵Enter
Enter the number of days elapsed since today: 31 ↵Enter
Today is Sunday and the future day is Wednesday
```



- *3.6** (*Health application: BMI*) Revise Listing 3.4, ComputeAndInterpretBMI.java, to let the user enter weight, feet, and inches. For example, if a person is 5 feet and 10 inches, you will enter 5 for feet and 10 for inches. Here is a sample run:

```
Enter weight in pounds: 140 ↵Enter
Enter feet: 5 ↵Enter
Enter inches: 10 ↵Enter
BMI is 20.087702275404553
Normal
```



- 3.7** (*Financial application: monetary units*) Modify Listing 2.10, ComputeChange.java, to display the nonzero denominations only, using singular words for single units such as 1 dollar and 1 penny, and plural words for more than one unit such as 2 dollars and 3 pennies.



VideoNote

Sort three integers

- *3.8** (*Sort three integers*) Write a program that prompts the user to enter three integers and display the integers in non-decreasing order.

- **3.9** (*Business: check ISBN-10*) An **ISBN-10** (International Standard Book Number) consists of 10 digits: $d_1d_2d_3d_4d_5d_6d_7d_8d_9d_{10}$. The last digit, d_{10} , is a checksum, which is calculated from the other nine digits using the following formula:

$$(d_1 \times 1 + d_2 \times 2 + d_3 \times 3 + d_4 \times 4 + d_5 \times 5 + \\ d_6 \times 6 + d_7 \times 7 + d_8 \times 8 + d_9 \times 9) \% 11$$

If the checksum is **10**, the last digit is denoted as X according to the ISBN-10 convention. Write a program that prompts the user to enter the first 9 digits and displays the 10-digit ISBN (including leading zeros). Your program should read the input as an integer. Here are sample runs:



Enter the first 9 digits of an ISBN as integer: 013601267
The ISBN-10 number is 0136012671



Enter the first 9 digits of an ISBN as integer: 013031997
The ISBN-10 number is 013031997X

- 3.10** (*Game: addition quiz*) Listing 3.3, SubtractionQuiz.java, randomly generates a subtraction question. Revise the program to randomly generate an addition question with two integers less than 100.

Sections 3.8–3.16

- *3.11** (*Find the number of days in a month*) Write a program that prompts the user to enter the month and year and displays the number of days in the month. For example, if the user entered month **2** and year **2012**, the program should display that February 2012 had 29 days. If the user entered month **3** and year **2015**, the program should display that March 2015 had 31 days.

- 3.12** (*Palindrome number*) Write a program that prompts the user to enter a three-digit integer and determines whether it is a palindrome number. A number is palindrome if it reads the same from right to left and from left to right. Here is a sample run of this program:



Enter a three-digit integer: 121
121 is a palindrome



Enter a three-digit integer: 123
123 is not a palindrome

- *3.13** (*Financial application: compute taxes*) Listing 3.5, ComputeTax.java, gives the source code to compute taxes for single filers. Complete Listing 3.5 to compute the taxes for all filing statuses.

- 3.14** (*Game: heads or tails*) Write a program that lets the user guess whether the flip of a coin results in heads or tails. The program randomly generates an integer **0** or **1**, which represents head or tail. The program prompts the user to enter a guess and reports whether the guess is correct or incorrect.

****3.15** (*Game: lottery*) Revise Listing 3.8, Lottery.java, to generate a lottery of a three-digit number. The program prompts the user to enter a three-digit number and determines whether the user wins according to the following rules:

1. If the user input matches the lottery number in the exact order, the award is \$10,000.
2. If all digits in the user input match all digits in the lottery number, the award is \$3,000.
3. If one digit in the user input matches a digit in the lottery number, the award is \$1,000.

3.16 (*Random point*) Write a program that displays a random coordinate in a rectangle. The rectangle is centered at (0, 0) with width 100 and height 200.

***3.17** (*Game: scissor, rock, paper*) Write a program that plays the popular scissor-rock-paper game. (A scissor can cut a paper, a rock can knock a scissor, and a paper can wrap a rock.) The program randomly generates a number 0, 1, or 2 representing scissor, rock, and paper. The program prompts the user to enter a number 0, 1, or 2 and displays a message indicating whether the user or the computer wins, loses, or draws. Here are sample runs:

```
scissor (0), rock (1), paper (2): 1 ↵Enter
The computer is scissor. You are rock. You won
```



```
scissor (0), rock (1), paper (2): 2 ↵Enter
The computer is paper. You are paper too. It is a draw
```



***3.18** (*Cost of shipping*) A shipping company uses the following function to calculate the cost (in dollars) of shipping based on the weight of the package (in pounds).

$$c(w) = \begin{cases} 3.5, & \text{if } 0 < w \leq 1 \\ 5.5, & \text{if } 1 < w \leq 3 \\ 8.5, & \text{if } 3 < w \leq 10 \\ 10.5, & \text{if } 10 < w \leq 20 \end{cases}$$

Write a program that prompts the user to enter the weight of the package and display the shipping cost. If the weight is greater than 50, display a message “the package cannot be shipped.”

****3.19** (*Compute the perimeter of a triangle*) Write a program that reads three edges for a triangle and computes the perimeter if the input is valid. Otherwise, display that the input is invalid. The input is valid if the sum of every pair of two edges is greater than the remaining edge.

***3.20** (*Science: wind-chill temperature*) Programming Exercise 2.17 gives a formula to compute the wind-chill temperature. The formula is valid for temperatures in the range between -58°F and 41°F and wind speed greater than or equal to 2. Write a program that prompts the user to enter a temperature and a wind speed. The program displays the wind-chill temperature if the input is valid; otherwise, it displays a message indicating whether the temperature and/or wind speed is invalid.

Comprehensive

****3.21** (*Science: day of the week*) Zeller's congruence is an algorithm developed by Christian Zeller to calculate the day of the week. The formula is

$$h = \left(q + \frac{26(m+1)}{10} + k + \frac{k}{4} + \frac{j}{4} + 5j \right) \% 7$$

where

- **h** is the day of the week (0: Saturday, 1: Sunday, 2: Monday, 3: Tuesday, 4: Wednesday, 5: Thursday, 6: Friday).
- **q** is the day of the month.
- **m** is the month (3: March, 4: April, ..., 12: December). January and February are counted as months 13 and 14 of the previous year.
- **j** is the century (i.e., $\frac{\text{year}}{100}$).
- **k** is the year of the century (i.e., $\text{year \% } 100$).

Note that the division in the formula performs an integer division. Write a program that prompts the user to enter a year, month, and day of the month, and displays the name of the day of the week. Here are some sample runs:



```
Enter year: (e.g., 2012): 2015 ↴Enter
Enter month: 1-12: 1 ↴Enter
Enter the day of the month: 1-31: 25 ↴Enter
Day of the week is Sunday
```



```
Enter year: (e.g., 2012): 2012 ↴Enter
Enter month: 1-12: 5 ↴Enter
Enter the day of the month: 1-31: 12 ↴Enter
Day of the week is Saturday
```

(Hint: January and February are counted as 13 and 14 in the formula, so you need to convert the user input 1 to 13 and 2 to 14 for the month and change the year to the previous year.)

****3.22**

(*Geometry: point in a circle?*) Write a program that prompts the user to enter a point (**x**, **y**) and checks whether the point is within the circle centered at (0, 0) with radius 10. For example, (4, 5) is inside the circle and (9, 9) is outside the circle, as shown in Figure 3.7a.

(Hint: A point is in the circle if its distance to (0, 0) is less than or equal to 10. The formula for computing the distance is $\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$. Test your program to cover all cases.) Two sample runs are shown below.



```
Enter a point with two coordinates: 4 5 ↴Enter
Point (4.0, 5.0) is in the circle
```



```
Enter a point with two coordinates: 9 9 ↴Enter
Point (9.0, 9.0) is not in the circle
```



VideoNote

Check point location



FIGURE 3.7 (a) Points inside and outside of the circle. (b) Points inside and outside of the rectangle.

****3.23** (*Geometry: point in a rectangle?*) Write a program that prompts the user to enter a point **(x, y)** and checks whether the point is within the rectangle centered at **(0, 0)** with width **10** and height **5**. For example, **(2, 2)** is inside the rectangle and **(6, 4)** is outside the rectangle, as shown in Figure 3.7b. (*Hint:* A point is in the rectangle if its horizontal distance to **(0, 0)** is less than or equal to **10 / 2** and its vertical distance to **(0, 0)** is less than or equal to **5.0 / 2**. Test your program to cover all cases.) Here are two sample runs.

Enter a point with two coordinates: 2 2
Point (2.0, 2.0) is in the rectangle



Enter a point with two coordinates: 6 4
Point (6.0, 4.0) is not in the rectangle



****3.24** (*Game: pick a card*) Write a program that simulates picking a card from a deck of **52** cards. Your program should display the rank (**Ace, 2, 3, 4, 5, 6, 7, 8, 9, 10, Jack, Queen, King**) and suit (**Clubs, Diamonds, Hearts, Spades**) of the card. Here is a sample run of the program:

The card you picked is Jack of Hearts



***3.25** (*Geometry: intersecting point*) Two points on line 1 are given as **(x1, y1)** and **(x2, y2)** and on line 2 as **(x3, y3)** and **(x4, y4)**, as shown in Figure 3.8a–b.

The intersecting point of the two lines can be found by solving the following linear equation:

$$(y_1 - y_2)x - (x_1 - x_2)y = (y_1 - y_2)x_1 - (x_1 - x_2)y_1$$

$$(y_3 - y_4)x - (x_3 - x_4)y = (y_3 - y_4)x_3 - (x_3 - x_4)y_3$$

This linear equation can be solved using Cramer's rule (see Programming Exercise 3.3). If the equation has no solutions, the two lines are parallel (Figure 3.8c).

Write a program that prompts the user to enter four points and displays the intersecting point. Here are sample runs:



FIGURE 3.8 Two lines intersect in (a and b) and two lines are parallel in (c).



Enter $x_1, y_1, x_2, y_2, x_3, y_3, x_4, y_4$: 2 2 5 -1.0 4.0 2.0 2.0 -1.0 -2.0

The intersecting point is at (2.88889, 1.1111)



Enter $x_1, y_1, x_2, y_2, x_3, y_3, x_4, y_4$: 2 2 7 6.0 4.0 2.0 2.0 -1.0 -2.0

The two lines are parallel

- 3.26** (Use the `&&`, `||` and `^` operators) Write a program that prompts the user to enter an integer and determines whether it is divisible by 5 and 6, whether it is divisible by 5 or 6, and whether it is divisible by 5 or 6, but not both. Here is a sample run of this program:



Enter an integer: 10

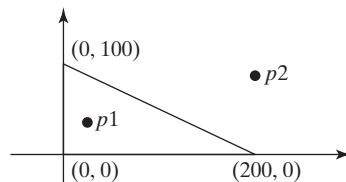
Is 10 divisible by 5 and 6? false

Is 10 divisible by 5 or 6? true

Is 10 divisible by 5 or 6, but not both? true

****3.27**

- (Geometry: points in triangle?) Suppose a right triangle is placed in a plane as shown below. The right-angle point is placed at (0, 0), and the other two points are placed at (200, 0), and (0, 100). Write a program that prompts the user to enter a point with x - and y -coordinates and determines whether the point is inside the triangle. Here are the sample runs:



Enter a point's x - and y -coordinates: 100.5 25.5

The point is in the triangle

Enter a point's x- and y-coordinates: 100.5 50.5

The point is not in the triangle



- **3.28** (*Geometry: two rectangles*) Write a program that prompts the user to enter the center x-, y-coordinates, width, and height of two rectangles and determines whether the second rectangle is inside the first or overlaps with the first, as shown in Figure 3.9. Test your program to cover all cases.

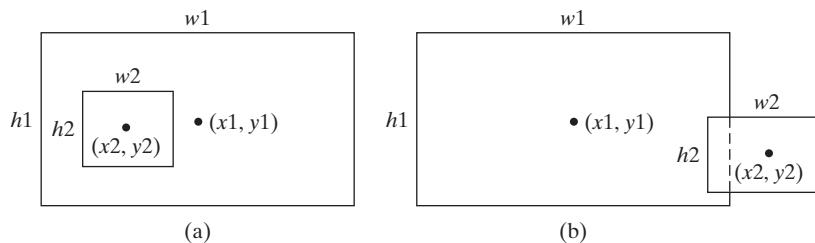


FIGURE 3.9 (a) A rectangle is inside another one. (b) A rectangle overlaps another one.

Here are the sample runs:

Enter r1's center x-, y-coordinates, width, and height: 2.5 4 2.5 43
 Enter r2's center x-, y-coordinates, width, and height: 1.5 5 0.5 3
 r2 is inside r1



Enter r1's center x-, y-coordinates, width, and height: 1 2 3 5.5
 Enter r2's center x-, y-coordinates, width, and height: 3 4 4.5 5
 r2 overlaps r1



Enter r1's center x-, y-coordinates, width, and height: 1 2 3 3
 Enter r2's center x-, y-coordinates, width, and height: 40 45 3 2
 r2 does not overlap r1



- **3.29** (*Geometry: two circles*) Write a program that prompts the user to enter the center coordinates and radii of two circles and determines whether the second circle is inside the first or overlaps with the first, as shown in Figure 3.10. (*Hint: circle2 is inside circle1 if the distance between the two centers $\leq |r1 - r2|$ and circle2 overlaps circle1 if the distance between the two centers $\leq r1 + r2$.* Test your program to cover all cases.)

Here are the sample runs:

Enter circle1's center x-, y-coordinates, and radius: 0.5 5.1 13
 Enter circle2's center x-, y-coordinates, and radius: 1 1.7 4.5
 circle2 is inside circle1



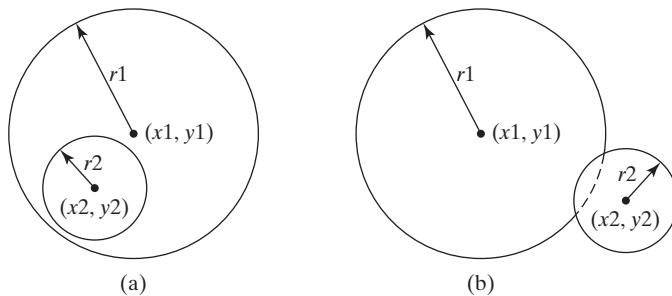


FIGURE 3.10 (a) A circle is inside another circle. (b) A circle overlaps another circle.



```
Enter circle1's center x-, y-coordinates, and radius: 3.4 5.7 5.5 ↵Enter
Enter circle2's center x-, y-coordinates, and radius: 6.7 3.5 3 ↵Enter
circle2 overlaps circle1
```



```
Enter circle1's center x-, y-coordinates, and radius: 3.4 5.5 1 ↵Enter
Enter circle2's center x-, y-coordinates, and radius: 5.5 7.2 1 ↵Enter
circle2 does not overlap circle1
```

- *3.30** (*Current time*) Revise Programming Exercise 2.8 to display the hour using a 12-hour clock. Here is a sample run:



```
Enter the time zone offset to GMT: -5 ↵Enter
The current time is 4:50:34 AM
```

- *3.31** (*Financials: currency exchange*) Write a program that prompts the user to enter the exchange rate from currency in U.S. dollars to Chinese RMB. Prompt the user to enter **0** to convert from U.S. dollars to Chinese RMB and **1** to convert from Chinese RMB and U.S. dollars. Prompt the user to enter the amount in U.S. dollars or Chinese RMB to convert it to Chinese RMB or U.S. dollars, respectively. Here are the sample runs:



```
Enter the exchange rate from dollars to RMB: 6.81 ↵Enter
Enter 0 to convert dollars to RMB and 1 vice versa: 0 ↵Enter
Enter the dollar amount: 100 ↵Enter
$100.0 is 681.0 yuan
```



```
Enter the exchange rate from dollars to RMB: 6.81 ↵Enter
Enter 0 to convert dollars to RMB and 1 vice versa: 5 ↵Enter
Enter the RMB amount: 10000 ↵Enter
10000.0 yuan is $1468.43
```

Enter the exchange rate from dollars to RMB: 6.81 ↵ Enter
 Enter 0 to convert dollars to RMB and 1 vice versa: 5 ↵ Enter
 Incorrect input



- *3.32** (*Geometry: point position*) Given a directed line from point $p_0(x_0, y_0)$ to $p_1(x_1, y_1)$, you can use the following condition to decide whether a point $p_2(x_2, y_2)$ is on the left of the line, on the right, or on the same line (see Figure 3.11):

$$(x_1 - x_0)(y_2 - y_0) - (x_2 - x_0)(y_1 - y_0) \begin{cases} >0 & p_2 \text{ is on the left side of the line} \\ =0 & p_2 \text{ is on the same line} \\ <0 & p_2 \text{ is on the right side of the line} \end{cases}$$

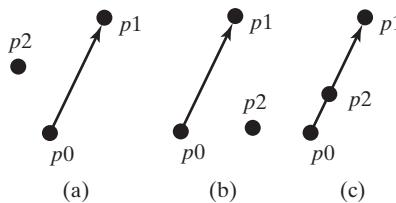


FIGURE 3.11 (a) p_2 is on the left of the line. (b) p_2 is on the right of the line. (c) p_2 is on the same line.

Write a program that prompts the user to enter the three points for p_0 , p_1 , and p_2 and displays whether p_2 is on the left of the line from p_0 to p_1 , on the right, or on the same line. Here are some sample runs:

Enter three points for p_0 , p_1 , and p_2 : 4.4 2 6.5 9.5 -5 4 ↵ Enter
 (-5.0, 4.0) is on the left side of the line from (4.4, 2.0) to (6.5, 9.5)



Enter three points for p_0 , p_1 , and p_2 : 1 1 5 5 2 2 ↵ Enter
 (2.0, 2.0) is on the line from (1.0, 1.0) to (5.0, 5.0)



Enter three points for p_0 , p_1 , and p_2 : 3.4 2 6.5 9.5 5 2.5 ↵ Enter
 (5.0, 2.5) is on the right side of the line from (3.4, 2.0) to (6.5, 9.5)



- *3.33** (*Financial: compare costs*) Suppose you shop for rice in two different packages. You would like to write a program to compare the cost. The program prompts the user to enter the weight and price of each package and displays the one with the better price. Here is a sample run:

Enter weight and price for package 1: 50 24.59 ↵ Enter
 Enter weight and price for package 2: 25 11.99 ↵ Enter
 Package 2 has a better price.





```
Enter weight and price for package 1: 50 25 ↵Enter  
Enter weight and price for package 2: 25 12.5 ↵Enter  
Two packages have the same price.
```

***3.34**

(*Geometry: point on line segment*) Programming Exercise 3.32 shows how to test whether a point is on an unbounded line. Revise Programming Exercise 3.32 to test whether a point is on a line segment. Write a program that prompts the user to enter the three points for p0, p1, and p2 and displays whether p2 is on the line segment from p0 to p1. Here are some sample runs:



```
Enter three points for p0, p1, and p2: 1 1 2.5 2.5 1.5 1.5 ↵Enter  
(1.5, 1.5) is on the line segment from (1.0, 1.0) to (2.5, 2.5) ↵Enter
```

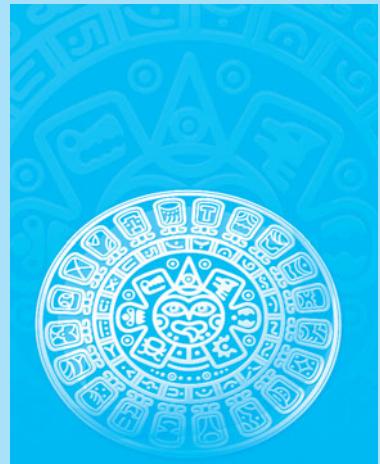


```
Enter three points for p0, p1, and p2: 1 1 2 2 3.5 3.5 ↵Enter  
(3.5, 3.5) is not on the line segment from (1.0, 1.0) to (2.0, 2.0)
```

MATHEMATICAL FUNCTIONS, CHARACTERS, AND STRINGS

Objectives

- To solve mathematical problems by using the methods in the `Math` class (§4.2).
- To represent characters using the `char` type (§4.3).
- To encode characters using ASCII and Unicode (§4.3.1).
- To represent special characters using the escape sequences (§4.4.2).
- To cast a numeric value to a character and cast a character to an integer (§4.3.3).
- To compare and test characters using the static methods in the `Character` class (§4.3.4).
- To introduce objects and instance methods (§4.4).
- To represent strings using the `String` object (§4.4).
- To return the string length using the `length()` method (§4.4.1).
- To return a character in the string using the `charAt(i)` method (§4.4.2).
- To use the `+` operator to concatenate strings (§4.4.3).
- To return an uppercase string or a lowercase string and to trim a string (§4.4.4).
- To read strings from the console (§4.4.5).
- To read a character from the console (§4.4.6).
- To compare strings using the `equals` method and the `compareTo` methods (§4.4.7).
- To obtain substrings (§4.4.8).
- To find a character or a substring in a string using the `indexOf` method (§4.4.9).
- To program using characters and strings (`GuessBirthday`) (§4.5.1).
- To convert a hexadecimal character to a decimal value (`HexDigit2Dec`) (§4.5.2).
- To revise the lottery program using strings (`LotteryUsingStrings`) (§4.5.3).
- To format output using the `System.out.printf` method (§4.6).



4.1 Introduction

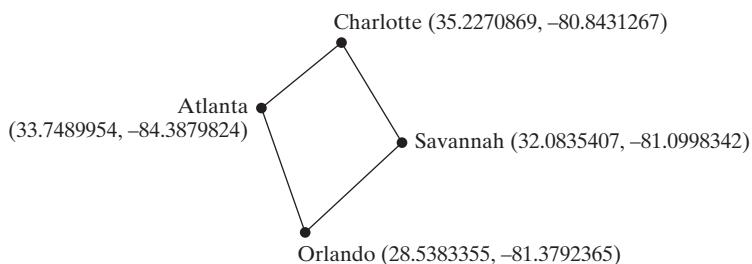


The focus of this chapter is to introduce mathematical functions, characters, string objects, and use them to develop programs.

The preceding chapters introduced fundamental programming techniques and taught you how to write simple programs to solve basic problems using selection statements. This chapter introduces methods for performing common mathematical operations. You will learn how to create custom methods in Chapter 6.

problem

Suppose you need to estimate the area enclosed by four cities, given the GPS locations (latitude and longitude) of these cities, as shown in the following diagram. How would you write a program to solve this problem? You will be able to write such a program after completing this chapter.



Because strings are frequently used in programming, it is beneficial to introduce strings early so that you can begin to use them to develop useful programs. This chapter gives a brief introduction to string objects; you will learn more on objects and strings in Chapters 9 and 10.

4.2 Common Mathematical Functions



Java provides many useful methods in the `Math` class for performing common mathematical functions.

A method is a group of statements that performs a specific task. You have already used the `pow(a, b)` method to compute a^b in Section 2.9.4, Exponent Operations and the `random()` method for generating a random number in Section 3.7. This section introduces other useful methods in the `Math` class. They can be categorized as *trigonometric methods*, *exponent methods*, and *service methods*. Service methods include the rounding, min, max, absolute, and random methods. In addition to methods, the `Math` class provides two useful `double` constants, `PI` and `E` (the base of natural logarithms). You can use these constants as `Math.PI` and `Math.E` in any program.



VideoNote

Introduce math functions

4.2.1 Trigonometric Methods

The `Math` class contains the following methods as shown in Table 4.1 for performing trigonometric functions:

TABLE 4.1 Trigonometric Methods in the Math Class

Method	Description
<code>sin(radians)</code>	Returns the trigonometric sine of an angle in radians.
<code>cos(radians)</code>	Returns the trigonometric cosine of an angle in radians.
<code>tan(radians)</code>	Returns the trigonometric tangent of an angle in radians.
<code>toRadians(degree)</code>	Returns the angle in radians for the angle in degree.
<code>toDegree(radians)</code>	Returns the angle in degrees for the angle in radians.
<code>asin(a)</code>	Returns the angle in radians for the inverse of sine.
<code>acos(a)</code>	Returns the angle in radians for the inverse of cosine.
<code>atan(a)</code>	Returns the angle in radians for the inverse of tangent.

The parameter for `sin`, `cos`, and `tan` is an angle in radians. The return value for `asin`, `acos`, and `atan` is a degree in radians in the range between $-\pi/2$ and $\pi/2$. One degree is equal to $\pi/180$ in radians, 90 degrees is equal to $\pi/2$ in radians, and 30 degrees is equal to $\pi/6$ in radians.

For example,

```
Math.toDegrees(Math.PI / 2) returns 90.0
Math.toRadians(30) returns 0.5236 (same as π/6)
Math.sin(0) returns 0.0
Math.sin(Math.toRadians(270)) returns -1.0
Math.sin(Math.PI / 6) returns 0.5
Math.sin(Math.PI / 2) returns 1.0
Math.cos(0) returns 1.0
Math.cos(Math.PI / 6) returns 0.866
Math.cos(Math.PI / 2) returns 0
Math.asin(0.5) returns 0.523598333 (same as π/6)
Math.acos(0.5) returns 1.0472 (same as π/3)
Math.atan(1.0) returns 0.785398 (same as π/4)
```

4.2.2 Exponent Methods

There are five methods related to exponents in the `Math` class as shown in Table 4.2.

TABLE 4.2 Exponent Methods in the Math Class

Method	Description
<code>exp(x)</code>	Returns e raised to power of x (e^x).
<code>log(x)</code>	Returns the natural logarithm of x ($\ln(x) = \log_e(x)$).
<code>log10(x)</code>	Returns the base 10 logarithm of x ($\log_{10}(x)$).
<code>pow(a, b)</code>	Returns a raised to the power of b (a^b).
<code>sqrt(x)</code>	Returns the square root of x (\sqrt{x}) for $x \geq 0$.

For example,

```
Math.exp(1) returns 2.71828
Math.log(Math.E) returns 1.0
Math.log10(10) returns 1.0
Math.pow(2, 3) returns 8.0
Math.pow(3, 2) returns 9.0
Math.pow(4.5, 2.5) returns 22.91765
Math.sqrt(4) returns 2.0
Math.sqrt(10.5) returns 4.24
```

4.2.3 The Rounding Methods

The `Math` class contains five rounding methods as shown in Table 4.3.

TABLE 4.3 Rounding Methods in the Math Class

Method	Description
<code>ceil(x)</code>	x is rounded up to its nearest integer. This integer is returned as a double value.
<code>floor(x)</code>	x is rounded down to its nearest integer. This integer is returned as a double value.
<code>rint(x)</code>	x is rounded up to its nearest integer. If x is equally close to two integers, the even one is returned as a double value.
<code>round(x)</code>	Returns (int)Math.floor(x + 0.5) if x is a float and returns (long)Math.floor(x + 0.5) if x is a double.

For example,

```
Math.ceil(2.1) returns 2.0
Math.ceil(2.0) returns 2.0
Math.ceil(-2.0) returns -2.0
Math.ceil(-2.1) returns -2.0
Math.floor(2.1) returns 2.0
Math.floor(2.0) returns 2.0
Math.floor(-2.0) returns -2.0
Math.floor(-2.1) returns -3.0
Math.rint(2.1) returns 2.0
Math.rint(-2.0) returns -2.0
Math.rint(-2.1) returns -2.0
Math.rint(2.5) returns 2.0
Math.rint(4.5) returns 4.0
Math.rint(-2.5) returns -2.0
Math.round(2.6f) returns 3 // Returns int
Math.round(2.0) returns 2 // Returns long
Math.round(-2.0f) returns -2 // Returns int
Math.round(-2.6) returns -3 // Returns long
Math.round(-2.4) returns -2 // Returns long
```

4.2.4 The `min`, `max`, and `abs` Methods

The `min` and `max` methods return the minimum and maximum numbers of two numbers (`int`, `long`, `float`, or `double`). For example, `max(4.4, 5.0)` returns `5.0`, and `min(3, 2)` returns `2`.

The `abs` method returns the absolute value of the number (`int`, `long`, `float`, or `double`). For example,

```
Math.max(2, 3) returns 3
Math.max(2.5, 3) returns 4.0
Math.min(2.5, 4.6) returns 2.5
Math.abs(-2) returns 2
Math.abs(-2.1) returns 2.1
```

4.2.5 The `random` Method

You have used the `random()` method in the preceding chapter. This method generates a random `double` value greater than or equal to `0.0` and less than `1.0` (`0 <= Math.random() < 1.0`). You can use it to write a simple expression to generate random numbers in any range. For example,

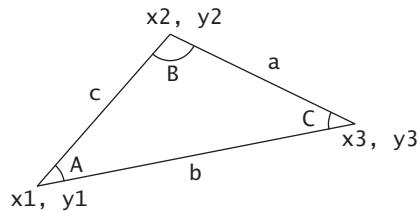
<code>(int)(Math.random() * 10)</code>	—————>	Returns a random integer between <code>0</code> and <code>9</code> .
<code>50 + (int)(Math.random() * 50)</code>	—————>	Returns a random integer between <code>50</code> and <code>99</code> .

In general,

<code>a + Math.random() * b</code>	—————>	Returns a random number between <code>a</code> and <code>a + b</code> , excluding <code>a + b</code> .
------------------------------------	--------	--

4.2.6 Case Study: Computing Angles of a Triangle

You can use the math methods to solve many computational problems. Given the three sides of a triangle, for example, you can compute the angles by using the following formula:



$$\begin{aligned} A &= \arccos\left(\frac{a^2 - b^2 - c^2}{-2bc}\right) \\ B &= \arccos\left(\frac{b^2 - a^2 - c^2}{-2ac}\right) \\ C &= \arccos\left(\frac{c^2 - b^2 - a^2}{-2ab}\right) \end{aligned}$$

Don't be intimidated by the mathematical formula. As we discussed early in Listing 2.9, ComuteLoan.java, you don't have to know how the mathematical formula is derived in order to write a program for computing the loan payments. Here in this example, given the length of three sides, you can use this formula to write a program to compute the angles without having to know how the formula is derived. In order to compute the lengths of the sides, we need to know the coordinates of three corner points and compute the distances between the points.

Listing 4.1 is an example of a program that prompts the user to enter the x- and y-coordinates of the three corner points in a triangle and then displays the three angles.

LISTING 4.1 ComputeAngles.java

```

1 import java.util.Scanner;
2
3 public class ComputeAngles {
4     public static void main(String[] args) {
5         Scanner input = new Scanner(System.in);
6
7         // Prompt the user to enter three points
8         System.out.print("Enter three points: ");
9         double x1 = input.nextDouble();                                enter three points
10        double y1 = input.nextDouble();
11        double x2 = input.nextDouble();
12        double y2 = input.nextDouble();
13        double x3 = input.nextDouble();
14        double y3 = input.nextDouble();
15
16        // Compute three sides
17        double a = Math.sqrt((x2 - x3) * (x2 - x3) + (y2 - y3) * (y2 - y3));    compute sides
18        double b = Math.sqrt((x1 - x3) * (x1 - x3) + (y1 - y3) * (y1 - y3));
19        double c = Math.sqrt((x1 - x2) * (x1 - x2) + (y1 - y2) * (y1 - y2));
20
21        // Compute three angles
22        double A = Math.toDegrees(Math.acos((a * a - b * b - c * c) / (-2 * b * c)));   display result
23        double B = Math.toDegrees(Math.acos((b * b - a * a - c * c) / (-2 * a * c)));
24        double C = Math.toDegrees(Math.acos((c * c - b * b - a * a) / (-2 * a * b)));
25
26        // Display results
27        System.out.println("The three angles are " +
28                           Math.round(A * 100) / 100.0 + " " +
29                           Math.round(B * 100) / 100.0 + " " +
30                           Math.round(C * 100) / 100.0);
31
32    }
33
34 }
```

```

35         Math.round(B * 100) / 100.0 + " " +
36         Math.round(C * 100) / 100.0;
37     }
38 }
```



Enter three points: 1 1 6.5 1 6.5 2.5

The three angles are 15.26 90.0 74.74

The program prompts the user to enter three points (line 8). This prompting message is not clear. You should give the user explicit instructions on how to enter these points as follows:

```
System.out.print("Enter the coordinates of three points separated "
+ "by spaces like x1 y1 x2 y2 x3 y3: ");
```

Note that the distance between two points (x_1, y_1) and (x_2, y_2) can be computed using the formula $\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$. The program computes the distances between two points (lines 17–22), and applies the formula to compute the angles (lines 25–30). The angles are rounded to display up to two digits after the decimal point (lines 34–36).

The **Math** class is used in the program, but not imported, because it is in the **java.lang** package. All the classes in the **java.lang** package are *implicitly* imported in a Java program.



4.1 Evaluate the following method calls:

- | | |
|---------------------------------|--------------------------------|
| (a) Math.sqrt(4) | (j) Math.floor(-2.5) |
| (b) Math.sin(2 * Math.PI) | (k) Math.round(-2.5f) |
| (c) Math.cos(2 * Math.PI) | (l) Math.round(-2.5) |
| (d) Math.pow(2, 2) | (m) Math.rint(2.5) |
| (e) Math.log(Math.E) | (n) Math.ceil(2.5) |
| (f) Math.exp(1) | (o) Math.floor(2.5) |
| (g) Math.max(2, Math.min(3, 4)) | (p) Math.round(2.5f) |
| (h) Math.rint(-2.5) | (q) Math.round(2.5) |
| (i) Math.ceil(-2.5) | (r) Math.round(Math.abs(-2.5)) |

4.2 True or false? The argument for trigonometric methods is an angle in radians.

4.3 Write a statement that converts 47 degrees to radians and assigns the result to a variable.

4.4 Write a statement that converts $\pi / 7$ to an angle in degrees and assigns the result to a variable.

4.5 Write an expression that obtains a random integer between 34 and 55. Write an expression that obtains a random integer between 0 and 999. Write an expression that obtains a random number between 5.5 and 55.5.

4.6 Why does the **Math** class not need to be imported?

4.7 What is **Math.log(Math.exp(5.5))**? What is **Math.exp(Math.log(5.5))**? What is **Math.asin(Math.sin(Math.PI / 6))**? What is **Math.sin(Math.asin(Math.PI / 6))**?

4.3 Character Data Type and Operations

A character data type represents a single character.

In addition to processing numeric values, you can process characters in Java. The character data type, `char`, is used to represent a single character. A character literal is enclosed in single quotation marks. Consider the following code:

```
char letter = 'A';
char numChar = '4';
```

The first statement assigns character `A` to the `char` variable `letter`. The second statement assigns digit character `4` to the `char` variable `numChar`.



char type



Caution

A string literal must be enclosed in quotation marks (""). A character literal is a single character enclosed in single quotation marks (''). Therefore, "A" is a string, but 'A' is a character.

char literal

4.3.1 Unicode and ASCII code

Computers use binary numbers internally. A character is stored in a computer as a sequence of 0s and 1s. *Mapping a character to its binary representation is called encoding.* There are different ways to encode a character. How characters are encoded is defined by an *encoding scheme*.

Java supports *Unicode*, an encoding scheme established by the Unicode Consortium to support the *interchange, processing, and display of written texts in the world's diverse languages.* Unicode was originally designed as a 16-bit character encoding. The primitive data type `char` was intended to take advantage of this design by providing a simple data type that could hold any character. However, it turned out that the 65,536 characters possible in a 16-bit encoding are not sufficient to represent all the characters in the world. The Unicode standard therefore has been extended to allow up to 1,112,064 characters. Those characters that go beyond the original 16-bit limit are called *supplementary characters*. Java supports the supplementary characters. The processing and representing of supplementary characters are beyond the scope of this book. For simplicity, this book considers only the original 16-bit Unicode characters. These characters can be stored in a `char` type variable.

A 16-bit Unicode takes two bytes, preceded by `\u`, expressed in four hexadecimal digits that run from `\u0000` to `\uFFFF`. Hexadecimal numbers are introduced in Appendix F, Number Systems. For example, the English word `welcome` is translated into Chinese using two characters, 欢迎. The Unicodes of these two characters are `\u6B22\u8FCE`. The Unicodes for the Greek letters α β γ are `\u03b1 \u03b2 \u03b4`.

Most computers use *ASCII* (*American Standard Code for Information Interchange*), an 8-bit encoding scheme for representing all uppercase and lowercase letters, digits, punctuation marks, and control characters. Unicode includes ASCII code, with `\u0000` to `\u007F` corresponding to the 128 ASCII characters. Table 4.4 shows the ASCII code for some commonly used characters. Appendix B, 'The ASCII Character Set,' gives a complete list of ASCII characters and their decimal and hexadecimal codes.

encoding

Unicode

original Unicode

supplementary Unicode

TABLE 4.4 ASCII Code for Commonly Used Characters

Characters	Code Value in Decimal	Unicode Value
'0' to '9'	48 to 57	\u0030 to \u0039
'A' to 'Z'	65 to 90	\u0041 to \u005A
'a' to 'z'	97 to 122	\u0061 to \u007A

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ASCII

You can use ASCII characters such as '**X**', '**1**', and '**\$**' in a Java program as well as Unicode. Thus, for example, the following statements are equivalent:

```
char letter = 'A';
char letter = '\u0041'; // Character A's Unicode is 0041
```

Both statements assign character **A** to the **char** variable **letter**.

char increment and decrement



Note

The increment and decrement operators can also be used on **char** variables to get the next or preceding Unicode character. For example, the following statements display character **b**.

```
char ch = 'a';
System.out.println(++ch);
```

4.3.2 Escape Sequences for Special Characters

escape sequence

Suppose you want to print a message with quotation marks in the output. Can you write a statement like this?

```
System.out.println("He said "Java is fun");
```

No, this statement has a compile error. The compiler thinks the second quotation character is the end of the string and does not know what to do with the rest of characters.

To overcome this problem, Java uses a special notation to represent special characters, as shown in Table 4.5. This special notation, called an *escape sequence*, consists of a backslash (\) followed by a character or a combination of digits. For example, \t is an escape sequence for the Tab character and an escape sequence such as \u03b1 is used to represent a Unicode. The symbols in an escape sequence are interpreted as a whole rather than individually. An escape sequence is considered as a single character.

So, now you can print the quoted message using the following statement:

```
System.out.println("He said \"Java is fun\"");
```

The output is

He said "Java is fun"

Note that the symbols \ and " together represent one character.

TABLE 4.5 Escape Sequences

Escape Sequence	Name	Unicode Code	Decimal Value
\b	Backspace	\u0008	8
\t	Tab	\u0009	9
\n	Linefeed	\u000A	10
\f	Formfeed	\u000C	12
\r	Carriage Return	\u000D	13
\\\	Backslash	\u005C	92
\"	Double Quote	\u0022	34

escape character

The backslash \ is called an *escape character*. It is a special character. To display this character, you have to use an escape sequence \\\. For example, the following code

```
System.out.println("\t is a tab character");
```

displays

\t is a tab character

4.3.3 Casting between `char` and Numeric Types

A `char` can be cast into any numeric type, and vice versa. When an integer is cast into a `char`, only its lower 16 bits of data are used; the other part is ignored. For example:

```
char ch = (char)0xAB0041; // The lower 16 bits hex code 0041 is
                           // assigned to ch
System.out.println(ch);   // ch is character A
```

When a floating-point value is cast into a `char`, the floating-point value is first cast into an `int`, which is then cast into a `char`.

```
char ch = (char)65.25;    // Decimal 65 is assigned to ch
System.out.println(ch);   // ch is character A
```

When a `char` is cast into a numeric type, the character's Unicode is cast into the specified numeric type.

```
int i = (int)'A'; // The Unicode of character A is assigned to i
System.out.println(i); // i is 65
```

Implicit casting can be used if the result of a casting fits into the target variable. Otherwise, explicit casting must be used. For example, since the Unicode of '`a`' is `97`, which is within the range of a byte, these implicit castings are fine:

```
byte b = 'a';
int i = 'a';
```

But the following casting is incorrect, because the Unicode `\uFFFF` cannot fit into a byte:

```
byte b = '\uFFFF';
```

To force this assignment, use explicit casting, as follows:

```
byte b = (byte) '\uFFFF';
```

Any positive integer between `0` and `FFFF` in hexadecimal can be cast into a character implicitly. Any number not in this range must be cast into a `char` explicitly.

All numeric operators can be applied to `char` operands. A `char` operand is automatically cast into a number if the other operand is a number or a character. If the other operand is a string, the character is concatenated with the string. For example, the following statements

numeric operators on
characters

```
int i = '2' + '3'; // (int)'2' is 50 and (int)'3' is 51
System.out.println("i is " + i); // i is 101
int j = 2 + 'a'; // (int)'a' is 97
System.out.println("j is " + j); // j is 99
System.out.println(j + " is the Unicode for character "
+ (char)j); // 99 is the Unicode for character c
System.out.println("Chapter " + '2');
```

display

```
i is 101
j is 99
99 is the Unicode for character c
Chapter 2
```

4.3.4 Comparing and Testing Characters

Two characters can be compared using the relational operators just like comparing two numbers. This is done by comparing the Unicodes of the two characters. For example,

`'a' < 'b'` is true because the Unicode for '`a`' (97) is less than the Unicode for '`b`' (98).

`'a' < 'A'` is false because the Unicode for '`a`' (97) is greater than the Unicode for '`A`' (65).

`'1' < '8'` is true because the Unicode for '`1`' (49) is less than the Unicode for '`8`' (56).

Often in the program, you need to test whether a character is a number, a letter, an uppercase letter, or a lowercase letter. As shown in Appendix B, the ASCII character set, that the Unicodes for lowercase letters are consecutive integers starting from the Unicode for '`a`', then for '`b`', '`c`', ..., and '`z`'. The same is true for the uppercase letters and for numeric characters. This property can be used to write the code to test characters. For example, the following code tests whether a character `ch` is an uppercase letter, a lowercase letter, or a digital character.

```
if (ch >= 'A' && ch <= 'Z')
    System.out.println(ch + " is an uppercase letter");
else if (ch >= 'a' && ch <= 'z')
    System.out.println(ch + " is a lowercase letter");
else if (ch >= '0' && ch <= '9')
    System.out.println(ch + " is a numeric character");
```

For convenience, Java provides the following methods in the `Character` class for testing characters as shown in Table 4.6.

TABLE 4.6 Methods in the Character Class

Method	Description
<code>isDigit(ch)</code>	Returns true if the specified character is a digit.
<code>isLetter(ch)</code>	Returns true if the specified character is a letter.
<code>isLetterOfDigit(ch)</code>	Returns true if the specified character is a letter or digit.
<code>isLowerCase(ch)</code>	Returns true if the specified character is a lowercase letter.
<code>isUpperCase(ch)</code>	Returns true if the specified character is an uppercase letter.
<code>toLowerCase(ch)</code>	Returns the lowercase of the specified character.
<code>toUpperCase(ch)</code>	Returns the uppercase of the specified character.

For example,

```
System.out.println("isDigit('a') is " + Character.isDigit('a'));
System.out.println("isLetter('a') is " + Character.isLetter('a'));
System.out.println("isLowerCase('a') is "
    + Character.isLowerCase('a'));
System.out.println("isUpperCase('a') is "
    + Character.isUpperCase('a'));
System.out.println("toLowerCase('T') is "
    + Character.toLowerCase('T'));
System.out.println("toUpperCase('q') is "
    + Character.toUpperCase('q'));
```

displays

```
isDigit('a') is false
isLetter('a') is true
```

```
isLowerCase('a') is true
isUpperCase('a') is false
toLowerCase('T') is t
toUpperCase('q') is Q
```

- 4.8** Use print statements to find out the ASCII code for '**1**', '**A**', '**B**', '**a**', and '**b**'.
 Use print statements to find out the character for the decimal codes **40**, **59**, **79**, **85**, and **90**. Use print statements to find out the character for the hexadecimal code **40**, **5A**, **71**, **72**, and **7A**.



- 4.9** Which of the following are correct literals for characters?

'**1**', '\u345dE', '\u3fFa', '\b', '\t'

- 4.10** How do you display the characters \ and "?

- 4.11** Evaluate the following:

```
int i = '1';
int j = '1' + '2' * ('4' - '3') + 'b' / 'a';
int k = 'a';
char c = 90;
```

- 4.12** Can the following conversions involving casting be allowed? If so, find the converted result.

```
char c = 'A';
int i = (int)c;

float f = 1000.34f;
int i = (int)f;

double d = 1000.34;
int i = (int)d;

int i = 97;
char c = (char)i;
```

- 4.13** Show the output of the following program:

```
public class Test {
    public static void main(String[] args) {
        char x = 'a';
        char y = 'c';
        System.out.println(++x);
        System.out.println(y++);
        System.out.println(x - y);
    }
}
```

- 4.14** Write the code that generates a random lowercase letter.

- 4.15** Show the output of the following statements:

```
System.out.println('a' < 'b');
System.out.println('a' <= 'A');
System.out.println('a' > 'b');
System.out.println('a' >= 'A');
System.out.println('a' == 'a');
System.out.println('a' != 'b');
```

4.4 The String Type



A string is a sequence of characters.

The `char` type represents only one character. To represent a string of characters, use the data type called `String`. For example, the following code declares `message` to be a string with the value "Welcome to Java".

```
String message = "Welcome to Java";
```

`String` is a predefined class in the Java library, just like the classes `System` and `Scanner`. The `String` type is not a primitive type. It is known as a *reference type*. Any Java class can be used as a reference type for a variable. The variable declared by a reference type is known as a reference variable that references an object. Here, `message` is a reference variable that references a string object with contents `Welcome to Java`.

Reference data types will be discussed in detail in Chapter 9, Objects and Classes. For the time being, you need to know only how to declare a `String` variable, how to assign a string to the variable, and how to use the methods in the `String` class. More details on using strings will be covered in Chapter 10.

Table 4.7 lists the `String` methods for obtaining string length, for accessing characters in the string, for concatenating strings, for converting a string to upper or lowercases, and for trimming a string.



VideoNote

Introduce strings and objects

TABLE 4.7 Simple Methods for `String` Objects

Method	Description
<code>length()</code>	Returns the number of characters in this string.
<code>charAt(index)</code>	Returns the character at the specified index from this string.
<code>concat(s1)</code>	Returns a new string that concatenates this string with string <code>s1</code> .
<code>toUpperCase()</code>	Returns a new string with all letters in uppercase.
<code>toLowerCase()</code>	Returns a new string with all letters in lowercase
<code>trim()</code>	Returns a new string with whitespace characters trimmed on both sides.

instance method
static method

Strings are objects in Java. The methods in Table 4.7 can only be invoked from a specific string instance. For this reason, these methods are called *instance methods*. A non-instance method is called a *static method*. A static method can be invoked without using an object. All the methods defined in the `Math` class are static methods. They are not tied to a specific object instance. The syntax to invoke an instance method is `reference-Variable.methodName(arguments)`. A method may have many arguments or no arguments. For example, the `charAt(index)` method has one argument, but the `length()` method has no arguments. Recall that the syntax to invoke a static method is `ClassName.methodName(arguments)`. For example, the `pow` method in the `Math` class can be invoked using `Math.pow(2, 2.5)`.

4.4.1 Getting String Length

You can use the `length()` method to return the number of characters in a string. For example, the following code

```
String message = "Welcome to Java";
System.out.println("The length of " + message + " is "
+ message.length());
```

displays

```
The length of Welcome to Java is 15
```



Note

When you use a string, you often know its literal value. For convenience, Java allows you to use the string literal to refer directly to strings without creating new variables. Thus, `"Welcome to Java".length()` is correct and returns **15**. Note that `""` denotes an *empty string* and `"".length()` is **0**.

string literal

empty string

4.4.2 Getting Characters from a String

The `s.charAt(index)` method can be used to retrieve a specific character in a string `s`, where the index is between **0** and `s.length() - 1`. For example, `message.charAt(0)` returns the character `W`, as shown in Figure 4.1. Note that the index for the first character in the string is **0**.

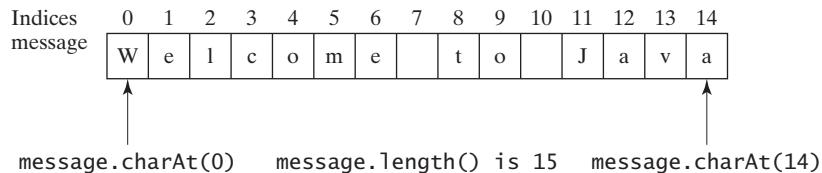


FIGURE 4.1 The characters in a `String` object can be accessed using its index.



Caution

Attempting to access characters in a string `s` out of bounds is a common programming error. To avoid it, make sure that you do not use an index beyond `s.length() - 1`. For example, `s.charAt(s.length())` would cause a `StringIndexOutOfBoundsException`.

string index range

4.4.3 Concatenating Strings

You can use the `concat` method to concatenate two strings. The statement shown below, for example, concatenates strings `s1` and `s2` into `s3`:

```
String s3 = s1.concat(s2);
```

`s1.concat(s2)`

Because string concatenation is heavily used in programming, Java provides a convenient way to accomplish it. You can use the plus (+) operator to concatenate two strings, so the previous statement is equivalent to

```
String s3 = s1 + s2;
```

`s1 + s2`

The following code combines the strings `message`, `" and "`, and `"HTML"` into one string:

```
String myString = message + " and " + "HTML";
```

Recall that the + operator can also concatenate a number with a string. In this case, the number is converted into a string and then concatenated. Note that at least one of the operands must be a string in order for concatenation to take place. If one of the operands is a nonstring

concatenate strings and numbers

(e.g., a number), the nonstring value is converted into a string and concatenated with the other string. Here are some examples:

```
// Three strings are concatenated
String message = "Welcome " + "to " + "Java";

// String Chapter is concatenated with number 2
String s = "Chapter" + 2; // s becomes Chapter2

// String Supplement is concatenated with character B
String s1 = "Supplement" + 'B'; // s1 becomes SupplementB
```

If neither of the operands is a string, the plus sign (+) is the addition operator that adds two numbers.

The augmented += operator can also be used for string concatenation. For example, the following code appends the string "and Java is fun" with the string "Welcome to Java" in `message`.

```
message += " and Java is fun";
```

So the new `message` is "Welcome to Java and Java is fun".

If `i = 1` and `j = 2`, what is the output of the following statement?

```
System.out.println("i + j is " + i + j);
```

The output is "i + j is 12" because "i + j is " is concatenated with the value of `i` first. To force `i + j` to be executed first, enclose `i + j` in the parentheses, as follows:

```
System.out.println("i + j is " + (i + j));
```

4.4.4 Converting Strings

The `toLowerCase()` method returns a new string with all lowercase letters and the `toUpperCase()` method returns a new string with all uppercase letters. For example,

`toLowerCase()`
`toUpperCase()`

"Welcome".`toLowerCase()` returns a new string `welcome`.
`"Welcome".toUpperCase()` returns a new string `WELCOME`.

The `trim()` method returns a new string by eliminating whitespace characters from both ends of the string. The characters ' ', \t, \f, \r, or \n are known as *whitespace characters*. For example,

`trim()`

"\t Good Night \n".`trim()` returns a new string `Good Night`.

4.4.5 Reading a String from the Console

read strings

To read a string from the console, invoke the `next()` method on a `Scanner` object. For example, the following code reads three strings from the keyboard:

```
Scanner input = new Scanner(System.in);
System.out.print("Enter three words separated by spaces: ");
String s1 = input.next();
String s2 = input.next();
String s3 = input.next();
System.out.println("s1 is " + s1);
System.out.println("s2 is " + s2);
System.out.println("s3 is " + s3);
```

```
Enter three words separated by spaces: Welcome to Java [Enter]
s1 is Welcome
s2 is to
s3 is Java
```



whitespace character

The `next()` method reads a string that ends with a whitespace character. You can use the `nextLine()` method to read an entire line of text. The `nextLine()` method reads a string that ends with the *Enter* key pressed. For example, the following statements read a line of text.

```
Scanner input = new Scanner(System.in);
System.out.println("Enter a line: ");
String s = input.nextLine();
System.out.println("The line entered is " + s);
```

```
Enter a line: Welcome to Java [Enter]
The line entered is Welcome to Java
```



Important Caution

To avoid input errors, do not use `nextLine()` after `nextByte()`, `nextShort()`, `nextInt()`, `nextLong()`, `nextFloat()`, `nextDouble()`, or `next()`. The reasons will be explained in Section 12.11.4, ‘How Does `Scanner` Work?’

avoid input errors

4.4.6 Reading a Character from the Console

To read a character from the console, use the `nextLine()` method to read a string and then invoke the `charAt(0)` method on the string to return a character. For example, the following code reads a character from the keyboard:

```
Scanner input = new Scanner(System.in);
System.out.print("Enter a character: ");
String s = input.nextLine();
char ch = s.charAt(0);
System.out.println("The character entered is " + ch);
```

4.4.7 Comparing Strings

The `String` class contains the methods as shown in Table 4.8 for comparing two strings.

TABLE 4.8 Comparison Methods for `String` Objects

Method	Description
<code>equals(s1)</code>	Returns true if this string is equal to string <code>s1</code> .
<code>equalsIgnoreCase(s1)</code>	Returns true if this string is equal to string <code>s1</code> ; it is case insensitive.
<code>compareTo(s1)</code>	Returns an integer greater than 0, equal to 0, or less than 0 to indicate whether this string is greater than, equal to, or less than <code>s1</code> .
<code>compareToIgnoreCase(s1)</code>	Same as <code>compareTo</code> except that the comparison is case insensitive.
<code>startsWith(prefix)</code>	Returns true if this string starts with the specified prefix.
<code>endsWith(suffix)</code>	Returns true if this string ends with the specified suffix.
<code>contains(s1)</code>	Returns true if <code>s1</code> is a substring in this string.

How do you compare the contents of two strings? You might attempt to use the `==` operator, as follows:

```
==  
if (string1 == string2)  
    System.out.println("string1 and string2 are the same object");  
else  
    System.out.println("string1 and string2 are different objects");
```

However, the `==` operator checks only whether `string1` and `string2` refer to the same object; it does not tell you whether they have the same contents. Therefore, you cannot use the `==` operator to find out whether two string variables have the same contents. Instead, you should use the `equals` method. The following code, for instance, can be used to compare two strings:

```
string1.equals(string2)  
if (string1.equals(string2))  
    System.out.println("string1 and string2 have the same contents");  
else  
    System.out.println("string1 and string2 are not equal");
```

For example, the following statements display `true` and then `false`.

```
String s1 = "Welcome to Java";  
String s2 = "Welcome to Java";  
String s3 = "Welcome to C++";  
System.out.println(s1.equals(s2)); // true  
System.out.println(s1.equals(s3)); // false
```

The `compareTo` method can also be used to compare two strings. For example, consider the following code:

```
s1.compareTo(s2)
```

The method returns the value `0` if `s1` is equal to `s2`, a value less than `0` if `s1` is lexicographically (i.e., in terms of Unicode ordering) less than `s2`, and a value greater than `0` if `s1` is lexicographically greater than `s2`.

The actual value returned from the `compareTo` method depends on the offset of the first two distinct characters in `s1` and `s2` from left to right. For example, suppose `s1` is `abc` and `s2` is `abg`, and `s1.compareTo(s2)` returns `-4`. The first two characters (`a` vs. `a`) from `s1` and `s2` are compared. Because they are equal, the second two characters (`b` vs. `b`) are compared. Because they are also equal, the third two characters (`c` vs. `g`) are compared. Since the character `c` is `4` less than `g`, the comparison returns `-4`.



Caution

Syntax errors will occur if you compare strings by using relational operators `>`, `>=`, `<`, or `<=`. Instead, you have to use `s1.compareTo(s2)`.



Note

The `equals` method returns `true` if two strings are equal and `false` if they are not. The `compareTo` method returns `0`, a positive integer, or a negative integer, depending on whether one string is equal to, greater than, or less than the other string.

The `String` class also provides the `equalsIgnoreCase` and `compareToIgnoreCase` methods for comparing strings. The `equalsIgnoreCase` and `compareToIgnoreCase` methods ignore the case of the letters when comparing two strings. You can also use `str.startsWith(prefix)` to check whether string `str` starts with a specified prefix, `str.endsWith(suffix)` to check whether string `str` ends with a specified suffix, and `str.contains(s1)` to check whether string `str` contains string `s1`. For example,

```
"Welcome to Java".startsWith("We") returns true.  
"Welcome to Java".startsWith("we") returns false.  
"Welcome to Java".endsWith("va") returns true.
```

```
"Welcome to Java".endsWith("v") returns false.
"Welcome to Java".contains("to") returns true.
"Welcome to Java".contains("To") returns false.
```

Listing 4.2 gives a program that prompts the user to enter two cities and displays them in alphabetical order.

LISTING 4.2 OrderTwoCities.java

```
1 import java.util.Scanner;
2
3 public class OrderTwoCities {
4     public static void main(String[] args) {
5         Scanner input = new Scanner(System.in);
6
7         // Prompt the user to enter two cities
8         System.out.print("Enter the first city: ");
9         String city1 = input.nextLine();           input city1
10        System.out.print("Enter the second city: ");
11        String city2 = input.nextLine();           input city2
12
13        if (city1.compareTo(city2) < 0)
14            System.out.println("The cities in alphabetical order are " +
15                city1 + " " + city2);                  compare two cities
16        else
17            System.out.println("The cities in alphabetical order are " +
18                city2 + " " + city1);
19    }
20 }
```

```
Enter the first city: New York ↵Enter
Enter the second city: Boston ↵Enter
The cities in alphabetical order are Boston New York
```



The program reads two strings for two cities (lines 9, 11). If `input.nextLine()` is replaced by `input.next()` (line 9), you cannot enter a string with spaces for `city1`. Since a city name may contain multiple words separated by spaces, the program uses the `nextLine` method to read a string (lines 9, 11). Invoking `city1.compareTo(city2)` compares two strings `city1` with `city2` (line 13). A negative return value indicates that `city1` is less than `city2`.

4.4.8 Obtaining Substrings

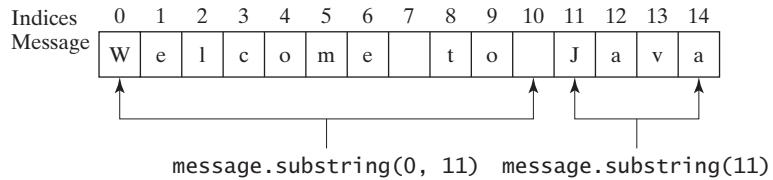
You can obtain a single character from a string using the `charAt` method. You can also obtain a substring from a string using the `substring` method in the `String` class, as shown in Table 4.9.

For example,

```
String message = "Welcome to Java";
String message = message.substring(0, 11) + "HTML";
The string message now becomes Welcome to HTML.
```

TABLE 4.9 The `String` class contains the methods for obtaining substrings.

Method	Description
<code>substring(beginIndex)</code>	Returns this string's substring that begins with the character at the specified <code>beginIndex</code> and extends to the end of the string, as shown in Figure 4.2.
<code>substring(beginIndex, endIndex)</code>	Returns this string's substring that begins at the specified <code>beginIndex</code> and extends to the character at index <code>endIndex - 1</code> , as shown in Figure 4.2. Note that the character at <code>endIndex</code> is not part of the substring.

FIGURE 4.2 The `substring` method obtains a substring from a string.

beginIndex <= endIndex

Note

If `beginIndex` is `endIndex`, `substring(beginIndex, endIndex)` returns an empty string with length 0. If `beginIndex > endIndex`, it would be a runtime error.

4.4.9 Finding a Character or a Substring in a String

The `String` class provides several versions of `indexOf` and `lastIndexOf` methods to find a character or a substring in a string, as shown in Table 4.10.

TABLE 4.10 The `String` class contains the methods for finding substrings.

<i>Method</i>	<i>Description</i>
<code>index(ch)</code>	Returns the index of the first occurrence of ch in the string. Returns -1 if not matched.
<code>indexOf(ch, fromIndex)</code>	Returns the index of the first occurrence of ch after fromIndex in the string. Returns -1 if not matched.
<code>indexOf(s)</code>	Returns the index of the first occurrence of string s in this string. Returns -1 if not matched.
<code>indexOf(s, fromIndex)</code>	Returns the index of the first occurrence of string s in this string after fromIndex. Returns -1 if not matched.
<code>lastIndexOf(ch)</code>	Returns the index of the last occurrence of ch in the string. Returns -1 if not matched.
<code>lastIndexOf(ch, fromIndex)</code>	Returns the index of the last occurrence of ch before fromIndex in this string. Returns -1 if not matched.
<code>lastIndexOf(s)</code>	Returns the index of the last occurrence of string s. Returns -1 if not matched.
<code>lastIndexOf(s, fromIndex)</code>	Returns the index of the last occurrence of string s before fromIndex. Returns -1 if not matched.

For example,

```

indexOf          "Welcome to Java".indexOf('W') returns 0.
                 "Welcome to Java".indexOf('o') returns 4.
                 "Welcome to Java".indexOf('o', 5) returns 9.
                 "Welcome to Java".indexOf("come") returns 3.
                 "Welcome to Java".indexOf("Java", 5) returns 11.
                 "Welcome to Java".indexOf("java", 5) returns -1.

lastIndexOf      "Welcome to Java".lastIndexOf('W') returns 0.
                 "Welcome to Java".lastIndexOf('o') returns 9.
                 "Welcome to Java".lastIndexOf('o', 5) returns 4.
                 "Welcome to Java".lastIndexOf("come") returns 3.
                 "Welcome to Java".lastIndexOf("Java", 5) returns -1.
                 "Welcome to Java".lastIndexOf("Java") returns 11.

```

Suppose a string `s` contains the first name and last name separated by a space. You can use the following code to extract the first name and last name from the string:

```

int k = s.indexOf(' ');
String firstName = s.substring(0, k);
String lastName = s.substring(k + 1);

```

For example, if `s` is **Kim Jones**, the following diagram illustrates how the first name and last name are extracted.



4.4.10 Conversion between Strings and Numbers

You can convert a numeric string into a number. To convert a string into an `int` value, use the `Integer.parseInt` method, as follows:

`Integer.parseInt` method

```
int intValue = Integer.parseInt(intString);
```

where `intString` is a numeric string such as "123".

To convert a string into a `double` value, use the `Double.parseDouble` method, as follows:

`Double.parseDouble` method

```
double doubleValue = Double.parseDouble(doubleString);
```

where `doubleString` is a numeric string such as "123.45".

If the string is not a numeric string, the conversion would cause a runtime error. The `Integer` and `Double` classes are both included in the `java.lang` package, and thus they are automatically imported.

You can convert a number into a string, simply use the string concatenating operator as follows:

```
String s = number + "";
```

number to string

4.16 Suppose that `s1`, `s2`, and `s3` are three strings, given as follows:



```
String s1 = "Welcome to Java";
String s2 = "Programming is fun";
String s3 = "Welcome to Java";
```

What are the results of the following expressions?

- | | |
|--------------------------------------|--|
| (a) <code>s1 == s2</code> | (l) <code>s1.lastIndexOf("o", 15)</code> |
| (b) <code>s2 == s3</code> | (m) <code>s1.length()</code> |
| (c) <code>s1.equals(s2)</code> | (n) <code>s1.substring(5)</code> |
| (d) <code>s1.equals(s3)</code> | (o) <code>s1.substring(5, 11)</code> |
| (e) <code>s1.compareTo(s2)</code> | (p) <code>s1.startsWith("We1")</code> |
| (f) <code>s2.compareTo(s3)</code> | (q) <code>s1.endsWith("Java")</code> |
| (g) <code>s2.compareTo(s2)</code> | (r) <code>s1.toLowerCase()</code> |
| (h) <code>s1.charAt(0)</code> | (s) <code>s1.toUpperCase()</code> |
| (i) <code>s1.indexOf('j')</code> | (t) <code>s1.concat(s2)</code> |
| (j) <code>s1.indexOf("to")</code> | (u) <code>s1.contains(s2)</code> |
| (k) <code>s1.lastIndexOf('a')</code> | (v) <code>"\t Wel \t".trim()</code> |

- 4.17** Suppose that `s1` and `s2` are two strings. Which of the following statements or expressions are incorrect?

```
String s = "Welcome to Java";
String s3 = s1 + s2;
String s3 = s1 - s2;
s1 == s2;
s1 >= s2;
s1.compareTo(s2);
int i = s1.length();
char c = s1(0);
char c = s1.charAt(s1.length());
```

- 4.18** Show the output of the following statements (write a program to verify your results):

```
System.out.println("1" + 1);
System.out.println('1' + 1);
System.out.println("1" + 1 + 1);
System.out.println("1" + (1 + 1));
System.out.println('1' + 1 + 1);
```

- 4.19** Evaluate the following expressions (write a program to verify your results):

```
1 + "Welcome " + 1 + 1
1 + "Welcome " + (1 + 1)
1 + "Welcome " + ('\u0001' + 1)
1 + "Welcome " + 'a' + 1
```

- 4.20** Let `s1` be " Welcome " and `s2` be " welcome ". Write the code for the following statements:

- Check whether `s1` is equal to `s2` and assign the result to a Boolean variable `isEqual`.
- Check whether `s1` is equal to `s2`, ignoring case, and assign the result to a Boolean variable `isEqual`.
- Compare `s1` with `s2` and assign the result to an `int` variable `x`.
- Compare `s1` with `s2`, ignoring case, and assign the result to an `int` variable `x`.
- Check whether `s1` has the prefix `AAA` and assign the result to a Boolean variable `b`.
- Check whether `s1` has the suffix `AAA` and assign the result to a Boolean variable `b`.
- Assign the length of `s1` to an `int` variable `x`.
- Assign the first character of `s1` to a `char` variable `x`.
- Create a new string `s3` that combines `s1` with `s2`.
- Create a substring of `s1` starting from index `1`.
- Create a substring of `s1` from index `1` to index `4`.
- Create a new string `s3` that converts `s1` to lowercase.
- Create a new string `s3` that converts `s1` to uppercase.
- Create a new string `s3` that trims whitespace characters on both ends of `s1`.

- (o) Assign the index of the first occurrence of the character `e` in `s1` to an `int` variable `x`.
- (p) Assign the index of the last occurrence of the string `abc` in `s1` to an `int` variable `x`.

4.5 Case Studies

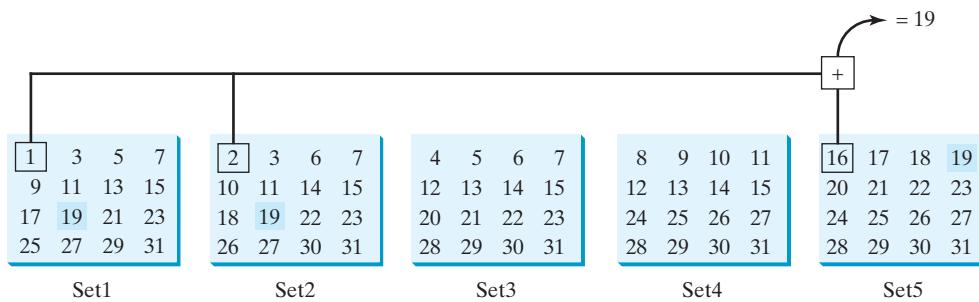
Strings are fundamental in programming. The ability to write programs using strings is essential in learning Java programming.



You will frequently use strings to write useful programs. This section presents three examples of solving problems using strings.

4.5.1 Case Study: Guessing Birthdays

You can find out the date of the month when your friend was born by asking five questions. Each question asks whether the day is in one of the five sets of numbers.



The birthday is the sum of the first numbers in the sets where the day appears. For example, if the birthday is **19**, it appears in Set1, Set2, and Set5. The first numbers in these three sets are **1**, **2**, and **16**. Their sum is **19**.

Listing 4.3 gives a program that prompts the user to answer whether the day is in Set1 (lines 41–44), in Set2 (lines 50–53), in Set3 (lines 59–62), in Set4 (lines 68–71), and in Set5 (lines 77–80). If the number is in the set, the program adds the first number in the set to `day` (lines 47, 56, 65, 74, 83).

LISTING 4.3 GuessBirthday.java

```

1 import java.util.Scanner;
2
3 public class GuessBirthday {
4     public static void main(String[] args) {
5         String set1 =
6             " 1 3 5 7\n" +
7             " 9 11 13 15\n" +
8             "17 19 21 23\n" +
9             "25 27 29 31";
10
11     String set2 =
12         " 2 3 6 7\n" +

```

```

13      "10 11 14 15\n" +
14      "18 19 22 23\n" +
15      "26 27 30 31";
16
17      String set3 =
18          " 4 5 6 7\n" +
19          "12 13 14 15\n" +
20          "20 21 22 23\n" +
21          "28 29 30 31";
22
23      String set4 =
24          " 8 9 10 11\n" +
25          "12 13 14 15\n" +
26          "24 25 26 27\n" +
27          "28 29 30 31";
28
29      String set5 =
30          "16 17 18 19\n" +
31          "20 21 22 23\n" +
32          "24 25 26 27\n" +
33          "28 29 30 31";
34
day to be determined
35      int day = 0;
36
37      // Create a Scanner
38      Scanner input = new Scanner(System.in);
39
40      // Prompt the user to answer questions
41      System.out.print("Is your birthday in Set1?\n");
42      System.out.print(set1);
43      System.out.print("\nEnter 0 for No and 1 for Yes: ");
44      int answer = input.nextInt();
45
in Set1?
46      if (answer == 1)
47          day += 1;
48
49      // Prompt the user to answer questions
50      System.out.print("\nIs your birthday in Set2?\n");
51      System.out.print(set2);
52      System.out.print("\nEnter 0 for No and 1 for Yes: ");
53      answer = input.nextInt();
54
in Set2?
55      if (answer == 1)
56          day += 2;
57
58      // Prompt the user to answer questions
59      System.out.print("Is your birthday in Set3?\n");
60      System.out.print(set3);
61      System.out.print("\nEnter 0 for No and 1 for Yes: ");
62      answer = input.nextInt();
63
in Set3?
64      if (answer == 1)
65          day += 4;
66
67      // Prompt the user to answer questions
68      System.out.print("\nIs your birthday in Set4?\n");
69      System.out.print(set4);
70      System.out.print("\nEnter 0 for No and 1 for Yes: ");
71      answer = input.nextInt();
72

```

```

73     if (answer == 1)                                in Set4?
74         day += 8;
75
76     // Prompt the user to answer questions
77     System.out.print("\nIs your birthday in Set5?\n");
78     System.out.print(set5);
79     System.out.print("\nEnter 0 for No and 1 for Yes: ");
80     answer = input.nextInt();
81
82     if (answer == 1)                                in Set5?
83         day += 16;
84
85     System.out.println("\nYour birthday is " + day + "!");
86 }
87 }
```



Is your birthday in Set1?

1 3 5 7
9 11 13 15
17 19 21 23
25 27 29 31

Enter 0 for No and 1 for Yes: 1

Is your birthday in Set2?

2 3 6 7
10 11 14 15
18 19 22 23
26 27 30 31

Enter 0 for No and 1 for Yes: 1

Is your birthday in Set3?

4 5 6 7
12 13 14 15
20 21 22 23
28 29 30 31

Enter 0 for No and 1 for Yes: 0

Is your birthday in Set4?

8 9 10 11
12 13 14 15
24 25 26 27
28 29 30 31

Enter 0 for No and 1 for Yes: 0

Is your birthday in Set5?

16 17 18 19
20 21 22 23
24 25 26 27
28 29 30 31

Enter 0 for No and 1 for Yes: 1

Your birthday is 19!



line#	day	answer	output
35	0		
44		1	
47	1		
53		1	
56	3		
62		0	
71		0	
80		1	
83	19		
85			Your birthday is 19!

mathematics behind the game

This game is easy to program. You may wonder how the game was created. The mathematics behind the game is actually quite simple. The numbers are not grouped together by accident—the way they are placed in the five sets is deliberate. The starting numbers in the five sets are **1**, **2**, **4**, **8**, and **16**, which correspond to **1**, **10**, **100**, **1000**, and **10000** in binary (binary numbers are introduced in Appendix F, Number Systems). A binary number for decimal integers between **1** and **31** has at most five digits, as shown in Figure 4.3a. Let it be $b_5 b_4 b_3 b_2 b_1$. Thus, $b_5 b_4 b_3 b_2 b_1 = b_5 0000 + b_4 000 + b_3 00 + b_2 0 + b_1$, as shown in Figure 4.3b. If a day's binary number has a digit **1** in b_k , the number should appear in Set k . For example, number **19** is binary **10011**, so it appears in Set1, Set2, and Set5. It is binary **1 + 10 + 10000 = 10011** or decimal **1 + 2 + 16 = 19**. Number **31** is binary **11111**, so it appears in Set1, Set2, Set3, Set4, and Set5. It is binary **1 + 10 + 100 + 1000 + 10000 = 11111** or decimal **1 + 2 + 4 + 8 + 16 = 31**.

Decimal	Binary		
1	00001	$b_5 \ 0 \ 0 \ 0 \ 0$	10000
2	00010	$b_4 \ 0 \ 0 \ 0$	1000
3	00011	$b_3 \ 0 \ 0$	100
...		$b_2 \ 0$	10
19	10011	$+ \ b_1$	10
...		\hline	10
31	11111	$b_5 b_4 b_3 b_2 b_1$	11111

(a)

(b)

FIGURE 4.3 (a) A number between **1** and **31** can be represented using a five-digit binary number. (b) A five-digit binary number can be obtained by adding binary numbers **1**, **10**, **100**, **1000**, or **10000**.



4.21 If you run Listing 4.3 GuessBirthday.java with input **1** for Set1, Set3, and Set4 and **0** for Set2 and Set5, what will be the birthday?

4.5.2 Case Study: Converting a Hexadecimal Digit to a Decimal Value

The hexadecimal number system has 16 digits: 0–9, A–F. The letters A, B, C, D, E, and F correspond to the decimal numbers 10, 11, 12, 13, 14, and 15. We now write a program that prompts the user to enter a hex digit and display its corresponding decimal value, as shown in Listing 4.4.

LISTING 4.4 HexDigit2Dec.java

```

1 import java.util.Scanner;
2
3 public class HexDigit2Dec {
4     public static void main(String[] args) {
5         Scanner input = new Scanner(System.in);
6         System.out.print("Enter a hex digit: ");
7         String hexString = input.nextLine();
8
9         // Check if the hex string has exactly one character
10        if (hexString.length() != 1) {
11            System.out.println("You must enter exactly one character");
12            System.exit(1);
13        }
14
15        // Display decimal value for the hex digit
16        char ch = hexString.charAt(0);
17        if (ch <= 'F' && ch >= 'A') {                                is A-F?
18            int value = ch - 'A' + 10;
19            System.out.println("The decimal value for hex digit "
20                + ch + " is " + value);
21        }
22        else if (Character.isDigit(ch)) {                            is 0-9?
23            System.out.println("The decimal value for hex digit "
24                + ch + " is " + ch);
25        }
26        else {
27            System.out.println(ch + " is an invalid input");
28        }
29    }
30 }
```



VideoNote

Convert hex to decimal

input string

check length

is A-F?

is 0-9?

Enter a hex digit: AB7C ↵Enter
You must enter exactly one character



Enter a hex digit: B ↵Enter
The decimal value for hex digit B is 11



Enter a hex digit: 8 ↵Enter
The decimal value for hex digit 8 is 8



Enter a hex digit: T ↵Enter
T is an invalid input



The program reads a string from the console (line 7) and checks if the string contains a single character (line 10). If not, report an error and exit the program (line 12).

The program invokes the `Character.toUpperCase` method to obtain the character `ch` as an uppercase letter (line 16). If `ch` is between '`A`' and '`F`' (line 17), the corresponding decimal value is `ch - 'A' + 10` (line 18). Note that `ch - 'A'` is `0` if `ch` is '`A`', `ch - 'A'` is `1`

if `ch` is '`B`', and so on. When two characters perform a numerical operation, the characters' Unicodes are used in the computation.

The program invokes the `Character.isDigit(ch)` method to check if `ch` is between '`0`' and '`9`' (line 22). If so, the corresponding decimal digit is the same as `ch` (lines 23–24).

If `ch` is not between '`A`' and '`F`' nor a digit character, the program displays an error message (line 27).

4.5.3 Case Study: Revising the Lottery Program Using Strings

The lottery program in Listing 3.8, `Lottery.java`, generates a random two-digit number, prompts the user to enter a two-digit number, and determines whether the user wins according to the following rule:

1. If the user input matches the lottery number in the exact order, the award is \$10,000.
2. If all the digits in the user input match all the digits in the lottery number, the award is \$3,000.
3. If one digit in the user input matches a digit in the lottery number, the award is \$1,000.

The program in Listing 3.8 uses an integer to store the number. Listing 4.5 gives a new program that generates a random two-digit string instead of a number and receives the user input as a string instead of a number.

LISTING 4.5 `LotteryUsingStrings.java`

generate a lottery

enter a guess

exact match?

match all digits?

match one digit?

```

1 import java.util.Scanner;
2
3 public class LotteryUsingStrings {
4     public static void main(String[] args) {
5         // Generate a lottery as a two-digit string
6         String lottery = "" + (int)(Math.random() * 10)
7             + (int)(Math.random() * 10);
8
9         // Prompt the user to enter a guess
10        Scanner input = new Scanner(System.in);
11        System.out.print("Enter your lottery pick (two digits): ");
12        String guess = input.nextLine();
13
14        // Get digits from lottery
15        char lotteryDigit1 = lottery.charAt(0);
16        char lotteryDigit2 = lottery.charAt(1);
17
18        // Get digits from guess
19        char guessDigit1 = guess.charAt(0);
20        char guessDigit2 = guess.charAt(1);
21
22        System.out.println("The lottery number is " + lottery);
23
24        // Check the guess
25        if (guess.equals(lottery))
26            System.out.println("Exact match: you win $10,000");
27        else if (guessDigit2 == lotteryDigit1
28                  && guessDigit1 == lotteryDigit2)
29            System.out.println("Match all digits: you win $3,000");
30        else if (guessDigit1 == lotteryDigit1
31                  || guessDigit1 == lotteryDigit2
32                  || guessDigit2 == lotteryDigit1
33                  || guessDigit2 == lotteryDigit2)
34            System.out.println("Match one digit: you win $1,000");

```

```

35     else
36         System.out.println("Sorry, no match");
37     }
38 }
```

Enter your lottery pick (two digits): 00

The lottery number is 00

Exact match: you win \$10,000



Enter your lottery pick (two digits): 45

The lottery number is 54

Match all digits: you win \$3,000



Enter your lottery pick: 23

The lottery number is 34

Match one digit: you win \$1,000



Enter your lottery pick: 23

The lottery number is 14

Sorry: no match



The program generates two random digits and concatenates them into the string **lottery** (lines 6–7). After this, **lottery** contains two random digits.

The program prompts the user to enter a guess as a two-digit string (line 12) and checks the guess against the lottery number in this order:

- First check whether the guess matches the lottery exactly (line 25).
- If not, check whether the reversal of the guess matches the lottery (line 27).
- If not, check whether one digit is in the lottery (lines 30–33).
- If not, nothing matches and display “Sorry, no match” (line 36).

4.6 Formatting Console Output

*You can use the **System.out.printf** method to display formatted output on the console.*



Often, it is desirable to display numbers in a certain format. For example, the following code computes interest, given the amount and the annual interest rate.

```

double amount = 12618.98;
double interestRate = 0.0013;
double interest = amount * interestRate;
System.out.println("Interest is $" + interest);
```

Interest is \$16.404674



Because the interest amount is currency, it is desirable to display only two digits after the decimal point. To do this, you can write the code as follows:

```
double amount = 12618.98;
double interestRate = 0.0013;
double interest = amount * interestRate;
System.out.println("Interest is $" +
+ (int)(interest * 100) / 100.0);
```

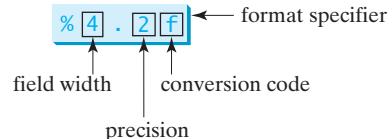


Interest is \$16.4

`printf`

However, the format is still not correct. There should be two digits after the decimal point: **16.40** rather than **16.4**. You can fix it by using the **printf** method, like this:

```
double amount = 12618.98;
double interestRate = 0.0013;
double interest = amount * interestRate;
System.out.printf("Interest is $%4.2f",
interest);
```



Interest is \$16.40

format specifier

The syntax to invoke this method is

```
System.out.printf(format, item1, item2, ..., itemk)
```

where **format** is a string that may consist of substrings and format specifiers.

A *format specifier* specifies how an item should be displayed. An item may be a numeric value, a character, a Boolean value, or a string. A simple format specifier consists of a percent sign (%) followed by a conversion code. Table 4.11 lists some frequently used simple format specifiers.

TABLE 4.11 Frequently Used Format Specifiers

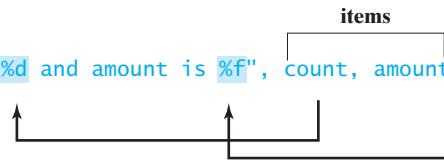
Format Specifier	Output	Example
%b	a Boolean value	true or false
%c	a character	'a'
%d	a decimal integer	200
%f	a floating-point number	45.460000
%e	a number in standard scientific notation	4.556000e+01
%s	a string	"Java is cool"

Here is an example:

```
int count = 5;
double amount = 45.56;
System.out.printf("count is %d and amount is %f", count, amount);
```

display

count is 5 and amount is 45.560000



Items must match the format specifiers in order, in number, and in exact type. For example, the format specifier for `count` is `%d` and for `amount` is `%f`. By default, a floating-point value is displayed with six digits after the decimal point. You can specify the width and precision in a format specifier, as shown in the examples in Table 4.12.

TABLE 4.12 Examples of Specifying Width and Precision

Example	Output
<code>%5c</code>	Output the character and add four spaces before the character item, because the width is 5.
<code>%6b</code>	Output the Boolean value and add one space before the false value and two spaces before the true value.
<code>%5d</code>	Output the integer item with width at least 5. If the number of digits in the item is < 5, add spaces before the number. If the number of digits in the item is > 5, the width is automatically increased.
<code>%10.2f</code>	Output the floating-point item with width at least 10 including a decimal point and two digits after the point. Thus, there are 7 digits allocated before the decimal point. If the number of digits before the decimal point in the item is < 7, add spaces before the number. If the number of digits before the decimal point in the item is > 7, the width is automatically increased.
<code>%10.2e</code>	Output the floating-point item with width at least 10 including a decimal point, two digits after the point and the exponent part. If the displayed number in scientific notation has width less than 10, add spaces before the number.
<code>%12s</code>	Output the string with width at least 12 characters. If the string item has fewer than 12 characters, add spaces before the string. If the string item has more than 12 characters, the width is automatically increased.

If an item requires more spaces than the specified width, the width is automatically increased. For example, the following code

```
System.out.printf("%3d%#2s%#4.2f\n", 1234, "Java", 51.6653);
```

displays

1234#Java#51.67

The specified width for `int` item `1234` is `3`, which is smaller than its actual size `4`. The width is automatically increased to `4`. The specified width for string item `Java` is `2`, which is smaller than its actual size `4`. The width is automatically increased to `4`. The specified width for `double` item `51.6653` is `4`, but it needs width `5` to display `51.67`, so the width is automatically increased to `5`.

By default, the output is right justified. You can put the minus sign (`-`) in the format specifier to specify that the item is left justified in the output within the specified field. For example, the following statements

```
System.out.printf("%8d%8s%8.1f\n", 1234, "Java", 5.63);
System.out.printf("%-8d%-8s%-8.1f \n", 1234, "Java", 5.63);
```

display



where the square box (□) denotes a blank space.

right justify
left justify

**Caution**

The items must match the format specifiers in exact type. The item for the format specifier `%f` or `%e` must be a floating-point type value such as `40.0`, not `40`. Thus, an `int` variable cannot match `%f` or `%e`.

**Tip**

The `%` sign denotes a format specifier. To output a literal `%` in the format string, use `%%`.

Listing 4.6 gives a program that uses `printf` to display a table.

LISTING 4.6 FormatDemo.java

display table header

values for 30 degrees

values for 60 degrees

```

1 public class FormatDemo {
2     public static void main(String[] args) {
3         // Display the header of the table
4         System.out.printf("%-10s%-10s%-10s%-10s%-10s\n", "Degrees",
5                           "Radians", "Sine", "Cosine", "Tangent");
6
7         // Display values for 30 degrees
8         int degrees = 30;
9         double radians = Math.toRadians(degrees);
10        System.out.printf("%-10d%-10.4f%-10.4f%-10.4f%-10.4f\n", degrees,
11                           radians, Math.sin(radians), Math.cos(radians),
12                           Math.tan(radians));
13
14        // Display values for 60 degrees
15        degrees = 60;
16        radians = Math.toRadians(degrees);
17        System.out.printf("%-10d%-10.4f%-10.4f%-10.4f%-10.4f\n", degrees,
18                           radians, Math.sin(radians), Math.cos(radians),
19                           Math.tan(radians));
20    }
21 }
```



Degrees	Radians	Sine	Cosine	Tangent
30	0.5236	0.5000	0.8660	0.5773
60	1.0472	0.8660	0.5000	1.7320

The statement in lines 4–5 displays the column names of the table. The column names are strings. Each string is displayed using the specifier `%-10s`, which left-justifies the string. The statement in lines 10–12 displays the degrees as an integer and four float values. The integer is displayed using the specifier `%-10d` and each float is displayed using the specifier `%-10.4f`, which specifies four digits after the decimal point.



4.22 What are the format specifiers for outputting a Boolean value, a character, a decimal integer, a floating-point number, and a string?

4.23 What is wrong in the following statements?

- (a) `System.out.printf("%5d %d", 1, 2, 3);`
- (b) `System.out.printf("%5d %f", 1);`
- (c) `System.out.printf("%5d %F", 1, 2);`

4.24 Show the output of the following statements.

- `System.out.printf("amount is %f %e\n", 32.32, 32.32);`
- `System.out.printf("amount is %5.2% %5.4e\n", 32.327, 32.32);`
- `System.out.printf("%6b\n", (1 > 2));`
- `System.out.printf("%6s\n", "Java");`
- `System.out.printf("%-6b%s\n", (1 > 2), "Java");`
- `System.out.printf("%6b%-8s\n", (1 > 2), "Java");`

KEY TERMS

<code>char</code> type	125	instance method	130
encoding	125	static method	130
escape character	127	supplementary Unicode	125
escape sequence	126	Unicode	125
format specifier	146	whitespace character	133

CHAPTER SUMMARY

- Java provides the mathematical methods `sin, cos, tan, asin, acos, atan, toRadians, toDegree, exp, log, log10, pow, sqrt, ceil, floor, rint, round, min, max, abs`, and `random` in the `Math` class for performing mathematical functions.
- The character type `char` represents a single character.
- An escape sequence consists of a backslash (\) followed by a character or a combination of digits.
- The character \ is called the escape character.
- The characters ' ', \t, \f, \r, and \n are known as the whitespace characters.
- Characters can be compared based on their Unicode using the relational operators.
- The `Character` class contains the methods `isDigit, isLetter, isLetterOrDigit, isLowerCase, isUpperCase` for testing whether a character is a digit, letter, lowercase, and uppercase. It also contains the `toLowerCase` and `toUpperCase` methods for returning a lowercase or uppercase letter.
- A *string* is a sequence of characters. A string value is enclosed in matching double quotes (""). A character value is enclosed in matching single quotes ('').
- Strings are objects in Java. A method that can only be invoked from a specific object is called an *instance method*. A non-instance method is called a static method, which can be invoked without using an object.

10. You can get the length of a string by invoking its `length()` method, retrieve a character at the specified index in the string using the `charAt(index)` method, and use the `indexOf` and `lastIndexOf` methods to find a character or a substring in a string.
11. You can use the `concat` method to concatenate two strings, or the plus (+) operator to concatenate two or more strings.
12. You can use the `substring` method to obtain a substring from the string.
13. You can use the `equals` and `compareTo` methods to compare strings. The `equals` method returns `true` if two strings are equal, and `false` if they are not equal. The `compareTo` method returns 0, a positive integer, or a negative integer, depending on whether one string is equal to, greater than, or less than the other string.
14. The `printf` method can be used to display a formatted output using format specifiers.

Quiz

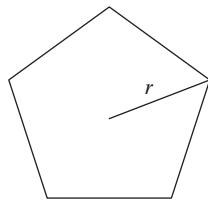
Answer the quiz for this chapter online at www.cs.armstrong.edu/liang/intro10e/quiz.html.

MyProgrammingLab™

PROGRAMMING EXERCISES

Section 4.2

- 4.1** (*Geometry: area of a pentagon*) Write a program that prompts the user to enter the length from the center of a pentagon to a vertex and computes the area of the pentagon, as shown in the following figure.



The formula for computing the area of a pentagon is $Area = \frac{5 \times s^2}{4 \times \tan\left(\frac{\pi}{5}\right)}$, where s is the length of a side. The side can be computed using the formula $s = 2r \sin \frac{\pi}{5}$, where r is the length from the center of a pentagon to a vertex. Round up two digits after the decimal point. Here is a sample run:



Enter the length from the center to a vertex: 5.5

- *4.2** (*Geometry: great circle distance*) The great circle distance is the distance between two points on the surface of a sphere. Let (x_1, y_1) and (x_2, y_2) be the geographical latitude and longitude of two points. The great circle distance between the two points can be computed using the following formula:

$$d = \text{radius} \times \arccos(\sin(x_1) \times \sin(x_2) + \cos(x_1) \times \cos(x_2) \times \cos(y_1 - y_2))$$

Write a program that prompts the user to enter the latitude and longitude of two points on the earth in degrees and displays its great circle distance. The average earth radius is 6,371.01 km. Note that you need to convert the degrees into radians using the `Math.toRadians` method since the Java trigonometric methods use radians. The latitude and longitude degrees in the formula are for north and west. Use negative to indicate south and east degrees. Here is a sample run:



Compute great circle distance

```
Enter point 1 (latitude and longitude) in degrees: 39.55, -116.25 ↵ Enter
Enter point 2 (latitude and longitude) in degrees: 41.5, 87.37 ↵ Enter
The distance between the two points is 10691.79183231593 km
```



- *4.3** (*Geography: estimate areas*) Find the GPS locations for Atlanta, Georgia; Orlando, Florida; Savannah, Georgia; and Charlotte, North Carolina from www.gps-data-team.com/map/ and compute the estimated area enclosed by these four cities. (Hint: Use the formula in Programming Exercise 4.2 to compute the distance between two cities. Divide the polygon into two triangles and use the formula in Programming Exercise 2.19 to compute the area of a triangle.)

- 4.4** (*Geometry: area of a hexagon*) The area of a hexagon can be computed using the following formula (`s` is the length of a side):

$$\text{Area} = \frac{6 \times s^2}{4 \times \tan\left(\frac{\pi}{6}\right)}$$

Write a program that prompts the user to enter the side of a hexagon and displays its area. Here is a sample run:

```
Enter the side: 5.5 ↵ Enter
The area of the hexagon is 78.59
```



- *4.5** (*Geometry: area of a regular polygon*) A regular polygon is an n -sided polygon in which all sides are of the same length and all angles have the same degree (i.e., the polygon is both equilateral and equiangular). The formula for computing the area of a regular polygon is

$$\text{Area} = \frac{n \times s^2}{4 \times \tan\left(\frac{\pi}{n}\right)}$$

Here, s is the length of a side. Write a program that prompts the user to enter the number of sides and their length of a regular polygon and displays its area. Here is a sample run:



```
Enter the number of sides: 5 ↵Enter
Enter the side: 6.5 ↵Enter
The area of the polygon is 74.69017017488385
```

- *4.6** (*Random points on a circle*) Write a program that generates three random points on a circle centered at $(0, 0)$ with radius 40 and display three angles in a triangle formed by these three points, as shown in Figure 4.7a. (Hint: Generate a random angle α in radians between 0 and 2π , as shown in Figure 4.7b and the point determined by this angle is $(r \cos(\alpha), r \sin(\alpha))$.)

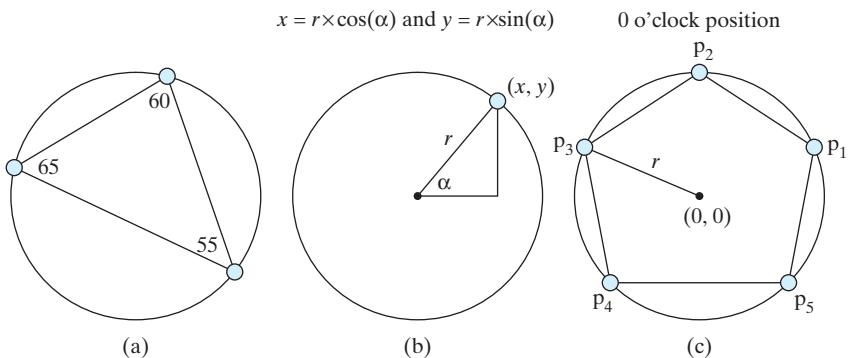


FIGURE 4.7 (a) A triangle is formed from three random points on the circle. (b) A random point on the circle can be generated using a random angle α . (c) A pentagon is centered at $(0, 0)$ with one point at the 0 o'clock position.

- *4.7** (*Corner point coordinates*) Suppose a pentagon is centered at $(0, 0)$ with one point at the 0 o'clock position, as shown in Figure 4.7c. Write a program that prompts the user to enter the radius of the bounding circle and displays the coordinates of the five corner points on the pentagon. Here is a sample run:



```
Enter the radius of the bounding circle: 100 ↵Enter
The coordinates of five points on the pentagon are
(95.1057, 30.9017)
(0.000132679, 100)
(-95.1056, 30.9019)
(-58.7788, -80.9015)
(58.7782, -80.902)
```

Sections 4.3–4.6

- *4.8** (*Find the character of an ASCII code*) Write a program that receives an ASCII code (an integer between 0 and 127) and displays its character. Here is a sample run:



```
Enter an ASCII code: 69 ↵Enter
The character for ASCII code 69 is E
```

- *4.9** (*Find the Unicode of a character*) Write a program that receives a character and displays its Unicode. Here is a sample run:

```
Enter a character: E ↵Enter
The Unicode for the character E is 69
```



- *4.10** (*Guess birthday*) Rewrite Listing 4.3, GuessBirthday.java, to prompt the user to enter the character **Y** for Yes and **N** for No rather than entering **1** for Yes and **0** for No.

- *4.11** (*Decimal to hex*) Write a program that prompts the user to enter an integer between **0** and **15** and displays its corresponding hex number. Here are some sample runs:

```
Enter a decimal value (0 to 15): 11 ↵Enter
The hex value is B
```



```
Enter a decimal value (0 to 15): 5 ↵Enter
The hex value is 5
```



```
Enter a decimal value (0 to 15): 31 ↵Enter
31 is an invalid input
```



- 4.12** (*Hex to binary*) Write a program that prompts the user to enter a hex digit and displays its corresponding binary number. Here is a sample run:



VideoNote

Convert hex to binary

```
Enter a hex digit: B ↵Enter
The binary value is 1011
```



```
Enter a hex digit: G ↵Enter
G is an invalid input
```



- *4.13** (*Vowel or consonant?*) Write a program that prompts the user to enter a letter and check whether the letter is a vowel or consonant. Here is a sample run:

```
Enter a letter: B ↵Enter
B is a consonant
```



```
Enter a letter grade: a ↵Enter
a is a vowel
```



```
Enter a letter grade: # ↵Enter
# is an invalid input
```



- *4.14** (*Convert letter grade to number*) Write a program that prompts the user to enter a letter grade A, B, C, D, or F and displays its corresponding numeric value 4, 3, 2, 1, or 0. Here is a sample run:



Enter a letter grade: B ↵Enter
The numeric value for grade B is 3



Enter a letter grade: T ↵Enter
T is an invalid grade

- *4.15** (*Phone key pads*) The international standard letter/number mapping found on the telephone is shown below:



Write a program that prompts the user to enter a letter and displays its corresponding number.



Enter a letter: A ↵Enter
The corresponding number is 2



Enter a letter: a ↵Enter
The corresponding number is 2



Enter a letter: + ↵Enter
+ is an invalid input

- 4.16** (*Random character*) Write a program that displays a random uppercase letter using the `Math.random()` method.

- *4.17** (*Days of a month*) Write a program that prompts the user to enter a year and the first three letters of a month name (with the first letter in uppercase) and displays the number of days in the month. Here is a sample run:



Enter a year: 2001 ↵Enter
Enter a month: Jan ↵Enter
Jan 2001 has 31 days

```
Enter a year: 2016 ↵Enter
Enter a month: Feb ↵Enter
Jan 2016 has 29 days
```



- *4.18** (*Student major and status*) Write a program that prompts the user to enter two characters and displays the major and status represented in the characters. The first character indicates the major and the second is number character 1, 2, 3, 4, which indicates whether a student is a freshman, sophomore, junior, or senior. Suppose the following characters are used to denote the majors:

M: Mathematics
C: Computer Science
I: Information Technology

Here is a sample run:

```
Enter two characters: M1 ↵Enter
Mathematics Freshman
```



```
Enter two characters: C3 ↵Enter
Computer Science Junior
```



```
Enter two characters: T3 ↵Enter
Invalid input
```



- 4.19** (*Business: check ISBN-10*) Rewrite the Programming Exercise 3.9 by entering the ISBN number as a string.

- 4.20** (*Process a string*) Write a program that prompts the user to enter a string and displays its length and its first character.

- *4.21** (*Check SSN*) Write a program that prompts the user to enter a Social Security number in the format DDD-DD-DDDD, where D is a digit. Your program should check whether the input is valid. Here are sample runs:

```
Enter a SSN: 232-23-5435 ↵Enter
232-23-5435 is a valid social security number
```



```
Enter a SSN: 23-23-5435 ↵Enter
23-23-5435 is an invalid social security number
```



- 4.22** (*Check substring*) Write a program that prompts the user to enter two strings and reports whether the second string is a substring of the first string.

```
Enter string s1: ABCD ↵Enter
Enter string s2: BC ↵Enter
BC is a substring of ABCD
```





```
Enter string s1: ABCD ↵Enter
Enter string s2: BDC ↵Enter
BDC is not a substring of ABCD
```

- *4.23** (*Financial application: payroll*) Write a program that reads the following information and prints a payroll statement:

Employee's name (e.g., Smith)
 Number of hours worked in a week (e.g., 10)
 Hourly pay rate (e.g., 9.75)
 Federal tax withholding rate (e.g., 20%)
 State tax withholding rate (e.g., 9%)

A sample run is shown below:



```
Enter employee's name: Smith ↵Enter
Enter number of hours worked in a week: 10 ↵Enter
Enter hourly pay rate: 9.75 ↵Enter
Enter federal tax withholding rate: 0.20 ↵Enter
Enter state tax withholding rate: 0.09 ↵Enter

Employee Name: Smith
Hours Worked: 10.0
Pay Rate: $9.75
Gross Pay: $97.5
Deductions:
    Federal Withholding (20.0%): $19.5
    State Withholding (9.0%): $8.77
    Total Deduction: $28.27
Net Pay: $69.22
```

- *4.24** (*Order three cities*) Write a program that prompts the user to enter three cities and displays them in ascending order. Here is a sample run:



```
Enter the first city: Chicago ↵Enter
Enter the second city: Los Angeles ↵Enter
Enter the third city: Atlanta ↵Enter
The three cities in alphabetical order are Atlanta Chicago Los Angeles
```

- *4.25** (*Generate vehicle plate numbers*) Assume a vehicle plate number consists of three uppercase letters followed by four digits. Write a program to generate a plate number.

- *4.26** (*Financial application: monetary units*) Rewrite Listing 2.10, ComputeChange.java, to fix the possible loss of accuracy when converting a float value to an `int` value. Read the input as a string such as "`11.56`". Your program should extract the dollar amount before the decimal point and the cents after the decimal amount using the `indexOf` and `substring` methods.

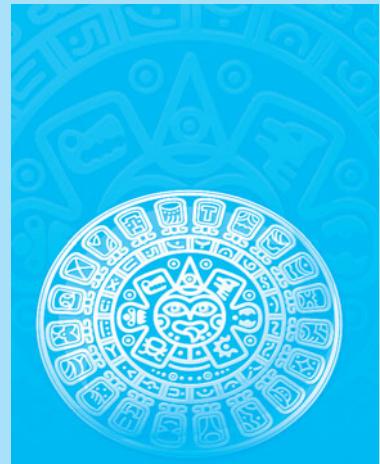
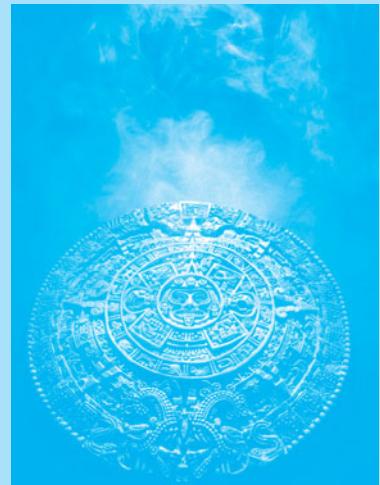
CHAPTER

5

LOOPS

Objectives

- To write programs for executing statements repeatedly using a **while** loop (§5.2).
- To follow the loop design strategy to develop loops (§§5.2.1–5.2.3).
- To control a loop with a sentinel value (§5.2.4).
- To obtain large input from a file using input redirection rather than typing from the keyboard (§5.2.5).
- To write loops using **do-while** statements (§5.3).
- To write loops using **for** statements (§5.4).
- To discover the similarities and differences of three types of loop statements (§5.5).
- To write nested loops (§5.6).
- To learn the techniques for minimizing numerical errors (§5.7).
- To learn loops from a variety of examples (**GCD**, **FutureTuition**, **Dec2Hex**) (§5.8).
- To implement program control with **break** and **continue** (§5.9).
- To process characters in a string using a loop in a case study for checking palindrome (§5.10).
- To write a program that displays prime numbers (§5.11).



problem



5.1 Introduction

A loop can be used to tell a program to execute statements repeatedly.

Suppose that you need to display a string (e.g., **Welcome to Java!**) a hundred times. It would be tedious to have to write the following statement a hundred times:

100 times {
 System.out.println("Welcome to Java!");
 System.out.println("Welcome to Java!");
 ...
 System.out.println("Welcome to Java!");

So, how do you solve this problem?

loop

Java provides a powerful construct called a *loop* that controls how many times an operation or a sequence of operations is performed in succession. Using a loop statement, you simply tell the computer to display a string a hundred times without having to code the print statement a hundred times, as follows:

```
int count = 0;
while (count < 100) {
    System.out.println("Welcome to Java!");
    count++;
}
```

The variable **count** is initially **0**. The loop checks whether **count < 100** is **true**. If so, it executes the loop body to display the message **Welcome to Java!** and increments **count** by **1**. It repeatedly executes the loop body until **count < 100** becomes **false**. When **count < 100** is **false** (i.e., when **count** reaches **100**), the loop terminates and the next statement after the loop statement is executed.

Loops are constructs that control repeated executions of a block of statements. The concept of looping is fundamental to programming. Java provides three types of loop statements: **while** loops, **do-while** loops, and **for** loops.



5.2 The **while** Loop

A **while** loop executes statements repeatedly while the condition is true.

The syntax for the **while** loop is:

while loop

```
while (loop-continuation-condition) {
    // Loop body
    Statement(s);
}
```

loop body
iteration
loop-continuation-
condition

Figure 5.1a shows the **while**-loop flowchart. The part of the loop that contains the statements to be repeated is called the *loop body*. A one-time execution of a loop body is referred to as an *iteration* (or *repetition*) of the loop. Each loop contains a *loop-continuation-condition*, a Boolean expression that controls the execution of the body. It is evaluated each time to determine if the loop body is executed. If its evaluation is **true**, the loop body is executed; if its evaluation is **false**, the entire loop terminates and the program control turns to the statement that follows the **while** loop.

The loop for displaying **Welcome to Java!** a hundred times introduced in the preceding section is an example of a **while** loop. Its flowchart is shown in Figure 5.1b. The

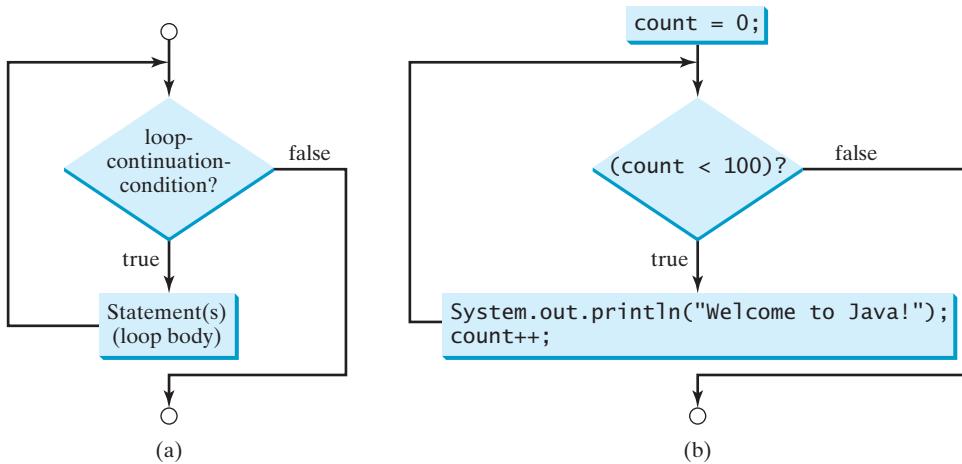


FIGURE 5.1 The `while` loop repeatedly executes the statements in the loop body when the **Loop-continuation-condition** evaluates to **true**.

Loop-continuation-condition is `count < 100` and the loop body contains the following two statements:

```

int count = 0;           ← loop-continuation-condition
while (count < 100) {
    System.out.println("Welcome to Java!");
    count++;
}

```

In this example, you know exactly how many times the loop body needs to be executed because the control variable `count` is used to count the number of executions. This type of loop is known as a *counter-controlled loop*.



Note

The **Loop-continuation-condition** must always appear inside the parentheses. The braces enclosing the loop body can be omitted only if the loop body contains one or no statement.

Here is another example to help understand how a loop works.

```

int sum = 0, i = 1;
while (i < 10) {
    sum = sum + i;
    i++;
}
System.out.println("sum is " + sum); // sum is 45

```

If `i < 10` is **true**, the program adds `i` to `sum`. Variable `i` is initially set to `1`, then is incremented to `2`, `3`, and up to `10`. When `i` is `10`, `i < 10` is **false**, so the loop exits. Therefore, the sum is `1 + 2 + 3 + ... + 9 = 45`.

What happens if the loop is mistakenly written as follows?

```

int sum = 0, i = 1;
while (i < 10) {
    sum = sum + i;
}

```

This loop is infinite, because `i` is always `1` and `i < 10` will always be **true**.

infinite loop

off-by-one error

generate number1
generate number2

show question

get first answer

check answer

read an answer

Note

Make sure that the **loop-continuation-condition** eventually becomes **false** so that the loop will terminate. A common programming error involves *infinite loops* (i. e., the loop runs forever). If your program takes an unusually long time to run and does not stop, it may have an infinite loop. If you are running the program from the command window, press **CTRL+C** to stop it.

Caution

Programmers often make the mistake of executing a loop one more or less time. This is commonly known as the *off-by-one error*. For example, the following loop displays **Welcome to Java** 101 times rather than 100 times. The error lies in the condition, which should be **count < 100** rather than **count <= 100**.

```
int count = 0;
while (count <= 100) {
    System.out.println("Welcome to Java!");
    count++;
}
```

Recall that Listing 3.1, *AdditionQuiz.java*, gives a program that prompts the user to enter an answer for a question on addition of two single digits. Using a loop, you can now rewrite the program to let the user repeatedly enter a new answer until it is correct, as shown in Listing 5.1.

LISTING 5.1 RepeatAdditionQuiz.java

```
1 import java.util.Scanner;
2
3 public class RepeatAdditionQuiz {
4     public static void main(String[] args) {
5         int number1 = (int)(Math.random() * 10);
6         int number2 = (int)(Math.random() * 10);
7
8         // Create a Scanner
9         Scanner input = new Scanner(System.in);
10
11        System.out.print(
12            "What is " + number1 + " + " + number2 + "? ");
13        int answer = input.nextInt();
14
15        while (number1 + number2 != answer) {
16            System.out.print("Wrong answer. Try again. What is "
17                + number1 + " + " + number2 + "? ");
18            answer = input.nextInt();
19        }
20
21        System.out.println("You got it!");
22    }
23 }
```



What is 5 + 9? 12 ↵Enter
 Wrong answer. Try again. What is 5 + 9? 34 ↵Enter
 Wrong answer. Try again. What is 5 + 9? 14 ↵Enter
 You got it!

The loop in lines 15–19 repeatedly prompts the user to enter an `answer` when `number1 + number2 != answer` is `true`. Once `number1 + number2 != answer` is `false`, the loop exits.

5.2.1 Case Study: Guessing Numbers

The problem is to guess what number a computer has in mind. You will write a program that randomly generates an integer between `0` and `100`, inclusive. The program prompts the user to enter a number continuously until the number matches the randomly generated number. For each user input, the program tells the user whether the input is too low or too high, so the user can make the next guess intelligently. Here is a sample run:

```
Guess a magic number between 0 and 100
Enter your guess: 50 ↵Enter
Your guess is too high
Enter your guess: 25 ↵Enter
Your guess is too low
Enter your guess: 42 ↵Enter
Your guess is too high
Enter your guess: 39 ↵Enter
Yes, the number is 39
```

The magic number is between `0` and `100`. To minimize the number of guesses, enter `50` first. If your guess is too high, the magic number is between `0` and `49`. If your guess is too low, the magic number is between `51` and `100`. So, you can eliminate half of the numbers from further consideration after one guess.

How do you write this program? Do you immediately begin coding? No. It is important to *think before coding*. Think how you would solve the problem without writing a program. You need first to generate a random number between `0` and `100`, inclusive, then to prompt the user to enter a guess, and then to compare the guess with the random number.

It is a good practice to *code incrementally* one step at a time. For programs involving loops, if you don't know how to write a loop right away, you may first write the code for executing the loop one time, and then figure out how to repeatedly execute the code in a loop. For this program, you may create an initial draft, as shown in Listing 5.2.

LISTING 5.2 GuessNumberOneTime.java

```
1 import java.util.Scanner;
2
3 public class GuessNumberOneTime {
4     public static void main(String[] args) {
5         // Generate a random number to be guessed
6         int number = (int)(Math.random() * 101);
7
8         Scanner input = new Scanner(System.in);
9         System.out.println("Guess a magic number between 0 and 100");
10
11        // Prompt the user to guess the number
12        System.out.print("\nEnter your guess: ");
13        int guess = input.nextInt();
14
15        if (guess == number)
16            System.out.println("Yes, the number is " + number);
```



intelligent guess

think before coding

code incrementally

generate a number

enter a guess

correct guess?

```

17     else if (guess > number)
18         System.out.println("Your guess is too high");
19     else
20         System.out.println("Your guess is too low");
21 }
22 }
```

When you run this program, it prompts the user to enter a guess only once. To let the user enter a guess repeatedly, you may wrap the code in lines 11–20 in a loop as follows:

```

while (true) {
    // Prompt the user to guess the number
    System.out.print("\nEnter your guess: ");
    guess = input.nextInt();

    if (guess == number)
        System.out.println("Yes, the number is " + number);
    else if (guess > number)
        System.out.println("Your guess is too high");
    else
        System.out.println("Your guess is too low");
} // End of loop
```

This loop repeatedly prompts the user to enter a guess. However, this loop is not correct, because it never terminates. When `guess` matches `number`, the loop should end. So, the loop can be revised as follows:

```

while (guess != number) {
    // Prompt the user to guess the number
    System.out.print("\nEnter your guess: ");
    guess = input.nextInt();

    if (guess == number)
        System.out.println("Yes, the number is " + number);
    else if (guess > number)
        System.out.println("Your guess is too high");
    else
        System.out.println("Your guess is too low");
} // End of loop
```

The complete code is given in Listing 5.3.

LISTING 5.3 GuessNumber.java

generate a number

```

1 import java.util.Scanner;
2
3 public class GuessNumber {
4     public static void main(String[] args) {
5         // Generate a random number to be guessed
6         int number = (int)(Math.random() * 101);
7
8         Scanner input = new Scanner(System.in);
9         System.out.println("Guess a magic number between 0 and 100");
10
11        int guess = -1;
12        while (guess != number) {
13            // Prompt the user to guess the number
14            System.out.print("\nEnter your guess: ");
```

```

15     guess = input.nextInt();           enter a guess
16
17     if (guess == number)
18         System.out.println("Yes, the number is " + number);
19     else if (guess > number)
20         System.out.println("Your guess is too high");    too high?
21     else
22         System.out.println("Your guess is too low");    too low?
23 } // End of loop
24
25 }

```

	line#	number	guess	output
	6	39		
	11		-1	
iteration 1	{ 15 20		50	Your guess is too high
iteration 2	{ 15 22		25	Your guess is too low
iteration 3	{ 15 20		42	Your guess is too high
iteration 4	{ 15 18		39	Yes, the number is 39



The program generates the magic number in line 6 and prompts the user to enter a guess continuously in a loop (lines 12–23). For each guess, the program checks whether the guess is correct, too high, or too low (lines 17–22). When the guess is correct, the program exits the loop (line 12). Note that `guess` is initialized to `-1`. Initializing it to a value between `0` and `100` would be wrong, because that could be the number to be guessed.

5.2.2 Loop Design Strategies

Writing a correct loop is not an easy task for novice programmers. Consider three steps when writing a loop.

Step 1: Identify the statements that need to be repeated.

Step 2: Wrap these statements in a loop like this:

```

while (true) {
    Statements;
}

```

Step 3: Code the **loop-continuation-condition** and add appropriate statements for controlling the loop.

```

while (loop-continuation-condition) {
    Statements;
    Additional statements for controlling the loop;
}

```



VideoNote

Multiple subtraction quiz

get start time

loop

display a question

grade an answer

increase correct count

increase control variable

prepare output

5.2.3 Case Study: Multiple Subtraction Quiz

The Math subtraction learning tool program in Listing 3.3, SubtractionQuiz.java, generates just one question for each run. You can use a loop to generate questions repeatedly. How do you write the code to generate five questions? Follow the loop design strategy. First identify the statements that need to be repeated. These are the statements for obtaining two random numbers, prompting the user with a subtraction question, and grading the question. Second, wrap the statements in a loop. Third, add a loop control variable and the **loop-continuation-condition** to execute the loop five times.

Listing 5.4 gives a program that generates five questions and, after a student answers all five, reports the number of correct answers. The program also displays the time spent on the test and lists all the questions.

LISTING 5.4 SubtractionQuizLoop.java

```

1 import java.util.Scanner;
2
3 public class SubtractionQuizLoop {
4     public static void main(String[] args) {
5         final int NUMBER_OF_QUESTIONS = 5; // Number of questions
6         int correctCount = 0; // Count the number of correct answers
7         int count = 0; // Count the number of questions
8         long startTime = System.currentTimeMillis();
9         String output = ""; // output string is initially empty
10        Scanner input = new Scanner(System.in);
11
12        while (count < NUMBER_OF_QUESTIONS) {
13            // 1. Generate two random single-digit integers
14            int number1 = (int)(Math.random() * 10);
15            int number2 = (int)(Math.random() * 10);
16
17            // 2. If number1 < number2, swap number1 with number2
18            if (number1 < number2) {
19                int temp = number1;
20                number1 = number2;
21                number2 = temp;
22            }
23
24            // 3. Prompt the student to answer "What is number1 - number2?"
25            System.out.print(
26                "What is " + number1 + " - " + number2 + "? ");
27            int answer = input.nextInt();
28
29            // 4. Grade the answer and display the result
30            if (number1 - number2 == answer) {
31                System.out.println("You are correct!");
32                correctCount++; // Increase the correct answer count
33            }
34            else
35                System.out.println("Your answer is wrong.\n" + number1
36                + " - " + number2 + " should be " + (number1 - number2));
37
38            // Increase the question count
39            count++;
40
41            output += "\n" + number1 + "-" + number2 + "=" + answer +
42            ((number1 - number2 == answer) ? " correct" : " wrong");

```

```

43     }
44
45     long endTime = System.currentTimeMillis();
46     long testTime = endTime - startTime;
47
48     System.out.println("Correct count is " + correctCount +
49         "\nTest time is " + testTime / 1000 + " seconds\n" + output);
50 }
51 }
```

end loop
get end time
test time
display result

What is $9 - 2$? 7 

You are correct!



What is $3 - 0$? 3 

You are correct!

What is $3 - 2$? 1 

You are correct!

What is $7 - 4$? 4 

Your answer is wrong.

$7 - 4$ should be 3

What is $7 - 5$? 4 

Your answer is wrong.

$7 - 5$ should be 2

Correct count is 3

Test time is 1021 seconds

$9-2=7$ correct

$3-0=3$ correct

$3-2=1$ correct

$7-4=4$ wrong

$7-5=4$ wrong

The program uses the control variable `count` to control the execution of the loop. `count` is initially **0** (line 7) and is increased by **1** in each iteration (line 39). A subtraction question is displayed and processed in each iteration. The program obtains the time before the test starts in line 8 and the time after the test ends in line 45, and computes the test time in line 46. The test time is in milliseconds and is converted to seconds in line 49.

5.2.4 Controlling a Loop with a Sentinel Value

Another common technique for controlling a loop is to designate a special value when reading and processing a set of values. This special input value, known as a *sentinel value*, signifies the end of the input. A loop that uses a sentinel value to control its execution is called a *sentinel-controlled loop*.

sentinel value

sentinel-controlled loop

Listing 5.5 writes a program that reads and calculates the sum of an unspecified number of integers. The input **0** signifies the end of the input. Do you need to declare a new variable for each input value? No. Just use one variable named `data` (line 12) to store the input value and use a variable named `sum` (line 15) to store the total. Whenever a value is read, assign it to `data` and, if it is not zero, add it to `sum` (line 17).

LISTING 5.5 *SentinelValue.java*

```

1 import java.util.Scanner;
2
3 public class SentinelValue {
4     /** Main method */
5     public static void main(String[] args) {
6         // Create a Scanner
7         Scanner input = new Scanner(System.in);
8
9         // Read an initial data
10        System.out.print(
11            "Enter an integer (the input ends if it is 0): ");
12        int data = input.nextInt();
13
14        // Keep reading data until the input is 0
15        int sum = 0;
16        while (data != 0) {
17            sum += data;
18
19            // Read the next data
20            System.out.print(
21                "Enter an integer (the input ends if it is 0): ");
22            data = input.nextInt();
23        }
24
25        System.out.println("The sum is " + sum);
26    }
27 }
```



```

Enter an integer (the input ends if it is 0): 2 ↵Enter
Enter an integer (the input ends if it is 0): 3 ↵Enter
Enter an integer (the input ends if it is 0): 4 ↵Enter
Enter an integer (the input ends if it is 0): 0 ↵Enter
The sum is 9

```



line#	Data	sum	output
12	2		
15		0	
iteration 1 17		2	
	3		
iteration 2 17		5	
	4		
iteration 3 17		9	
	0		
25			The sum is 9

If **data** is not **0**, it is added to **sum** (line 17) and the next item of input data is read (lines 20–22). If **data** is **0**, the loop body is no longer executed and the **while** loop terminates. The input value **0** is the sentinel value for this loop. Note that if the first input read is **0**, the loop body never executes, and the resulting sum is **0**.

**Caution**

Don't use floating-point values for equality checking in a loop control. Because floating-point values are approximations for some values, using them could result in imprecise counter values and inaccurate results.

Consider the following code for computing `1 + 0.9 + 0.8 + ... + 0.1`:

```
double item = 1; double sum = 0;
while (item != 0) { // No guarantee item will be 0
    sum += item;
    item -= 0.1;
}
System.out.println(sum);
```

Variable `item` starts with `1` and is reduced by `0.1` every time the loop body is executed. The loop should terminate when `item` becomes `0`. However, there is no guarantee that `item` will be exactly `0`, because the floating-point arithmetic is approximated. This loop seems okay on the surface, but it is actually an infinite loop.

numeric error

5.2.5 Input and Output Redirections

In the preceding example, if you have a large number of data to enter, it would be cumbersome to type from the keyboard. You can store the data separated by whitespaces in a text file, say `input.txt`, and run the program using the following command:

```
java SentinelValue < input.txt
```

This command is called *input redirection*. The program takes the input from the file `input.txt` rather than having the user type the data from the keyboard at runtime. Suppose the contents of the file are

```
2 3 4 5 6 7 8 9 12 23 32
23 45 67 89 92 12 34 35 3 1 2 4 0
```

The program should get `sum` to be **518**.

Similarly, there is *output redirection*, which sends the output to a file rather than displaying it on the console. The command for output redirection is:

```
java ClassName > output.txt
```

Input and output redirection can be used in the same command. For example, the following command gets input from `input.txt` and sends output to `output.txt`:

```
java SentinelValue > output.txt
```

Try running the program to see what contents are in `output.txt`.

- 5.1** Analyze the following code. Is `count < 100` always `true`, always `false`, or sometimes `true` or sometimes `false` at Point A, Point B, and Point C?



```
int count = 0;
while (count < 100) {
    // Point A
    System.out.println("Welcome to Java!");
    count++;
    // Point B
}
// Point C
```

- 5.2** What is wrong if `guess` is initialized to `0` in line 11 in Listing 5.3?
- 5.3** How many times are the following loop bodies repeated? What is the output of each loop?

```
int i = 1;
while (i < 10)
    if (i % 2 == 0)
        System.out.println(i);
```

(a)

```
int i = 1;
while (i < 10)
    if (i % 2 == 0)
        System.out.println(i++);
```

(b)

```
int i = 1;
while (i < 10)
    if ((i++) % 2 == 0)
        System.out.println(i);
```

(c)

- 5.4** Suppose the input is `2 3 4 5 0`. What is the output of the following code?

```
import java.util.Scanner;

public class Test {
    public static void main(String[] args) {
        Scanner input = new Scanner(System.in);

        int number, max;
        number = input.nextInt();
        max = number;

        while (number != 0) {
            number = input.nextInt();
            if (number > max)
                max = number;
        }

        System.out.println("max is " + max);
        System.out.println("number " + number);
    }
}
```

- 5.5** What is the output of the following code? Explain the reason.

```
int x = 80000000;
while (x > 0)
    x++;
System.out.println("x is " + x);
```

5.3 The do-while Loop



A **do-while loop** is the same as a **while loop** except that it executes the loop body first and then checks the loop continuation condition.

The **do-while** loop is a variation of the **while** loop. Its syntax is:

do-while loop

```
do {
    // Loop body;
    Statement(s);
} while (loop-continuation-condition);
```

Its execution flowchart is shown in Figure 5.2.

The loop body is executed first, and then the **loop-continuation-condition** is evaluated. If the evaluation is **true**, the loop body is executed again; if it is **false**, the **do-while**

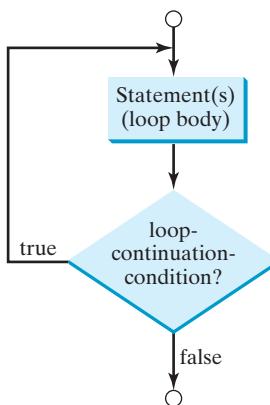


FIGURE 5.2 The `do-while` loop executes the loop body first, then checks the `loop-continuation-condition` to determine whether to continue or terminate the loop.

loop terminates. The difference between a `while` loop and a `do-while` loop is the order in which the `loop-continuation-condition` is evaluated and the loop body executed. You can write a loop using either the `while` loop or the `do-while` loop. Sometimes one is a more convenient choice than the other. For example, you can rewrite the `while` loop in Listing 5.5 using a `do-while` loop, as shown in Listing 5.6.

LISTING 5.6 TestDoWhile.java

```

1 import java.util.Scanner;
2
3 public class TestDoWhile {
4     /** Main method */
5     public static void main(String[] args) {
6         int data;
7         int sum = 0;
8
9         // Create a Scanner
10        Scanner input = new Scanner(System.in);
11
12        // Keep reading data until the input is 0
13        do {                                         loop
14            // Read the next data
15            System.out.print(
16                "Enter an integer (the input ends if it is 0): ");
17            data = input.nextInt();
18
19            sum += data;
20        } while (data != 0);                         end loop
21
22        System.out.println("The sum is " + sum);
23    }
24 }
  
```

```

Enter an integer (the input ends if it is 0): 3 ↵ Enter
Enter an integer (the input ends if it is 0): 5 ↵ Enter
Enter an integer (the input ends if it is 0): 6 ↵ Enter
Enter an integer (the input ends if it is 0): 0 ↵ Enter
The sum is 14
  
```



**Tip**

Use a **do-while** loop if you have statements inside the loop that must be executed *at least once*, as in the case of the **do-while** loop in the preceding **TestDoWhile** program. These statements must appear before the loop as well as inside it if you use a **while** loop.

- 5.6** Suppose the input is **2 3 4 5 0**. What is the output of the following code?

```
import java.util.Scanner;

public class Test {
    public static void main(String[] args) {
        Scanner input = new Scanner(System.in);

        int number, max;
        number = input.nextInt();
        max = number;

        do {
            number = input.nextInt();
            if (number > max)
                max = number;
        } while (number != 0);

        System.out.println("max is " + max);
        System.out.println("number " + number);
    }
}
```

- 5.7** What are the differences between a **while** loop and a **do-while** loop? Convert the following **while** loop into a **do-while** loop.

```
Scanner input = new Scanner(System.in);
int sum = 0;
System.out.println("Enter an integer " +
    "(the input ends if it is 0)");
int number = input.nextInt();
while (number != 0) {
    sum += number;
    System.out.println("Enter an integer " +
        "(the input ends if it is 0)");
    number = input.nextInt();
}
```

5.4 The for Loop



A **for** loop has a concise syntax for writing loops.

Often you write a loop in the following common form:

```
i = initialValue; // Initialize loop control variable
while (i < endValue)
    // Loop body
    ...
    i++; // Adjust loop control variable
}
```

A **for** loop can be used to simplify the preceding loop as:

```
for (i = initialValue; i < endValue; i++)
    // Loop body
    ...
}
```

In general, the syntax of a **for** loop is:

```
for (initial-action; loop-continuation-condition;
      action-after-each-iteration) {
    // Loop body;
    Statement(s);
}
```

for loop

The flowchart of the **for** loop is shown in Figure 5.3a.

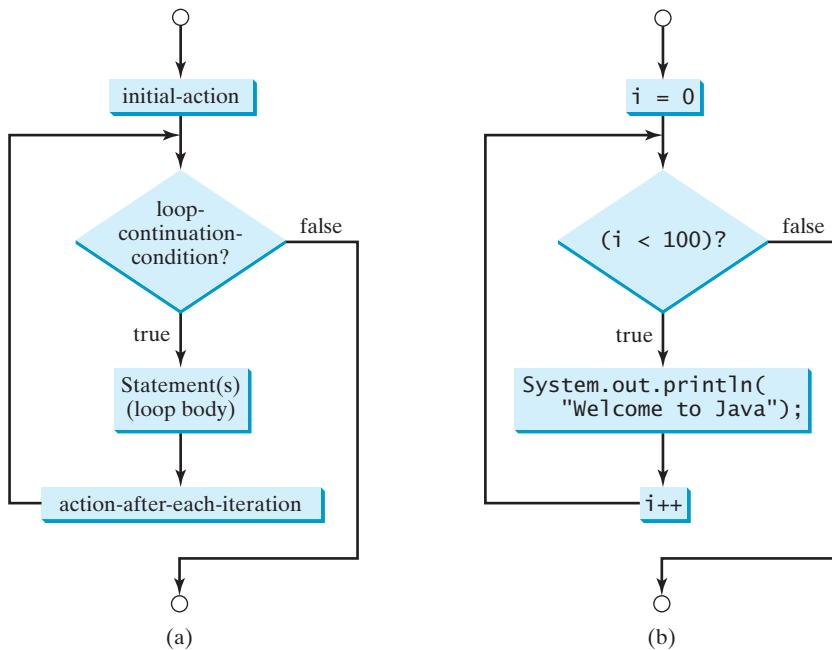


FIGURE 5.3 A **for** loop performs an initial action once, then repeatedly executes the statements in the loop body, and performs an action after an iteration when the **loop-continuation-condition** evaluates to **true**.

The **for** loop statement starts with the keyword **for**, followed by a pair of parentheses enclosing the control structure of the loop. This structure consists of **initial-action**, **loop-continuation-condition**, and **action-after-each-iteration**. The control structure is followed by the loop body enclosed inside braces. The **initial-action**, **loop-continuation-condition**, and **action-after-each-iteration** are separated by semicolons.

A **for** loop generally uses a variable to control how many times the loop body is executed and when the loop terminates. This variable is referred to as a *control variable*. The **initial-action** often initializes a control variable, the **action-after-each-iteration** usually increments or decrements the control variable, and the **loop-continuation-condition**

control variable

tests whether the control variable has reached a termination value. For example, the following **for** loop prints **Welcome to Java!** a hundred times:

```
int i;
for (i = 0; i < 100; i++) {
    System.out.println("Welcome to Java!");
}
```

The flowchart of the statement is shown in Figure 5.3b. The **for** loop initializes **i** to **0**, then repeatedly executes the **println** statement and evaluates **i++** while **i** is less than **100**.

The **initial-action**, **i = 0**, initializes the control variable, **i**. The **loop-continuation-condition**, **i < 100**, is a Boolean expression. The expression is evaluated right after the initialization and at the beginning of each iteration. If this condition is **true**, the loop body is executed. If it is **false**, the loop terminates and the program control turns to the line following the loop.

The **action-after-each-iteration**, **i++**, is a statement that adjusts the control variable. This statement is executed after each iteration and increments the control variable. Eventually, the value of the control variable should force the **loop-continuation-condition** to become **false**; otherwise, the loop is infinite.

The loop control variable can be declared and initialized in the **for** loop. Here is an example:

```
for (int i = 0; i < 100; i++) {
    System.out.println("Welcome to Java!");
}
```

initial-action

action-after-each-iteration

omitting braces

declare control variable

for loop variations



Tip

The control variable must be declared inside the control structure of the loop or before the loop. If the loop control variable is used only in the loop, and not elsewhere, it is a good programming practice to declare it in the **initial-action** of the **for** loop. If the variable is declared inside the loop control structure, it cannot be referenced outside the loop. In the preceding code, for example, you cannot reference **i** outside the **for** loop, because it is declared inside the **for** loop.



Note

The **initial-action** in a **for** loop can be a list of zero or more comma-separated variable declaration statements or assignment expressions. For example:

```
for (int i = 0, j = 0; i + j < 10; i++, j++) {
    // Do something
}
```

The **action-after-each-iteration** in a **for** loop can be a list of zero or more comma-separated statements. For example:

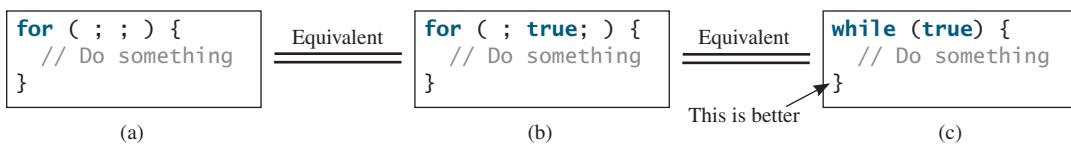
```
for (int i = 1; i < 100; System.out.println(i), i++);
```

This example is correct, but it is a bad example, because it makes the code difficult to read. Normally, you declare and initialize a control variable as an initial action and increment or decrement the control variable as an action after each iteration.



Note

If the **loop-continuation-condition** in a **for** loop is omitted, it is implicitly **true**. Thus the statement given below in (a), which is an infinite loop, is the same as in (b). To avoid confusion, though, it is better to use the equivalent loop in (c).



5.8 Do the following two loops result in the same value in `sum`?



```
for (int i = 0; i < 10; ++i) {
    sum += i;
}
```

(a)

```
for (int i = 0; i < 10; i++) {
    sum += i;
}
```

(b)

5.9 What are the three parts of a **for** loop control? Write a **for** loop that prints the numbers from **1** to **100**.

5.10 Suppose the input is **2 3 4 5 0**. What is the output of the following code?

```
import java.util.Scanner;

public class Test {
    public static void main(String[] args) {
        Scanner input = new Scanner(System.in);

        int number, sum = 0, count;

        for (count = 0; count < 5; count++) {
            number = input.nextInt();
            sum += number;
        }

        System.out.println("sum is " + sum);
        System.out.println("count is " + count);
    }
}
```

5.11 What does the following statement do?

```
for ( ; ; ) {
    // Do something
}
```

5.12 If a variable is declared in a **for** loop control, can it be used after the loop exits?

5.13 Convert the following **for** loop statement to a **while** loop and to a **do-while** loop:

```
long sum = 0;
for (int i = 0; i <= 1000; i++)
    sum = sum + i;
```

5.14 Count the number of iterations in the following loops.

```
int count = 0;
while (count < n) {
    count++;
}
```

(a)

```
for (int count = 0;
     count <= n; count++) {
```

(b)

```
int count = 5;
while (count < n) {
    count++;
}
```

(c)

```
int count = 5;
while (count < n) {
    count = count + 3;
}
```

(d)

5.5 Which Loop to Use?



pretest loop
posttest loop

*You can use a **for** loop, a **while** loop, or a **do-while** loop, whichever is convenient.*

The **while** loop and **for** loop are called *pretest loops* because the continuation condition is checked before the loop body is executed. The **do-while** loop is called a *posttest loop* because the condition is checked after the loop body is executed. The three forms of loop statements—**while**, **do-while**, and **for**—are expressively equivalent; that is, you can write a loop in any of these three forms. For example, a **while** loop in (a) in the following figure can always be converted into the **for** loop in (b).

```
while (loop-continuation-condition) {
    // Loop body
}
```

(a)

Equivalent

```
for ( ; loop-continuation-condition; ) {
    // Loop body
}
```

(b)

A **for** loop in (a) in the next figure can generally be converted into the **while** loop in (b) except in certain special cases (see Checkpoint Question 5.25 for such a case).

```
for (initial-action;
    loop-continuation-condition;
    action-after-each-iteration) {
    // Loop body;
}
```

(a)

Equivalent

```
initial-action;
while (loop-continuation-condition) {
    // Loop body;
    action-after-each-iteration;
}
```

(b)

Use the loop statement that is most intuitive and comfortable for you. In general, a **for** loop may be used if the number of repetitions is known in advance, as, for example, when you need to display a message a hundred times. A **while** loop may be used if the number of repetitions is not fixed, as in the case of reading the numbers until the input is **0**. A **do-while** loop can be used to replace a **while** loop if the loop body has to be executed before the continuation condition is tested.



Caution

Adding a semicolon at the end of the **for** clause before the loop body is a common mistake, as shown below in (a). In (a), the semicolon signifies the end of the loop prematurely. The loop body is actually empty, as shown in (b). (a) and (b) are equivalent. Both are incorrect.

```
for (int i = 0; i < 10; i++) ;
{
    System.out.println("i is " + i);
}
```

(a)

```
for (int i = 0; i < 10; i++) {};
{
    System.out.println("i is " + i);
}
```

(b)

Error

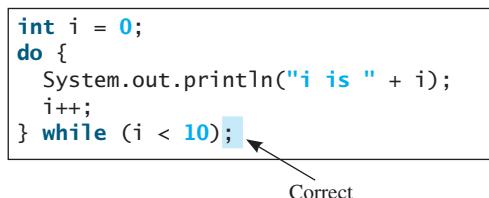
Empty body

Similarly, the loop in (c) is also wrong. (c) is equivalent to (d). Both are incorrect.



These errors often occur when you use the next-line block style. Using the end-of-line block style can avoid errors of this type.

In the case of the **do-while** loop, the semicolon is needed to end the loop.



5.15 Can you convert a **for** loop to a **while** loop? List the advantages of using **for** loops.

5.16 Can you always convert a **while** loop into a **for** loop? Convert the following **while** loop into a **for** loop.

```

int i = 1;
int sum = 0;
while (sum < 10000) {
    sum = sum + i;
    i++;
}
  
```

5.17 Identify and fix the errors in the following code:

```

1 public class Test {
2     public void main(String[] args) {
3         for (int i = 0; i < 10; i++);
4             sum += i;
5
6         if (i < j);
7             System.out.println(i)
8         else
9             System.out.println(j);
10
11        while (j < 10);
12        {
13            j++;
14        }
15
16        do {
17            j++;
18        } while (j < 10)
19    }
20 }
  
```

5.18

What is wrong with the following programs?

```

1 public class ShowErrors {
2     public static void main(String[] args) {
3         int i = 0;
4         do {
5             System.out.println(i + 4);
6             i++;
7         }
8         while (i < 10)
9     }
10 }
```

(a)

```

1 public class ShowErrors {
2     public static void main(String[] args) {
3         for (int i = 0; i < 10; i++);
4             System.out.println(i + 4);
5     }
6 }
```

(b)

5.6 Nested Loops



nested loop

A loop can be nested inside another loop.

Nested loops consist of an outer loop and one or more inner loops. Each time the outer loop is repeated, the inner loops are reentered, and started anew.

Listing 5.7 presents a program that uses nested **for** loops to display a multiplication table.

LISTING 5.7 MultiplicationTable.java

table title

outer loop

inner loop

```

1 public class MultiplicationTable {
2     /** Main method */
3     public static void main(String[] args) {
4         // Display the table heading
5         System.out.println("      Multiplication Table");
6
7         // Display the number title
8         System.out.print("      ");
9         for (int j = 1; j <= 9; j++)
10             System.out.print("      " + j);
11
12         System.out.println("\n-----");
13
14         // Display table body
15         for (int i = 1; i <= 9; i++) {
16             System.out.print(i + " | ");
17             for (int j = 1; j <= 9; j++) {
18                 // Display the product and align properly
19                 System.out.printf("%4d", i * j);
20             }
21             System.out.println();
22         }
23     }
24 }
```



Multiplication Table

	1	2	3	4	5	6	7	8	9
1	1	2	3	4	5	6	7	8	9
2	2	4	6	8	10	12	14	16	18
3	3	6	9	12	15	18	21	24	27
4	4	8	12	16	20	24	28	32	36
5	5	10	15	20	25	30	35	40	45
6	6	12	18	24	30	36	42	48	54
7	7	14	21	28	35	42	49	56	63
8	8	16	24	32	40	48	56	64	72
9	9	18	27	36	45	54	63	72	81

The program displays a title (line 5) on the first line in the output. The first **for** loop (lines 9–10) displays the numbers **1** through **9** on the second line. A dashed (**-**) line is displayed on the third line (line 12).

The next loop (lines 15–22) is a nested **for** loop with the control variable **i** in the outer loop and **j** in the inner loop. For each **i**, the product **i * j** is displayed on a line in the inner loop, with **j** being **1, 2, 3, ..., 9**.



Note

Be aware that a nested loop may take a long time to run. Consider the following loop nested in three levels:

```
for (int i = 0; i < 10000; i++)
    for (int j = 0; j < 10000; j++)
        for (int k = 0; k < 10000; k++)
            Perform an action
```

The action is performed one trillion times. If it takes 1 microsecond to perform the action, the total time to run the loop would be more than 277 hours. Note that 1 microsecond is one millionth (10^{-6}) of a second.

- 5.19** How many times is the **println** statement executed?

```
for (int i = 0; i < 10; i++)
    for (int j = 0; j < i; j++)
        System.out.println(i * j)
```



- 5.20** Show the output of the following programs. (*Hint:* Draw a table and list the variables in the columns to trace these programs.)

```
public class Test {
    public static void main(String[] args) {
        for (int i = 1; i < 5; i++) {
            int j = 0;
            while (j < i) {
                System.out.print(j + " ");
                j++;
            }
        }
    }
}
```

(a)

```
public class Test {
    public static void main(String[] args) {
        int i = 0;
        while (i < 5) {
            for (int j = i; j > 1; j--) {
                System.out.print(j + " ");
            }
            System.out.println("****");
            i++;
        }
    }
}
```

(b)

```
public class Test {
    public static void main(String[] args) {
        int i = 5;
        while (i >= 1) {
            int num = 1;
            for (int j = 1; j <= i; j++) {
                System.out.print(num + "xxx");
                num *= 2;
            }

            System.out.println();
            i--;
        }
    }
}
```

(c)

```
public class Test {
    public static void main(String[] args) {
        int i = 1;
        do {
            int num = 1;
            for (int j = 1; j <= i; j++) {
                System.out.print(num + "G");
                num += 2;
            }

            System.out.println();
            i++;
        } while (i <= 5);
    }
}
```

(d)



VideoNote

Minimize numeric errors

loop

double precision

numeric error

5.7 Minimizing Numeric Errors

Using floating-point numbers in the loop continuation condition may cause numeric errors.

Numeric errors involving floating-point numbers are inevitable, because floating-point numbers are represented in approximation in computers by nature. This section discusses how to minimize such errors through an example.

Listing 5.8 presents an example summing a series that starts with **0.01** and ends with **1.0**. The numbers in the series will increment by **0.01**, as follows: **0.01 + 0.02 + 0.03**, and so on.

LISTING 5.8 TestSum.java

```

1  public class TestSum {
2      public static void main(String[] args) {
3          // Initialize sum
4          float sum = 0;
5
6          // Add 0.01, 0.02, ..., 0.99, 1 to sum
7          for (float i = 0.01f; i <= 1.0f; i = i + 0.01f)
8              sum += i;
9
10         // Display result
11         System.out.println("The sum is " + sum);
12     }
13 }
```



The sum is 50.499985

The **for** loop (lines 7–8) repeatedly adds the control variable **i** to **sum**. This variable, which begins with **0.01**, is incremented by **0.01** after each iteration. The loop terminates when **i** exceeds **1.0**.

The **for** loop initial action can be any statement, but it is often used to initialize a control variable. From this example, you can see that a control variable can be a **float** type. In fact, it can be any data type.

The exact **sum** should be **50.50**, but the answer is **50.499985**. The result is imprecise because computers use a fixed number of bits to represent floating-point numbers, and thus they cannot represent some floating-point numbers exactly. If you change **float** in the program to **double**, as follows, you should see a slight improvement in precision, because a **double** variable holds 64 bits, whereas a **float** variable holds 32 bits.

```

// Initialize sum
double sum = 0;

// Add 0.01, 0.02, ..., 0.99, 1 to sum
for (double i = 0.01; i <= 1.0; i = i + 0.01)
    sum += i;
```

However, you will be stunned to see that the result is actually **49.50000000000003**. What went wrong? If you display **i** for each iteration in the loop, you will see that the last **i** is slightly larger than **1** (not exactly **1**). This causes the last **i** not to be added into **sum**. The fundamental problem is that the floating-point numbers are represented by approximation. To fix the problem, use an integer count to ensure that all the numbers are added to **sum**. Here is the new loop:

```

double currentValue = 0.01;

for (int count = 0; count < 100; count++) {
```

```

    sum += currentValue;
    currentValue += 0.01;
}

```

After this loop, `sum` is **50.5000000000003**. This loop adds the numbers from smallest to biggest. What happens if you add numbers from biggest to smallest (i.e., **1.0, 0.99, 0.98, ..., 0.02, 0.01** in this order) as follows:

```

double currentValue = 1.0;

for (int count = 0; count < 100; count++) {
    sum += currentValue;
    currentValue -= 0.01;
}

```

After this loop, `sum` is **50.4999999999995**. Adding from biggest to smallest is less accurate than adding from smallest to biggest. This phenomenon is an artifact of the finite-precision arithmetic. Adding a very small number to a very big number can have no effect if the result requires more precision than the variable can store. For example, the inaccurate result of **100000000.0 + 0.00000001** is **100000000.0**. To obtain more accurate results, carefully select the order of computation. Adding smaller numbers before bigger numbers is one way to minimize errors.

avoiding numeric error

5.8 Case Studies

Loops are fundamental in programming. The ability to write loops is essential in learning Java programming.



If you can write programs using loops, you know how to program! For this reason, this section presents four additional examples of solving problems using loops.

5.8.1 Case Study: Finding the Greatest Common Divisor

The greatest common divisor (gcd) of the two integers **4** and **2** is **2**. The greatest common divisor of the two integers **16** and **24** is **8**. How would you write this program to find the greatest common divisor? Would you immediately begin to write the code? No. It is important to *think before you code*. Thinking enables you to generate a logical solution for the problem without concern about how to write the code.

gcd

Let the two input integers be `n1` and `n2`. You know that number **1** is a common divisor, but it may not be the greatest common divisor. So, you can check whether `k` (for `k = 2, 3, 4`, and so on) is a common divisor for `n1` and `n2`, until `k` is greater than `n1` or `n2`. Store the common divisor in a variable named `gcd`. Initially, `gcd` is **1**. Whenever a new common divisor is found, it becomes the new gcd. When you have checked all the possible common divisors from **2** up to `n1` or `n2`, the value in variable `gcd` is the greatest common divisor. Once you have a logical solution, type the code to translate the solution into a Java program as follows:

think before you code

```

int gcd = 1; // Initial gcd is 1
int k = 2; // Possible gcd

while (k <= n1 && k <= n2) {
    if (n1 % k == 0 && n2 % k == 0)
        gcd = k; // Update gcd
    k++; // Next possible gcd
}

// After the loop, gcd is the greatest common divisor for n1 and n2

```

logical solution

Listing 5.9 presents the program that prompts the user to enter two positive integers and finds their greatest common divisor.

LISTING 5.9 GreatestCommonDivisor.java

```

1 import java.util.Scanner;
2
3 public class GreatestCommonDivisor {
4     /** Main method */
5     public static void main(String[] args) {
6         // Create a Scanner
7         Scanner input = new Scanner(System.in);
8
9         // Prompt the user to enter two integers
10        System.out.print("Enter first integer: ");
11        int n1 = input.nextInt();
12        System.out.print("Enter second integer: ");
13        int n2 = input.nextInt();
14
15        int gcd = 1; // Initial gcd is 1
16        int k = 2; // Possible gcd
17        while (k <= n1 && k <= n2) {
18            if (n1 % k == 0 && n2 % k == 0)
19                gcd = k; // Update gcd
20            k++;
21        }
22
23        System.out.println("The greatest common divisor for " + n1 +
24                    " and " + n2 + " is " + gcd);
25    }
26 }
```



```

Enter first integer: 125 ↵Enter
Enter second integer: 2525 ↵Enter
The greatest common divisor for 125 and 2525 is 25

```

Translating a logical solution to Java code is not unique. For example, you could use a **for** loop to rewrite the code as follows:

```

for (int k = 2; k <= n1 && k <= n2; k++) {
    if (n1 % k == 0 && n2 % k == 0)
        gcd = k;
}
```

multiple solutions

A problem often has multiple solutions, and the gcd problem can be solved in many ways. Programming Exercise 5.14 suggests another solution. A more efficient solution is to use the classic Euclidean algorithm (see Section 22.6).

erroneous solutions

You might think that a divisor for a number **n1** cannot be greater than **n1 / 2** and would attempt to improve the program using the following loop:

```

for (int k = 2; k <= n1 / 2 && k <= n2 / 2; k++) {
    if (n1 % k == 0 && n2 % k == 0)
        gcd = k;
}
```

This revision is wrong. Can you find the reason? See Checkpoint Question 5.21 for the answer.

5.8.2 Case Study: Predicting the Future Tuition

Suppose that the tuition for a university is **\$10,000** this year and tuition increases **7%** every year. In how many years will the tuition be doubled?

Before you can write a program to solve this problem, first consider how to solve it by hand. The tuition for the second year is the tuition for the first year * **1.07**. The tuition for a future year is the tuition of its preceding year * **1.07**. Thus, the tuition for each year can be computed as follows:

```
double tuition = 10000;    int year = 0;    // Year 0
tuition = tuition * 1.07;   year++;        // Year 1
tuition = tuition * 1.07;   year++;        // Year 2
tuition = tuition * 1.07;   year++;        // Year 3
...
...
```

Keep computing the tuition for a new year until it is at least **20000**. By then you will know how many years it will take for the tuition to be doubled. You can now translate the logic into the following loop:

```
double tuition = 10000;    // Year 0
int year = 0;
while (tuition < 20000) {
    tuition = tuition * 1.07;
    year++;
}
```

The complete program is shown in Listing 5.10.

LISTING 5.10 FutureTuition.java

```
1  public class FutureTuition {
2      public static void main(String[] args) {
3          double tuition = 10000;    // Year 0
4          int year = 0;
5          while (tuition < 20000) {
6              tuition = tuition * 1.07;
7              year++;
8          }
9
10         System.out.println("Tuition will be doubled in "
11             + year + " years");
12         System.out.printf("Tuition will be $%.2f in %d years",
13             tuition, year);
14     }
15 }
```

loop
next year's tuition

```
Tuition will be doubled in 11 years
Tuition will be $21048.52 in 11 years
```



The **while** loop (lines 5–8) is used to repeatedly compute the tuition for a new year. The loop terminates when the tuition is greater than or equal to **20000**.

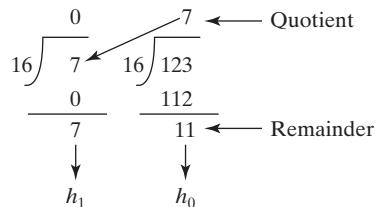
5.8.3 Case Study: Converting Decimals to Hexadecimals

Hexadecimals are often used in computer systems programming (see Appendix F for an introduction to number systems). How do you convert a decimal number to a hexadecimal number? To convert a decimal number d to a hexadecimal number is to find the hexadecimal digits $h_n, h_{n-1}, h_{n-2}, \dots, h_2, h_1$, and h_0 such that

$$d = h_n \times 16^n + h_{n-1} \times 16^{n-1} + h_{n-2} \times 16^{n-2} + \dots + h_2 \times 16^2 + h_1 \times 16^1 + h_0 \times 16^0$$

These hexadecimal digits can be found by successively dividing d by 16 until the quotient is 0. The remainders are $h_0, h_1, h_2, \dots, h_{n-2}, h_{n-1}$, and h_n . The hexadecimal digits include the decimal digits 0, 1, 2, 3, 4, 5, 6, 7, 8, and 9, plus A, which is the decimal value 10; B, which is the decimal value 11; C, which is 12; D, which is 13; E, which is 14; and F, which is 15.

For example, the decimal number 123 is 7B in hexadecimal. The conversion is done as follows. Divide 123 by 16. The remainder is 11 (B in hexadecimal) and the quotient is 7. Continue divide 7 by 16. The remainder is 7 and the quotient is 0. Therefore 7B is the hexadecimal number for 123.



Listing 5.11 gives a program that prompts the user to enter a decimal number and converts it into a hex number as a string.

LISTING 5.11 Dec2Hex.java

```

1 import java.util.Scanner;
2
3 public class Dec2Hex {
4     /** Main method */
5     public static void main(String[] args) {
6         // Create a Scanner
7         Scanner input = new Scanner(System.in);
8
9         // Prompt the user to enter a decimal integer
10        System.out.print("Enter a decimal number: ");
11        int decimal = input.nextInt();
12
13        // Convert decimal to hex
14        String hex = "";
15
16        while (decimal != 0) {
17            int hexValue = decimal % 16;
18
19            // Convert a decimal value to a hex digit
20            char hexDigit = (hexValue <= 9 && hexValue >= 0) ?
21                (char)(hexValue + '0') : (char)(hexValue - 10 + 'A');
22
23            hex = hexDigit + hex;
    
```

input decimal

decimal to hex

```

24     decimal = decimal / 16;
25 }
26
27 System.out.println("The hex number is " + hex);           get a hex char
28 }
29 }
```

get a letter

Enter a decimal number: 1234 
The hex number is 4D2



	line#	decimal	hex	hexValue	hexDigit
iteration 1	14	1234	""		
	17			2	
	23		"2"		2
iteration 2	24	77			
	17			13	
	23		"D2"		D
iteration 3	24	4			
	17			4	
	23		"4D2"		4
	24	0			

The program prompts the user to enter a decimal integer (line 11), converts it to a hex number as a string (lines 14–25), and displays the result (line 27). To convert a decimal to a hex number, the program uses a loop to successively divide the decimal number by 16 and obtain its remainder (line 17). The remainder is converted into a hex character (lines 20–21). The character is then appended to the hex string (line 23). The hex string is initially empty (line 14). Divide the decimal number by 16 to remove a hex digit from the number (line 24). The loop ends when the remaining decimal number becomes 0.

The program converts a `hexValue` between 0 and 15 into a hex character. If `hexValue` is between 0 and 9, it is converted to `(char)(hexValue + '0')` (line 21). Recall that when adding a character with an integer, the character's Unicode is used in the evaluation. For example, if `hexValue` is 5, `(char)(hexValue + '0')` returns 5. Similarly, if `hexValue` is between 10 and 15, it is converted to `(char)(hexValue - 10 + 'A')` (line 21). For instance, if `hexValue` is 11, `(char)(hexValue - 10 + 'A')` returns B.

- 5.21 Will the program work if `n1` and `n2` are replaced by `n1 / 2` and `n2 / 2` in line 17 in Listing 5.9?
- 5.22 In Listing 5.11, why is it wrong if you change the code `(char)(hexValue + '0')` to `hexValue + '0'` in line 21?
- 5.23 In Listing 5.11, how many times the loop body is executed for a decimal number 245 and how many times the loop body is executed for a decimal number 3245?



5.9 Keywords **break** and **continue**



The **break** and **continue** keywords provide additional controls in a loop.



Pedagogical Note

Two keywords, **break** and **continue**, can be used in loop statements to provide additional controls. Using **break** and **continue** can simplify programming in some cases. Overusing or improperly using them, however, can make programs difficult to read and debug. (Note to instructors: You may skip this section without affecting students' understanding of the rest of the book.)

break statement

You have used the keyword **break** in a **switch** statement. You can also use **break** in a loop to immediately terminate the loop. Listing 5.12 presents a program to demonstrate the effect of using **break** in a loop.

LISTING 5.12 TestBreak.java

```

1  public class TestBreak {
2      public static void main(String[] args) {
3          int sum = 0;
4          int number = 0;
5
6          while (number < 20) {
7              number++;
8              sum += number;
9              if (sum >= 100)
10                 break;
11         }
12
13         System.out.println("The number is " + number);
14         System.out.println("The sum is " + sum);
15     }
16 }
```

break



The number is 14
The sum is 105

The program in Listing 5.12 adds integers from **1** to **20** in this order to **sum** until **sum** is greater than or equal to **100**. Without the **if** statement (line 9), the program calculates the sum of the numbers from **1** to **20**. But with the **if** statement, the loop terminates when **sum** becomes greater than or equal to **100**. Without the **if** statement, the output would be:



The number is 20
The sum is 210

continue statement

You can also use the **continue** keyword in a loop. When it is encountered, it ends the current iteration and program control goes to the end of the loop body. In other words, **continue** breaks out of an iteration while the **break** keyword breaks out of a loop. Listing 5.13 presents a program to demonstrate the effect of using **continue** in a loop.

LISTING 5.13 TestContinue.java

```

1  public class TestContinue {
2      public static void main(String[] args) {
3          int sum = 0;
```

```

4     int number = 0;
5
6     while (number < 20) {
7         number++;
8         if (number == 10 || number == 11)
9             continue;
10        sum += number;
11    }
12
13    System.out.println("The sum is " + sum);
14 }
15 }
```

continue

The sum is 189



The program in Listing 5.13 adds integers from **1** to **20** except **10** and **11** to **sum**. With the **if** statement in the program (line 8), the **continue** statement is executed when **number** becomes **10** or **11**. The **continue** statement ends the current iteration so that the rest of the statement in the loop body is not executed; therefore, **number** is not added to **sum** when it is **10** or **11**. Without the **if** statement in the program, the output would be as follows:

The sum is 210



In this case, all of the numbers are added to **sum**, even when **number** is **10** or **11**. Therefore, the result is **210**, which is **21** more than it was with the **if** statement.

**Note**

The **continue** statement is always inside a loop. In the **while** and **do-while** loops, the **loop-continuation-condition** is evaluated immediately after the **continue** statement. In the **for** loop, the **action-after-each-iteration** is performed, then the **loop-continuation-condition** is evaluated, immediately after the **continue** statement.

You can always write a program without using **break** or **continue** in a loop (see Checkpoint Question 5.26). In general, though, using **break** and **continue** is appropriate if it simplifies coding and makes programs easier to read.

Suppose you need to write a program to find the smallest factor other than **1** for an integer **n** (assume **n >= 2**). You can write a simple and intuitive code using the **break** statement as follows:

```

int factor = 2;
while (factor <= n) {
    if (n % factor == 0)
        break;
    factor++;
}
System.out.println("The smallest factor other than 1 for "
    + n + " is " + factor);
```

You may rewrite the code without using **break** as follows:

```

boolean found = false;
int factor = 2;
while (factor <= n && !found) {
    if (n % factor == 0)
```

```

        found = true;
else
    factor++;
}
System.out.println("The smallest factor other than 1 for "
+ n + " is " + factor);

```

Obviously, the **break** statement makes this program simpler and easier to read in this case. However, you should use **break** and **continue** with caution. Too many **break** and **continue** statements will produce a loop with many exit points and make the program difficult to read.

goto

**Note**

Some programming languages have a **goto** statement. The **goto** statement indiscriminately transfers control to any statement in the program and executes it. This makes your program vulnerable to errors. The **break** and **continue** statements in Java are different from **goto** statements. They operate only in a loop or a **switch** statement. The **break** statement breaks out of the loop, and the **continue** statement breaks out of the current iteration in the loop.

**Note**

Programming is a creative endeavor. There are many different ways to write code. In fact, you can find a smallest factor using a rather simple code as follows:

```

int factor = 2;
while (factor <= n && n % factor != 0)
    factor++;

```



- 5.24** What is the keyword **break** for? What is the keyword **continue** for? Will the following programs terminate? If so, give the output.

```

int balance = 10;
while (true) {
    if (balance < 9)
        break;
    balance = balance - 9;
}

System.out.println("Balance is "
+ balance);

```

(a)

```

int balance = 10;
while (true) {
    if (balance < 9)
        continue;
    balance = balance - 9;
}

System.out.println("Balance is "
+ balance);

```

(b)

- 5.25** The **for** loop on the left is converted into the **while** loop on the right. What is wrong? Correct it.

```

int sum = 0;
for (int i = 0; i < 4; i++) {
    if (i % 3 == 0) continue;
    sum += i;
}

```

Converted
Wrong conversion

```

int i = 0, sum = 0;
while (i < 4) {
    if (i % 3 == 0) continue;
    sum += i;
    i++;
}

```

- 5.26** Rewrite the programs **TestBreak** and **TestContinue** in Listings 5.12 and 5.13 without using **break** and **continue**.

- 5.27** After the **break** statement in (a) is executed in the following loop, which statement is executed? Show the output. After the **continue** statement in (b) is executed in the following loop, which statement is executed? Show the output.

```

for (int i = 1; i < 4; i++) {
    for (int j = 1; j < 4; j++) {
        if (i * j > 2)
            break;

        System.out.println(i * j);
    }

    System.out.println(i);
}

```

(a)

```

for (int i = 1; i < 4; i++) {
    for (int j = 1; j < 4; j++) {
        if (i * j > 2)
            continue;

        System.out.println(i * j);
    }

    System.out.println(i);
}

```

(b)

5.10 Case Study: Checking Palindromes

This section presents a program that checks whether a string is a palindrome.

A string is a palindrome if it reads the same forward and backward. The words “mom,” “dad,” and “noon,” for instance, are all palindromes.

The problem is to write a program that prompts the user to enter a string and reports whether the string is a palindrome. One solution is to check whether the first character in the string is the same as the last character. If so, check whether the second character is the same as the second-to-last character. This process continues until a mismatch is found or all the characters in the string are checked, except for the middle character if the string has an odd number of characters.

Listing 5.14 gives the program.

LISTING 5.14 Palindrome.java

```

1 import java.util.Scanner;
2
3 public class Palindrome {
4     /** Main method */
5     public static void main(String[] args) {
6         // Create a Scanner
7         Scanner input = new Scanner(System.in);
8
9         // Prompt the user to enter a string
10        System.out.print("Enter a string: ");
11        String s = input.nextLine();
12
13        // The index of the first character in the string
14        int low = 0;
15
16        // The index of the last character in the string
17        int high = s.length() - 1;
18
19        boolean isPalindrome = true;
20        while (low < high) {
21            if (s.charAt(low) != s.charAt(high)) {
22                isPalindrome = false;
23                break;
24            }
25        }

```



think before you code

input string

low index

high index

update indices

```

26     low++;
27     high--;
28 }
29
30 if (isPalindrome)
31     System.out.println(s + " is a palindrome");
32 else
33     System.out.println(s + " is not a palindrome");
34 }
35 }
```



Enter a string: noon

noon is a palindrome



Enter a string: moon

moon is not a palindrome

The program uses two variables, `low` and `high`, to denote the position of the two characters at the beginning and the end in a string `s` (lines 14, 17). Initially, `low` is `0` and `high` is `s.length() - 1`. If the two characters at these positions match, increment `low` by `1` and decrement `high` by `1` (lines 26–27). This process continues until (`low >= high`) or a mismatch is found (line 21).

The program uses a `boolean` variable `isPalindrome` to denote whether the string `s` is palindrome. Initially, it is set to `true` (line 19). When a mismatch is discovered (line 21), `isPalindrome` is set to `false` (line 22) and the loop is terminated with a break statement (line 23).

5.11 Case Study: Displaying Prime Numbers



This section presents a program that displays the first fifty prime numbers in five lines, each containing ten numbers.

An integer greater than `1` is *prime* if its only positive divisor is `1` or itself. For example, `2`, `3`, `5`, and `7` are prime numbers, but `4`, `6`, `8`, and `9` are not.

The problem is to display the first 50 prime numbers in five lines, each of which contains ten numbers. The problem can be broken into the following tasks:

- Determine whether a given number is prime.
- For `number = 2, 3, 4, 5, 6, ...`, test whether it is prime.
- Count the prime numbers.
- Display each prime number, and display ten numbers per line.

Obviously, you need to write a loop and repeatedly test whether a new `number` is prime. If the `number` is prime, increase the count by `1`. The `count` is `0` initially. When it reaches `50`, the loop terminates.

Here is the algorithm for the problem:

```

Set the number of prime numbers to be printed as
    a constant NUMBER_OF_PRIMES;
Use count to track the number of prime numbers and
    set an initial count to 0;
Set an initial number to 2;
```

```

while (count < NUMBER_OF_PRIMES) {
    Test whether number is prime;

    if number is prime {
        Display the prime number and increase the count;
    }

    Increment number by 1;
}

```

To test whether a number is prime, check whether it is divisible by 2, 3, 4, and so on up to **number/2**. If a divisor is found, the number is not a prime. The algorithm can be described as follows:

Use a boolean variable `isPrime` to denote whether the number is prime; Set `isPrime` to true initially;

```

for (int divisor = 2; divisor <= number / 2; divisor++) {
    if (number % divisor == 0) {
        Set isPrime to false
        Exit the loop;
    }
}

```

The complete program is given in Listing 5.15.

LISTING 5.15 PrimeNumber.java

```

1  public class PrimeNumber {
2      public static void main(String[] args) {
3          final int NUMBER_OF_PRIMES = 50; // Number of primes to display
4          final int NUMBER_OF_PRIMES_PER_LINE = 10; // Display 10 per line
5          int count = 0; // Count the number of prime numbers
6          int number = 2; // A number to be tested for primeness
7
8          System.out.println("The first 50 prime numbers are \n");
9
10         // Repeatedly find prime numbers
11         while (count < NUMBER_OF_PRIMES) {                                count prime numbers
12             // Assume the number is prime
13             boolean isPrime = true; // Is the current number prime?
14
15             // Test whether number is prime
16             for (int divisor = 2; divisor <= number / 2; divisor++) {      check primeness
17                 if (number % divisor == 0) { // If true, number is not prime
18                     isPrime = false; // Set isPrime to false
19                     break; // Exit the for loop
20                 }
21             }
22
23             // Display the prime number and increase the count
24             if (isPrime) {                                                 display if prime
25                 count++; // Increase the count
26
27                 if (count % NUMBER_OF_PRIMES_PER_LINE == 0) {
28                     // Display the number and advance to the new line
29                     System.out.println(number);
30                 }
31             else
32                 System.out.print(number + " ");

```

```

33         }
34
35     // Check if the next number is prime
36     number++;
37 }
38 }
39 }
```



The first 50 prime numbers are
 2 3 5 7 11 13 17 19 23 29
 31 37 41 43 47 53 59 61 67 71
 73 79 83 89 97 101 103 107 109 113
 127 131 137 139 149 151 157 163 167 173
 179 181 191 193 197 199 211 223 227 229

subproblem

This is a complex program for novice programmers. The key to developing a programmatic solution for this problem, and for many other problems, is to break it into subproblems and develop solutions for each of them in turn. Do not attempt to develop a complete solution in the first trial. Instead, begin by writing the code to determine whether a given number is prime, then expand the program to test whether other numbers are prime in a loop.

To determine whether a number is prime, check whether it is divisible by a number between **2** and **number/2** inclusive (lines 16–21). If so, it is not a prime number (line 18); otherwise, it is a prime number. For a prime number, display it. If the count is divisible by **10** (lines 27–30), advance to a new line. The program ends when the count reaches **50**.

The program uses the **break** statement in line 19 to exit the **for** loop as soon as the number is found to be a nonprime. You can rewrite the loop (lines 16–21) without using the **break** statement, as follows:

```

for (int divisor = 2; divisor <= number / 2 && isPrime;
      divisor++) {
    // If true, the number is not prime
    if (number % divisor == 0) {
        // Set isPrime to false, if the number is not prime
        isPrime = false;
    }
}
```

However, using the **break** statement makes the program simpler and easier to read in this case.

KEY TERMS

break statement	184	loop body	158
continue statement	184	nested loop	176
do-while loop	168	off-by-one error	160
for loop	171	output redirection	167
infinite loop	160	posttest loop	174
input redirection	167	pretest loop	174
iteration	158	sentinel value	165
loop	158	while loop	158

CHAPTER SUMMARY

1. There are three types of repetition statements: the **while** loop, the **do-while** loop, and the **for** loop.
2. The part of the loop that contains the statements to be repeated is called the *loop body*.
3. A one-time execution of a loop body is referred to as an *iteration of the loop*.
4. An *infinite loop* is a loop statement that executes infinitely.
5. In designing loops, you need to consider both the *loop control structure* and the loop body.
6. The **while** loop checks the **Loop-continuation-condition** first. If the condition is **true**, the loop body is executed; if it is **false**, the loop terminates.
7. The **do-while** loop is similar to the **while** loop, except that the **do-while** loop executes the loop body first and then checks the **Loop-continuation-condition** to decide whether to continue or to terminate.
8. The **while** loop and the **do-while** loop often are used when the number of repetitions is not predetermined.
9. A *sentinel value* is a special value that signifies the end of the loop.
10. The **for** loop generally is used to execute a loop body a fixed number of times.
11. The **for** loop control has three parts. The first part is an initial action that often initializes a control variable. The second part, the **Loop-continuation-condition**, determines whether the loop body is to be executed. The third part is executed after each iteration and is often used to adjust the control variable. Usually, the loop control variables are initialized and changed in the control structure.
12. The **while** loop and **for** loop are called *pretest loops* because the continuation condition is checked before the loop body is executed.
13. The **do-while** loop is called a *posttest loop* because the condition is checked after the loop body is executed.
14. Two keywords, **break** and **continue**, can be used in a loop.
15. The **break** keyword immediately ends the innermost loop, which contains the break.
16. The **continue** keyword only ends the current iteration.

Quiz

Answer the quiz for this chapter online at www.cs.armstrong.edu/liang/intro10e/quiz.html.

PROGRAMMING EXERCISES

MyProgrammingLab™



Pedagogical Note

Read each problem several times until you understand it. Think how to solve the problem before starting to write code. Translate your logic into a program.

A problem often can be solved in many different ways. Students are encouraged to explore various solutions.

read and think before coding

explore solutions

Sections 5.2–5.7

- *5.1** (*Count positive and negative numbers and compute the average of numbers*) Write a program that reads an unspecified number of integers, determines how many positive and negative values have been read, and computes the total and average of the input values (not counting zeros). Your program ends with the input **0**. Display the average as a floating-point number. Here is a sample run:



```
Enter an integer, the input ends if it is 0: 1 2 -1 3 0 ↵Enter
The number of positives is 3
The number of negatives is 1
The total is 5.0
The average is 1.25
```



```
Enter an integer, the input ends if it is 0: 0 ↵Enter
No numbers are entered except 0
```

- 5.2** (*Repeat additions*) Listing 5.4, SubtractionQuizLoop.java, generates five random subtraction questions. Revise the program to generate ten random addition questions for two integers between **1** and **15**. Display the correct count and test time.

- 5.3** (*Conversion from kilograms to pounds*) Write a program that displays the following table (note that **1** kilogram is **2.2** pounds):

Kilograms	Pounds
1	2.2
3	6.6
...	
197	433.4
199	437.8

- 5.4** (*Conversion from miles to kilometers*) Write a program that displays the following table (note that **1** mile is **1.609** kilometers):

Miles	Kilometers
1	1.609
2	3.218
...	
9	14.481
10	16.090

- 5.5** (*Conversion from kilograms to pounds and pounds to kilograms*) Write a program that displays the following two tables side by side:

Kilograms	Pounds		Pounds	Kilograms
1	2.2		20	9.09
3	6.6		25	11.36
...				
197	433.4		510	231.82
199	437.8		515	234.09

- 5.6** (*Conversion from miles to kilometers*) Write a program that displays the following two tables side by side:

Miles	Kilometers	Kilometers	Miles
1	1.609	20	12.430
2	3.218	25	15.538
...			
9	14.481	60	37.290
10	16.090	65	40.398

- **5.7** (*Financial application: compute future tuition*) Suppose that the tuition for a university is \$10,000 this year and increases 5% every year. In one year, the tuition will be \$10,500. Write a program that computes the tuition in ten years and the total cost of four years' worth of tuition after the tenth year.
- 5.8** (*Find the highest score*) Write a program that prompts the user to enter the number of students and each student's name and score, and finally displays the name of the student with the highest score.
- *5.9** (*Find the two highest scores*) Write a program that prompts the user to enter the number of students and each student's name and score, and finally displays the student with the highest score and the student with the second-highest score.
- 5.10** (*Find numbers divisible by 5 and 6*) Write a program that displays all the numbers from 100 to 1,000, ten per line, that are divisible by 5 and 6. Numbers are separated by exactly one space.
- 5.11** (*Find numbers divisible by 5 or 6, but not both*) Write a program that displays all the numbers from 100 to 200, ten per line, that are divisible by 5 or 6, but not both. Numbers are separated by exactly one space.
- 5.12** (*Find the smallest n such that $n^2 > 12,000$*) Use a **while** loop to find the smallest integer n such that n^2 is greater than 12,000.
- 5.13** (*Find the largest n such that $n^3 < 12,000$*) Use a **while** loop to find the largest integer n such that n^3 is less than 12,000.

Sections 5.8–5.10

- *5.14** (*Compute the greatest common divisor*) Another solution for Listing 5.9 to find the greatest common divisor of two integers **n1** and **n2** is as follows: First find **d** to be the minimum of **n1** and **n2**, then check whether **d**, **d-1**, **d-2**, ..., **2**, or **1** is a divisor for both **n1** and **n2** in this order. The first such common divisor is the greatest common divisor for **n1** and **n2**. Write a program that prompts the user to enter two positive integers and displays the gcd.
- *5.15** (*Display the ASCII character table*) Write a program that prints the characters in the ASCII character table from **!** to **~**. Display ten characters per line. The ASCII table is shown in Appendix B. Characters are separated by exactly one space.
- *5.16** (*Find the factors of an integer*) Write a program that reads an integer and displays all its smallest factors in increasing order. For example, if the input integer is **120**, the output should be as follows: **2, 2, 2, 3, 5**.
- **5.17** (*Display pyramid*) Write a program that prompts the user to enter an integer from **1** to **15** and displays a pyramid, as shown in the following sample run:

Enter the number of lines: 7	<input type="button" value="Enter"/>
<pre> 1 2 1 2 3 2 1 2 3 4 3 2 1 2 3 4 5 4 3 2 1 2 3 4 5 6 5 4 3 2 1 2 3 4 5 6 7 6 5 4 3 2 1 2 3 4 5 6 7 </pre>	



- *5.18** (*Display four patterns using loops*) Use nested loops that display the following patterns in four separate programs:

Pattern A	Pattern B	Pattern C	Pattern D
1	1 2 3 4 5 6		1 2 3 4 5 6
1 2	1 2 3 4 5		2 1 1 2 3 4 5
1 2 3	1 2 3 4		3 2 1 1 2 3 4
1 2 3 4	1 2 3		4 3 2 1 1 2 3
1 2 3 4 5	1 2		5 4 3 2 1 1 2
1 2 3 4 5 6	1		6 5 4 3 2 1 1

- **5.19** (*Display numbers in a pyramid pattern*) Write a nested **for** loop that prints the following output:

```

          1
        1   2   1
      1   2   4   2   1
    1   2   4   8   4   2   1
  1   2   4   8   16  8   4   2   1
1   2   4   8   16  32  16  8   4   2   1
1   2   4   8   16  32  64  32  16  8   4   2   1
1   2   4   8   16  32  64  128 64  32  16  8   4   2   1

```

- *5.20** (*Display prime numbers between 2 and 1,000*) Modify Listing 5.15 to display all the prime numbers between 2 and 1,000, inclusive. Display eight prime numbers per line. Numbers are separated by exactly one space.

Comprehensive

- **5.21** (*Financial application: compare loans with various interest rates*) Write a program that lets the user enter the loan amount and loan period in number of years and displays the monthly and total payments for each interest rate starting from 5% to 8%, with an increment of 1/8. Here is a sample run:



Loan Amount: <input type="text" value="10000"/>	<input type="button" value="Enter"/>	
Number of Years: <input type="text" value="5"/>	<input type="button" value="Enter"/>	
Interest Rate	Monthly Payment	Total Payment
5.000%	188.71	11322.74
5.125%	189.29	11357.13
5.250%	189.86	11391.59
...		
7.875%	202.17	12129.97
8.000%	202.76	12165.84

For the formula to compute monthly payment, see Listing 2.9, ComputeLoan.java.

- **5.22** (*Financial application: loan amortization schedule*) The monthly payment for a given loan pays the principal and the interest. The monthly interest is computed by multiplying the monthly interest rate and the balance (the remaining principal). The principal paid for the month is therefore the monthly payment minus the monthly interest. Write a program that lets the user enter the loan amount,



VideoNote

Display loan schedule

number of years, and interest rate and displays the amortization schedule for the loan. Here is a sample run:



Loan Amount: 10000	<input type="button" value="→ Enter"/>		
Number of Years: 1	<input type="button" value="→ Enter"/>		
Annual Interest Rate: 7	<input type="button" value="→ Enter"/>		
Monthly Payment: 865.26			
Total Payment: 10383.21			
Payment#	Interest	Principal	Balance
1	58.33	806.93	9193.07
2	53.62	811.64	8381.43
...			
11	10.0	855.26	860.27
12	5.01	860.25	0.01



Note

The balance after the last payment may not be zero. If so, the last payment should be the normal monthly payment plus the final balance.

Hint: Write a loop to display the table. Since the monthly payment is the same for each month, it should be computed before the loop. The balance is initially the loan amount. For each iteration in the loop, compute the interest and principal, and update the balance. The loop may look like this:

```
for (i = 1; i <= number_of_years * 12; i++) {
    interest = monthly_interest_rate * balance;
    principal = monthly_payment - interest;
    balance = balance - principal;
    System.out.println(i + "\t\t" + interest
        + "\t\t" + principal + "\t\t" + balance);
}
```

- *5.23** (*Demonstrate cancellation errors*) A cancellation error occurs when you are manipulating a very large number with a very small number. The large number may cancel out the smaller number. For example, the result of **100000000.0 + 0.00000001** is equal to **100000000.0**. To avoid cancellation errors and obtain more accurate results, carefully select the order of computation. For example, in computing the following series, you will obtain more accurate results by computing from right to left rather than from left to right:

$$1 + \frac{1}{2} + \frac{1}{3} + \dots + \frac{1}{n}$$

Write a program that compares the results of the summation of the preceding series, computing from left to right and from right to left with **n = 50000**.

- *5.24** (*Sum a series*) Write a program to sum the following series:

$$\frac{1}{3} + \frac{3}{5} + \frac{5}{7} + \frac{7}{9} + \frac{9}{11} + \frac{11}{13} + \dots + \frac{95}{97} + \frac{97}{99}$$



VideoNote
Sum a series

****5.25** (*Compute π*) You can approximate π by using the following series:

$$\pi = 4 \left(1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \frac{1}{9} - \frac{1}{11} + \dots + \frac{(-1)^{i+1}}{2i-1} \right)$$

Write a program that displays the π value for $i = 10000, 20000, \dots$, and 100000 .

****5.26** (*Compute e*) You can approximate e using the following series:

$$e = 1 + \frac{1}{1!} + \frac{1}{2!} + \frac{1}{3!} + \frac{1}{4!} + \dots + \frac{1}{i!}$$

Write a program that displays the e value for $i = 10000, 20000, \dots$, and 100000 . (*Hint:* Because $i! = i \times (i-1) \times \dots \times 2 \times 1$, then

$$\frac{1}{i!} \text{ is } \frac{1}{i(i-1)!}$$

Initialize e and $item$ to be 1 and keep adding a new $item$ to e . The new item is the previous item divided by i for $i = 2, 3, 4, \dots$)

****5.27** (*Display leap years*) Write a program that displays all the leap years, ten per line, from 101 to 2100, separated by exactly one space. Also display the number of leap years in this period.

****5.28** (*Display the first days of each month*) Write a program that prompts the user to enter the year and first day of the year, and displays the first day of each month in the year. For example, if the user entered the year **2013**, and **2** for Tuesday, January 1, 2013, your program should display the following output:

January 1, 2013 is Tuesday

...

December 1, 2013 is Sunday

****5.29** (*Display calendars*) Write a program that prompts the user to enter the year and first day of the year and displays the calendar table for the year on the console. For example, if the user entered the year **2013**, and **2** for Tuesday, January 1, 2013, your program should display the calendar for each month in the year, as follows:

January 2013						
Sun	Mon	Tue	Wed	Thu	Fri	Sat
		1	2	3	4	5
6	7	8	9	10	11	12
13	14	15	16	17	18	19
20	21	22	23	24	25	26
27	28	29	30	31		

December 2013						
Sun	Mon	Tue	Wed	Thu	Fri	Sat
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30	31				

- *5.30** (*Financial application: compound value*) Suppose you save \$100 *each* month into a savings account with the annual interest rate 5%. So, the monthly interest rate is $0.05 / 12 = 0.00417$. After the first month, the value in the account becomes

$$100 * (1 + 0.00417) = 100.417$$

After the second month, the value in the account becomes

$$(100 + 100.417) * (1 + 0.00417) = 201.252$$

After the third month, the value in the account becomes

$$(100 + 201.252) * (1 + 0.00417) = 302.507$$

and so on.

Write a program that prompts the user to enter an amount (e.g., **100**), the annual interest rate (e.g., **5**), and the number of months (e.g., **6**) and displays the amount in the savings account after the given month.

- *5.31** (*Financial application: compute CD value*) Suppose you put \$10,000 into a CD with an annual percentage yield of 5.75%. After one month, the CD is worth

$$10000 + 10000 * 5.75 / 1200 = 10047.92$$

After two months, the CD is worth

$$10047.91 + 10047.91 * 5.75 / 1200 = 10096.06$$

After three months, the CD is worth

$$10096.06 + 10096.06 * 5.75 / 1200 = 10144.44$$

and so on.

Write a program that prompts the user to enter an amount (e.g., **10000**), the annual percentage yield (e.g., **5.75**), and the number of months (e.g., **18**) and displays a table as shown in the sample run.



```

Enter the initial deposit amount: 10000 ↵Enter
Enter annual percentage yield: 5.75 ↵Enter
Enter maturity period (number of months): 18 ↵Enter

Month CD Value
1    10047.92
2    10096.06
...
17   10846.57
18   10898.54

```

****5.32** (*Game: lottery*) Revise Listing 3.8, Lottery.java, to generate a lottery of a two-digit number. The two digits in the number are distinct. (*Hint:* Generate the first digit. Use a loop to continuously generate the second digit until it is different from the first digit.)

****5.33** (*Perfect number*) A positive integer is called a *perfect number* if it is equal to the sum of all of its positive divisors, excluding itself. For example, 6 is the first perfect number because $6 = 3 + 2 + 1$. The next is $28 = 14 + 7 + 4 + 2 + 1$. There are four perfect numbers less than 10,000. Write a program to find all these four numbers.

*****5.34** (*Game: scissor, rock, paper*) Programming Exercise 3.17 gives a program that plays the scissor-rock-paper game. Revise the program to let the user continuously play until either the user or the computer wins more than two times than its opponent.

***5.35** (*Summation*) Write a program to compute the following summation.

$$\frac{1}{1 + \sqrt{2}} + \frac{1}{\sqrt{2} + \sqrt{3}} + \frac{1}{\sqrt{3} + \sqrt{4}} + \dots + \frac{1}{\sqrt{624} + \sqrt{625}}$$

****5.36** (*Business application: checking ISBN*) Use loops to simplify Programming Exercise 3.9.

****5.37** (*Decimal to binary*) Write a program that prompts the user to enter a decimal integer and displays its corresponding binary value. Don't use Java's `Integer.toBinaryString(int)` in this program.

****5.38** (*Decimal to octal*) Write a program that prompts the user to enter a decimal integer and displays its corresponding octal value. Don't use Java's `Integer.toOctalString(int)` in this program.

***5.39** (*Financial application: find the sales amount*) You have just started a sales job in a department store. Your pay consists of a base salary and a commission. The base salary is \$5,000. The scheme shown below is used to determine the commission rate.

Sales Amount	Commission Rate
\$0.01–\$5,000	8 percent
\$5,000.01–\$10,000	10 percent
\$10,000.01 and above	12 percent

Note that this is a graduated rate. The rate for the first \$5,000 is at 8%, the next \$5000 is at 10%, and the rest is at 12%. If the sales amount is 25,000, the commission is $5,000 * 8\% + 5,000 * 10\% + 15,000 * 12\% = 2,700$.

Your goal is to earn \$30,000 a year. Write a program that finds the minimum sales you have to generate in order to make \$30,000.

- 5.40** (*Simulation: heads or tails*) Write a program that simulates flipping a coin one million times and displays the number of heads and tails.

- *5.41** (*Occurrence of max numbers*) Write a program that reads integers, finds the largest of them, and counts its occurrences. Assume that the input ends with number 0. Suppose that you entered 3 5 2 5 5 5 0; the program finds that the largest is 5 and the occurrence count for 5 is 4.

(Hint: Maintain two variables, `max` and `count`. `max` stores the current max number, and `count` stores its occurrences. Initially, assign the first number to `max` and 1 to `count`. Compare each subsequent number with `max`. If the number is greater than `max`, assign it to `max` and reset `count` to 1. If the number is equal to `max`, increment `count` by 1.)

```
Enter numbers: 3 5 2 5 5 5 0 [Enter]
The largest number is 5
The occurrence count of the largest number is 4
```



- *5.42** (*Financial application: find the sales amount*) Rewrite Programming Exercise 5.39 as follows:

- Use a `for` loop instead of a `do-while` loop.
- Let the user enter `COMMISSION_SOUGHT` instead of fixing it as a constant.

- *5.43** (*Math: combinations*) Write a program that displays all possible combinations for picking two numbers from integers 1 to 7. Also display the total number of all combinations.

```
1 2
1 3
...
...
The total number of all combinations is 21
```



- *5.44** (*Computer architecture: bit-level operations*) A `short` value is stored in 16 bits. Write a program that prompts the user to enter a short integer and displays the 16 bits for the integer. Here are sample runs:

```
Enter an integer: 5 [Enter]
The bits are 00000000000000101
```



```
Enter an integer: -5 [Enter]
The bits are 1111111111111011
```



(Hint: You need to use the bitwise right shift operator (`>>`) and the bitwise `AND` operator (`&`), which are covered in Appendix G, Bitwise Operations.)

- **5.45** (*Statistics: compute mean and standard deviation*) In business applications, you are often asked to compute the mean and standard deviation of data. The mean is simply the average of the numbers. The standard deviation is a statistic that tells

you how tightly all the various data are clustered around the mean in a set of data. For example, what is the average age of the students in a class? How close are the ages? If all the students are the same age, the deviation is 0.

Write a program that prompts the user to enter ten numbers, and displays the mean and standard deviations of these numbers using the following formula:

$$\text{mean} = \frac{\sum_{i=1}^n x_i}{n} = \frac{x_1 + x_2 + \dots + x_n}{n} \quad \text{deviation} = \sqrt{\frac{\sum_{i=1}^n x_i^2 - \left(\frac{\sum_{i=1}^n x_i}{n}\right)^2}{n-1}}$$

Here is a sample run:



```
Enter ten numbers: 1 2 3 4.5 5.6 6 7 8 9 10 ↵ Enter
The mean is 5.61
The standard deviation is 2.99794
```

- *5.46** (*Reverse a string*) Write a program that prompts the user to enter a string and displays the string in reverse order.



```
Enter a string: ABCD ↵ Enter
The reversed string is DCBA
```

- *5.47** (*Business: check ISBN-13*) **ISBN-13** is a new standard for identifying books. It uses 13 digits $d_1d_2d_3d_4d_5d_6d_7d_8d_9d_{10}d_{11}d_{12}d_{13}$. The last digit d_{13} is a checksum, which is calculated from the other digits using the following formula:

$$10 - (d_1 + 3d_2 + d_3 + 3d_4 + d_5 + 3d_6 + d_7 + 3d_8 + d_9 + 3d_{10} + d_{11} + 3d_{12}) \% 10$$

If the checksum is **10**, replace it with **0**. Your program should read the input as a string. Here are sample runs:



```
Enter the first 12 digits of an ISBN-13 as a string: 978013213080 ↵ Enter
The ISBN-13 number is 9780132130806
```



```
Enter the first 12 digits of an ISBN-13 as a string: 978013213079 ↵ Enter
The ISBN-13 number is 9780132130790
```



```
Enter the first 12 digits of an ISBN-13 as a string: 97801320 ↵ Enter
97801320 is an invalid input
```

- *5.48** (*Process string*) Write a program that prompts the user to enter a string and displays the characters at odd positions. Here is a sample run:



```
Enter a string: Beijing Chicago ↵ Enter
BiigCiao
```

- *5.49** (*Count vowels and consonants*) Assume letters **A**, **E**, **I**, **O**, and **U** as the vowels. Write a program that prompts the user to enter a string and displays the number of vowels and consonants in the string.

```
Enter a string: Programming is fun ↵Enter  
The number of vowels is 5  
The number of consonants is 11
```



- *5.50** (*Count uppercase letters*) Write a program that prompts the user to enter a string and displays the number of the uppercase letters in the string.

```
Enter a string: Welcome to Java ↵Enter  
The number of uppercase letters is 2
```



- *5.51** (*Longest common prefix*) Write a program that prompts the user to enter two strings and displays the largest common prefix of the two strings. Here are some sample runs:

```
Enter the first string: Welcome to C++ ↵Enter  
Enter the second string: Welcome to programming ↵Enter  
The common prefix is Welcome to
```



```
Enter the first string: Atlanta ↵Enter  
Enter the second string: Macon ↵Enter  
Atlanta and Macon have no common prefix
```

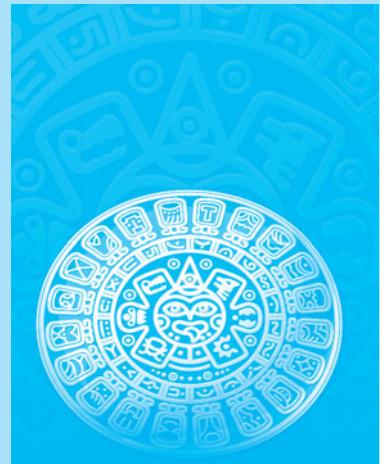
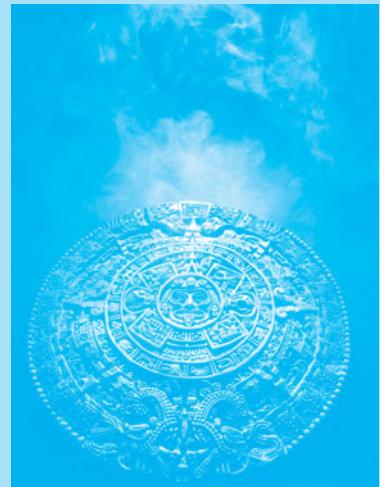


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METHODS

Objectives

- To define methods with formal parameters (§6.2).
- To invoke methods with actual parameters (i.e., arguments) (§6.2).
- To define methods with a return value (§6.3).
- To define methods without a return value (§6.4).
- To pass arguments by value (§6.5).
- To develop reusable code that is modular, easy to read, easy to debug, and easy to maintain (§6.6).
- To write a method that converts hexadecimals to decimals (§6.7).
- To use method overloading and understand ambiguous overloading (§6.8).
- To determine the scope of variables (§6.9).
- To apply the concept of method abstraction in software development (§6.10).
- To design and implement methods using stepwise refinement (§6.10).





problem

6.1 Introduction

Methods can be used to define reusable code and organize and simplify coding.

Suppose that you need to find the sum of integers from **1** to **10**, from **20** to **37**, and from **35** to **49**, respectively. You may write the code as follows:

```
int sum = 0;
for (int i = 1; i <= 10; i++)
    sum += i;
System.out.println("Sum from 1 to 10 is " + sum);

sum = 0;
for (int i = 20; i <= 37; i++)
    sum += i;
System.out.println("Sum from 20 to 37 is " + sum);

sum = 0;
for (int i = 35; i <= 49; i++)
    sum += i;
System.out.println("Sum from 35 to 49 is " + sum);
```

why methods?

You may have observed that computing these sums from **1** to **10**, from **20** to **37**, and from **35** to **49** are very similar except that the starting and ending integers are different. Wouldn't it be nice if we could write the common code once and reuse it? We can do so by defining a method and invoking it.

The preceding code can be simplified as follows:

define sum method

```
1 public static int sum(int i1, int i2) {
2     int result = 0;
3     for (int i = i1; i <= i2; i++)
4         result += i;
5
6     return result;
7 }
8
9 public static void main(String[] args) {
10    System.out.println("Sum from 1 to 10 is " + sum(1, 10));
11    System.out.println("Sum from 20 to 37 is " + sum(20, 37));
12    System.out.println("Sum from 35 to 49 is " + sum(35, 49));
13 }
```

main method
invoke sum

method

Lines 1–7 define the method named **sum** with two parameters **i1** and **i2**. The statements in the **main** method invoke **sum(1, 10)** to compute the sum from **1** to **10**, **sum(20, 37)** to compute the sum from **20** to **37**, and **sum(35, 49)** to compute the sum from **35** to **49**.

A *method* is a collection of statements grouped together to perform an operation. In earlier chapters you have used predefined methods such as **System.out.println**, **System.exit**, **Math.pow**, and **Math.random**. These methods are defined in the Java library. In this chapter, you will learn how to define your own methods and apply method abstraction to solve complex problems.

6.2 Defining a Method



A method definition consists of its method name, parameters, return value type, and body.

The syntax for defining a method is as follows:

```
modifier returnType methodName(list of parameters) {
    // Method body;
}
```

Let's look at a method defined to find the larger between two integers. This method, named `max`, has two `int` parameters, `num1` and `num2`, the larger of which is returned by the method. Figure 6.1 illustrates the components of this method.

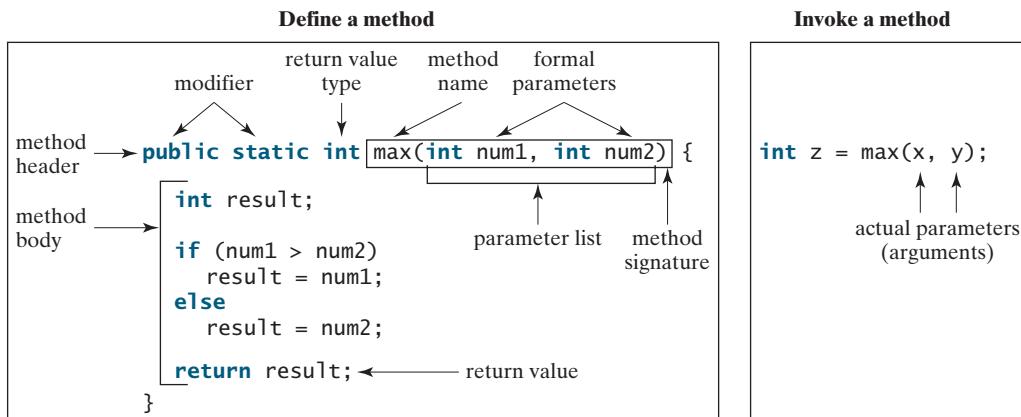


FIGURE 6.1 A method definition consists of a method header and a method body.

The *method header* specifies the *modifiers*, *return value type*, *method name*, and *parameters* of the method. The `static` modifier is used for all the methods in this chapter. The reason for using it will be discussed in Chapter 8, Objects and Classes.

method header
modifier

A method may return a value. The `returnValueType` is the data type of the value the method returns. Some methods perform desired operations without returning a value. In this case, the `returnValueType` is the keyword `void`. For example, the `returnValueType` is `void` in the `main` method, as well as in `System.exit`, and `System.out.println`. If a method returns a value, it is called a *value-returning method*; otherwise it is called a *void method*.

value-returning method
void method
formal parameter
parameter
actual parameter
argument
parameter list
method signature

The variables defined in the method header are known as *formal parameters* or simply *parameters*. A parameter is like a placeholder: when a method is invoked, you pass a value to the parameter. This value is referred to as an *actual parameter* or *argument*. The *parameter list* refers to the method's type, order, and number of the parameters. The method name and the parameter list together constitute the *method signature*. Parameters are optional; that is, a method may contain no parameters. For example, the `Math.random()` method has no parameters.

The method body contains a collection of statements that implement the method. The method body of the `max` method uses an `if` statement to determine which number is larger and return the value of that number. In order for a value-returning method to return a result, a return statement using the keyword `return` is *required*. The method terminates when a return statement is executed.



Note

Some programming languages refer to methods as *procedures* and *functions*. In those languages, a value-returning method is called a *function* and a void method is called a *procedure*.



Caution

In the method header, you need to declare each parameter separately. For instance, `max(int num1, int num2)` is correct, but `max(int num1, num2)` is wrong.

define vs. declare

**Note**

We say “*define* a method” and “*declare* a variable.” We are making a subtle distinction here. A definition defines what the defined item is, but a declaration usually involves allocating memory to store data for the declared item.

6.3 Calling a Method

Calling a method executes the code in the method.

In a method definition, you define what the method is to do. To execute the method, you have to *call* or *invoke* it. There are two ways to call a method, depending on whether the method returns a value or not.

If a method returns a value, a call to the method is usually treated as a value. For example,

```
int larger = max(3, 4);
```

calls `max(3, 4)` and assigns the result of the method to the variable `Larger`. Another example of a call that is treated as a value is

```
System.out.println(max(3, 4));
```

which prints the return value of the method call `max(3, 4)`.

If a method returns `void`, a call to the method must be a statement. For example, the method `println` returns `void`. The following call is a statement:

```
System.out.println("Welcome to Java!");
```

Note

A value-returning method can also be invoked as a statement in Java. In this case, the caller simply ignores the return value. This is not often done, but it is permissible if the caller is not interested in the return value.

When a program calls a method, program control is transferred to the called method. A called method returns control to the caller when its return statement is executed or when its method-ending closing brace is reached.

Listing 6.1 shows a complete program that is used to test the `max` method.



VideoNote

Define/invoke `max` method

main method

invoke `max`

define method

LISTING 6.1 TestMax.java

```

1  public class TestMax {
2      /** Main method */
3      public static void main(String[] args) {
4          int i = 5;
5          int j = 2;
6          int k = max(i, j);
7          System.out.println("The maximum of " + i +
8              " and " + j + " is " + k);
9      }
10
11     /** Return the max of two numbers */
12     public static int max(int num1, int num2) {
13         int result;
14
15         if (num1 > num2)
16             result = num1;
17         else
18             result = num2;
19
20         return result;
21     }
22 }
```




line#	i	j	k	num1	num2	result
4	5					
5		2				
12				5	2	
13						undefined
16						5
6			5			

Invoking max { }

This program contains the `main` method and the `max` method. The `main` method is just like any other method except that it is invoked by the JVM to start the program.

main method

The `main` method's header is always the same. Like the one in this example, it includes the modifiers `public` and `static`, return value type `void`, method name `main`, and a parameter of the `String[]` type. `String[]` indicates that the parameter is an array of `String`, a subject addressed in Chapter 7.

main method

The statements in `main` may invoke other methods that are defined in the class that contains the `main` method or in other classes. In this example, the `main` method invokes `max(i, j)`, which is defined in the same class with the `main` method.

max method

When the `max` method is invoked (line 6), variable `i`'s value 5 is passed to `num1`, and variable `j`'s value 2 is passed to `num2` in the `max` method. The flow of control transfers to the `max` method, and the `max` method is executed. When the `return` statement in the `max` method is executed, the `max` method returns the control to its caller (in this case the caller is the `main` method). This process is illustrated in Figure 6.2.

max method

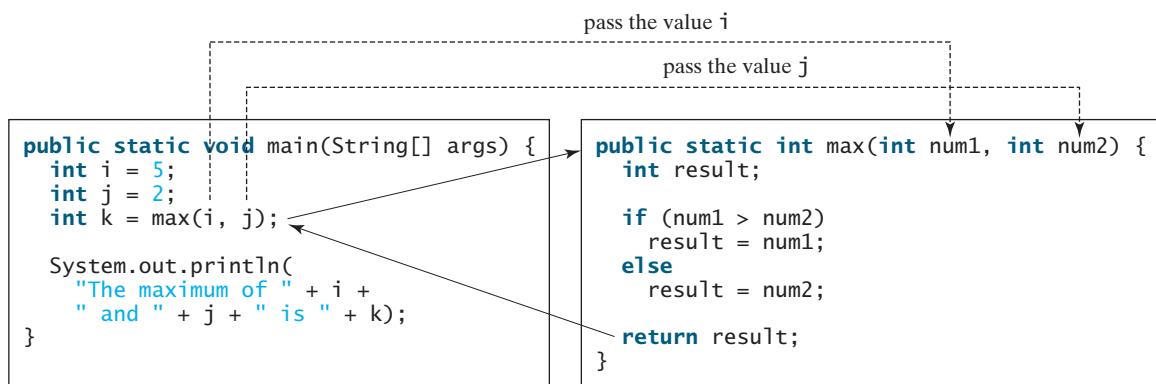


FIGURE 6.2 When the `max` method is invoked, the flow of control transfers to it. Once the `max` method is finished, it returns control back to the caller.



Caution

A `return` statement is required for a value-returning method. The method shown below in (a) is logically correct, but it has a compile error because the Java compiler thinks that this method might not return a value.



To fix this problem, delete `else if (n < 0)` in (a), so the compiler will see a `return` statement to be reached regardless of how the `if` statement is evaluated.

reusing method



Note

Methods enable code sharing and reuse. The `max` method can be invoked from any class, not just `TestMax`. If you create a new class, you can invoke the `max` method using `ClassName.methodName` (i.e., `TestMax.max`).

activation record

call stack

Each time a method is invoked, the system creates an *activation record* (also called an *activation frame*) that stores parameters and variables for the method and places the activation record in an area of memory known as a *call stack*. A call stack is also known as an *execution stack*, *runtime stack*, or *machine stack*, and it is often shortened to just “the stack.” When a method calls another method, the caller’s activation record is kept intact, and a new activation record is created for the new method called. When a method finishes its work and returns to its caller, its activation record is removed from the call stack.

A call stack stores the activation records in a last-in, first-out fashion: The activation record for the method that is invoked last is removed first from the stack. For example, suppose method `m1` calls method `m2`, and `m2` calls method `m3`. The runtime system pushes `m1`’s activation record into the stack, then `m2`’s, and then `m3`’s. After `m3` is finished, its activation record is removed from the stack. After `m2` is finished, its activation record is removed from the stack. After `m1` is finished, its activation record is removed from the stack.

Understanding call stacks helps you to comprehend how methods are invoked. The variables defined in the `main` method in Listing 6.1 are `i`, `j`, and `k`. The variables defined in the `max` method are `num1`, `num2`, and `result`. The variables `num1` and `num2` are defined in the method signature and are parameters of the `max` method. Their values are passed through method invocation. Figure 6.3 illustrates the activation records for method calls in the stack.

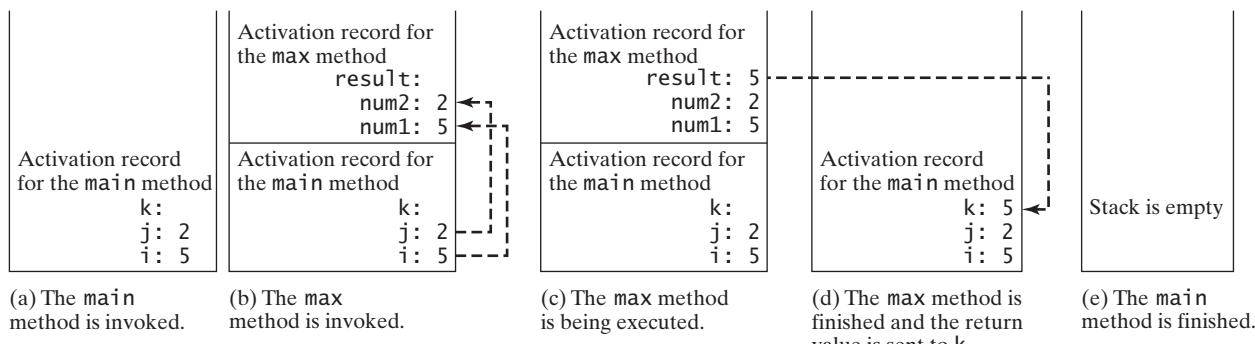


FIGURE 6.3 When the `max` method is invoked, the flow of control transfers to the `max` method. Once the `max` method is finished, it returns control back to the caller.

6.4 void Method Example

A **void** method does not return a value.

The preceding section gives an example of a value-returning method. This section shows how to define and invoke a **void** method. Listing 6.2 gives a program that defines a method named **printGrade** and invokes it to print the grade for a given score.

LISTING 6.2 TestVoidMethod.java

```

1  public class TestVoidMethod {
2      public static void main(String[] args) {
3          System.out.print("The grade is ");
4          printGrade(78.5);
5
6          System.out.print("The grade is ");
7          printGrade(59.5);
8      }
9
10     public static void printGrade(double score) {
11         if (score >= 90.0) {
12             System.out.println('A');
13         }
14         else if (score >= 80.0) {
15             System.out.println('B');
16         }
17         else if (score >= 70.0) {
18             System.out.println('C');
19         }
20         else if (score >= 60.0) {
21             System.out.println('D');
22         }
23         else {
24             System.out.println('F');
25         }
26     }
27 }
```

The grade is C
The grade is F



Use void method

main method

invoke printGrade

printGrade method



The **printGrade** method is a **void** method because it does not return any value. A call to a **void** method must be a statement. Therefore, it is invoked as a statement in line 4 in the **main** method. Like any Java statement, it is terminated with a semicolon.

To see the differences between a **void** and value-returning method, let's redesign the **printGrade** method to return a value. The new method, which we call **getGrade**, returns the grade as shown in Listing 6.3.

invoke void method

void vs. value Returned

LISTING 6.3 TestReturnGradeMethod.java

```

1  public class TestReturnGradeMethod {
2      public static void main(String[] args) {
3          System.out.print("The grade is " + getGrade(78.5));
4          System.out.print("\nThe grade is " + getGrade(59.5));
5      }
6  }
```

main method

invoke getGrade

getGrade method

```

7  public static char getGrade(double score) {
8      if (score >= 90.0)
9          return 'A';
10     else if (score >= 80.0)
11         return 'B';
12     else if (score >= 70.0)
13         return 'C';
14     else if (score >= 60.0)
15         return 'D';
16     else
17         return 'F';
18 }
19 }
```



The grade is C
The grade is F

return in void method

**Note**

A **return** statement is not needed for a **void** method, but it can be used for terminating the method and returning to the method's caller. The syntax is simply

return;

This is not often done, but sometimes it is useful for circumventing the normal flow of control in a **void** method. For example, the following code has a return statement to terminate the method when the score is invalid.

```

public static void printGrade(double score) {
    if (score < 0 || score > 100) {
        System.out.println("Invalid score");
        return;
    }

    if (score >= 90.0) {
        System.out.println('A');
    }
    else if (score >= 80.0) {
        System.out.println('B');
    }
    else if (score >= 70.0) {
        System.out.println('C');
    }
    else if (score >= 60.0) {
        System.out.println('D');
    }
    else {
        System.out.println('F');
    }
}
```



- 6.1** What are the benefits of using a method?
- 6.2** How do you define a method? How do you invoke a method?
- 6.3** How do you simplify the `max` method in Listing 6.1 using the conditional operator?
- 6.4** True or false? A call to a method with a `void` return type is always a statement itself, but a call to a value-returning method cannot be a statement by itself.
- 6.5** What is the `return` type of a `main` method?
- 6.6** What would be wrong with not writing a `return` statement in a value-returning method? Can you have a `return` statement in a `void` method? Does the `return` statement in the following method cause syntax errors?

```
public static void xMethod(double x, double y) {
    System.out.println(x + y);
    return x + y;
}
```

- 6.7** Define the terms parameter, argument, and method signature.
- 6.8** Write method headers (not the bodies) for the following methods:
- Return a sales commission, given the sales amount and the commission rate.
 - Display the calendar for a month, given the month and year.
 - Return a square root of a number.
 - Test whether a number is even, and returning `true` if it is.
 - Display a message a specified number of times.
 - Return the monthly payment, given the loan amount, number of years, and annual interest rate.
 - Return the corresponding uppercase letter, given a lowercase letter.

- 6.9** Identify and correct the errors in the following program:

```
1 public class Test {
2     public static method1(int n, m) {
3         n += m;
4         method2(3.4);
5     }
6
7     public static int method2(int n) {
8         if (n > 0) return 1;
9         else if (n == 0) return 0;
10        else if (n < 0) return -1;
11    }
12 }
```

- 6.10** Reformat the following program according to the programming style and documentation guidelines proposed in Section 1.9, Programming Style and Documentation. Use the next-line brace style.

```
public class Test {
    public static double method(double i, double j)
    {
        while (i < j) {
            j--;
        }

        return j;
    }
}
```

6.5 Passing Arguments by Values



The arguments are passed by value to parameters when invoking a method.

parameter order association

The power of a method is its ability to work with parameters. You can use `println` to print any string and `max` to find the maximum of any two `int` values. When calling a method, you need to provide arguments, which must be given in the same order as their respective parameters in the method signature. This is known as *parameter order association*. For example, the following method prints a message `n` times:

```
public static void nPrintln(String message, int n) {
    for (int i = 0; i < n; i++)
        System.out.println(message);
}
```

You can use `nPrintln("Hello", 3)` to print `Hello` three times. The `nPrintln("Hello", 3)` statement passes the actual string parameter `Hello` to the parameter `message`, passes `3` to `n`, and prints `Hello` three times. However, the statement `nPrintln(3, "Hello")` would be wrong. The data type of `3` does not match the data type for the first parameter, `message`, nor does the second argument, `Hello`, match the second parameter, `n`.



Caution

The arguments must match the parameters in *order*, *number*, and *compatible type*, as defined in the method signature. Compatible type means that you can pass an argument to a parameter without explicit casting, such as passing an `int` value argument to a `double` value parameter.

pass-by-value

When you invoke a method with an argument, the value of the argument is passed to the parameter. This is referred to as *pass-by-value*. If the argument is a variable rather than a literal value, the value of the variable is passed to the parameter. The variable is not affected, regardless of the changes made to the parameter inside the method. As shown in Listing 6.4, the value of `x` (1) is passed to the parameter `n` to invoke the `increment` method (line 5). The parameter `n` is incremented by 1 in the method (line 10), but `x` is not changed no matter what the method does.

invoke increment

increment n

LISTING 6.4 Increment.java

```
1 public class Increment {
2     public static void main(String[] args) {
3         int x = 1;
4         System.out.println("Before the call, x is " + x);
5         increment(x);
6         System.out.println("After the call, x is " + x);
7     }
8
9     public static void increment(int n) {
10        n++;
11        System.out.println("n inside the method is " + n);
12    }
13 }
```



Before the call, x is 1
n inside the method is 2
After the call, x is 1

Listing 6.5 gives another program that demonstrates the effect of passing by value. The program creates a method for swapping two variables. The `swap` method is invoked by passing two arguments. Interestingly, the values of the arguments are not changed after the method is invoked.

LISTING 6.5 TestPassByValue.java

```

1  public class TestPassByValue {
2      /** Main method */
3      public static void main(String[] args) {
4          // Declare and initialize variables
5          int num1 = 1;
6          int num2 = 2;
7
8          System.out.println("Before invoking the swap method, num1 is " +
9              num1 + " and num2 is " + num2);
10
11         // Invoke the swap method to attempt to swap two variables
12         swap(num1, num2);                                false swap
13
14         System.out.println("After invoking the swap method, num1 is " +
15             num1 + " and num2 is " + num2);
16     }
17
18     /** Swap two variables */
19     public static void swap(int n1, int n2) {
20         System.out.println("\tInside the swap method");
21         System.out.println("\t\tBefore swapping, n1 is " + n1
22             + " and n2 is " + n2);
23
24         // Swap n1 with n2
25         int temp = n1;
26         n1 = n2;
27         n2 = temp;
28
29         System.out.println("\t\tAfter swapping, n1 is " + n1
30             + " and n2 is " + n2);
31     }
32 }
```

```

Before invoking the swap method, num1 is 1 and num2 is 2
Inside the swap method
    Before swapping, n1 is 1 and n2 is 2
    After swapping, n1 is 2 and n2 is 1
After invoking the swap method, num1 is 1 and num2 is 2

```



Before the `swap` method is invoked (line 12), `num1` is 1 and `num2` is 2. After the `swap` method is invoked, `num1` is still 1 and `num2` is still 2. Their values have not been swapped. As shown in Figure 6.4, the values of the arguments `num1` and `num2` are passed to `n1` and `n2`, but `n1` and `n2` have their own memory locations independent of `num1` and `num2`. Therefore, changes in `n1` and `n2` do not affect the contents of `num1` and `num2`.

Another twist is to change the parameter name `n1` in `swap` to `num1`. What effect does this have? No change occurs, because it makes no difference whether the parameter and the argument have the same name. The parameter is a variable in the method with its own memory space. The variable is allocated when the method is invoked, and it disappears when the method is returned to its caller.

**FIGURE 6.4** The values of the variables are passed to the method's parameters.**Note**

For simplicity, Java programmers often say *passing x to y*, which actually means *passing the value of argument x to parameter y*.

6.11 How is an argument passed to a method? Can the argument have the same name as its parameter?

6.12 Identify and correct the errors in the following program:

```

1  public class Test {
2      public static void main(String[] args) {
3          nPrintln(5, "Welcome to Java!");
4      }
5
6      public static void nPrintln(String message, int n) {
7          int i = 1;
8          for (int i = 0; i < n; i++)
9              System.out.println(message);
10     }
11 }
```

6.13 What is pass-by-value? Show the result of the following programs.

```

public class Test {
    public static void main(String[] args) {
        int max = 0;
        max(1, 2, max);
        System.out.println(max);
    }

    public static void max(
        int value1, int value2, int max) {
        if (value1 > value2)
            max = value1;
        else
            max = value2;
    }
}
```

```

public class Test {
    public static void main(String[] args) {
        int i = 1;
        while (i <= 6) {
            method1(i, 2);
            i++;
        }
    }

    public static void method1(
        int i, int num) {
        for (int j = 1; j <= i; j++) {
            System.out.print(num + " ");
            num *= 2;
        }
        System.out.println();
    }
}
```

(a)

(b)

```

public class Test {
    public static void main(String[] args) {
        // Initialize times
        int times = 3;
        System.out.println("Before the call,"
            + " variable times is " + times);

        // Invoke nPrintln and display times
        nPrintln("Welcome to Java!", times);
        System.out.println("After the call,"
            + " variable times is " + times);
    }

    // Print the message n times
    public static void nPrintln(
        String message, int n) {
        while (n > 0) {
            System.out.println("n = " + n);
            System.out.println(message);
            n--;
        }
    }
}

```

(c)

```

public class Test {
    public static void main(String[] args) {
        int i = 0;
        while (i <= 4) {
            method1(i);
            i++;
        }

        System.out.println("i is " + i);
    }

    public static void method1(int i) {
        do {
            if (i % 3 != 0)
                System.out.print(i + " ");
            i--;
        } while (i >= 1);

        System.out.println();
    }
}

```

(d)

- 6.14** For (a) in the preceding question, show the contents of the activation records in the call stack just before the method `max` is invoked, just as `max` is entered, just before `max` is returned, and right after `max` is returned.

6.6 Modularizing Code

Modularizing makes the code easy to maintain and debug and enables the code to be reused.



Methods can be used to reduce redundant code and enable code reuse. Methods can also be used to modularize code and improve the quality of the program.

Listing 5.9 gives a program that prompts the user to enter two integers and displays their greatest common divisor. You can rewrite the program using a method, as shown in Listing 6.6.

VideoNote

Modularize code

LISTING 6.6 GreatestCommonDivisorMethod.java

```

1 import java.util.Scanner;
2
3 public class GreatestCommonDivisorMethod {
4     /** Main method */
5     public static void main(String[] args) {
6         // Create a Scanner
7         Scanner input = new Scanner(System.in);
8
9         // Prompt the user to enter two integers
10        System.out.print("Enter first integer: ");
11        int n1 = input.nextInt();
12        System.out.print("Enter second integer: ");
13        int n2 = input.nextInt();
14

```

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```
invoke gcd          15     System.out.println("The greatest common divisor for " + n1 +
16             " and " + n2 + " is " + gcd(n1, n2));
17 }
18
compute gcd       19     /** Return the gcd of two integers */
20     public static int gcd(int n1, int n2) {
21         int gcd = 1; // Initial gcd is 1
22         int k = 2; // Possible gcd
23
24         while (k <= n1 && k <= n2) {
25             if (n1 % k == 0 && n2 % k == 0)
26                 gcd = k; // Update gcd
27             k++;
28         }
29
30     return gcd; // Return gcd
31 }
32 }
```



```
Enter first integer: 45 ↵Enter
Enter second integer: 75 ↵Enter
The greatest common divisor for 45 and 75 is 15
```

By encapsulating the code for obtaining the gcd in a method, this program has several advantages:

1. It isolates the problem for computing the gcd from the rest of the code in the main method. Thus, the logic becomes clear and the program is easier to read.
2. The errors on computing the gcd are confined in the **gcd** method, which narrows the scope of debugging.
3. The **gcd** method now can be reused by other programs.

Listing 6.7 applies the concept of code modularization to improve Listing 5.15, PrimeNumber.java.

LISTING 6.7 PrimeNumberMethod.java

```
invoke printPrimeNumbers 1  public class PrimeNumberMethod {
2      public static void main(String[] args) {
3          System.out.println("The first 50 prime numbers are \n");
4          printPrimeNumbers(50);
5      }
6
printPrimeNumbers    7      public static void printPrimeNumbers(int number_of_primes) {
method               8          final int NUMBER_OF_PRIMES_PER_LINE = 10; // Display 10 per line
9          int count = 0; // Count the number of prime numbers
10         int number = 2; // A number to be tested for primeness
11
12         // Repeatedly find prime numbers
13         while (count < number_of_primes) {
14             // Print the prime number and increase the count
15             if (isPrime(number)) {
16                 count++; // Increase the count
17             }
18         }
19     }
20 }
```

```

18     if (count % NUMBER_OF_PRIMES_PER_LINE == 0) {
19         // Print the number and advance to the new line
20         System.out.printf("%-5s\n", number);
21     }
22     else
23         System.out.printf("%-5s", number);
24 }
25
26     // Check whether the next number is prime
27     number++;
28 }
29
30
31 /** Check whether number is prime */
32 public static boolean isPrime(int number) { isPrime method
33     for (int divisor = 2; divisor <= number / 2; divisor++) {
34         if (number % divisor == 0) { // If true, number is not prime
35             return false; // Number is not a prime
36         }
37     }
38
39     return true; // Number is prime
40 }
41 }
```

The first 50 prime numbers are

2	3	5	7	11	13	17	19	23	29
31	37	41	43	47	53	59	61	67	71
73	79	83	89	97	101	103	107	109	113
127	131	137	139	149	151	157	163	167	173
179	181	191	193	197	199	211	223	227	229



We divided a large problem into two subproblems: determining whether a number is a prime and printing the prime numbers. As a result, the new program is easier to read and easier to debug. Moreover, the methods `printPrimeNumbers` and `isPrime` can be reused by other programs.

6.7 Case Study: Converting Hexadecimals to Decimals

This section presents a program that converts a hexadecimal number into a decimal number.



Listing 5.11, Dec2Hex.java, gives a program that converts a decimal to a hexadecimal. How would you convert a hex number into a decimal?

Given a hexadecimal number $h_nh_{n-1}h_{n-2}\dots h_2h_1h_0$, the equivalent decimal value is

$$h_n \times 16^n + h_{n-1} \times 16^{n-1} + h_{n-2} \times 16^{n-2} + \dots + h_2 \times 16^2 + h_1 \times 16^1 + h_0 \times 16^0$$

For example, the hex number **AB8C** is

$$10 \times 16^3 + 11 \times 16^2 + 8 \times 16^1 + 12 \times 16^0 = 43916$$

Our program will prompt the user to enter a hex number as a string and convert it into a decimal using the following method:

```
public static int hexToDecimal(String hex)
```

A brute-force approach is to convert each hex character into a decimal number, multiply it by 16^i for a hex digit at the i 's position, and then add all the items together to obtain the equivalent decimal value for the hex number.

Note that

$$\begin{aligned} h_n \times 16^n + h_{n-1} \times 16^{n-1} + h_{n-2} \times 16^{n-2} + \dots + h_1 \times 16^1 + h_0 \times 16^0 \\ = (\dots ((h_n \times 16 + h_n - 1) \times 16 + h_n - 2) \times 16 + \dots + h_1) \times 16 + h_0 \end{aligned}$$

This observation, known as the Horner's algorithm, leads to the following efficient code for converting a hex string to a decimal number:

```
int decimalValue = 0;
for (int i = 0; i < hex.length(); i++) {
    char hexChar = hex.charAt(i);
    decimalValue = decimalValue * 16 + hexCharToDecimal(hexChar);
}
```

Here is a trace of the algorithm for hex number **AB8C**:



	i	hexChar	hexCharToDecimal (hexChar)	decimalValue
before the loop				0
after the 1st iteration	0	A	10	10
after the 2nd iteration	1	B	11	10 * 16 + 11
after the 3rd iteration	2	8	8	(10 * 16 + 11) * 16 + 8
after the 4th iteration	3	C	12	((10 * 16 + 11) * 16 + 8) * 16 + 12

Listing 6.8 gives the complete program.

LISTING 6.8 Hex2Dec.java

```
1 import java.util.Scanner;
2
3 public class Hex2Dec {
4     /** Main method */
5     public static void main(String[] args) {
6         // Create a Scanner
7         Scanner input = new Scanner(System.in);
8
9         // Prompt the user to enter a string
10        System.out.print("Enter a hex number: ");
11        String hex = input.nextLine();
12
13        System.out.println("The decimal value for hex number "
14            + hex + " is " + hexToDecimal(hex.toUpperCase()));
15    }
16
17    public static int hexToDecimal(String hex) {
18        int decimalValue = 0;
19        for (int i = 0; i < hex.length(); i++) {
20            char hexChar = hex.charAt(i);
21            decimalValue = decimalValue * 16 + hexCharToDecimal(hexChar);
```

input string

hex to decimal

```

22     }
23
24     return decimalValue;
25 }
26
27 public static int hexCharToDecimal(char ch) {
28     if (ch >= 'A' && ch <= 'F')
29         return 10 + ch - 'A';
30     else // ch is '0', '1', ..., or '9'
31         return ch - '0';
32 }
33 }
```

hex char to decimal
check uppercase

Enter a hex number: AB8C ↵Enter
The decimal value for hex number AB8C is 43916



Enter a hex number: af71 ↵Enter
The decimal value for hex number af71 is 44913



The program reads a string from the console (line 11), and invokes the `hexToDecimal` method to convert a hex string to decimal number (line 14). The characters can be in either lowercase or uppercase. They are converted to uppercase before invoking the `hexToDecimal` method.

The `hexToDecimal` method is defined in lines 17–25 to return an integer. The length of the string is determined by invoking `hex.length()` in line 19.

The `hexCharToDecimal` method is defined in lines 27–32 to return a decimal value for a hex character. The character can be in either lowercase or uppercase. Recall that to subtract two characters is to subtract their Unicodes. For example, '`5`' – '`0`' is `5`.

6.8 Overloading Methods

Overloading methods enables you to define the methods with the same name as long as their signatures are different.



The `max` method that was used earlier works only with the `int` data type. But what if you need to determine which of two floating-point numbers has the maximum value? The solution is to create another method with the same name but different parameters, as shown in the following code:

```

public static double max(double num1, double num2) {
    if (num1 > num2)
        return num1;
    else
        return num2;
}
```

If you call `max` with `int` parameters, the `max` method that expects `int` parameters will be invoked; if you call `max` with `double` parameters, the `max` method that expects `double` parameters will be invoked. This is referred to as *method overloading*; that is, two methods have the same name but different parameter lists within one class. The Java compiler determines which method to use based on the method signature.

method overloading

Listing 6.9 is a program that creates three methods. The first finds the maximum integer, the second finds the maximum double, and the third finds the maximum among three double values. All three methods are named `max`.

LISTING 6.9 TestMethodOverloading.java

```

1  public class TestMethodOverloading {
2      /** Main method */
3      public static void main(String[] args) {
4          // Invoke the max method with int parameters
5          System.out.println("The maximum of 3 and 4 is "
6              + max(3, 4));
7
8          // Invoke the max method with the double parameters
9          System.out.println("The maximum of 3.0 and 5.4 is "
10             + max(3.0, 5.4));
11
12         // Invoke the max method with three double parameters
13         System.out.println("The maximum of 3.0, 5.4, and 10.14 is "
14             + max(3.0, 5.4, 10.14));
15     }
16
17     /** Return the max of two int values */
18     public static int max(int num1, int num2) {
19         if (num1 > num2)
20             return num1;
21         else
22             return num2;
23     }
24
25     /** Find the max of two double values */
26     public static double max(double num1, double num2) {
27         if (num1 > num2)
28             return num1;
29         else
30             return num2;
31     }
32
33     /** Return the max of three double values */
34     public static double max(double num1, double num2, double num3) {
35         return max(max(num1, num2), num3);
36     }
37 }
```



```

The maximum of 3 and 4 is 4
The maximum of 3.0 and 5.4 is 5.4
The maximum of 3.0, 5.4, and 10.14 is 10.14

```

When calling `max(3, 4)` (line 6), the `max` method for finding the maximum of two integers is invoked. When calling `max(3.0, 5.4)` (line 10), the `max` method for finding the maximum of two doubles is invoked. When calling `max(3.0, 5.4, 10.14)` (line 14), the `max` method for finding the maximum of three double values is invoked.

Can you invoke the `max` method with an `int` value and a `double` value, such as `max(2, 2.5)`? If so, which of the `max` methods is invoked? The answer to the first question is yes. The answer to the second question is that the `max` method for finding the maximum of two `double` values is invoked. The argument value `2` is automatically converted into a `double` value and passed to this method.

You may be wondering why the method `max(double, double)` is not invoked for the call `max(3, 4)`. Both `max(double, double)` and `max(int, int)` are possible matches for `max(3, 4)`. The Java compiler finds the method that best matches a method invocation. Since the method `max(int, int)` is a better matches for `max(3, 4)` than `max(double, double)`, `max(int, int)` is used to invoke `max(3, 4)`.



Tip

Overloading methods can make programs clearer and more readable. Methods that perform the same function with different types of parameters should be given the same name.



Note

Overloaded methods must have different parameter lists. You cannot overload methods based on different modifiers or return types.



Note

Sometimes there are two or more possible matches for the invocation of a method, but the compiler cannot determine the best match. This is referred to as *ambiguous invocation*. Ambiguous invocation causes a compile error. Consider the following code:

ambiguous invocation

```
public class AmbiguousOverloading {
    public static void main(String[] args) {
        System.out.println(max(1, 2));
    }

    public static double max(int num1, double num2) {
        if (num1 > num2)
            return num1;
        else
            return num2;
    }

    public static double max(double num1, int num2) {
        if (num1 > num2)
            return num1;
        else
            return num2;
    }
}
```

Both `max(int, double)` and `max(double, int)` are possible candidates to match `max(1, 2)`. Because neither is better than the other, the invocation is ambiguous, resulting in a compile error.



- 6.15** What is method overloading? Is it permissible to define two methods that have the same name but different parameter types? Is it permissible to define two methods in a class that have identical method names and parameter lists but different return value types or different modifiers?

- 6.16** What is wrong in the following program?

```
public class Test {
    public static void method(int x) {
    }

    public static int method(int y) {
```

```

        return y;
    }
}
```

- 6.17** Given two method definitions,

```

public static double m(double x, double y)
public static double m(int x, double y)
```

tell which of the two methods is invoked for:

- double** z = m(4, 5);
- double** z = m(4, 5.4);
- double** z = m(4.5, 5.4);

6.9 The Scope of Variables



The scope of a variable is the part of the program where the variable can be referenced.

scope of variables
local variable

Section 2.5 introduced the scope of a variable. This section discusses the scope of variables in detail. A variable defined inside a method is referred to as a *local variable*. The scope of a local variable starts from its declaration and continues to the end of the block that contains the variable. A local variable must be declared and assigned a value before it can be used.

A parameter is actually a local variable. The scope of a method parameter covers the entire method. A variable declared in the initial-action part of a **for**-loop header has its scope in the entire loop. However, a variable declared inside a **for**-loop body has its scope limited in the loop body from its declaration to the end of the block that contains the variable, as shown in Figure 6.5.

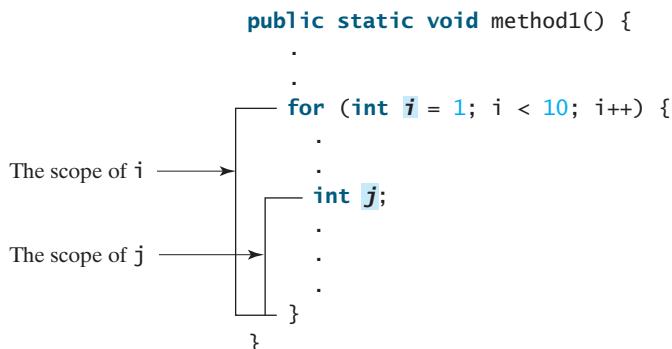


FIGURE 6.5 A variable declared in the initial action part of a **for**-loop header has its scope in the entire loop.

You can declare a local variable with the same name in different blocks in a method, but you cannot declare a local variable twice in the same block or in nested blocks, as shown in Figure 6.6.

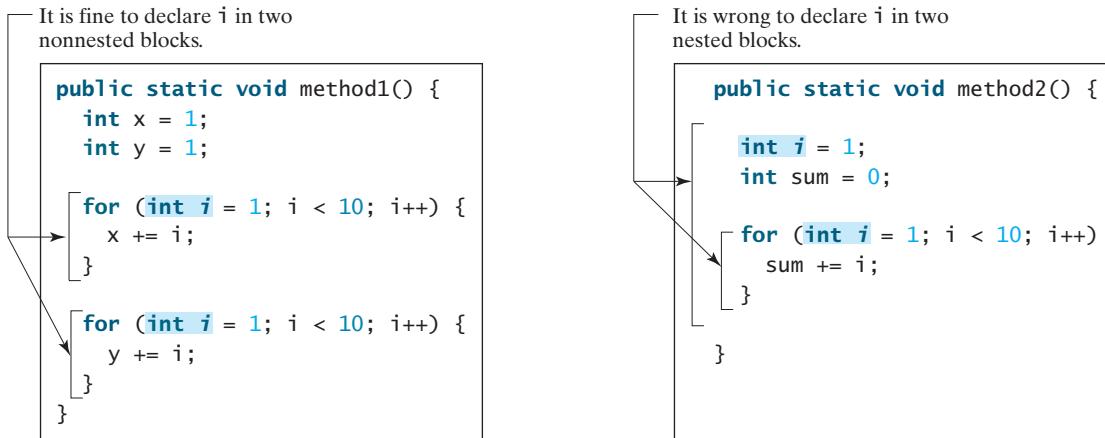


FIGURE 6.6 A variable can be declared multiple times in nonnested blocks, but only once in nested blocks.



Caution

Do not declare a variable inside a block and then attempt to use it outside the block.
Here is an example of a common mistake:

```
for (int i = 0; i < 10; i++) {
}

System.out.println(i);
```

The last statement would cause a syntax error, because variable `i` is not defined outside of the `for` loop.

6.18 What is a local variable?

6.19 What is the scope of a local variable?



6.10 Case Study: Generating Random Characters

A character is coded using an integer. Generating a random character is to generate an integer.



Computer programs process numerical data and characters. You have seen many examples that involve numerical data. It is also important to understand characters and how to process them. This section presents an example of generating random characters.

As introduced in Section 4.3, every character has a unique Unicode between `0` and `FFFF` in hexadecimal (`65535` in decimal). To generate a random character is to generate a random integer between `0` and `65535` using the following expression (note that since `0 <= Math.random() < 1.0`, you have to add `1` to `65535`):

```
(int)(Math.random() * (65535 + 1))
```

Now let's consider how to generate a random lowercase letter. The Unicodes for lowercase letters are consecutive integers starting from the Unicode for `a`, then that for `b`, `c`, . . . , and `z`. The Unicode for `a` is

```
(int)'a'
```

Thus, a random integer between `(int)'a'` and `(int)'z'` is

```
(int)((int)'a' + Math.random() * ((int)'z' - (int)'a' + 1))
```

As discussed in Section 4.3.3, all numeric operators can be applied to the `char` operands. The `char` operand is cast into a number if the other operand is a number or a character. Therefore, the preceding expression can be simplified as follows:

```
'a' + Math.random() * ('z' - 'a' + 1)
```

and a random lowercase letter is

```
(char)('a' + Math.random() * ('z' - 'a' + 1))
```

Hence, a random character between any two characters `ch1` and `ch2` with `ch1 < ch2` can be generated as follows:

```
(char)(ch1 + Math.random() * (ch2 - ch1 + 1))
```

This is a simple but useful discovery. Listing 6.10 defines a class named `RandomCharacter` with five overloaded methods to get a certain type of character randomly. You can use these methods in your future projects.

LISTING 6.10 RandomCharacter.java

```
1 public class RandomCharacter {
2     /** Generate a random character between ch1 and ch2 */
3     public static char getRandomCharacter(char ch1, char ch2) {
4         return (char)(ch1 + Math.random() * (ch2 - ch1 + 1));
5     }
6
7     /** Generate a random lowercase letter */
8     public static char getRandomLowerCaseLetter() {
9         return getRandomCharacter('a', 'z');
10    }
11
12    /** Generate a random uppercase letter */
13    public static char getRandomUpperCaseLetter() {
14        return getRandomCharacter('A', 'Z');
15    }
16
17    /** Generate a random digit character */
18    public static char getRandomDigitCharacter() {
19        return getRandomCharacter('0', '9');
20    }
21
22    /** Generate a random character */
23    public static char getRandomCharacter() {
24        return getRandomCharacter('\u0000', '\uFFFF');
25    }
26 }
```

getRandomCharacter

getRandomLower
CaseLetter()

getRandomUpper
CaseLetter()

getRandomDigit
Character()

getRandomCharacter()

Listing 6.11 gives a test program that displays 175 random lowercase letters.

LISTING 6.11 TestRandomCharacter.java

constants

```
1 public class TestRandomCharacter {
2     /** Main method */
3     public static void main(String[] args) {
4         final int NUMBER_OF_CHARS = 175;
5         final int CHARS_PER_LINE = 25;
6
7         // Print random characters between 'a' and 'z', 25 chars per line
8         for (int i = 0; i < NUMBER_OF_CHARS; i++) {
```

```

9     char ch = RandomCharacter.getRandomLowerCaseLetter();           lower-case letter
10    if ((i + 1) % CHARS_PER_LINE == 0)
11        System.out.println(ch);
12    else
13        System.out.print(ch);
14    }
15 }
16 }
```

gmjsuhezfkgtazqgmswfc1rao
pnrunulnwmaztlfjedmpchcif
1alqdgivxkxpzbzulrmqmbhikr
1bnrjlsoptfxahssqhwuuljvbe
xbhdotzhpehbqmwsfktsol1i
cbuwkzgxpmtzihgatds1vbwbz
bfesoklwbhnooyigzdxuqni



Line 9 invokes `getRandomLowerCaseLetter()` defined in the `RandomCharacter` class. Note that `getRandomLowerCaseLetter()` does not have any parameters, but you still have to use the parentheses when defining and invoking the method.

parentheses required

6.11 Method Abstraction and Stepwise Refinement

The key to developing software is to apply the concept of abstraction.

You will learn many levels of abstraction from this book. *Method abstraction* is achieved by separating the use of a method from its implementation. The client can use a method without knowing how it is implemented. The details of the implementation are encapsulated in the method and hidden from the client who invokes the method. This is also known as *information hiding* or *encapsulation*. If you decide to change the implementation, the client program will not be affected, provided that you do not change the method signature. The implementation of the method is hidden from the client in a “black box,” as shown in Figure 6.7.



VideoNote
Stepwise refinement
method abstraction
information hiding

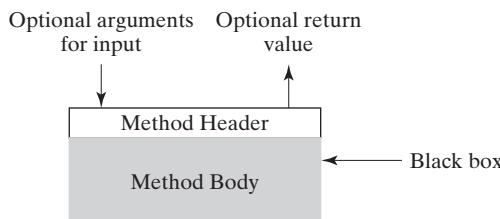


FIGURE 6.7 The method body can be thought of as a black box that contains the detailed implementation for the method.

You have already used the `System.out.print` method to display a string and the `max` method to find the maximum number. You know how to write the code to invoke these methods in your program, but as a user of these methods, you are not required to know how they are implemented.

The concept of method abstraction can be applied to the process of developing programs. When writing a large program, you can use the *divide-and-conquer* strategy, also known as *stepwise refinement*, to decompose it into subproblems. The subproblems can be further decomposed into smaller, more manageable problems.

Suppose you write a program that displays the calendar for a given month of the year. The program prompts the user to enter the year and the month, then displays the entire calendar for the month, as shown in the following sample run.

divide and conquer
stepwise refinement



```

Enter full year (e.g., 2012): 2012 ↵ Enter
Enter month as number between 1 and 12: 3 ↵ Enter
March 2012
-----
Sun Mon Tue Wed Thu Fri Sat
      1   2   3
    4   5   6   7   8   9   10
  11  12  13  14  15  16  17
  18  19  20  21  22  23  24
  25  26  27  28  29  30

```

Let us use this example to demonstrate the divide-and-conquer approach.

6.11.1 Top-Down Design

How would you get started on such a program? Would you immediately start coding? Beginning programmers often start by trying to work out the solution to every detail. Although details are important in the final program, concern for detail in the early stages may block the problem-solving process. To make problem solving flow as smoothly as possible, this example begins by using method abstraction to isolate details from design and only later implements the details.

For this example, the problem is first broken into two subproblems: get input from the user and print the calendar for the month. At this stage, you should be concerned with what the subproblems will achieve, not with how to get input and print the calendar for the month. You can draw a structure chart to help visualize the decomposition of the problem (see Figure 6.8a).



FIGURE 6.8 The structure chart shows that the `printCalendar` problem is divided into two subproblems, `readInput` and `printMonth` in (a), and that `printMonth` is divided into two smaller subproblems, `printMonthTitle` and `printMonthBody` in (b).

You can use `Scanner` to read input for the year and the month. The problem of printing the calendar for a given month can be broken into two subproblems: print the month title and print the month body, as shown in Figure 6.8b. The month title consists of three lines: month and year, a dashed line, and the names of the seven days of the week. You need to get the month name (e.g., January) from the numeric month (e.g., 1). This is accomplished in `getMonthName` (see Figure 6.9a).

In order to print the month body, you need to know which day of the week is the first day of the month (`getStartDay`) and how many days the month has (`getNumberOfDaysInMonth`),



FIGURE 6.9 (a) To `printMonthTitle`, you need `getMonthName`. (b) The `printMonthBody` problem is refined into several smaller problems.

as shown in Figure 6.9b. For example, December 2013 has 31 days, and December 1, 2013, is a Sunday.

How would you get the start day for the first date in a month? There are several ways to do so. For now, we'll use an alternative approach. Assume you know that the start day for January 1, 1800, was a Wednesday (`START_DAY_FOR_JAN_1_1800 = 3`). You could compute the total number of days (`totalNumberOfDays`) between January 1, 1800, and the first date of the calendar month. The start day for the calendar month is `(totalNumberOfDays + START_DAY_FOR_JAN_1_1800) % 7`, since every week has seven days. Thus, the `getStartDay` problem can be further refined as `getTotalNumberOfDays`, as shown in Figure 6.10a.



FIGURE 6.10 (a) To `getStartDay`, you need `getTotalNumberOfDays`. (b) The `getTotalNumberOfDays` problem is refined into two smaller problems.

To get the total number of days, you need to know whether the year is a leap year and the number of days in each month. Thus, `getTotalNumberOfDays` can be further refined into two subproblems: `isLeapYear` and `getNumberOfDaysInMonth`, as shown in Figure 6.10b. The complete structure chart is shown in Figure 6.11.

6.11.2 Top-Down and/or Bottom-Up Implementation

Now we turn our attention to implementation. In general, a subproblem corresponds to a method in the implementation, although some are so simple that this is unnecessary. You would need to decide which modules to implement as methods and which to combine with other methods. Decisions of this kind should be based on whether the overall program will be easier to read as a result of your choice. In this example, the subproblem `readInput` can be simply implemented in the `main` method.

You can use either a “top-down” or a “bottom-up” approach. The top-down approach implements one method in the structure chart at a time from the top to the bottom. *Stubs*—a simple but incomplete version of a method—can be used for the methods waiting to be implemented. The use of stubs enables you to quickly build the framework of the program. Implement the `main` method first, and then use a stub for the `printMonth` method. For example,

top-down approach
stub



FIGURE 6.11 The structure chart shows the hierarchical relationship of the subproblems in the program.

let `printMonth` display the year and the month in the stub. Thus, your program may begin like this:

```

public class PrintCalendar {
    /** Main method */
    public static void main(String[] args) {
        Scanner input = new Scanner(System.in);

        // Prompt the user to enter year
        System.out.print("Enter full year (e.g., 2012): ");
        int year = input.nextInt();

        // Prompt the user to enter month
        System.out.print("Enter month as a number between 1 and 12: ");
        int month = input.nextInt();

        // Print calendar for the month of the year
        printMonth(year, month);
    }

    /** A stub for printMonth may look like this */
    public static void printMonth(int year, int month){
        System.out.print(month + " " + year);
    }

    /** A stub for printMonthTitle may look like this */
    public static void printMonthTitle(int year, int month){
    }

    /** A stub for getMonthBody may look like this */
    public static void printMonthBody(int year, int month){
    }
}
  
```

```

/** A stub for getMonthName may look like this */
public static String getMonthName(int month) {
    return "January"; // A dummy value
}

/** A stub for getStartDay may look like this */
public static int getStartDay(int year, int month) {
    return 1; // A dummy value
}

/** A stub for getTotalNumberOfDays may look like this */
public static int getTotalNumberOfDays(int year, int month) {
    return 10000; // A dummy value
}

/** A stub for getNumberOfDaysInMonth may look like this */
public static int getNumberOfDaysInMonth(int year, int month) {
    return 31; // A dummy value
}

/** A stub for isLeapYear may look like this */
public static Boolean isLeapYear(int year) {
    return true; // A dummy value
}
}

```

Compile and test the program, and fix any errors. You can now implement the `printMonth` method. For methods invoked from the `printMonth` method, you can again use stubs.

The bottom-up approach implements one method in the structure chart at a time from the bottom to the top. For each method implemented, write a test program, known as the *driver*, to test it. The top-down and bottom-up approaches are equally good: Both approaches implement methods incrementally, help to isolate programming errors, and make debugging easy. They can be used together.

bottom-up approach
driver

6.11.3 Implementation Details

The `isLeapYear(int year)` method can be implemented using the following code from Section 3.11:

```
return year % 400 == 0 || (year % 4 == 0 && year % 100 != 0);
```

Use the following facts to implement `getTotalNumberOfDaysInMonth(int year, int month)`:

- January, March, May, July, August, October, and December have 31 days.
- April, June, September, and November have 30 days.
- February has 28 days during a regular year and 29 days during a leap year. A regular year, therefore, has 365 days, a leap year 366 days.

To implement `getTotalNumberOfDays(int year, int month)`, you need to compute the total number of days (`totalNumberOfDays`) between January 1, 1800, and the first day of the calendar month. You could find the total number of days between the year 1800 and the calendar year and then figure out the total number of days prior to the calendar month in the calendar year. The sum of these two totals is `totalNumberOfDays`.

To print a body, first pad some space before the start day and then print the lines for every week.

The complete program is given in Listing 6.12.

LISTING 6.12 PrintCalendar.java

```

1 import java.util.Scanner;
2
3 public class PrintCalendar {
4     /** Main method */
5     public static void main(String[] args) {
6         Scanner input = new Scanner(System.in);
7
8         // Prompt the user to enter year
9         System.out.print("Enter full year (e.g., 2012): ");
10        int year = input.nextInt();
11
12        // Prompt the user to enter month
13        System.out.print("Enter month as a number between 1 and 12: ");
14        int month = input.nextInt();
15
16        // Print calendar for the month of the year
17        printMonth(year, month);
18    }
19
20    /** Print the calendar for a month in a year */
21    public static void printMonth(int year, int month) {
22        // Print the headings of the calendar
23        printMonthTitle(year, month);
24
25        // Print the body of the calendar
26        printMonthBody(year, month);
27    }
28
29    /** Print the month title, e.g., March 2012 */
30    public static void printMonthTitle(int year, int month) {
31        System.out.println(" " + getMonthName(month)
32                    + " " + year);
33        System.out.println("-----");
34        System.out.println(" Sun Mon Tue Wed Thu Fri Sat");
35    }
36
37    /** Get the English name for the month */
38    public static String getMonthName(int month) {
39        String monthName = "";
40        switch (month) {
41            case 1: monthName = "January"; break;
42            case 2: monthName = "February"; break;
43            case 3: monthName = "March"; break;
44            case 4: monthName = "April"; break;
45            case 5: monthName = "May"; break;
46            case 6: monthName = "June"; break;
47            case 7: monthName = "July"; break;
48            case 8: monthName = "August"; break;
49            case 9: monthName = "September"; break;
50            case 10: monthName = "October"; break;
51            case 11: monthName = "November"; break;
52            case 12: monthName = "December";
53        }
54
55        return monthName;
56    }
57
58    /** Print month body */

```

printMonth

printMonthTitle

getMonthName

```

59 public static void printMonthBody(int year, int month) {           printMonthBody
60     // Get start day of the week for the first date in the month
61     int startDay = getStartDay(year, month)
62
63     // Get number of days in the month
64     int numberOfDaysInMonth = getNumberOfDaysInMonth(year, month);
65
66     // Pad space before the first day of the month
67     int i = 0;
68     for (i = 0; i < startDay; i++)
69         System.out.print("   ");
70
71     for (i = 1; i <= numberOfDaysInMonth; i++) {
72         System.out.printf("%4d", i);
73
74         if ((i + startDay) % 7 == 0)
75             System.out.println();
76     }
77
78     System.out.println();
79 }
80
81 /** Get the start day of month/1/year */
82 public static int getStartDay(int year, int month) {           getStartDay
83     final int START_DAY_FOR_JAN_1_1800 = 3;
84     // Get total number of days from 1/1/1800 to month/1/year
85     int totalNumberOfDays = getTotalNumberOfDays(year, month);
86
87     // Return the start day for month/1/year
88     return (totalNumberOfDays + START_DAY_FOR_JAN_1_1800) % 7;
89 }
90
91 /** Get the total number of days since January 1, 1800 */
92 public static int getTotalNumberOfDays(int year, int month) {           getTotalNumberOfDays
93     int total = 0;
94
95     // Get the total days from 1800 to 1/1/year
96     for (int i = 1800; i < year; i++)
97         if (isLeapYear(i))
98             total = total + 366;
99         else
100            total = total + 365;
101
102     // Add days from Jan to the month prior to the calendar month
103     for (int i = 1; i < month; i++)
104         total = total + getNumberOfDaysInMonth(year, i);
105
106     return total;
107 }
108
109 /** Get the number of days in a month */
110 public static int getNumberOfDaysInMonth(int year, int month) {           getNumberOfDaysInMonth
111     if (month == 1 || month == 3 || month == 5 || month == 7 ||
112         month == 8 || month == 10 || month == 12)
113         return 31;
114
115     if (month == 4 || month == 6 || month == 9 || month == 11)
116         return 30;
117
118     if (month == 2) return isLeapYear(year) ? 29 : 28;

```

```

119
120     return 0; // If month is incorrect
121 }
122
123 /** Determine if it is a leap year */
124 public static boolean isLeapYear(int year) {
125     return year % 400 == 0 || (year % 4 == 0 && year % 100 != 0);
126 }
127 }
```

isLeapYear

The program does not validate user input. For instance, if the user enters either a month not in the range between 1 and 12 or a year before 1800, the program displays an erroneous calendar. To avoid this error, add an `if` statement to check the input before printing the calendar.

This program prints calendars for a month but could easily be modified to print calendars for a whole year. Although it can print months only after January 1800, it could be modified to print months before 1800.

6.11.4 Benefits of Stepwise Refinement

Stepwise refinement breaks a large problem into smaller manageable subproblems. Each subproblem can be implemented using a method. This approach makes the program easier to write, reuse, debug, test, modify, and maintain.

Simpler Program

The print calendar program is long. Rather than writing a long sequence of statements in one method, stepwise refinement breaks it into smaller methods. This simplifies the program and makes the whole program easier to read and understand.

Reusing Methods

Stepwise refinement promotes code reuse within a program. The `isLeapYear` method is defined once and invoked from the `getTotalNumberOfDays` and `getNumberOfDayInMonth` methods. This reduces redundant code.

Easier Developing, Debugging, and Testing

Since each subproblem is solved in a method, a method can be developed, debugged, and tested individually. This isolates the errors and makes developing, debugging, and testing easier.

When implementing a large program, use the top-down and/or bottom-up approach. Do not write the entire program at once. Using these approaches seems to take more development time (because you repeatedly compile and run the program), but it actually saves time and makes debugging easier.

incremental development and testing

Better Facilitating Teamwork

When a large problem is divided into subprograms, subproblems can be assigned to different programmers. This makes it easier for programmers to work in teams.

KEY TERMS

actual parameter 205

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divide and conquer 225

formal parameter (i.e., parameter) 205

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CHAPTER SUMMARY

1. Making programs modular and reusable is one of the central goals in software engineering. Java provides many powerful constructs that help to achieve this goal. *Methods* are one such construct.
2. The method header specifies the *modifiers*, *return value type*, *method name*, and *parameters* of the method. The **static** modifier is used for all the methods in this chapter.
3. A method may return a value. The **returnValueType** is the data type of the value the method returns. If the method does not return a value, the **returnValueType** is the keyword **void**.
4. The *parameter list* refers to the type, order, and number of a method's parameters. The method name and the parameter list together constitute the *method signature*. Parameters are optional; that is, a method doesn't need to contain any parameters.
5. A return statement can also be used in a **void** method for terminating the method and returning to the method's caller. This is useful occasionally for circumventing the normal flow of control in a method.
6. The arguments that are passed to a method should have the same number, type, and order as the parameters in the method signature.
7. When a program calls a method, program control is transferred to the called method. A called method returns control to the caller when its return statement is executed or when its method-ending closing brace is reached.
8. A value-returning method can also be invoked as a statement in Java. In this case, the caller simply ignores the return value.
9. A method can be overloaded. This means that two methods can have the same name, as long as their method parameter lists differ.
10. A variable declared in a method is called a local variable. The *scope of a local variable* starts from its declaration and continues to the end of the block that contains the variable. A local variable must be declared and initialized before it is used.
11. *Method abstraction* is achieved by separating the use of a method from its implementation. The client can use a method without knowing how it is implemented. The details of the implementation are encapsulated in the method and hidden from the client who invokes the method. This is known as *information hiding* or *encapsulation*.
12. Method abstraction modularizes programs in a neat, hierarchical manner. Programs written as collections of concise methods are easier to write, debug, maintain, and modify than would otherwise be the case. This writing style also promotes method reusability.
13. When implementing a large program, use the top-down and/or bottom-up coding approach. Do not write the entire program at once. This approach may seem to take more time for coding (because you are repeatedly compiling and running the program), but it actually saves time and makes debugging easier.

Quiz

Answer the quiz for this chapter online at www.cs.armstrong.edu/liang/intro10e/quiz.html.

**PROGRAMMING EXERCISES****Note**

A common error for the exercises in this chapter is that students don't implement the methods to meet the requirements even though the output from the main program is correct. For an example of this type of error see www.cs.armstrong.edu/liang/CommonMethodErrorJava.pdf.

Sections 6.2–6.9

- 6.1** (*Math: pentagonal numbers*) A pentagonal number is defined as $n(3n-1)/2$ for $n = 1, 2, \dots$, and so on. Therefore, the first few numbers are 1, 5, 12, 22, Write a method with the following header that returns a pentagonal number:

```
public static int getPentagonalNumber(int n)
```

Write a test program that uses this method to display the first 100 pentagonal numbers with 10 numbers on each line.

- *6.2** (*Sum the digits in an integer*) Write a method that computes the sum of the digits in an integer. Use the following method header:

```
public static int sumDigits(long n)
```

For example, `sumDigits(234)` returns 9 (2 + 3 + 4). (*Hint:* Use the % operator to extract digits, and the / operator to remove the extracted digit. For instance, to extract 4 from 234, use `234 % 10` (= 4). To remove 4 from 234, use `234 / 10` (= 23). Use a loop to repeatedly extract and remove the digit until all the digits are extracted. Write a test program that prompts the user to enter an integer and displays the sum of all its digits.)

- **6.3** (*Palindrome integer*) Write the methods with the following headers

```
// Return the reversal of an integer, i.e., reverse(456) returns 654
public static int reverse(int number)
```

```
// Return true if number is a palindrome
public static boolean isPalindrome(int number)
```

Use the `reverse` method to implement `isPalindrome`. A number is a palindrome if its reversal is the same as itself. Write a test program that prompts the user to enter an integer and reports whether the integer is a palindrome.

- *6.4** (*Display an integer reversed*) Write a method with the following header to display an integer in reverse order:

```
public static void reverse(int number)
```

For example, `reverse(3456)` displays 6543. Write a test program that prompts the user to enter an integer and displays its reversal.

- *6.5** (*Sort three numbers*) Write a method with the following header to display three numbers in increasing order:

```
public static void displaySortedNumbers(
    double num1, double num2, double num3)
```



VideoNote

Reverse an integer

Write a test program that prompts the user to enter three numbers and invokes the method to display them in increasing order.

- *6.6** (*Display patterns*) Write a method to display a pattern as follows:

```

    1
   2 1
  3 2 1
 ...
n n-1 ... 3 2 1

```

The method header is

```
public static void displayPattern(int n)
```

- *6.7** (*Financial application: compute the future investment value*) Write a method that computes future investment value at a given interest rate for a specified number of years. The future investment is determined using the formula in Programming Exercise 2.21.

Use the following method header:

```
public static double futureInvestmentValue(
    double investmentAmount, double monthlyInterestRate, int years)
```

For example, `futureInvestmentValue(10000, 0.05/12, 5)` returns **12833.59**.

Write a test program that prompts the user to enter the investment amount (e.g., 1000) and the interest rate (e.g., 9%) and prints a table that displays future value for the years from 1 to 30, as shown below:

The amount invested: 1000

Annual interest rate: 9

Years	Future Value
1	1093.80
2	1196.41
...	
29	13467.25
30	14730.57



- 6.8** (*Conversions between Celsius and Fahrenheit*) Write a class that contains the following two methods:

```
/** Convert from Celsius to Fahrenheit */
public static double celsiusToFahrenheit(double celsius)

/** Convert from Fahrenheit to Celsius */
public static double fahrenheitToCelsius(double fahrenheit)
```

The formula for the conversion is:

```
fahrenheit = (9.0 / 5) * celsius + 32
celsius = (5.0 / 9) * (fahrenheit - 32)
```

Write a test program that invokes these methods to display the following tables:

Celsius	Fahrenheit		Fahrenheit	Celsius
40.0	104.0		120.0	48.89
39.0	102.2		110.0	43.33
...				
32.0	89.6		40.0	4.44
31.0	87.8		30.0	-1.11

- 6.9** (*Conversions between feet and meters*) Write a class that contains the following two methods:

```
/** Convert from feet to meters */
public static double footToMeter(double foot)

/** Convert from meters to feet */
public static double meterToFoot(double meter)
```

The formula for the conversion is:

```
meter = 0.305 * foot
foot = 3.279 * meter
```

Write a test program that invokes these methods to display the following tables:

Feet	Meters		Meters	Feet
1.0	0.305		20.0	65.574
2.0	0.610		25.0	81.967
...				
9.0	2.745		60.0	196.721
10.0	3.050		65.0	213.115

- 6.10** (*Use the `isPrime` Method*) Listing 6.7, PrimeNumberMethod.java, provides the `isPrime(int number)` method for testing whether a number is prime. Use this method to find the number of prime numbers less than **10000**.

- 6.11** (*Financial application: compute commissions*) Write a method that computes the commission, using the scheme in Programming Exercise 5.39. The header of the method is as follows:

```
public static double computeCommission(double salesAmount)
```

Write a test program that displays the following table:

Sales Amount	Commission
10000	900.0
15000	1500.0
...	
95000	11100.0
100000	11700.0

- 6.12** (*Display characters*) Write a method that prints characters using the following header:

```
public static void printChars(char ch1, char ch2, int
    numberPerLine)
```

This method prints the characters between **ch1** and **ch2** with the specified numbers per line. Write a test program that prints ten characters per line from **1** to **Z**. Characters are separated by exactly one space.

- *6.13** (*Sum series*) Write a method to compute the following series:

$$m(i) = \frac{1}{2} + \frac{2}{3} + \dots + \frac{i}{i+1}$$

Write a test program that displays the following table:

i	m(i)
1	0.5000
2	1.1667
...	
19	16.4023
20	17.3546

- *6.14** (*Estimate π*) π can be computed using the following series:

$$m(i) = 4 \left(1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \frac{1}{9} - \frac{1}{11} + \dots + \frac{(-1)^{i+1}}{2i-1} \right)$$



VideoNote
Estimate π

Write a method that returns **m(i)** for a given **i** and write a test program that displays the following table:

i	m(i)
1	4.0000
101	3.1515
201	3.1466
301	3.1449
401	3.1441
501	3.1436
601	3.1433
701	3.1430
801	3.1428
901	3.1427

- *6.15** (*Financial application: print a tax table*) Listing 3.5 gives a program to compute tax. Write a method for computing tax using the following header:

```
public static double computeTax(int status, double taxableIncome)
```

Use this method to write a program that prints a tax table for taxable income from \$50,000 to \$60,000 with intervals of \$50 for all the following statuses:

Taxable Income	Single	Married Joint or Qualifying Widow(er)	Married Separate	Head of a House
50000	8688	6665	8688	7353
50050	8700	6673	8700	7365
...				
59950	11175	8158	11175	9840
60000	11188	8165	11188	9853

Hint: round the tax into integers using `Math.round` (i.e., `Math.round(computeTax(status, taxableIncome))`).

*6.16

(Number of days in a year) Write a method that returns the number of days in a year using the following header:

```
public static int numberOfDaysInAYear(int year)
```

Write a test program that displays the number of days in year from 2000 to 2020.

Sections 6.10–6.11

*6.17

(Display matrix of 0s and 1s) Write a method that displays an n -by- n matrix using the following header:

```
public static void printMatrix(int n)
```

Each element is 0 or 1, which is generated randomly. Write a test program that prompts the user to enter `n` and displays an n -by- n matrix. Here is a sample run:



```
Enter n: 3 ↵Enter
0 1 0
0 0 0
1 1 1
```

**6.18

(Check password) Some websites impose certain rules for passwords. Write a method that checks whether a string is a valid password. Suppose the password rules are as follows:

- A password must have at least eight characters.
- A password consists of only letters and digits.
- A password must contain at least two digits.

Write a program that prompts the user to enter a password and displays `Valid Password` if the rules are followed or `Invalid Password` otherwise.

*6.19

(The `MyTriangle` class) Create a class named `MyTriangle` that contains the following two methods:

```
/** Return true if the sum of any two sides is
 * greater than the third side. */
public static boolean isValid(
    double side1, double side2, double side3)
```

```
/** Return the area of the triangle. */
public static double area(
    double side1, double side2, double side3)
```

Write a test program that reads three sides for a triangle and computes the area if the input is valid. Otherwise, it displays that the input is invalid. The formula for computing the area of a triangle is given in Programming Exercise 2.19.

- *6.20** (*Count the letters in a string*) Write a method that counts the number of letters in a string using the following header:

```
public static int countLetters(String s)
```

Write a test program that prompts the user to enter a string and displays the number of letters in the string.

- *6.21** (*Phone keypads*) The international standard letter/number mapping for telephones is shown in Programming Exercise 4.15. Write a method that returns a number, given an uppercase letter, as follows:

```
int getNumber(char uppercaseLetter)
```

Write a test program that prompts the user to enter a phone number as a string. The input number may contain letters. The program translates a letter (uppercase or lowercase) to a digit and leaves all other characters intact. Here is a sample run of the program:

Enter a string: 1-800-Flowers ↵ Enter
1-800-3569377



Enter a string: 1800flowers ↵ Enter
18003569377



- **6.22** (*Math: approximate the square root*) There are several techniques for implementing the `sqrt` method in the `Math` class. One such technique is known as the *Babylonian method*. It approximates the square root of a number, `n`, by repeatedly performing a calculation using the following formula:

```
nextGuess = (lastGuess + n / lastGuess) / 2
```

When `nextGuess` and `lastGuess` are almost identical, `nextGuess` is the approximated square root. The initial guess can be any positive value (e.g., `1`). This value will be the starting value for `lastGuess`. If the difference between `nextGuess` and `lastGuess` is less than a very small number, such as `0.0001`, you can claim that `nextGuess` is the approximated square root of `n`. If not, `nextGuess` becomes `lastGuess` and the approximation process continues. Implement the following method that returns the square root of `n`.

```
public static double sqrt(long n)
```

- *6.23** (*Occurrences of a specified character*) Write a method that finds the number of occurrences of a specified character in a string using the following header:

```
public static int count(String str, char a)
```

For example, `count("Welcome", 'e')` returns `2`. Write a test program that prompts the user to enter a string followed by a character and displays the number of occurrences of the character in the string.

Sections 6.10–6.12

****6.24** (*Display current date and time*) Listing 2.7, ShowCurrentTime.java, displays the current time. Improve this example to display the current date and time. The calendar example in Listing 6.12, PrintCalendar.java, should give you some ideas on how to find the year, month, and day.

****6.25** (*Convert milliseconds to hours, minutes, and seconds*) Write a method that converts milliseconds to hours, minutes, and seconds using the following header:

```
public static String convertMillis(long millis)
```

The method returns a string as `hours:minutes:seconds`. For example, `convertMillis(5500)` returns a string `0:0:5`, `convertMillis(100000)` returns a string `0:1:40`, and `convertMillis(555550000)` returns a string `154:19:10`.

Comprehensive

****6.26** (*Palindromic prime*) A *palindromic prime* is a prime number and also palindromic. For example, 131 is a prime and also a palindromic prime, as are 313 and 757. Write a program that displays the first 100 palindromic prime numbers. Display 10 numbers per line, separated by exactly one space, as follows:

```
2 3 5 7 11 101 131 151 181 191
313 353 373 383 727 757 787 797 919 929
...
```

****6.27** (*Emirp*) An *emirp* (prime spelled backward) is a nonpalindromic prime number whose reversal is also a prime. For example, 17 is a prime and 71 is a prime, so 17 and 71 are emirps. Write a program that displays the first 100 emirps. Display 10 numbers per line, separated by exactly one space, as follows:

```
13 17 31 37 71 73 79 97 107 113
149 157 167 179 199 311 337 347 359 389
...
```

****6.28** (*Mersenne prime*) A prime number is called a *Mersenne prime* if it can be written in the form $2^p - 1$ for some positive integer p . Write a program that finds all Mersenne primes with $p \leq 31$ and displays the output as follows:

<u>p</u>	<u>$2^p - 1$</u>
2	3
3	7
5	31
...	

****6.29** (*Twin primes*) Twin primes are a pair of prime numbers that differ by 2. For example, 3 and 5 are twin primes, 5 and 7 are twin primes, and 11 and 13 are twin primes. Write a program to find all twin primes less than 1,000. Display the output as follows:

```
(3, 5)
(5, 7)
...
```

- **6.30** (*Game: craps*) Craps is a popular dice game played in casinos. Write a program to play a variation of the game, as follows:

Roll two dice. Each die has six faces representing values 1, 2, ..., and 6, respectively. Check the sum of the two dice. If the sum is 2, 3, or 12 (called *craps*), you lose; if the sum is 7 or 11 (called *natural*), you win; if the sum is another value (i.e., 4, 5, 6, 8, 9, or 10), a point is established. Continue to roll the dice until either a 7 or the same point value is rolled. If 7 is rolled, you lose. Otherwise, you win.

Your program acts as a single player. Here are some sample runs.

```
You rolled 5 + 6 = 11
You win
```



```
You rolled 1 + 2 = 3
You lose
```



```
You rolled 4 + 4 = 8
point is 8
You rolled 6 + 2 = 8
You win
```



```
You rolled 3 + 2 = 5
point is 5
You rolled 2 + 5 = 7
You lose
```

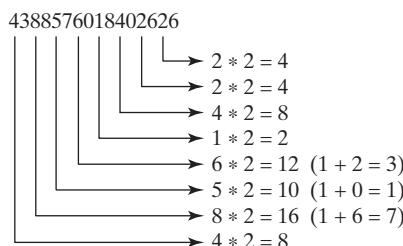


- **6.31** (*Financial: credit card number validation*) Credit card numbers follow certain patterns. A credit card number must have between 13 and 16 digits. It must start with:

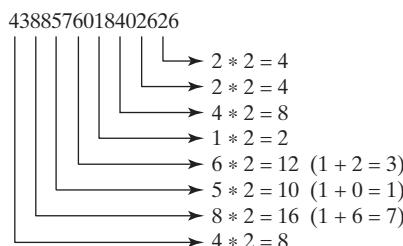
- 4 for Visa cards
- 5 for Master cards
- 37 for American Express cards
- 6 for Discover cards

In 1954, Hans Luhn of IBM proposed an algorithm for validating credit card numbers. The algorithm is useful to determine whether a card number is entered correctly or whether a credit card is scanned correctly by a scanner. Credit card numbers are generated following this validity check, commonly known as the *Luhn check* or the *Mod 10 check*, which can be described as follows (for illustration, consider the card number 4388576018402626):

1. Double every second digit from right to left. If doubling of a digit results in a two-digit number, add up the two digits to get a single-digit number.



1. Double every second digit from right to left. If doubling of a digit results in a two-digit number, add up the two digits to get a single-digit number.



2. Now add all single-digit numbers from Step 1.
- $$4 + 4 + 8 + 2 + 3 + 1 + 7 + 8 = 37$$

3. Add all digits in the odd places from right to left in the card number.
- $$6 + 6 + 0 + 8 + 0 + 7 + 8 + 3 = 38$$

4. Sum the results from Step 2 and Step 3.

$$37 + 38 = 75$$

5. If the result from Step 4 is divisible by 10, the card number is valid; otherwise, it is invalid. For example, the number 4388576018402626 is invalid, but the number 4388576018410707 is valid.

Write a program that prompts the user to enter a credit card number as a `long` integer. Display whether the number is valid or invalid. Design your program to use the following methods:

```
/** Return true if the card number is valid */
public static boolean isValid(long number)

/** Get the result from Step 2 */
public static int sumOfDoubleEvenPlace(long number)

/** Return this number if it is a single digit, otherwise,
 * return the sum of the two digits */
public static int getDigit(int number)

/** Return sum of odd-place digits in number */
public static int sumOfOddPlace(long number)

/** Return true if the digit d is a prefix for number */
public static boolean prefixMatched(long number, int d)

/** Return the number of digits in d */
public static int getSize(long d)

/** Return the first k number of digits from number. If the
 * number of digits in number is less than k, return number. */
public static long getPrefix(long number, int k)
```

Here are sample runs of the program: (You may also implement this program by reading the input as a string and processing the string to validate the credit card.)



```
Enter a credit card number as a long integer:
4388576018410707 ↵Enter
4388576018410707 is valid
```



```
Enter a credit card number as a long integer:
4388576018402626 ↵Enter
4388576018402626 is invalid
```

****6.32** (*Game: chance of winning at craps*) Revise Exercise 6.30 to run it 10,000 times and display the number of winning games.

****6.33** (*Current date and time*) Invoking `System.currentTimeMillis()` returns the elapsed time in milliseconds since midnight of January 1, 1970. Write a program that displays the date and time. Here is a sample run:



```
Current date and time is May 16, 2012 10:34:23
```

****6.34** (*Print calendar*) Programming Exercise 3.21 uses Zeller's congruence to calculate the day of the week. Simplify Listing 6.12, PrintCalendar.java, using Zeller's algorithm to get the start day of the month.

6.35 (*Geometry: area of a pentagon*) The area of a pentagon can be computed using the following formula:

$$\text{Area} = \frac{5 \times s^2}{4 \times \tan\left(\frac{\pi}{5}\right)}$$

Write a method that returns the area of a pentagon using the following header:

```
public static double area(double side)
```

Write a main method that prompts the user to enter the side of a pentagon and displays its area. Here is a sample run:

Enter the side: 5.5 ↵ Enter
The area of the pentagon is 52.04444136781625



***6.36** (*Geometry: area of a regular polygon*) A regular polygon is an n -sided polygon in which all sides are of the same length and all angles have the same degree (i.e., the polygon is both equilateral and equiangular). The formula for computing the area of a regular polygon is

$$\text{Area} = \frac{n \times s^2}{4 \times \tan\left(\frac{\pi}{n}\right)}$$

Write a method that returns the area of a regular polygon using the following header:

```
public static double area(int n, double side)
```

Write a main method that prompts the user to enter the number of sides and the side of a regular polygon and displays its area. Here is a sample run:

Enter the number of sides: 5 ↵ Enter
Enter the side: 6.5 ↵ Enter
The area of the polygon is 72.69017017488385



6.37 (*Format an integer*) Write a method with the following header to format the integer with the specified width.

```
public static String format(int number, int width)
```

The method returns a string for the number with one or more prefix 0s. The size of the string is the width. For example, `format(34, 4)` returns `0034` and `format(34, 5)` returns `00034`. If the number is longer than the width, the method

returns the string representation for the number. For example, `format(34, 1)` returns `34`.

Write a test program that prompts the user to enter a number and its width and displays a string returned by invoking `format(number, width)`.

***6.38**

(*Generate random characters*) Use the methods in `RandomCharacter` in Listing 6.10 to print 100 uppercase letters and then 100 single digits, printing ten per line.

6.39

(*Geometry: point position*) Programming Exercise 3.32 shows how to test whether a point is on the left side of a directed line, on the right, or on the same line. Write the methods with the following headers:

```
/** Return true if point (x2, y2) is on the left side of the
 * directed line from (x0, y0) to (x1, y1) */
public static boolean leftOfTheLine(double x0, double y0,
    double x1, double y1, double x2, double y2)

/** Return true if point (x2, y2) is on the same
 * line from (x0, y0) to (x1, y1) */
public static boolean onTheSameLine(double x0, double y0,
    double x1, double y1, double x2, double y2)

/** Return true if point (x2, y2) is on the
 * line segment from (x0, y0) to (x1, y1) */
public static boolean onTheLineSegment(double x0, double y0,
    double x1, double y1, double x2, double y2)
```

Write a program that prompts the user to enter the three points for `p0`, `p1`, and `p2` and displays whether `p2` is on the left of the line from `p0` to `p1`, right, the same line, or on the line segment. Here are some sample runs:



Enter three points for p0, p1, and p2: 1 1 2 2 1.5 1.5 ↵ Enter
(1.5, 1.5) is on the line segment from (1.0, 1.0) to (2.0, 2.0)



Enter three points for p0, p1, and p2: 1 1 2 2 3 3 ↵ Enter
(3.0, 3.0) is on the same line from (1.0, 1.0) to (2.0, 2.0)



Enter three points for p0, p1, and p2: 1 1 2 2 1 1.5 ↵ Enter
(1.0, 1.5) is on the left side of the line
from (1.0, 1.0) to (2.0, 2.0)

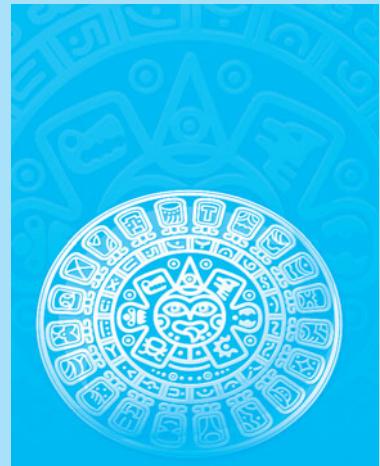
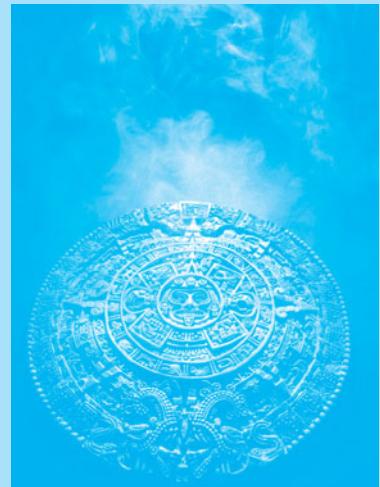


Enter three points for p0, p1, and p2: 1 1 2 2 1 -1 ↵ Enter
(1.0, -1.0) is on the right side of the line
from (1.0, 1.0) to (2.0, 2.0)

SINGLE-DIMENSIONAL ARRAYS

Objectives

- To describe why arrays are necessary in programming (§7.1).
- To declare array reference variables and create arrays (§§7.2.1–7.2.2).
- To obtain array size using `arrayRefVar.length` and know default values in an array (§7.2.3).
- To access array elements using indexes (§7.2.4).
- To declare, create, and initialize an array using an array initializer (§7.2.5).
- To program common array operations (displaying arrays, summing all elements, finding the minimum and maximum elements, random shuffling, and shifting elements) (§7.2.6).
- To simplify programming using the for each loops (§7.2.7).
- To apply arrays in application development ([AnalyzeNumbers](#), [DeckOfCards](#)) (§§7.3–7.4).
- To copy contents from one array to another (§7.5).
- To develop and invoke methods with array arguments and return values (§§7.6–7.8).
- To define a method with a variable-length argument list (§7.9).
- To search elements using the linear (§7.10.1) or binary (§7.10.2) search algorithm.
- To sort an array using the selection sort approach (§7.11).
- To use the methods in the `java.util.Arrays` class (§7.12).
- To pass arguments to the main method from the command line (§7.13).





problem
why array?

7.1 Introduction

A single array variable can reference a large collection of data.

Often you will have to store a large number of values during the execution of a program. Suppose, for instance, that you need to read 100 numbers, compute their average, and find out how many numbers are above the average. Your program first reads the numbers and computes their average, then compares each number with the average to determine whether it is above the average. In order to accomplish this task, the numbers must all be stored in variables. You have to declare 100 variables and repeatedly write almost identical code 100 times. Writing a program this way would be impractical. So, how do you solve this problem?

An efficient, organized approach is needed. Java and most other high-level languages provide a data structure, the *array*, which stores a fixed-size sequential collection of elements of the same type. In the present case, you can store all 100 numbers into an array and access them through a single array variable.

This chapter introduces single-dimensional arrays. The next chapter will introduce two-dimensional and multidimensional arrays.



index

7.2 Array Basics

Once an array is created, its size is fixed. An array reference variable is used to access the elements in an array using an index.

An array is used to store a collection of data, but often we find it more useful to think of an array as a collection of variables of the same type. Instead of declaring individual variables, such as `number0`, `number1`, . . . , and `number99`, you declare one array variable such as `numbers` and use `numbers[0]`, `numbers[1]`, . . . , and `numbers[99]` to represent individual variables. This section introduces how to declare array variables, create arrays, and process arrays using indexes.

7.2.1 Declaring Array Variables

element type

To use an array in a program, you must declare a variable to reference the array and specify the array's *element type*. Here is the syntax for declaring an array variable:

```
elementType[] arrayRefVar;
```

The `elementType` can be any data type, and all elements in the array will have the same data type. For example, the following code declares a variable `myList` that references an array of double elements.

```
double[] myList;
```



Note

You can also use `elementType arrayRefVar[]` to declare an array variable. This style comes from the C/C++ language and was adopted in Java to accommodate C/C++ programmers. The style `elementType[] arrayRefVar` is preferred.

preferred syntax

7.2.2 Creating Arrays

null

Unlike declarations for primitive data type variables, the declaration of an array variable does not allocate any space in memory for the array. It creates only a storage location for the reference to an array. If a variable does not contain a reference to an array, the value of the variable is `null`. You cannot assign elements to an array unless it has already been created. After an

array variable is declared, you can create an array by using the `new` operator and assign its reference to the variable with the following syntax:

```
arrayRefVar = new elementType[arraySize];
```

new operator

This statement does two things: (1) it creates an array using `new elementType[arraySize]`; (2) it assigns the reference of the newly created array to the variable `arrayRefVar`.

Declaring an array variable, creating an array, and assigning the reference of the array to the variable can be combined in one statement as:

```
elementType[] arrayRefVar = new elementType[arraySize];
```

or

```
elementType arrayRefVar[] = new elementType[arraySize];
```

Here is an example of such a statement:

```
double[] myList = new double[10];
```

This statement declares an array variable, `myList`, creates an array of ten elements of `double` type, and assigns its reference to `myList`. To assign values to the elements, use the syntax:

```
arrayRefVar[index] = value;
```

For example, the following code initializes the array.

```
myList[0] = 5.6;
myList[1] = 4.5;
myList[2] = 3.3;
myList[3] = 13.2;
myList[4] = 4.0;
myList[5] = 34.33;
myList[6] = 34.0;
myList[7] = 45.45;
myList[8] = 99.993;
myList[9] = 11123;
```

This array is illustrated in Figure 7.1.

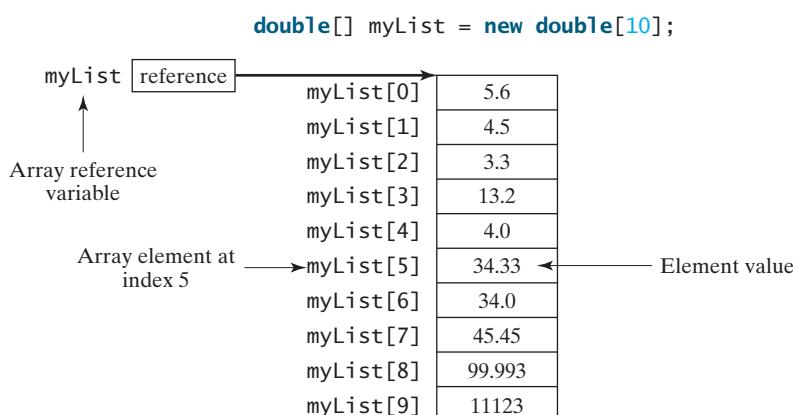


FIGURE 7.1 The array `myList` has ten elements of `double` type and `int` indices from 0 to 9.

array vs. array variable

**Note**

An array variable that appears to hold an array actually contains a reference to that array. Strictly speaking, an array variable and an array are different, but most of the time the distinction can be ignored. Thus it is all right to say, for simplicity, that `myList` is an array, instead of stating, at greater length, that `myList` is a variable that contains a reference to an array of ten double elements.

array length

default values

0 based

indexed variable

7.2.3 Array Size and Default Values

When space for an array is allocated, the array size must be given, specifying the number of elements that can be stored in it. The size of an array cannot be changed after the array is created. Size can be obtained using `arrayRefVar.length`. For example, `myList.length` is **10**.

When an array is created, its elements are assigned the default value of **0** for the numeric primitive data types, **\u0000** for `char` types, and `false` for `boolean` types.

7.2.4 Accessing Array Elements

The array elements are accessed through the index. Array indices are **0** based; that is, they range from **0** to `arrayRefVar.length-1`. In the example in Figure 7.1, `myList` holds ten `double` values, and the indices are from **0** to **9**.

Each element in the array is represented using the following syntax, known as an *indexed variable*:

```
arrayRefVar[index];
```

For example, `myList[9]` represents the last element in the array `myList`.

**Caution**

Some programming languages use parentheses to reference an array element, as in `myList(9)`, but Java uses brackets, as in `myList[9]`.

An indexed variable can be used in the same way as a regular variable. For example, the following code adds the values in `myList[0]` and `myList[1]` to `myList[2]`.

```
myList[2] = myList[0] + myList[1];
```

The following loop assigns **0** to `myList[0]`, **1** to `myList[1]`, . . . , and **9** to `myList[9]`:

```
for (int i = 0; i < myList.length; i++) {
    myList[i] = i;
}
```

7.2.5 Array Initializers

array initializer

Java has a shorthand notation, known as the *array initializer*, which combines the declaration, creation, and initialization of an array in one statement using the following syntax:

```
elementType[] arrayRefVar = {value0, value1, ..., valuek};
```

For example, the statement

```
double[] myList = {1.9, 2.9, 3.4, 3.5};
```

declares, creates, and initializes the array `myList` with four elements, which is equivalent to the following statements:

```
double[] myList = new double[4];
myList[0] = 1.9;
myList[1] = 2.9;
```

```
myList[2] = 3.4;
myList[3] = 3.5;
```



Caution

The `new` operator is not used in the array-initializer syntax. Using an array initializer, you have to declare, create, and initialize the array all in one statement. Splitting it would cause a syntax error. Thus, the next statement is wrong:

```
double[] myList;
myList = {1.9, 2.9, 3.4, 3.5};
```

7.2.6 Processing Arrays

When processing array elements, you will often use a `for` loop—for two reasons:

- All of the elements in an array are of the same type. They are evenly processed in the same fashion repeatedly using a loop.
- Since the size of the array is known, it is natural to use a `for` loop.

Assume the array is created as follows:

```
double[] myList = new double[10];
```

The following are some examples of processing arrays.

1. *Initializing arrays with input values:* The following loop initializes the array `myList` with user input values.

```
java.util.Scanner input = new java.util.Scanner(System.in);
System.out.print("Enter " + myList.length + " values: ");
for (int i = 0; i < myList.length; i++)
    myList[i] = input.nextDouble();
```

2. *Initializing arrays with random values:* The following loop initializes the array `myList` with random values between `0.0` and `100.0`, but less than `100.0`.

```
for (int i = 0; i < myList.length; i++) {
    myList[i] = Math.random() * 100;
}
```

3. *Displaying arrays:* To print an array, you have to print each element in the array using a loop like the following:

```
for (int i = 0; i < myList.length; i++) {
    System.out.print(myList[i] + " ");
```



Tip

For an array of the `char[]` type, it can be printed using one print statement. For example, the following code displays `Dallas`:

```
char[] city = {'D', 'a', 'l', 'l', 'a', 's'};
System.out.println(city);
```

print character array

4. *Summing all elements:* Use a variable named `total` to store the sum. Initially `total` is `0`. Add each element in the array to `total` using a loop like this:

```
double total = 0;
for (int i = 0; i < myList.length; i++) {
    total += myList[i];
}
```

5. *Finding the largest element:* Use a variable named `max` to store the largest element. Initially `max` is `myList[0]`. To find the largest element in the array `myList`, compare each element with `max`, and update `max` if the element is greater than `max`.

```
double max = myList[0];
for (int i = 1; i < myList.length; i++) {
    if (myList[i] > max) max = myList[i];
}
```

6. *Finding the smallest index of the largest element:* Often you need to locate the largest element in an array. If an array has multiple elements with the same largest value, find the smallest index of such an element. Suppose the array `myList` is `{1, 5, 3, 4, 5, 5}`. The largest element is `5` and the smallest index for `5` is `1`. Use a variable named `max` to store the largest element and a variable named `indexOfMax` to denote the index of the largest element. Initially `max` is `myList[0]`, and `indexOfMax` is `0`. Compare each element in `myList` with `max`, and update `max` and `indexOfMax` if the element is greater than `max`.

```
double max = myList[0];
int indexOfMax = 0;
for (int i = 1; i < myList.length; i++) {
    if (myList[i] > max) {
        max = myList[i];
        indexOfMax = i;
    }
}
```

Random shuffling



VideoNote

Random shuffling

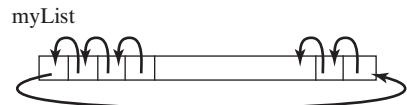
7. *Random shuffling:* In many applications, you need to randomly reorder the elements in an array. This is called *shuffling*. To accomplish this, for each element `myList[i]`, randomly generate an index `j` and swap `myList[i]` with `myList[j]`, as follows:

```
for (int i = myList.length - 1; i > 0; i--) {
    // Generate an index j randomly with 0 <= j <= i
    int j = (int)(Math.random() * (i + 1));
    // Swap myList[i] with myList[j]
    double temp = myList[i];
    myList[i] = myList[j];
    myList[j] = temp;
}
```

The diagram shows an array `myList` with several boxes representing elements. One box is labeled `[i]`. Another box is labeled `A random index [j]`. Arrows point from the `[i]` box to the `[j]` box, and from the `[j]` box back to the `[i]` box, indicating they are swapped.

8. *Shifting elements:* Sometimes you need to shift the elements left or right. Here is an example of shifting the elements one position to the left and filling the last element with the first element:

```
double temp = myList[0]; // Retain the first element
// Shift elements left
for (int i = 1; i < myList.length; i++) {
    myList[i - 1] = myList[i];
}
// Move the first element to fill in the last position
myList[myList.length - 1] = temp;
```



9. *Simplifying coding:* Arrays can be used to greatly simplify coding for certain tasks. For example, suppose you wish to obtain the English name of a given month. If the month names are stored in an array, the month name for a given month can be

accessed simply via the index. The following code prompts the user to enter a month number and displays its month name:

```
String[] months = {"January", "February", ..., "December"};
System.out.print("Enter a month number (1 to 12): ");
int monthNumber = input.nextInt();
System.out.println("The month is " + months[monthNumber - 1]);
```

If you didn't use the `months` array, you would have to determine the month name using a lengthy multi-way `if-else` statement as follows:

```
if (monthNumber == 1)
    System.out.println("The month is January");
else if (monthNumber == 2)
    System.out.println("The month is February");
...
else
    System.out.println("The month is December");
```

7.2.7 Foreach Loops

Java supports a convenient `for` loop, known as a *foreach loop*, which enables you to traverse the array sequentially without using an index variable. For example, the following code displays all the elements in the array `myList`:

```
for (double e: myList) {
    System.out.println(e);
}
```

You can read the code as “for each element `e` in `myList`, do the following.” Note that the variable, `e`, must be declared as the same type as the elements in `myList`.

In general, the syntax for a foreach loop is

```
for (elementType element: arrayRefVar) {
    // Process the element
}
```

You still have to use an index variable if you wish to traverse the array in a different order or change the elements in the array.



Caution

Accessing an array out of bounds is a common programming error that throws a runtime `ArrayIndexOutOfBoundsException`. To avoid it, make sure that you do not use an index beyond `arrayRefVar.length - 1`.

ArrayIndexOutOfBoundsException

Programmers often mistakenly reference the first element in an array with index `1`, but it should be `0`. This is called the *off-by-one error*. Another common off-by-one error in a loop is using `<=` where `<` should be used. For example, the following loop is wrong.

off-by-one error

```
for (int i = 0; i <= list.length; i++)
    System.out.print(list[i] + " ");
```

The `<=` should be replaced by `<`.

- 7.1** How do you declare an array reference variable and how do you create an array?
- 7.2** When is the memory allocated for an array?



7.3 What is the output of the following code?

```
int x = 30;
int[] numbers = new int[x];
x = 60;
System.out.println("x is " + x);
System.out.println("The size of numbers is " + numbers.length);
```

7.4 Indicate **true** or **false** for the following statements:

- Every element in an array has the same type.
- The array size is fixed after an array reference variable is declared.
- The array size is fixed after it is created.
- The elements in an array must be a primitive data type.

7.5 Which of the following statements are valid?

```
int i = new int(30);
double d[] = new double[30];
char[] r = new char(1..30);
int i[] = (3, 4, 3, 2);
float f[] = {2.3, 4.5, 6.6};
char[] c = new char();
```

7.6 How do you access elements in an array?

7.7 What is the array index type? What is the lowest index? What is the representation of the third element in an array named **a**?

7.8 Write statements to do the following:

- a. Create an array to hold **10** double values.
- b. Assign the value **5.5** to the last element in the array.
- c. Display the sum of the first two elements.
- d. Write a loop that computes the sum of all elements in the array.
- e. Write a loop that finds the minimum element in the array.
- f. Randomly generate an index and display the element of this index in the array.
- g. Use an array initializer to create another array with the initial values **3.5, 5.5, 4.52**, and **5.6**.

7.9 What happens when your program attempts to access an array element with an invalid index?

7.10 Identify and fix the errors in the following code:

```
1 public class Test {
2     public static void main(String[] args) {
3         double[100] r;
4
5         for (int i = 0; i < r.length(); i++) {
6             r(i) = Math.random * 100;
7         }
8     }
}
```

7.11 What is the output of the following code?

```
1 public class Test {
2     public static void main(String[] args) {
3         int list[] = {1, 2, 3, 4, 5, 6};
```

```

4   for (int i = 1; i < list.length; i++)
5     list[i] = list[i - 1];
6
7   for (int i = 0; i < list.length; i++)
8     System.out.print(list[i] + " ");
9 }
10 }
```

7.3 Case Study: Analyzing Numbers

The problem is to write a program that finds the number of items above the average of all items.



Now you can write a program using arrays to solve the problem proposed at the beginning of this chapter. The problem is to read 100 numbers, get the average of these numbers, and find the number of the items greater than the average. To be flexible for handling any number of input, we will let the user enter the number of input, rather than fixing it to 100. Listing 7.1 gives a solution.

LISTING 7.1 AnalyzeNumbers.java

```

1 public class AnalyzeNumbers {
2   public static void main(String[] args) {
3     java.util.Scanner input = new java.util.Scanner(System.in);
4     System.out.print("Enter the number of items: ");
5     int n = input.nextInt();
6     double [] numbers = new double[n];
7     double sum = 0;
8
9     System.out.print("Enter the numbers: ");
10    for (int i = 0; i < n; i++) {
11      numbers[i] = input.nextDouble();
12      sum += numbers[i];
13    }
14
15    double average = sum / n;
16
17    int count = 0; // The number of elements above average
18    for (int i = 0; i < n; i++)
19      if (numbers[i] > average)
20        count++;
21
22    System.out.println("Average is " + average);
23    System.out.println("Number of elements above the average is "
24      + count);
25  }
26 }
```

numbers[0]:	[]
numbers[1]:	[]
numbers[2]:	[]
numbers[i]:	[] . . . []
numbers[n - 3]:	[]
numbers[n - 2]:	[]
numbers[n - 1]:	[]

. create array
.
.
get average
above average?

store number in array

Enter the number of items: 10

Enter the numbers: 3.4 5 6 1 6.5 7.8 3.5 8.5 6.3 9.5

Average is 5.75

Number of elements above the average is 6



The program prompts the user to enter the array size (line 5) and creates an array with the specified size (line 6). The program reads the input, stores numbers into the array (line 11), adds each number to **sum** in line 11, and obtains the average (line 15). It then compares

each number in the array with the average to count the number of values above the average (lines 17–20).

7.4 Case Study: Deck of Cards



The problem is to create a program that will randomly select four cards from a deck of cards.

Say you want to write a program that will pick four cards at random from a deck of 52 cards. All the cards can be represented using an array named **deck**, filled with initial values 0 to 51, as follows:



Deck of cards

```
int[] deck = new int[52];  
  
// Initialize cards  
for (int i = 0; i < deck.length; i++)  
    deck[i] = i;
```

Card numbers 0 to 12, 13 to 25, 26 to 38, and 39 to 51 represent 13 Spades, 13 Hearts, 13 Diamonds, and 13 Clubs, respectively, as shown in Figure 7.2. **cardNumber / 13** determines the suit of the card and **cardNumber % 13** determines the rank of the card, as shown in Figure 7.3. After shuffling the array **deck**, pick the first four cards from **deck**. The program displays the cards from these four card numbers.

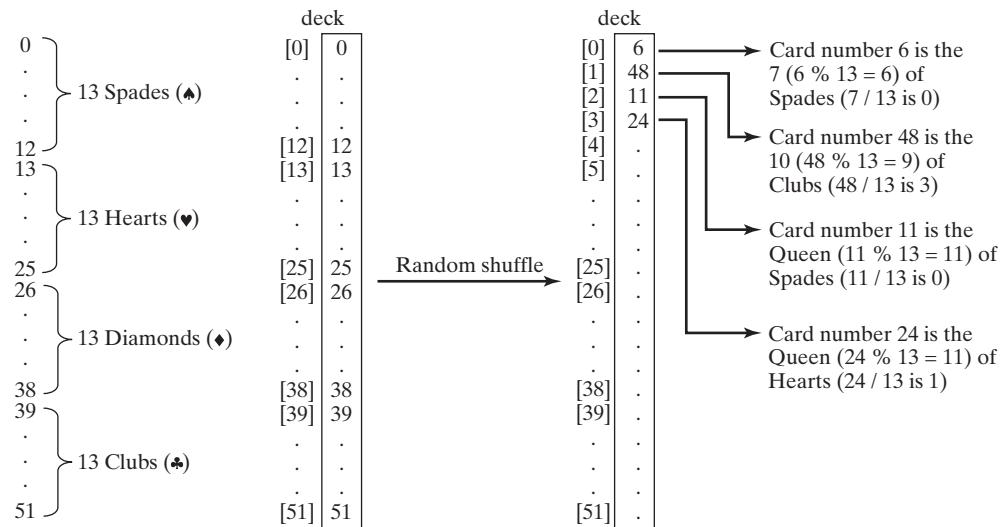


FIGURE 7.2 52 cards are stored in an array named **deck**.

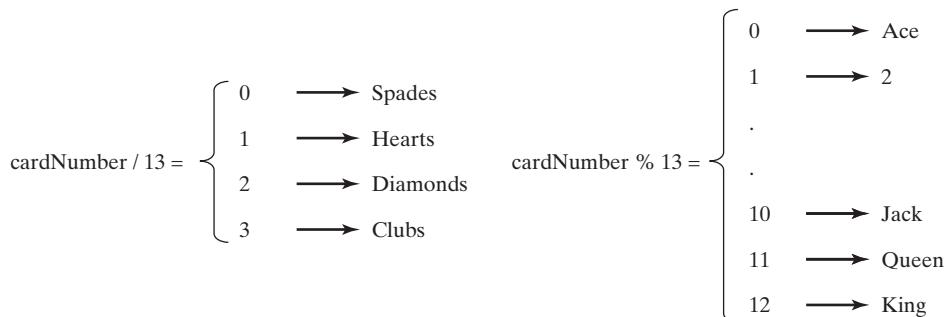


FIGURE 7.3 **CardNumber** identifies a card's suit and rank number.

Listing 7.2 gives the solution to the problem.

LISTING 7.2 DeckOfCards.java

```

1  public class DeckOfCards {
2      public static void main(String[] args) {
3          int[] deck = new int[52];
4          String[] suits = {"Spades", "Hearts", "Diamonds", "Clubs"};
5          String[] ranks = {"Ace", "2", "3", "4", "5", "6", "7", "8", "9",
6              "10", "Jack", "Queen", "King"};
7
8          // Initialize the cards
9          for (int i = 0; i < deck.length; i++)
10             deck[i] = i;
11
12         // Shuffle the cards
13         for (int i = 0; i < deck.length; i++) {
14             // Generate an index randomly
15             int index = (int)(Math.random() * deck.length);
16             int temp = deck[i];
17             deck[i] = deck[index];
18             deck[index] = temp;
19         }
20
21         // Display the first four cards
22         for (int i = 0; i < 4; i++) {
23             String suit = suits[deck[i] / 13];
24             String rank = ranks[deck[i] % 13];
25             System.out.println("Card number " + deck[i] + ": "
26                 + rank + " of " + suit);
27         }
28     }
29 }
```

```

Card number 6: 7 of Spades
Card number 48: 10 of Clubs
Card number 11: Queen of Spades
Card number 24: Queen of Hearts
```



The program creates an array **suits** for four suits (line 4) and an array **ranks** for 13 cards in a suit (lines 5–6). Each element in these arrays is a string.

The program initializes **deck** with values **0** to **51** in lines 9–10. The **deck** value **0** represents the card Ace of Spades, **1** represents the card 2 of Spades, **13** represents the card Ace of Hearts, and **14** represents the card 2 of Hearts.

Lines 13–19 randomly shuffle the deck. After a deck is shuffled, **deck[i]** contains an arbitrary value. **deck[i] / 13** is **0**, **1**, **2**, or **3**, which determines the suit (line 23). **deck[i] % 13** is a value between **0** and **12**, which determines the rank (line 24). If the **suits** array is not defined, you would have to determine the suit using a lengthy multi-way **if-else** statement as follows:

```

if (deck[i] / 13 == 0)
    System.out.print("suit is Spades");
else if (deck[i] / 13 == 1)
    System.out.print("suit is Hearts");
else if (deck[i] / 13 == 2)
    System.out.print("suit is Diamonds");
else
    System.out.print("suit is Clubs");
```

With `suits = {"Spades", "Hearts", "Diamonds", "Clubs"}` created in an array, `suits[deck / 13]` gives the suit for the `deck`. Using arrays greatly simplifies the solution for this program.



7.12 Will the program pick four random cards if you replace lines 22–27 in Listing 7.2, DeckOfCards.java with the following code?

```
for (int i = 0; i < 4; i++) {
    int cardNumber = (int)(Math.random() * deck.length);
    String suit = suits[cardNumber / 13];
    String rank = ranks[cardNumber % 13];
    System.out.println("Card number " + cardNumber + ": "
        + rank + " of " + suit);
}
```



7.5 Copying Arrays

To copy the contents of one array into another, you have to copy the array's individual elements into the other array.

Often, in a program, you need to duplicate an array or a part of an array. In such cases you could attempt to use the assignment statement (`=`), as follows:

```
list2 = list1;
```

copy reference

garbage collection

However, this statement does not copy the contents of the array referenced by `list1` to `list2`, but instead merely copies the reference value from `list1` to `list2`. After this statement, `list1` and `list2` reference the same array, as shown in Figure 7.4. The array previously referenced by `list2` is no longer referenced; it becomes garbage, which will be automatically collected by the Java Virtual Machine (this process is called *garbage collection*).

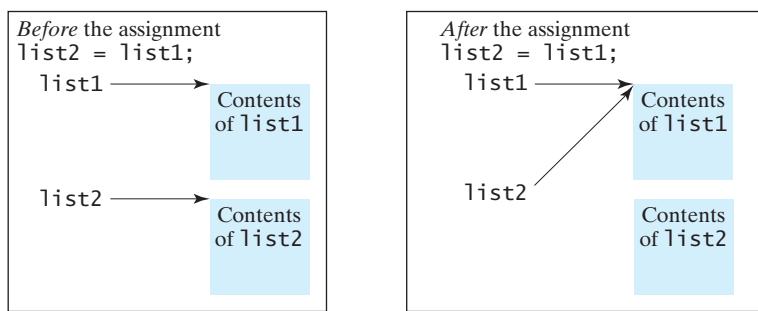


FIGURE 7.4 Before the assignment statement, `list1` and `list2` point to separate memory locations. After the assignment, the reference of the `list1` array is passed to `list2`.

In Java, you can use assignment statements to copy primitive data type variables, but not arrays. Assigning one array variable to another array variable actually copies one reference to another and makes both variables point to the same memory location.

There are three ways to copy arrays:

- Use a loop to copy individual elements one by one.
- Use the static `arraycopy` method in the `System` class.
- Use the `clone` method to copy arrays; this will be introduced in Chapter 13, Abstract Classes and Interfaces.

You can write a loop to copy every element from the source array to the corresponding element in the target array. The following code, for instance, copies `sourceArray` to `targetArray` using a `for` loop.

```
int[] sourceArray = {2, 3, 1, 5, 10};
int[] targetArray = new int[sourceArray.length];
for (int i = 0; i < sourceArray.length; i++) {
    targetArray[i] = sourceArray[i];
}
```

Another approach is to use the `arraycopy` method in the `java.lang.System` class to copy arrays instead of using a loop. The syntax for `arraycopy` is:

```
arraycopy(sourceArray, srcPos, targetArray, tarPos, length);
```

The parameters `srcPos` and `tarPos` indicate the starting positions in `sourceArray` and `targetArray`, respectively. The number of elements copied from `sourceArray` to `targetArray` is indicated by `length`. For example, you can rewrite the loop using the following statement:

```
System.arraycopy(sourceArray, 0, targetArray, 0, sourceArray.length);
```

The `arraycopy` method does not allocate memory space for the target array. The target array must have already been created with its memory space allocated. After the copying takes place, `targetArray` and `sourceArray` have the same content but independent memory locations.



Note

The `arraycopy` method violates the Java naming convention. By convention, this method should be named `arrayCopy` (i.e., with an uppercase C).

- 7.13** Use the `arraycopy` method to copy the following array to a target array `t`:

```
int[] source = {3, 4, 5};
```



- 7.14** Once an array is created, its size cannot be changed. Does the following code resize the array?

```
int[] myList;
myList = new int[10];
// Sometime later you want to assign a new array to myList
myList = new int[20];
```

7.6 Passing Arrays to Methods

When passing an array to a method, the reference of the array is passed to the method.

Just as you can pass primitive type values to methods, you can also pass arrays to methods. For example, the following method displays the elements in an `int` array:

```
public static void printArray(int[] array) {
    for (int i = 0; i < array.length; i++) {
        System.out.print(array[i] + " ");
    }
}
```



You can invoke it by passing an array. For example, the following statement invokes the `printArray` method to display 3, 1, 2, 6, 4, and 2.

```
printArray(new int[]{3, 1, 2, 6, 4, 2});
```

**Note**

The preceding statement creates an array using the following syntax:

```
new elementType[] {value0, value1, ..., valuek};
```

anonymous array

There is no explicit reference variable for the array. Such array is called an *anonymous array*.

pass-by-value

Java uses *pass-by-value* to pass arguments to a method. There are important differences between passing the values of variables of primitive data types and passing arrays.

pass-by-sharing

- For an argument of a primitive type, the argument's value is passed.
- For an argument of an array type, the value of the argument is a reference to an array; this reference value is passed to the method. Semantically, it can be best described as *pass-by-sharing*, that is, the array in the method is the same as the array being passed. Thus, if you change the array in the method, you will see the change outside the method.

Take the following code, for example:

```
public class Test {
    public static void main(String[] args) {
        int x = 1; // x represents an int value
        int[] y = new int[10]; // y represents an array of int values

        m(x, y); // Invoke m with arguments x and y

        System.out.println("x is " + x);
        System.out.println("y[0] is " + y[0]);
    }

    public static void m(int number, int[] numbers) {
        number = 1001; // Assign a new value to number
        numbers[0] = 5555; // Assign a new value to numbers[0]
    }
}
```



```
x is 1
y[0] is 5555
```

You may wonder why after `m` is invoked, `x` remains `1`, but `y[0]` become `5555`. This is because `y` and `numbers`, although they are independent variables, reference the same array, as illustrated in Figure 7.5. When `m(x, y)` is invoked, the values of `x` and `y` are passed to `number` and `numbers`. Since `y` contains the reference value to the array, `numbers` now contains the same reference value to the same array.

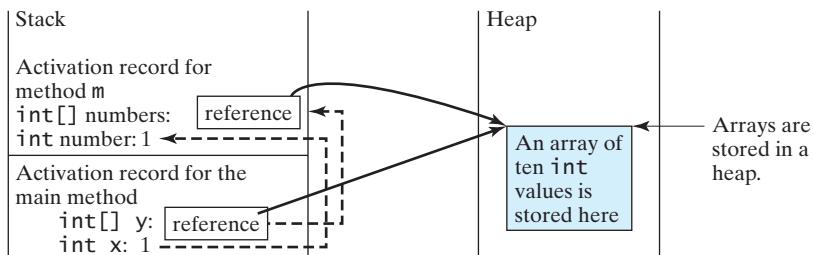


FIGURE 7.5 The primitive type value in `x` is passed to `number`, and the reference value in `y` is passed to `numbers`.

**Note**

Arrays are objects in Java (objects are introduced in Chapter 9). The JVM stores the objects in an area of memory called the *heap*, which is used for dynamic memory allocation.

heap

Listing 7.3 gives another program that shows the difference between passing a primitive data type value and an array reference variable to a method.

The program contains two methods for swapping elements in an array. The first method, named `swap`, fails to swap two `int` arguments. The second method, named `swapFirstTwoInArray`, successfully swaps the first two elements in the array argument.

LISTING 7.3 TestPassArray.java

```

1  public class TestPassArray {
2      /** Main method */
3      public static void main(String[] args) {
4          int[] a = {1, 2};
5
6          // Swap elements using the swap method
7          System.out.println("Before invoking swap");
8          System.out.println("array is {" + a[0] + ", " + a[1] + "}");
9          swap(a[0], a[1]);
10         System.out.println("After invoking swap");
11         System.out.println("array is {" + a[0] + ", " + a[1] + "}");
12
13         // Swap elements using the swapFirstTwoInArray method
14         System.out.println("Before invoking swapFirstTwoInArray");
15         System.out.println("array is {" + a[0] + ", " + a[1] + "}");
16         swapFirstTwoInArray(a);
17         System.out.println("After invoking swapFirstTwoInArray");
18         System.out.println("array is {" + a[0] + ", " + a[1] + "}");
19     }
20
21     /** Swap two variables */
22     public static void swap(int n1, int n2) {
23         int temp = n1;
24         n1 = n2;
25         n2 = temp;
26     }
27
28     /** Swap the first two elements in the array */
29     public static void swapFirstTwoInArray(int[] array) {
30         int temp = array[0];
31         array[0] = array[1];
32         array[1] = temp;
33     }
34 }
```

false swap

swap array elements

```

Before invoking swap
array is {1, 2}
After invoking swap
array is {1, 2}
Before invoking swapFirstTwoInArray
array is {1, 2}
After invoking swapFirstTwoInArray
array is {2, 1}
```



As shown in Figure 7.6, the two elements are not swapped using the `swap` method. However, they are swapped using the `swapFirstTwoInArray` method. Since the parameters in the `swap` method are primitive type, the values of `a[0]` and `a[1]` are passed to `n1` and `n2` inside the method when invoking `swap(a[0], a[1])`. The memory locations for `n1` and `n2` are independent of the ones for `a[0]` and `a[1]`. The contents of the array are not affected by this call.

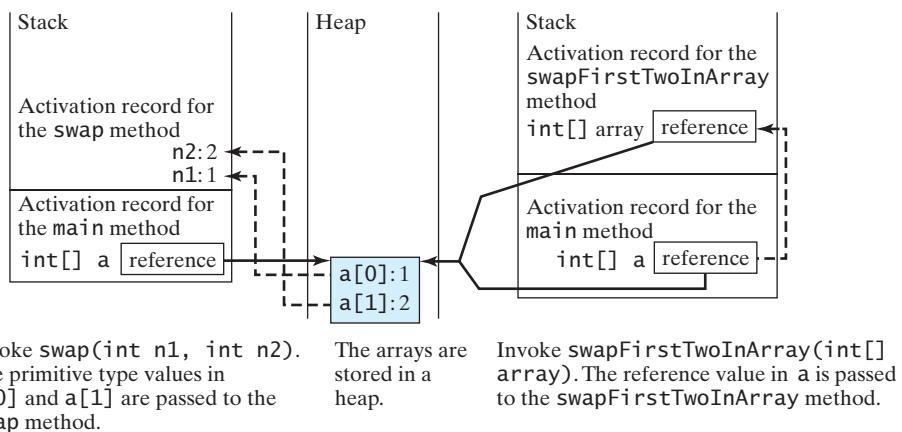


FIGURE 7.6 When passing an array to a method, the reference of the array is passed to the method.

The parameter in the `swapFirstTwoInArray` method is an array. As shown in Figure 7.6, the reference of the array is passed to the method. Thus the variables `a` (outside the method) and `array` (inside the method) both refer to the same array in the same memory location. Therefore, swapping `array[0]` with `array[1]` inside the method `swapFirstTwoInArray` is the same as swapping `a[0]` with `a[1]` outside of the method.

7.7 Returning an Array from a Method



When a method returns an array, the reference of the array is returned.

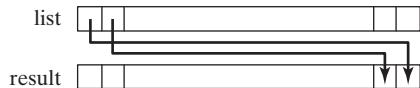
You can pass arrays when invoking a method. A method may also return an array. For example, the following method returns an array that is the reversal of another array.

create array

```

1 public static int[] reverse(int[] list) {
2     int[] result = new int[list.length];
3
4     for (int i = 0, j = result.length - 1;
5          i < list.length; i++, j--) {
6         result[j] = list[i];
7     }
8
9     return result;
10 }
```

return array



Line 2 creates a new array `result`. Lines 4–7 copy elements from array `list` to array `result`. Line 9 returns the array. For example, the following statement returns a new array `list2` with elements `6, 5, 4, 3, 2, 1`.

```

int[] list1 = {1, 2, 3, 4, 5, 6};
int[] list2 = reverse(list1);
```

- 7.15** Suppose the following code is written to reverse the contents in an array, explain why it is wrong. How do you fix it?



```
int[] list = {1, 2, 3, 5, 4};

for (int i = 0, j = list.length - 1; i < list.length; i++, j--) {
    // Swap list[i] with list[j]
    int temp = list[i];
    list[i] = list[j];
    list[j] = temp;
}
```

7.8 Case Study: Counting the Occurrences of Each Letter

This section presents a program to count the occurrences of each letter in an array of characters.



The program given in Listing 7.4 does the following:

- Generates 100 lowercase letters randomly and assigns them to an array of characters, as shown in Figure 7.7a. You can obtain a random letter by using the `getRandomLower-CaseLetter()` method in the `RandomCharacter` class in Listing 6.10.
- Count the occurrences of each letter in the array. To do so, create an array, say `counts`, of 26 `int` values, each of which counts the occurrences of a letter, as shown in Figure 7.7b. That is, `counts[0]` counts the number of `a`'s, `counts[1]` counts the number of `b`'s, and so on.

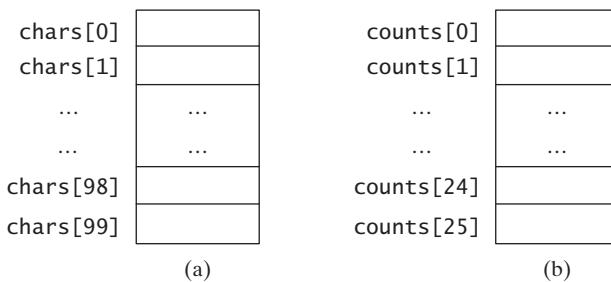


FIGURE 7.7 The `chars` array stores 100 characters, and the `counts` array stores 26 counts, each of which counts the occurrences of a letter.

LISTING 7.4 CountLettersInArray.java

```
1 public class CountLettersInArray {
2     /** Main method */
3     public static void main(String[] args) {
4         // Declare and create an array
5         char[] chars = createArray();           create array
6
7         // Display the array
8         System.out.println("The lowercase letters are:");
9         displayArray(chars);                  pass array
10    }
```

```

return array          11     // Count the occurrences of each letter
12     int[] counts = countLetters(chars);
13
14     // Display counts
15     System.out.println();
16     System.out.println("The occurrences of each letter are:");
17     displayCounts(counts);
18 }
19
20 /** Create an array of characters */
21 public static char[] createArray() {
22     // Declare an array of characters and create it
23     char[] chars = new char[100];
24
25     // Create lowercase letters randomly and assign
26     // them to the array
27     for (int i = 0; i < chars.length; i++)
28         chars[i] = RandomCharacter.getRandomLowerCaseLetter();
29
30     // Return the array
31     return chars;
32 }
33
34 /** Display the array of characters */
35 public static void displayArray(char[] chars) {
36     // Display the characters in the array 20 on each line
37     for (int i = 0; i < chars.length; i++) {
38         if ((i + 1) % 20 == 0)
39             System.out.println(chars[i]);
40         else
41             System.out.print(chars[i] + " ");
42     }
43 }
44
45 /** Count the occurrences of each letter */
46 public static int[] countLetters(char[] chars) {
47     // Declare and create an array of 26 int
48     int[] counts = new int[26];
49
50     // For each lowercase letter in the array, count it
51     for (int i = 0; i < chars.length; i++)
52         counts[chars[i] - 'a']++;
53
54     return counts;
55 }
56
57 /** Display counts */
58 public static void displayCounts(int[] counts) {
59     for (int i = 0; i < counts.length; i++) {
60         if ((i + 1) % 10 == 0)
61             System.out.println(counts[i] + " " + (char)(i + 'a'));
62         else
63             System.out.print(counts[i] + " " + (char)(i + 'a') + " ");
64     }
65 }
66 }
```

increase count



```
The lowercase letters are:  
e y l s r i b k j v j h a b z n w b t v  
s c c k r d w a m p w v u n q a m p l o  
a z g d e g f i n d x m z o u l o z j v  
h w i w n t g x w c d o t x h y v z y z  
q e a m f w p g u q t r e n n w f c r f
```

```
The occurrences of each letter are:  
5 a 3 b 4 c 4 d 4 e 4 f 4 g 3 h 3 i 3 j  
2 k 3 l 4 m 6 n 4 o 3 p 3 q 4 r 2 s 4 t  
3 u 5 v 8 w 3 x 3 y 6 z
```

The `createArray` method (lines 21–32) generates an array of **100** random lowercase letters. Line 5 invokes the method and assigns the array to `chars`. What would be wrong if you rewrote the code as follows?

```
char[] chars = new char[100];  
chars = createArray();
```

You would be creating two arrays. The first line would create an array by using `new char[100]`. The second line would create an array by invoking `createArray()` and assign the reference of the array to `chars`. The array created in the first line would be garbage because it is no longer referenced, and as mentioned earlier Java automatically collects garbage behind the scenes. Your program would compile and run correctly, but it would create an array unnecessarily.

Invoking `getRandomLowerCaseLetter()` (line 28) returns a random lowercase letter. This method is defined in the `RandomCharacter` class in Listing 6.10.

The `countLetters` method (lines 46–55) returns an array of **26 int** values, each of which stores the number of occurrences of a letter. The method processes each letter in the array and increases its count by one. A brute-force approach to count the occurrences of each letter might be as follows:

```
for (int i = 0; i < chars.length; i++)  
    if (chars[i] == 'a')  
        counts[0]++;
    else if (chars[i] == 'b')  
        counts[1]++;
    ...
```

But a better solution is given in lines 51–52.

```
for (int i = 0; i < chars.length; i++)  
    counts[chars[i] - 'a']++;
```

If the letter (`chars[i]`) is `a`, the corresponding count is `counts['a' - 'a']` (i.e., `counts[0]`). If the letter is `b`, the corresponding count is `counts['b' - 'a']` (i.e., `counts[1]`), since the Unicode of `b` is one more than that of `a`. If the letter is `z`, the corresponding count is `counts['z' - 'a']` (i.e., `counts[25]`), since the Unicode of `z` is **25** more than that of `a`.

Figure 7.8 shows the call stack and heap *during* and *after* executing `createArray`. See Checkpoint Question 7.18 to show the call stack and heap for other methods in the program.

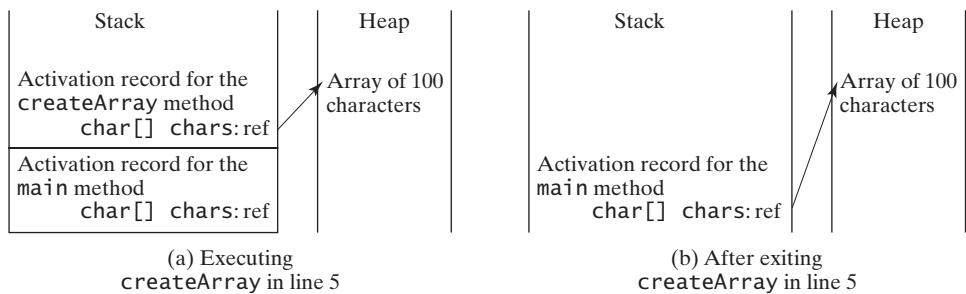


FIGURE 7.8 (a) An array of 100 characters is created when executing `createArray`.
(b) This array is returned and assigned to the variable `chars` in the `main` method.



7.16 True or false? When an array is passed to a method, a new array is created and passed to the method.

7.17 Show the output of the following two programs:

```
public class Test {
    public static void main(String[] args) {
        int number = 0;
        int[] numbers = new int[1];

        m(number, numbers);

        System.out.println("number is " + number
            + " and numbers[0] is " + numbers[0]);
    }

    public static void m(int x, int[] y) {
        x = 3;
        y[0] = 3;
    }
}
```

(a)

```
public class Test {
    public static void main(String[] args) {
        int[] list = {1, 2, 3, 4, 5};
        reverse(list);
        for (int i = 0; i < list.length; i++)
            System.out.print(list[i] + " ");
    }

    public static void reverse(int[] list) {
        int[] newList = new int[list.length];

        for (int i = 0; i < list.length; i++)
            newList[i] = list[list.length - 1 - i];

        list = newList;
    }
}
```

(b)

7.18 Where are the arrays stored during execution? Show the contents of the stack and heap during and after executing `displayArray`, `countLetters`, `displayCounts` in Listing 7.4.

7.9 Variable-Length Argument Lists



A variable number of arguments of the same type can be passed to a method and treated as an array.

You can pass a variable number of arguments of the same type to a method. The parameter in the method is declared as follows:

`typeName... parameterName`

In the method declaration, you specify the type followed by an ellipsis (`...`). Only one variable-length parameter may be specified in a method, and this parameter must be the last parameter. Any regular parameters must precede it.

Java treats a variable-length parameter as an array. You can pass an array or a variable number of arguments to a variable-length parameter. When invoking a method with a variable number of arguments, Java creates an array and passes the arguments to it. Listing 7.5 contains a method that prints the maximum value in a list of an unspecified number of values.

LISTING 7.5 VarArgsDemo.java

```

1  public class VarArgsDemo {
2      public static void main(String[] args) {
3          printMax(34, 3, 3, 2, 56.5);
4          printMax(new double[]{1, 2, 3});
5      }
6
7      public static void printMax(double... numbers) {
8          if (numbers.length == 0) {
9              System.out.println("No argument passed");
10             return;
11         }
12
13         double result = numbers[0];
14
15         for (int i = 1; i < numbers.length; i++)
16             if (numbers[i] > result)
17                 result = numbers[i];
18
19         System.out.println("The max value is " + result);
20     }
21 }
```

pass variable-length arg list
pass an array arg

a variable-length arg
parameter

Line 3 invokes the `printMax` method with a variable-length argument list passed to the array `numbers`. If no arguments are passed, the length of the array is `0` (line 8).

Line 4 invokes the `printMax` method with an array.

7.19 What is wrong in the following method header?

```

public static void print(String... strings, double... numbers)
public static void print(double... numbers, String name)
public static double... print(double d1, double d2)
```



7.20 Can you invoke the `printMax` method in Listing 7.5 using the following statements?

```

printMax(1, 2, 2, 1, 4);
printMax(new double[]{1, 2, 3});
printMax(new int[]{1, 2, 3});
```

7.10 Searching Arrays

If an array is sorted, binary search is more efficient than linear search for finding an element in the array.



Searching is the process of looking for a specific element in an array—for example, discovering whether a certain score is included in a list of scores. Searching is a common task in computer programming. Many algorithms and data structures are devoted to searching. This section discusses two commonly used approaches, *linear search* and *binary search*.

linear search
binary search

7.10.1 The Linear Search Approach

The linear search approach compares the key element `key` sequentially with each element in the array. It continues to do so until the key matches an element in the array or the array is exhausted without a match being found. If a match is made, the linear search returns the index



linear search animation on
Companion Website

of the element in the array that matches the key. If no match is found, the search returns **-1**. The **LinearSearch** method in Listing 7.6 gives the solution.

LISTING 7.6 LinearSearch.java

```

1 public class LinearSearch {
2     /** The method for finding a key in the list */
3     public static int linearSearch(int[] list, int key) {
4         for (int i = 0; i < list.length; i++) {
5             if (key == list[i])
6                 return i;
7         }
8         return -1;
9     }
10 }
```

The diagram shows a horizontal row of boxes representing an array. The first three boxes are labeled [0], [1], and [2] with ellipses after them. Below the row, the word "list" is followed by a sequence of four empty boxes. To the right of the list, the word "key" is followed by the text "Compare key with list[i] for i = 0, 1, ...".

To better understand this method, trace it with the following statements:

```

1 int[] list = {1, 4, 4, 2, 5, -3, 6, 2};
2 int i = linearSearch(list, 4); // Returns 1
3 int j = linearSearch(list, -4); // Returns -1
4 int k = linearSearch(list, -3); // Returns 5
```

The linear search method compares the key with each element in the array. The elements can be in any order. On average, the algorithm will have to examine half of the elements in an array before finding the key, if it exists. Since the execution time of a linear search increases linearly as the number of array elements increases, linear search is inefficient for a large array.

7.10.2 The Binary Search Approach

Binary search is the other common search approach for a list of values. For binary search to work, the elements in the array must already be ordered. Assume that the array is in ascending order. The binary search first compares the key with the element in the middle of the array. Consider the following three cases:

- If the key is less than the middle element, you need to continue to search for the key only in the first half of the array.
- If the key is equal to the middle element, the search ends with a match.
- If the key is greater than the middle element, you need to continue to search for the key only in the second half of the array.

Clearly, the binary search method eliminates at least half of the array after each comparison. Sometimes you eliminate half of the elements, and sometimes you eliminate half plus one. Suppose that the array has n elements. For convenience, let n be a power of 2 . After the first comparison, $n/2$ elements are left for further search; after the second comparison, $(n/2)/2$ elements are left. After the k th comparison, $n/2^k$ elements are left for further search. When $k = \log_2 n$, only one element is left in the array, and you need only one more comparison. Therefore, in the worst case when using the binary search approach, you need $\log_2 n + 1$ comparisons to find an element in the sorted array. In the worst case for a list of 1024 (2^{10}) elements, binary search requires only 11 comparisons, whereas a linear search requires 1023 comparisons in the worst case.

The portion of the array being searched shrinks by half after each comparison. Let **low** and **high** denote, respectively, the first index and last index of the array that is currently being searched. Initially, **low** is **0** and **high** is **list.length-1**. Let **mid** denote the index of the middle element, so **mid** is **(low + high)/2**. Figure 7.9 shows how to find key **11** in the list **{2, 4, 7, 10, 11, 45, 50, 59, 60, 66, 69, 70, 79}** using binary search.



binary search animation on
Companion Website

You now know how the binary search works. The next task is to implement it in Java. Don't rush to give a complete implementation. Implement it incrementally, one step at a time. You may start with the first iteration of the search, as shown in Figure 7.10a. It compares the key with the middle element in the list whose `low` index is `0` and `high` index is `list.length - 1`. If `key < list[mid]`, set the `high` index to `mid - 1`; if `key == list[mid]`, a match is found and return `mid`; if `key > list[mid]`, set the `low` index to `mid + 1`.

Next consider implementing the method to perform the search repeatedly by adding a loop, as shown in Figure 7.10b. The search ends if the key is found, or if the key is not found when `low > high`.

When the key is not found, `low` is the insertion point where a key would be inserted to maintain the order of the list. It is more useful to return the insertion point than `-1`. The method must return a negative value to indicate that the key is not in the list. Can it simply return `-low`? No. If the key is less than `list[0]`, `low` would be `0`. `-0` is `0`. This would indicate that the key matches `list[0]`. A good choice is to let the method return `-low - 1` if the key is not in the list. Returning `-low - 1` indicates not only that the key is not in the list, but also where the key would be inserted.

why not `-1`?

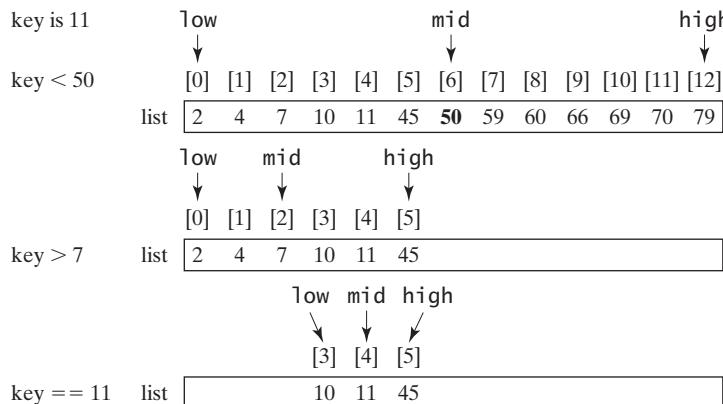


FIGURE 7.9 Binary search eliminates half of the list from further consideration after each comparison.

```
public static int binarySearch(
    int[] list, int key) {
    int low = 0;
    int high = list.length - 1;

    int mid = (low + high) / 2;
    if (key < list[mid])
        high = mid - 1;
    else if (key == list[mid])
        return mid;
    else
        low = mid + 1;

}
```

```
public static int binarySearch(
    int[] list, int key) {
    int low = 0;
    int high = list.length - 1;

    while (high >= low) {
        int mid = (low + high) / 2;
        if (key < list[mid])
            high = mid - 1;
        else if (key == list[mid])
            return mid;
        else
            low = mid + 1;
    }

    return -1; // Not found
}
```

(a) Version 1

(b) Version 2

FIGURE 7.10 Binary search is implemented incrementally.

The complete program is given in Listing 7.7.

LISTING 7.7 BinarySearch.java

```

1  public class BinarySearch {
2      /** Use binary search to find the key in the list */
3      public static int binarySearch(int[] list, int key) {
4          int low = 0;
5          int high = list.length - 1;
6
7          while (high >= low) {
8              int mid = (low + high) / 2;
9              if (key < list[mid])
10                  high = mid - 1;
11              else if (key == list[mid])
12                  return mid;
13              else
14                  low = mid + 1;
15          }
16
17          return -low - 1; // Now high < low, key not found
18      }
19  }

```

first half

second half

The binary search returns the index of the search key if it is contained in the list (line 12). Otherwise, it returns `-low - 1` (line 17).

What would happen if we replaced `(high >= low)` in line 7 with `(high > low)`? The search would miss a possible matching element. Consider a list with just one element. The search would miss the element.

Does the method still work if there are duplicate elements in the list? Yes, as long as the elements are sorted in increasing order. The method returns the index of one of the matching elements if the element is in the list.

To better understand this method, trace it with the following statements and identify `low` and `high` when the method returns.

```

int[] list = {2, 4, 7, 10, 11, 45, 50, 59, 60, 66, 69, 70, 79};
int i = BinarySearch.binarySearch(list, 2); // Returns 0
int j = BinarySearch.binarySearch(list, 11); // Returns 4
int k = BinarySearch.binarySearch(list, 12); // Returns -6
int l = BinarySearch.binarySearch(list, 1); // Returns -1
int m = BinarySearch.binarySearch(list, 3); // Returns -2

```

Here is the table that lists the `low` and `high` values when the method exits and the value returned from invoking the method.

Method	Low	High	Value Returned
<code>binarySearch(list, 2)</code>	0	1	0
<code>binarySearch(list, 11)</code>	3	5	4
<code>binarySearch(list, 12)</code>	5	4	-6
<code>binarySearch(list, 1)</code>	0	-1	-1
<code>binarySearch(list, 3)</code>	1	0	-2



Note

Linear search is useful for finding an element in a small array or an unsorted array, but it is inefficient for large arrays. Binary search is more efficient, but it requires that the array be presorted.

binary search benefits

- 7.21** If `high` is a very large integer such as the maximum `int` value `2147483647`, `(low + high) / 2` may cause overflow. How do you fix it to avoid overflow?
- 7.22** Use Figure 7.9 as an example to show how to apply the binary search approach to a search for key `10` and key `12` in list `{2, 4, 7, 10, 11, 45, 50, 59, 60, 66, 69, 70, 79}`.
- 7.23** If the binary search method returns `-4`, is the key in the list? Where should the key be inserted if you wish to insert the key into the list?



7.11 Sorting Arrays

Sorting, like searching, is a common task in computer programming. Many different algorithms have been developed for sorting. This section introduces an intuitive sorting algorithm: selection sort.



Suppose that you want to sort a list in ascending order. Selection sort finds the smallest number in the list and swaps it with the first element. It then finds the smallest number remaining and swaps it with the second element, and so on, until only a single number remains. Figure 7.11 shows how to sort the list `{2, 9, 5, 4, 8, 1, 6}` using selection sort.



VideoNote

Selection sort
selection sort

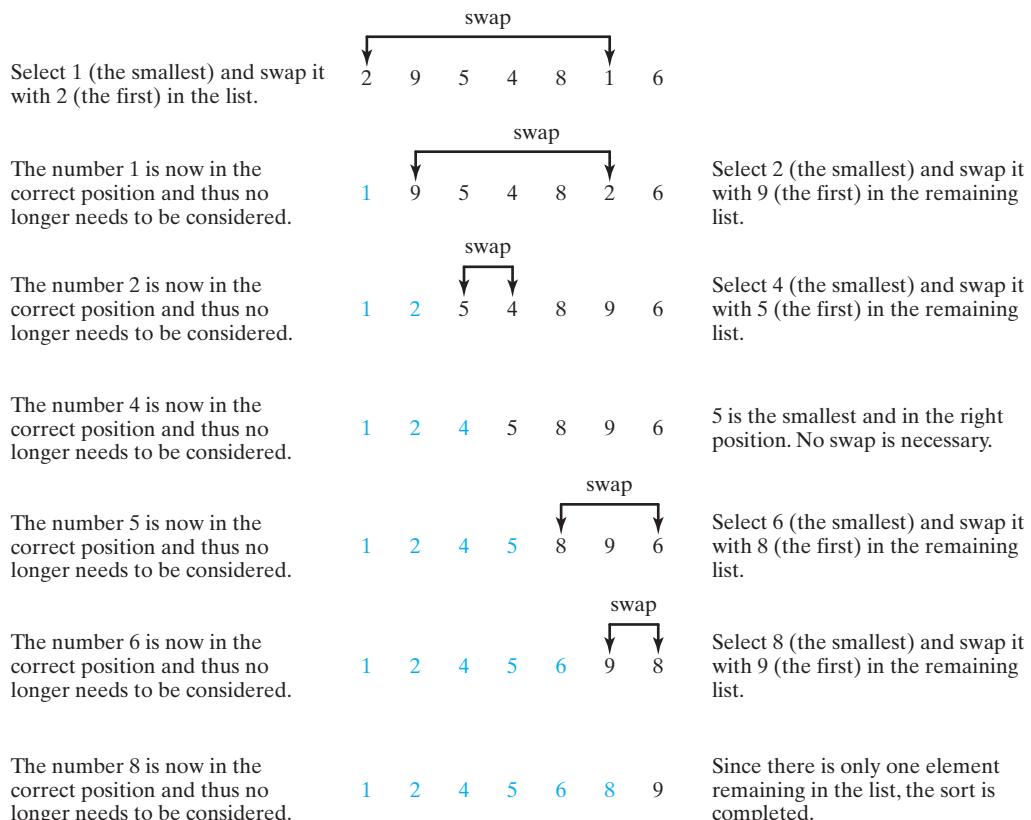


FIGURE 7.11 Selection sort repeatedly selects the smallest number and swaps it with the first number in the list.

You know how the selection-sort approach works. The task now is to implement it in Java. Beginners find it difficult to develop a complete solution on the first attempt. Start by writing the code for the first iteration to find the smallest element in the list and swap it with the first element, and then observe what would be different for the second iteration, the third, and so on. The insight this gives will enable you to write a loop that generalizes all the iterations.



selection sort animation on Companion Website

The solution can be described as follows:

```
for (int i = 0; i < list.length - 1; i++) {
    select the smallest element in list[i..list.length-1];
    swap the smallest with list[i], if necessary;
    // list[i] is in its correct position.
    // The next iteration applies on list[i+1..list.length-1]
}
```

Listing 7.8 implements the solution.

LISTING 7.8 SelectionSort.java

```
1 public class SelectionSort {
2     /** The method for sorting the numbers */
3     public static void selectionSort(double[] list) {
4         for (int i = 0; i < list.length - 1; i++) {
5             // Find the minimum in the list[i..list.length-1]
6             double currentMin = list[i];
7             int currentMinIndex = i;
8
9             for (int j = i + 1; j < list.length; j++) {
10                 if (currentMin > list[j]) {
11                     currentMin = list[j];
12                     currentMinIndex = j;
13                 }
14             }
15
16             // Swap list[i] with list[currentMinIndex] if necessary
17             if (currentMinIndex != i) {
18                 list[currentMinIndex] = list[i];
19                 list[i] = currentMin;
20             }
21         }
22     }
23 }
```

select
swap

The `selectionSort(double[] list)` method sorts any array of `double` elements. The method is implemented with a nested `for` loop. The outer loop (with the loop control variable `i`) (line 4) is iterated in order to find the smallest element in the list, which ranges from `list[i]` to `list[list.length-1]`, and exchange it with `list[i]`.

The variable `i` is initially `0`. After each iteration of the outer loop, `list[i]` is in the right place. Eventually, all the elements are put in the right place; therefore, the whole list is sorted.

To understand this method better, trace it with the following statements:

```
double[] list = {1, 9, 4.5, 6.6, 5.7, -4.5};
SelectionSort.selectionSort(list);
```



7.24 Use Figure 7.11 as an example to show how to apply the selection-sort approach to sort `{3.4, 5, 3, 3.5, 2.2, 1.9, 2}`.

7.25 How do you modify the `selectionSort` method in Listing 7.8 to sort numbers in decreasing order?

7.12 The Arrays Class



The `java.util.Arrays` class contains useful methods for common array operations such as sorting and searching.

The `java.util.Arrays` class contains various static methods for sorting and searching arrays, comparing arrays, filling array elements, and returning a string representation of the array. These methods are overloaded for all primitive types.

You can use the `sort` or `parallelSort` method to sort a whole array or a partial array. For example, the following code sorts an array of numbers and an array of characters.

`sort`
`parallelSort`

```
double[] numbers = {6.0, 4.4, 1.9, 2.9, 3.4, 3.5};
java.util.Arrays.sort(numbers); // Sort the whole array
java.util.Arrays.parallelSort(numbers); // Sort the whole array

char[] chars = {'a', 'A', '4', 'F', 'D', 'P'};
java.util.Arrays.sort(chars, 1, 3); // Sort part of the array
java.util.Arrays.parallelSort(chars, 1, 3); // Sort part of the array
```

Invoking `sort(numbers)` sorts the whole array `numbers`. Invoking `sort(chars, 1, 3)` sorts a partial array from `chars[1]` to `chars[3-1]`. `parallelSort` is more efficient if your computer has multiple processors.

You can use the `binarySearch` method to search for a key in an array. The array must be pre-sorted in increasing order. If the key is not in the array, the method returns `- (insertionIndex + 1)`. For example, the following code searches the keys in an array of integers and an array of characters.

`binarySearch`

```
int[] list = {2, 4, 7, 10, 11, 45, 50, 59, 60, 66, 69, 70, 79};
System.out.println("1. Index is " +
    java.util.Arrays.binarySearch(list, 11));
System.out.println("2. Index is " +
    java.util.Arrays.binarySearch(list, 12));

char[] chars = {'a', 'c', 'g', 'x', 'y', 'z'};
System.out.println("3. Index is " +
    java.util.Arrays.binarySearch(chars, 'a'));
System.out.println("4. Index is " +
    java.util.Arrays.binarySearch(chars, 't'));
```

The output of the preceding code is

1. Index is 4
2. Index is -6
3. Index is 0
4. Index is -4

You can use the `equals` method to check whether two arrays are strictly equal. Two arrays are strictly equal if their corresponding elements are the same. In the following code, `list1` and `list2` are equal, but `list2` and `list3` are not.

`equals`

```
int[] list1 = {2, 4, 7, 10};
int[] list2 = {2, 4, 7, 10};
int[] list3 = {4, 2, 7, 10};
System.out.println(java.util.Arrays.equals(list1, list2)); // true
System.out.println(java.util.Arrays.equals(list2, list3)); // false
```

You can use the `fill` method to fill in all or part of the array. For example, the following code fills `list1` with `5` and fills `8` into elements `list2[1]` through `list2[5-1]`.

`fill`

```
int[] list1 = {2, 4, 7, 10};
int[] list2 = {2, 4, 7, 7, 7, 10};
java.util.Arrays.fill(list1, 5); // Fill 5 to the whole array
java.util.Arrays.fill(list2, 1, 5, 8); // Fill 8 to a partial array
```

toString

You can also use the **toString** method to return a string that represents all elements in the array. This is a quick and simple way to display all elements in the array. For example, the following code

```
int[] list = {2, 4, 7, 10};
System.out.println(Arrays.toString(list));
```

displays **[2, 4, 7, 10]**.



7.26 What types of array can be sorted using the **java.util.Arrays.sort** method? Does this **sort** method create a new array?

7.27 To apply **java.util.Arrays.binarySearch(array, key)**, should the array be sorted in increasing order, in decreasing order, or neither?

7.28 Show the output of the following code:

```
int[] list1 = {2, 4, 7, 10};
java.util.Arrays.fill(list1, 7);
System.out.println(java.util.Arrays.toString(list1));

int[] list2 = {2, 4, 7, 10};
System.out.println(java.util.Arrays.toString(list2));
System.out.print(java.util.Arrays.equals(list1, list2));
```

7.13 Command-Line Arguments



The **main** method can receive string arguments from the command line.

**VideoNote**

Command-line arguments

Perhaps you have already noticed the unusual header for the **main** method, which has the parameter **args** of **String[]** type. It is clear that **args** is an array of strings. The **main** method is just like a regular method with a parameter. You can call a regular method by passing actual parameters. Can you pass arguments to **main**? Yes, of course you can. In the following examples, the **main** method in class **TestMain** is invoked by a method in **A**.

```
public class A {
    public static void main(String[] args) {
        String[] strings = {"New York",
                           "Boston", "Atlanta"};
        TestMain.main(strings);
    }
}
```

```
public class TestMain {
    public static void main(String[] args) {
        for (int i = 0; i < args.length; i++)
            System.out.println(args[i]);
    }
}
```

A **main** method is just a regular method. Furthermore, you can pass arguments from the command line.

7.13.1 Passing Strings to the **main** Method

You can pass strings to a **main** method from the command line when you run the program. The following command line, for example, starts the program **TestMain** with three strings: **arg0**, **arg1**, and **arg2**:

```
java TestMain arg0 arg1 arg2
```

arg0, **arg1**, and **arg2** are strings, but they don't have to appear in double quotes on the command line. The strings are separated by a space. A string that contains a space must be enclosed in double quotes. Consider the following command line:

```
java TestMain "First num" alpha 53
```

It starts the program with three strings: `First num`, `alpha`, and `53`. Since `First num` is a string, it is enclosed in double quotes. Note that `53` is actually treated as a string. You can use `"53"` instead of `53` in the command line.

When the `main` method is invoked, the Java interpreter creates an array to hold the command-line arguments and pass the array reference to `args`. For example, if you invoke a program with `n` arguments, the Java interpreter creates an array like this one:

```
args = new String[n];
```

The Java interpreter then passes `args` to invoke the `main` method.



Note

If you run the program with no strings passed, the array is created with `new String[0]`.

In this case, the array is empty with length `0`. `args` references to this empty array.

Therefore, `args` is not `null`, but `args.length` is `0`.

7.13.2 Case Study: Calculator

Suppose you are to develop a program that performs arithmetic operations on integers. The program receives an expression in one string argument. The expression consists of an integer followed by an operator and another integer. For example, to add two integers, use this command:

```
java Calculator 2 + 3
```

The program will display the following output:

```
2 + 3 = 5
```

Figure 7.12 shows sample runs of the program.

The strings passed to the main program are stored in `args`, which is an array of strings. The first string is stored in `args[0]`, and `args.length` is the number of strings passed.

Here are the steps in the program:

1. Use `args.length` to determine whether the expression has been provided as three arguments in the command line. If not, terminate the program using `System.exit(1)`.
2. Perform a binary arithmetic operation on the operands `args[0]` and `args[2]` using the operator in `args[1]`.



VideoNote

Command-line argument

The screenshot shows a Windows Command Prompt window titled "Administrator: Command Prompt". It displays four separate runs of the "Calculator" program. Each run takes three command-line arguments: the first is an operand, the second is an operator (+, -, *, or /), and the third is another operand. The program outputs the result of the arithmetic operation. Arrows on the left point from the text labels to the corresponding command-line inputs in the screenshot.

Action	Command Line	Result
Add	c:\book>java Calculator 45 + 56	45 + 56 = 101
Subtract	c:\book>java Calculator 45 - 56	45 - 56 = -11
Multiply	c:\book>java Calculator 45 . 56	45 . 56 = 2520
Divide	c:\book>java Calculator 45 / 56	45 / 56 = 0

FIGURE 7.12 The program takes three arguments (`operand1 operator operand2`) from the command line and displays the expression and the result of the arithmetic operation.

The program is shown in Listing 7.9.

LISTING 7.9 Calculator.java

```

1  public class Calculator {
2      /** Main method */
3      public static void main(String[] args) {
4          // Check number of strings passed
5          if (args.length != 3) {
6              System.out.println(
7                  "Usage: java Calculator operand1 operator operand2");
8              System.exit(0);
9          }
10         // The result of the operation
11         int result = 0;
12
13         // Determine the operator
14         switch (args[1].charAt(0)) {
15             case '+': result = Integer.parseInt(args[0]) +
16                         Integer.parseInt(args[2]);
17                         break;
18             case '-': result = Integer.parseInt(args[0]) -
19                         Integer.parseInt(args[2]);
20                         break;
21             case '.': result = Integer.parseInt(args[0]) *
22                         Integer.parseInt(args[2]);
23                         break;
24             case '/': result = Integer.parseInt(args[0]) /
25                         Integer.parseInt(args[2]);
26         }
27
28         // Display result
29         System.out.println(args[0] + ' ' + args[1] + ' ' + args[2]
30                             + " = " + result);
31     }
32 }
33 }
```

check argument

check operator

`Integer.parseInt(args[0])` (line 16) converts a digital string into an integer. The string must consist of digits. If not, the program will terminate abnormally.

We used the `.` symbol for multiplication, not the common `*` symbol. The reason for this is that the `*` symbol refers to all the files in the current directory when it is used on a command line. The following program displays all the files in the current directory when issuing the command `java Test *`:

```

public class Test {
    public static void main(String[] args) {
        for (int i = 0; i < args.length; i++)
            System.out.println(args[i]);
    }
}
```

To circumvent this problem, we will have to use a different symbol for the multiplication operator.



7.29 This book declares the `main` method as

`public static void main(String[] args)`

Can it be replaced by one of the following lines?

`public static void main(String args[])
public static void main(String[] x)`

```
public static void main(String x[])
static void main(String x[])
```

- 7.30** Show the output of the following program when invoked using

1. **java Test I have a dream**
2. **java Test “1 2 3”**
3. **java Test**

```
public class Test {
    public static void main(String[] args) {
        System.out.println("Number of strings is " + args.length);
        for (int i = 0; i < args.length; i++)
            System.out.println(args[i]);
    }
}
```

KEY TERMS

anonymous array	258	index	246
array	246	indexed variable	248
array initializer	248	linear search	265
binary search	265	off-by-one error	251
garbage collection	256	selection sort	269

CHAPTER SUMMARY

1. A variable is declared as an *array* type using the syntax **elementType[] arrayRefVar** or **elementType arrayRefVar[]**. The style **elementType[] arrayRefVar** is preferred, although **elementType arrayRefVar[]** is legal.
2. Unlike declarations for primitive data type variables, the declaration of an array variable does not allocate any space in memory for the array. An array variable is not a primitive data type variable. An array variable contains a reference to an array.
3. You cannot assign elements to an array unless it has already been created. You can create an array by using the **new** operator with the following syntax: **new elementType[arraySize]**.
4. Each element in the array is represented using the syntax **arrayRefVar[index]**. An *index* must be an integer or an integer expression.
5. After an array is created, its size becomes permanent and can be obtained using **arrayRefVar.length**. Since the index of an array always begins with **0**, the last index is always **arrayRefVar.length - 1**. An out-of-bounds error will occur if you attempt to reference elements beyond the bounds of an array.
6. Programmers often mistakenly reference the first element in an array with index **1**, but it should be **0**. This is called the index *off-by-one error*.

7. When an array is created, its elements are assigned the default value of `0` for the numeric primitive data types, `\u0000` for char types, and `false` for `boolean` types.
8. Java has a shorthand notation, known as the *array initializer*, which combines declaring an array, creating an array, and initializing an array in one statement, using the syntax `elementType[] arrayRefVar = {value0, value1, ..., valuek}`.
9. When you pass an array argument to a method, you are actually passing the reference of the array; that is, the called method can modify the elements in the caller's original array.
10. If an array is sorted, *binary search* is more efficient than *linear search* for finding an element in the array.
11. *Selection sort* finds the smallest number in the list and swaps it with the first element. It then finds the smallest number remaining and swaps it with the first element in the remaining list, and so on, until only a single number remains.

QUIZ

Answer the quiz for this chapter online at www.cs.armstrong.edu/liang/intro10e/quiz.html.



PROGRAMMING EXERCISES

Sections 7.2–7.5

- *7.1 (*Assign grades*) Write a program that reads student scores, gets the best score, and then assigns grades based on the following scheme:

Grade is A if score is \geq best – 10
 Grade is B if score is \geq best – 20;
 Grade is C if score is \geq best – 30;
 Grade is D if score is \geq best – 40;
 Grade is F otherwise.

The program prompts the user to enter the total number of students, then prompts the user to enter all of the scores, and concludes by displaying the grades. Here is a sample run:



```
Enter the number of students: 4 ↵ Enter
Enter 4 scores: 40 55 70 58 ↵ Enter
Student 0 score is 40 and grade is C
Student 1 score is 55 and grade is B
Student 2 score is 70 and grade is A
Student 3 score is 58 and grade is B
```

- 7.2 (*Reverse the numbers entered*) Write a program that reads ten integers and displays them in the reverse of the order in which they were read.

- **7.3** (*Count occurrence of numbers*) Write a program that reads the integers between 1 and 100 and counts the occurrences of each. Assume the input ends with 0. Here is a sample run of the program:

```
Enter the integers between 1 and 100: 2 5 6 5 4 3 23 43 2 0 ↴Enter
2 occurs 2 times
3 occurs 1 time
4 occurs 1 time
5 occurs 2 times
6 occurs 1 time
23 occurs 1 time
43 occurs 1 time
```



Note that if a number occurs more than one time, the plural word “times” is used in the output.

- 7.4** (*Analyze scores*) Write a program that reads an unspecified number of scores and determines how many scores are above or equal to the average and how many scores are below the average. Enter a negative number to signify the end of the input. Assume that the maximum number of scores is 100.
- **7.5** (*Print distinct numbers*) Write a program that reads in ten numbers and displays the number of distinct numbers and the distinct numbers separated by exactly one space (i.e., if a number appears multiple times, it is displayed only once). (*Hint:* Read a number and store it to an array if it is new. If the number is already in the array, ignore it.) After the input, the array contains the distinct numbers. Here is the sample run of the program:

```
Enter ten numbers: 1 2 3 2 1 6 3 4 5 2 ↴Enter
The number of distinct number is 6
The distinct numbers are: 1 2 3 6 4 5
```



- *7.6** (*Revise Listing 5.15, PrimeNumber.java*) Listing 5.15 determines whether a number *n* is prime by checking whether 2, 3, 4, 5, 6, ..., *n*/2 is a divisor. If a divisor is found, *n* is not prime. A more efficient approach is to check whether any of the prime numbers less than or equal to \sqrt{n} can divide *n* evenly. If not, *n* is prime. Rewrite Listing 5.15 to display the first 50 prime numbers using this approach. You need to use an array to store the prime numbers and later use them to check whether they are possible divisors for *n*.
- *7.7** (*Count single digits*) Write a program that generates 100 random integers between 0 and 9 and displays the count for each number. (*Hint:* Use an array of ten integers, say *counts*, to store the counts for the number of 0s, 1s, ..., 9s.)

Sections 7.6–7.8

- 7.8** (*Average an array*) Write two overloaded methods that return the average of an array with the following headers:

```
public static int average(int[] array)
public static double average(double[] array)
```

Write a test program that prompts the user to enter ten double values, invokes this method, and displays the average value.

- 7.9** (*Find the smallest element*) Write a method that finds the smallest element in an array of double values using the following header:

```
public static double min(double[] array)
```

Write a test program that prompts the user to enter ten numbers, invokes this method to return the minimum value, and displays the minimum value. Here is a sample run of the program:



Enter ten numbers: 1.9 2.5 3.7 2 1.5 6 3 4 5 2

The minimum number is: 1.5

- 7.10** (*Find the index of the smallest element*) Write a method that returns the index of the smallest element in an array of integers. If the number of such elements is greater than 1, return the smallest index. Use the following header:

```
public static int indexOfSmallestElement(double[] array)
```

Write a test program that prompts the user to enter ten numbers, invokes this method to return the index of the smallest element, and displays the index.

- *7.11** (*Statistics: compute deviation*) Programming Exercise 5.45 computes the standard deviation of numbers. This exercise uses a different but equivalent formula to compute the standard deviation of **n** numbers.

$$\text{mean} = \frac{\sum_{i=1}^n x_i}{n} = \frac{x_1 + x_2 + \dots + x_n}{n} \quad \text{deviation} = \sqrt{\frac{\sum_{i=1}^n (x_i - \text{mean})^2}{n-1}}$$

To compute the standard deviation with this formula, you have to store the individual numbers using an array, so that they can be used after the mean is obtained.

Your program should contain the following methods:

```
/** Compute the deviation of double values */
public static double deviation(double[] x)
```

```
/** Compute the mean of an array of double values */
public static double mean(double[] x)
```

Write a test program that prompts the user to enter ten numbers and displays the mean and standard deviation, as shown in the following sample run:



Enter ten numbers: 1.9 2.5 3.7 2 1 6 3 4 5 2

The mean is 3.11

The standard deviation is 1.55738

- *7.12** (*Reverse an array*) The **reverse** method in Section 7.7 reverses an array by copying it to a new array. Rewrite the method that reverses the array passed in the argument and returns this array. Write a test program that prompts the user to

enter ten numbers, invokes the method to reverse the numbers, and displays the numbers.

Section 7.9

- *7.13** (*Random number chooser*) Write a method that returns a random number between 1 and 54, excluding the numbers passed in the argument. The method header is specified as follows:

```
public static int getRandom(int... numbers)
```

- 7.14** (*Computing gcd*) Write a method that returns the gcd of an unspecified number of integers. The method header is specified as follows:

```
public static int gcd(int... numbers)
```

Write a test program that prompts the user to enter five numbers, invokes the method to find the gcd of these numbers, and displays the gcd.

Sections 7.10–7.12

- 7.15** (*Eliminate duplicates*) Write a method that returns a new array by eliminating the duplicate values in the array using the following method header:

```
public static int[] eliminateDuplicates(int[] list)
```

Write a test program that reads in ten integers, invokes the method, and displays the result. Here is the sample run of the program:

```
Enter ten numbers: 1 2 3 2 1 6 3 4 5 2 ↵ Enter
The distinct numbers are: 1 2 3 6 4 5
```



- 7.16** (*Execution time*) Write a program that randomly generates an array of 100,000 integers and a key. Estimate the execution time of invoking the `LinearSearch` method in Listing 7.6. Sort the array and estimate the execution time of invoking the `binarySearch` method in Listing 7.7. You can use the following code template to obtain the execution time:

```
long startTime = System.currentTimeMillis();
perform the task;
long endTime = System.currentTimeMillis();
long executionTime = endTime - startTime;
```

- **7.17** (*Sort students*) Write a program that prompts the user to enter the number of students, the students' names, and their scores, and prints student names in decreasing order of their scores.

- **7.18** (*Bubble sort*) Write a sort method that uses the bubble-sort algorithm. The bubble-sort algorithm makes several passes through the array. On each pass, successive neighboring pairs are compared. If a pair is not in order, its values are swapped; otherwise, the values remain unchanged. The technique is called a *bubble sort* or *sinking sort* because the smaller values gradually “bubble” their way to the top and the larger values “sink” to the bottom. Write a test program that reads in ten double numbers, invokes the method, and displays the sorted numbers.

- **7.19** (*Sorted?*) Write the following method that returns true if the list is already sorted in increasing order.

```
public static boolean isSorted(int[] list)
```

Write a test program that prompts the user to enter a list and displays whether the list is sorted or not. Here is a sample run. Note that the first number in the input indicates the number of the elements in the list. This number is not part of the list.



Enter list: 8 10 1 5 16 61 9 11 1 ↵ Enter
The list is not sorted



Enter list: 10 1 1 3 4 4 5 7 9 11 21 ↵ Enter
The list is already sorted

- *7.20** (*Revise selection sort*) In Section 7.11, you used selection sort to sort an array. The selection-sort method repeatedly finds the smallest number in the current array and swaps it with the first. Rewrite this program by finding the largest number and swapping it with the last. Write a test program that reads in ten double numbers, invokes the method, and displays the sorted numbers.

- ***7.21** (*Game: bean machine*) The bean machine, also known as a quincunx or the Galton box, is a device for statistics experiments named after English scientist Sir Francis Galton. It consists of an upright board with evenly spaced nails (or pegs) in a triangular form, as shown in Figure 7.13.

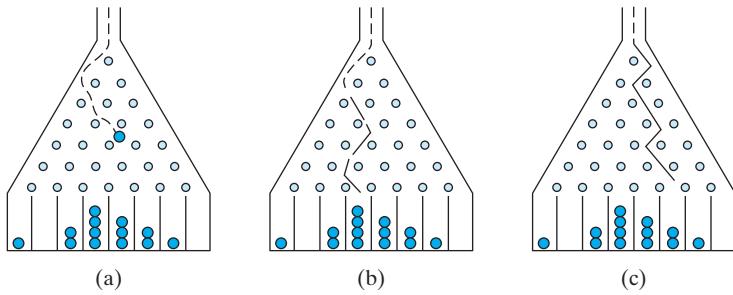


FIGURE 7.13 Each ball takes a random path and falls into a slot.

Balls are dropped from the opening of the board. Every time a ball hits a nail, it has a 50% chance of falling to the left or to the right. The piles of balls are accumulated in the slots at the bottom of the board.

Write a program that simulates the bean machine. Your program should prompt the user to enter the number of the balls and the number of the slots in the machine. Simulate the falling of each ball by printing its path. For example, the path for the ball in Figure 7.13b is LLRRLLR and the path for the ball in Figure 7.13c is

RLRRLR. Display the final buildup of the balls in the slots in a histogram. Here is a sample run of the program:



```

Enter the number of balls to drop: 5 ↵Enter
Enter the number of slots in the bean machine: 8 ↵Enter

LRLRLR
RLLLLR
LLRLLR
RLLLLL
LRLRLR

0
0
000

```

(*Hint:* Create an array named `slots`. Each element in `slots` stores the number of balls in a slot. Each ball falls into a slot via a path. The number of Rs in a path is the position of the slot where the ball falls. For example, for the path LRLRLR, the ball falls into `slots[4]`, and for the path is RLLLLL, the ball falls into `slots[2]`.)

- ***7.22** (*Game: Eight Queens*) The classic Eight Queens puzzle is to place eight queens on a chessboard such that no two queens can attack each other (i.e., no two queens are on the same row, same column, or same diagonal). There are many possible solutions. Write a program that displays one such solution. A sample output is shown below:

Q							
			Q				
					Q		
						Q	
		Q					
						Q	
							Q
	Q						

- **7.23** (*Game: locker puzzle*) A school has 100 lockers and 100 students. All lockers are closed on the first day of school. As the students enter, the first student, denoted S1, opens every locker. Then the second student, S2, begins with the second locker, denoted L2, and closes every other locker. Student S3 begins with the third locker and changes every third locker (closes it if it was open, and opens it if it was closed). Student S4 begins with locker L4 and changes every fourth locker. Student S5 starts with L5 and changes every fifth locker, and so on, until student S100 changes L100.

After all the students have passed through the building and changed the lockers, which lockers are open? Write a program to find your answer and display all open locker numbers separated by exactly one space.

(*Hint:* Use an array of 100 Boolean elements, each of which indicates whether a locker is open (`true`) or closed (`false`). Initially, all lockers are closed.)

- **7.24** (*Simulation: coupon collector's problem*) Coupon collector is a classic statistics problem with many practical applications. The problem is to pick objects from a set of objects repeatedly and find out how many picks are needed for all the



VideoNote

Coupon collector's problem

objects to be picked at least once. A variation of the problem is to pick cards from a shuffled deck of 52 cards repeatedly and find out how many picks are needed before you see one of each suit. Assume a picked card is placed back in the deck before picking another. Write a program to simulate the number of picks needed to get four cards from each suit and display the four cards picked (it is possible a card may be picked twice). Here is a sample run of the program:



```
Queen of Spades
5 of Clubs
Queen of Hearts
4 of Diamonds
Number of picks: 12
```

- 7.25** (*Algebra: solve quadratic equations*) Write a method for solving a quadratic equation using the following header:

```
public static int solveQuadratic(double[] eqn, double[] roots)
```

The coefficients of a quadratic equation $ax^2 + bx + c = 0$ are passed to the array `eqn` and the real roots are stored in `roots`. The method returns the number of real roots. See Programming Exercise 3.1 on how to solve a quadratic equation.

Write a program that prompts the user to enter values for a , b , and c and displays the number of real roots and all real roots.

- 7.26** (*Strictly identical arrays*) The arrays `list1` and `list2` are *strictly identical* if their corresponding elements are equal. Write a method that returns `true` if `list1` and `list2` are strictly identical, using the following header:

```
public static boolean equals(int[] list1, int[] list2)
```

Write a test program that prompts the user to enter two lists of integers and displays whether the two are strictly identical. Here are the sample runs. Note that the first number in the input indicates the number of the elements in the list. This number is not part of the list.



```
Enter list1: 5 2 5 6 1 6 ↵ Enter
Enter list2: 5 2 5 6 1 6 ↵ Enter
Two lists are strictly identical
```



```
Enter list1: 5 2 5 6 6 1 ↵ Enter
Enter list2: 5 2 5 6 1 6 ↵ Enter
Two lists are not strictly identical
```

- 7.27** (*Identical arrays*) The arrays `list1` and `list2` are *identical* if they have the same contents. Write a method that returns `true` if `list1` and `list2` are identical, using the following header:

```
public static boolean equals(int[] list1, int[] list2)
```

Write a test program that prompts the user to enter two lists of integers and displays whether the two are identical. Here are the sample runs. Note that the first number in the input indicates the number of the elements in the list. This number is not part of the list.

```
Enter list1: 5 2 5 6 6 1 ↵Enter
Enter list2: 5 5 2 6 1 6 ↵Enter
Two lists are identical
```



```
Enter list1: 5 5 5 6 6 1 ↵Enter
Enter list2: 5 2 5 6 1 6 ↵Enter
Two lists are not identical
```



***7.28** (*Math: combinations*) Write a program that prompts the user to enter 10 integers and displays all combinations of picking two numbers from the 10.

***7.29** (*Game: pick four cards*) Write a program that picks four cards from a deck of 52 cards and computes their sum. An Ace, King, Queen, and Jack represent 1, 13, 12, and 11, respectively. Your program should display the number of picks that yields the sum of 24.

***7.30** (*Pattern recognition: consecutive four equal numbers*) Write the following method that tests whether the array has four consecutive numbers with the same value.

```
public static boolean isConsecutiveFour(int[] values)
```



VideoNote

Consecutive four

Write a test program that prompts the user to enter a series of integers and displays if the series contains four consecutive numbers with the same value. Your program should first prompt the user to enter the input size—i.e., the number of values in the series. Here are sample runs:

```
Enter the number of values: 8 ↵Enter
Enter the values: 3 4 5 5 5 5 4 5 ↵Enter
The list has consecutive fours
```



```
Enter the number of values: 9 ↵Enter
Enter the values: 3 4 5 5 6 5 5 4 5 ↵Enter
The list has no consecutive fours
```



****7.31** (*Merge two sorted lists*) Write the following method that merges two sorted lists into a new sorted list.

```
public static int[] merge(int[] list1, int[] list2)
```

Implement the method in a way that takes at most `List1.length + List2.length` comparisons. Write a test program that prompts the user to enter two sorted lists and displays the merged list. Here is a sample run. Note that the first number in the input indicates the number of the elements in the list. This number is not part of the list.



```
Enter list1: 5 1 5 16 61 111 ↵ Enter
Enter list2: 4 2 4 5 6 ↵ Enter
The merged list is 1 2 4 5 5 6 16 61 111
```

- **7.32** (*Partition of a list*) Write the following method that partitions the list using the first element, called a *pivot*.

```
public static int partition(int[] list)
```

After the partition, the elements in the list are rearranged so that all the elements before the pivot are less than or equal to the pivot and the elements after the pivot are greater than the pivot. The method returns the index where the pivot is located in the new list. For example, suppose the list is {5, 2, 9, 3, 6, 8}. After the partition, the list becomes {3, 2, 5, 9, 6, 8}. Implement the method in a way that takes at most `List.length` comparisons. Write a test program that prompts the user to enter a list and displays the list after the partition. Here is a sample run. Note that the first number in the input indicates the number of the elements in the list. This number is not part of the list.



```
Enter list: 8 10 1 5 16 61 9 11 1 ↵ Enter
After the partition, the list is 9 1 5 1 10 61 11 16
```

- *7.33** (*Culture: Chinese Zodiac*) Simplify Listing 3.9 using an array of strings to store the animal names.

- **7.34** (*Sort characters in a string*) Write a method that returns a sorted string using the following header:

```
public static String sort(String s)
```

For example, `sort("acb")` returns `abc`.

Write a test program that prompts the user to enter a string and displays the sorted string.

- ***7.35** (*Game: hangman*) Write a hangman game that randomly generates a word and prompts the user to guess one letter at a time, as shown in the sample run. Each letter in the word is displayed as an asterisk. When the user makes a correct guess, the actual letter is then displayed. When the user finishes a word, display

the number of misses and ask the user whether to continue to play with another word. Declare an array to store words, as follows:

```
// Add any words you wish in this array  
String[] words = {"write", "that", ...};
```

```
(Guess) Enter a letter in word ***** > p ↵Enter  
(Guess) Enter a letter in word p***** > r ↵Enter  
(Guess) Enter a letter in word pr**r** > p ↵Enter  
    p is already in the word  
(Guess) Enter a letter in word pr**r** > o ↵Enter  
(Guess) Enter a letter in word pro*r** > g ↵Enter  
(Guess) Enter a letter in word progr** > n ↵Enter  
    n is not in the word  
(Guess) Enter a letter in word progr** > m ↵Enter  
(Guess) Enter a letter in word progr*m > a ↵Enter  
The word is program. You missed 1 time  
Do you want to guess another word? Enter y or n>
```



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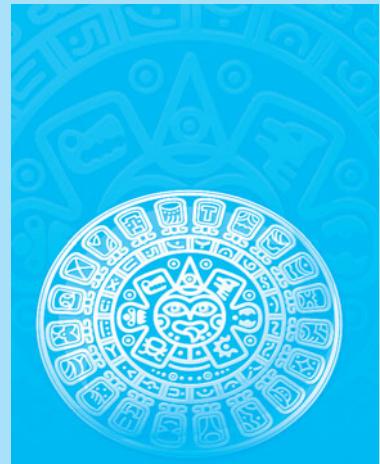
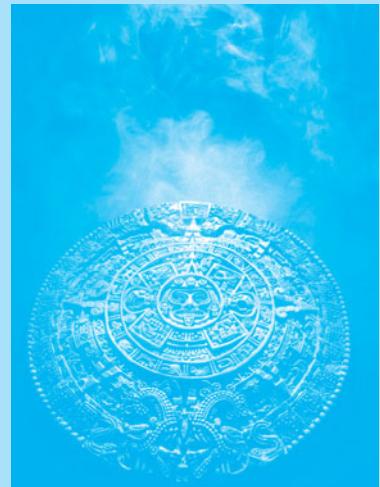
CHAPTER

8

MULTIDIMENSIONAL ARRAYS

Objectives

- To give examples of representing data using two-dimensional arrays (§8.1).
- To declare variables for two-dimensional arrays, create arrays, and access array elements in a two-dimensional array using row and column indexes (§8.2).
- To program common operations for two-dimensional arrays (displaying arrays, summing all elements, finding the minimum and maximum elements, and random shuffling) (§8.3).
- To pass two-dimensional arrays to methods (§8.4).
- To write a program for grading multiple-choice questions using two-dimensional arrays (§8.5).
- To solve the closest-pair problem using two-dimensional arrays (§8.6).
- To check a Sudoku solution using two-dimensional arrays (§8.7).
- To use multidimensional arrays (§8.8).



8.1 Introduction



Data in a table or a matrix can be represented using a two-dimensional array.

problem

The preceding chapter introduced how to use one-dimensional arrays to store linear collections of elements. You can use a two-dimensional array to store a matrix or a table. For example, the following table that lists the distances between cities can be stored using a two-dimensional array named **distances**.

Distance Table (in miles)							
	Chicago	Boston	New York	Atlanta	Miami	Dallas	Houston
Chicago	0	983	787	714	1375	967	1087
Boston	983	0	214	1102	1763	1723	1842
New York	787	214	0	888	1549	1548	1627
Atlanta	714	1102	888	0	661	781	810
Miami	1375	1763	1549	661	0	1426	1187
Dallas	967	1723	1548	781	1426	0	239
Houston	1087	1842	1627	810	1187	239	0

```
double[][] distances = {
    {0, 983, 787, 714, 1375, 967, 1087},
    {983, 0, 214, 1102, 1763, 1723, 1842},
    {787, 214, 0, 888, 1549, 1548, 1627},
    {714, 1102, 888, 0, 661, 781, 810},
    {1375, 1763, 1549, 661, 0, 1426, 1187},
    {967, 1723, 1548, 781, 1426, 0, 239},
    {1087, 1842, 1627, 810, 1187, 239, 0},
};
```

8.2 Two-Dimensional Array Basics



An element in a two-dimensional array is accessed through a row and column index.

How do you declare a variable for two-dimensional arrays? How do you create a two-dimensional array? How do you access elements in a two-dimensional array? This section addresses these issues.

8.2.1 Declaring Variables of Two-Dimensional Arrays and Creating Two-Dimensional Arrays

The syntax for declaring a two-dimensional array is:

```
elementType[][] arrayRefVar;
```

or

```
elementType arrayRefVar[][]; // Allowed, but not preferred
```

As an example, here is how you would declare a two-dimensional array variable **matrix** of **int** values:

```
int[][] matrix;
```

or

```
int matrix[][]; // This style is allowed, but not preferred
```

You can create a two-dimensional array of 5-by-5 `int` values and assign it to `matrix` using this syntax:

```
matrix = new int[5][5];
```

Two subscripts are used in a two-dimensional array, one for the row and the other for the column. As in a one-dimensional array, the index for each subscript is of the `int` type and starts from `0`, as shown in Figure 8.1a.

[0][1][2][3][4]				
[0]	0	0	0	0
[1]	0	0	0	0
[2]	0	0	0	0
[3]	0	0	0	0
[4]	0	0	0	0

```
matrix = new int[5][5];
```

[0][1][2][3][4]				
[0]	0	0	0	0
[1]	0	0	0	0
[2]	0	7	0	0
[3]	0	0	0	0
[4]	0	0	0	0

```
matrix[2][1] = 7;
```

[0][1][2]			
[0]	1	2	3
[1]	4	5	6
[2]	7	8	9
[3]	10	11	12

```
int[][] array = {
    {1, 2, 3},
    {4, 5, 6},
    {7, 8, 9},
    {10, 11, 12}
};
```

(a)

(b)

(c)

FIGURE 8.1 The index of each subscript of a two-dimensional array is an `int` value, starting from `0`.

To assign the value `7` to a specific element at row `2` and column `1`, as shown in Figure 8.1b, you can use the following syntax:

```
matrix[2][1] = 7;
```



Caution

It is a common mistake to use `matrix[2, 1]` to access the element at row `2` and column `1`. In Java, each subscript must be enclosed in a pair of square brackets.

You can also use an array initializer to declare, create, and initialize a two-dimensional array. For example, the following code in (a) creates an array with the specified initial values, as shown in Figure 8.1c. This is equivalent to the code in (b).

```
int[][] array = {
    {1, 2, 3},
    {4, 5, 6},
    {7, 8, 9},
    {10, 11, 12}
};
```

Equivalent

```
int[][] array = new int[4][3];
array[0][0] = 1; array[0][1] = 2; array[0][2] = 3;
array[1][0] = 4; array[1][1] = 5; array[1][2] = 6;
array[2][0] = 7; array[2][1] = 8; array[2][2] = 9;
array[3][0] = 10; array[3][1] = 11; array[3][2] = 12;
```

(a)

(b)

8.2.2 Obtaining the Lengths of Two-Dimensional Arrays

A two-dimensional array is actually an array in which each element is a one-dimensional array. The length of an array `x` is the number of elements in the array, which can be obtained using `x.length`. `x[0], x[1], ...,` and `x[x.length-1]` are arrays. Their lengths can be obtained using `x[0].length, x[1].length, ...,` and `x[x.length-1].length`.

For example, suppose `x = new int[3][4]`, `x[0]`, `x[1]`, and `x[2]` are one-dimensional arrays and each contains four elements, as shown in Figure 8.2. `x.length` is 3, and `x[0].length`, `x[1].length`, and `x[2].length` are 4.

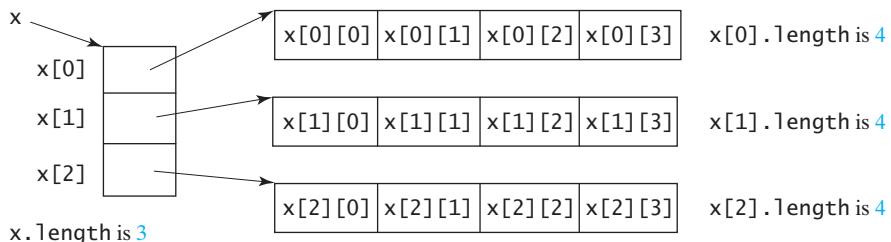
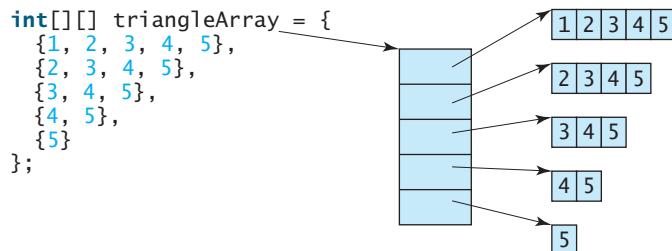


FIGURE 8.2 A two-dimensional array is a one-dimensional array in which each element is another one-dimensional array.

8.2.3 Ragged Arrays

ragged array

Each row in a two-dimensional array is itself an array. Thus, the rows can have different lengths. An array of this kind is known as a *ragged array*. Here is an example of creating a ragged array:



As you can see, `triangleArray[0].length` is 5, `triangleArray[1].length` is 4, `triangleArray[2].length` is 3, `triangleArray[3].length` is 2, and `triangleArray[4].length` is 1.

If you don't know the values in a ragged array in advance, but do know the sizes—say, the same as before—you can create a ragged array using the following syntax:

```
int[][] triangleArray = new int[5][];
triangleArray[0] = new int[5];
triangleArray[1] = new int[4];
triangleArray[2] = new int[3];
triangleArray[3] = new int[2];
triangleArray[4] = new int[1];
```

You can now assign values to the array. For example,

```
triangleArray[0][3] = 50;
triangleArray[4][0] = 45;
```



Note

The syntax `new int[5][]` for creating an array requires the first index to be specified. The syntax `new int[][],` would be wrong.

- 8.1** Declare an array reference variable for a two-dimensional array of `int` values, create a 4-by-5 `int` matrix, and assign it to the variable.
- 8.2** Can the rows in a two-dimensional array have different lengths?
- 8.3** What is the output of the following code?



```
int[][] array = new int[5][6];
int[] x = {1, 2};
array[0] = x;
System.out.println("array[0][1] is " + array[0][1]);
```

- 8.4** Which of the following statements are valid?

```
int[][] r = new int[2];
int[] x = new int[];
int[][] y = new int[3][];
int[][] z = {{1, 2}};
int[][] m = {{1, 2}, {2, 3}};
int[][] n = {{1, 2}, {2, 3}, };
```



8.3 Processing Two-Dimensional Arrays

Nested for loops are often used to process a two-dimensional array.

Suppose an array `matrix` is created as follows:

```
int[][] matrix = new int[10][10];
```

The following are some examples of processing two-dimensional arrays.

1. *Initializing arrays with input values.* The following loop initializes the array with user input values:

```
java.util.Scanner input = new Scanner(System.in);
System.out.println("Enter " + matrix.length + " rows and " +
    matrix[0].length + " columns: ");
for (int row = 0; row < matrix.length; row++) {
    for (int column = 0; column < matrix[row].length; column++) {
        matrix[row][column] = input.nextInt();
    }
}
```

2. *Initializing arrays with random values.* The following loop initializes the array with random values between 0 and 99:

```
for (int row = 0; row < matrix.length; row++) {
    for (int column = 0; column < matrix[row].length; column++) {
        matrix[row][column] = (int)(Math.random() * 100);
    }
}
```

3. *Printing arrays.* To print a two-dimensional array, you have to print each element in the array using a loop like the following:

```
for (int row = 0; row < matrix.length; row++) {
    for (int column = 0; column < matrix[row].length; column++) {
        System.out.print(matrix[row][column] + " ");
    }
    System.out.println();
```

4. *Summing all elements.* Use a variable named **total** to store the sum. Initially **total** is **0**. Add each element in the array to **total** using a loop like this:

```
int total = 0;
for (int row = 0; row < matrix.length; row++) {
    for (int column = 0; column < matrix[row].length; column++) {
        total += matrix[row][column];
    }
}
```

5. *Summing elements by column.* For each column, use a variable named **total** to store its sum. Add each element in the column to **total** using a loop like this:

```
for (int column = 0; column < matrix[0].length; column++) {
    int total = 0;
    for (int row = 0; row < matrix.length; row++)
        total += matrix[row][column];
    System.out.println("Sum for column " + column + " is "
        + total);
}
```

6. *Which row has the largest sum?* Use variables **maxRow** and **indexOfMaxRow** to track the largest sum and index of the row. For each row, compute its sum and update **maxRow** and **indexOfMaxRow** if the new sum is greater.

```
int maxRow = 0;
int indexOfMaxRow = 0;

// Get sum of the first row in maxRow
for (int column = 0; column < matrix[0].length; column++) {
    maxRow += matrix[0][column];
}

for (int row = 1; row < matrix.length; row++) {
    int totalOfThisRow = 0;
    for (int column = 0; column < matrix[row].length; column++)
        totalOfThisRow += matrix[row][column];

    if (totalOfThisRow > maxRow) {
        maxRow = totalOfThisRow;
        indexOfMaxRow = row;
    }
}

System.out.println("Row " + indexOfMaxRow
    + " has the maximum sum of " + maxRow);
```

7. *Random shuffling.* Shuffling the elements in a one-dimensional array was introduced in Section 7.2.6. How do you shuffle all the elements in a two-dimensional array? To accomplish this, for each element **matrix[i][j]**, randomly generate indices **i1** and **j1** and swap **matrix[i][j]** with **matrix[i1][j1]**, as follows:

```
for (int i = 0; i < matrix.length; i++) {
    for (int j = 0; j < matrix[i].length; j++) {
        int i1 = (int)(Math.random() * matrix.length);
        int j1 = (int)(Math.random() * matrix[i].length);

        // Swap matrix[i][j] with matrix[i1][j1]
```



VideoNote

Find the row with the largest sum

```

    int temp = matrix[i][j];
    matrix[i][j] = matrix[i1][j1];
    matrix[i1][j1] = temp;
}
}

```

- 8.5** Show the output of the following code:



```

int[][] array = {{1, 2}, {3, 4}, {5, 6}};
for (int i = array.length - 1; i >= 0; i--) {
    for (int j = array[i].length - 1; j >= 0; j--)
        System.out.print(array[i][j] + " ");
    System.out.println();
}

```

- 8.6** Show the output of the following code:

```

int[][] array = {{1, 2}, {3, 4}, {5, 6}};
int sum = 0;
for (int i = 0; i < array.length; i++)
    sum += array[i][0];
System.out.println(sum);

```

8.4 Passing Two-Dimensional Arrays to Methods

When passing a two-dimensional array to a method, the reference of the array is passed to the method.



You can pass a two-dimensional array to a method just as you pass a one-dimensional array. You can also return an array from a method. Listing 8.1 gives an example with two methods. The first method, `getArray()`, returns a two-dimensional array, and the second method, `sum(int[][] m)`, returns the sum of all the elements in a matrix.

LISTING 8.1 PassTwoDimensionalArray.java

```

1 import java.util.Scanner;
2
3 public class PassTwoDimensionalArray {
4     public static void main(String[] args) {
5         int[][] m = getArray(); // Get an array
6
7         // Display sum of elements
8         System.out.println("\nSum of all elements is " + sum(m));
9     }
10
11     public static int[][] getArray() {
12         // Create a Scanner
13         Scanner input = new Scanner(System.in);
14
15         // Enter array values
16         int[][] m = new int[3][4];
17         System.out.println("Enter " + m.length + " rows and "
18             + m[0].length + " columns: ");
19         for (int i = 0; i < m.length; i++)
20             for (int j = 0; j < m[i].length; j++)
21                 m[i][j] = input.nextInt();
22
23     }
24
25     int sum(int[][] m) {
26         int sum = 0;
27         for (int i = 0; i < m.length; i++)
28             for (int j = 0; j < m[i].length; j++)
29                 sum += m[i][j];
30
31         return sum;
32     }
33 }

```

get array

pass array

getArray method

```

return array          23      return m;
                     24  }
                     25
sum method          26  public static int sum(int[][] m) {
                     27      int total = 0;
                     28      for (int row = 0; row < m.length; row++) {
                     29          for (int column = 0; column < m[row].length; column++) {
                     30              total += m[row][column];
                     31          }
                     32      }
                     33
                     34      return total;
                     35  }
                     36 }

```



Enter 3 rows and 4 columns:

```

1 2 3 4 ↵Enter
5 6 7 8 ↵Enter
9 10 11 12 ↵Enter

```

Sum of all elements is 78

The method `getArray` prompts the user to enter values for the array (lines 11–24) and returns the array (line 23).

The method `sum` (lines 26–35) has a two-dimensional array argument. You can obtain the number of rows using `m.length` (line 28) and the number of columns in a specified row using `m[row].length` (line 29).



8.7 Show the output of the following code:

```

public class Test {
    public static void main(String[] args) {
        int[][] array = {{1, 2, 3, 4}, {5, 6, 7, 8}};
        System.out.println(m1(array)[0]);
        System.out.println(m1(array)[1]);
    }

    public static int[] m1(int[][] m) {
        int[] result = new int[2];
        result[0] = m.length;
        result[1] = m[0].length;
        return result;
    }
}

```

8.5 Case Study: Grading a Multiple-Choice Test

The problem is to write a program that will grade multiple-choice tests.



VideoNote



Grade multiple-choice test

Suppose you need to write a program that grades multiple-choice tests. Assume there are eight students and ten questions, and the answers are stored in a two-dimensional array. Each row records a student's answers to the questions, as shown in the following array.

Students' Answers to the Questions:

0 1 2 3 4 5 6 7 8 9

Student 0	A	B	A	C	C	D	E	E	A	D
Student 1	D	B	A	B	C	A	E	E	A	D
Student 2	E	D	D	A	C	B	E	E	A	D
Student 3	C	B	A	E	D	C	E	E	A	D
Student 4	A	B	D	C	C	D	E	E	A	D
Student 5	B	B	E	C	C	D	E	E	A	D
Student 6	B	B	A	C	C	D	E	E	A	D
Student 7	E	B	E	C	C	D	E	E	A	D

The key is stored in a one-dimensional array:

Key to the Questions:

0 1 2 3 4 5 6 7 8 9

Key D B D C C D A E A D

Your program grades the test and displays the result. It compares each student's answers with the key, counts the number of correct answers, and displays it. Listing 8.2 gives the program.

LISTING 8.2 GradeExam.java

```

1  public class GradeExam {
2      /** Main method */
3      public static void main(String[] args) {
4          // Students' answers to the questions
5          char[][] answers = {                                         2-D array
6              {'A', 'B', 'A', 'C', 'C', 'D', 'E', 'E', 'A', 'D'},
7              {'D', 'B', 'A', 'B', 'C', 'A', 'E', 'E', 'A', 'D'},
8              {'E', 'D', 'D', 'A', 'C', 'B', 'E', 'E', 'A', 'D'},
9              {'C', 'B', 'A', 'E', 'D', 'C', 'E', 'E', 'A', 'D'},
10             {'A', 'B', 'D', 'C', 'C', 'D', 'E', 'E', 'A', 'D'},
11             {'B', 'B', 'E', 'C', 'C', 'D', 'E', 'E', 'A', 'D'},
12             {'B', 'B', 'A', 'C', 'C', 'D', 'E', 'E', 'A', 'D'},
13             {'E', 'B', 'E', 'C', 'C', 'D', 'E', 'E', 'A', 'D'}};
14
15         // Key to the questions
16         char[] keys = {'D', 'B', 'D', 'C', 'C', 'D', 'A', 'E', 'A', 'D'};    1-D array
17
18         // Grade all answers
19         for (int i = 0; i < answers.length; i++) {
20             // Grade one student
21             int correctCount = 0;
22             for (int j = 0; j < answers[i].length; j++) {
23                 if (answers[i][j] == keys[j])                                compare with key
24                     correctCount++;
25             }
26
27             System.out.println("Student " + i + "'s correct count is " +
28                 correctCount);
29         }
30     }
31 }
```



```

Student 0's correct count is 7
Student 1's correct count is 6
Student 2's correct count is 5
Student 3's correct count is 4
Student 4's correct count is 8
Student 5's correct count is 7
Student 6's correct count is 7
Student 7's correct count is 7

```

The statement in lines 5–13 declares, creates, and initializes a two-dimensional array of characters and assigns the reference to `answers` of the `char[][]` type.

The statement in line 16 declares, creates, and initializes an array of `char` values and assigns the reference to `keys` of the `char[]` type.

Each row in the array `answers` stores a student's answer, which is graded by comparing it with the key in the array `keys`. The result is displayed immediately after a student's answer is graded.

8.6 Case Study: Finding the Closest Pair

This section presents a geometric problem for finding the closest pair of points.



closest-pair animation on the Companion Website

Given a set of points, the closest-pair problem is to find the two points that are nearest to each other. In Figure 8.3, for example, points **(1, 1)** and **(2, 0.5)** are closest to each other. There are several ways to solve this problem. An intuitive approach is to compute the distances between all pairs of points and find the one with the minimum distance, as implemented in Listing 8.3.

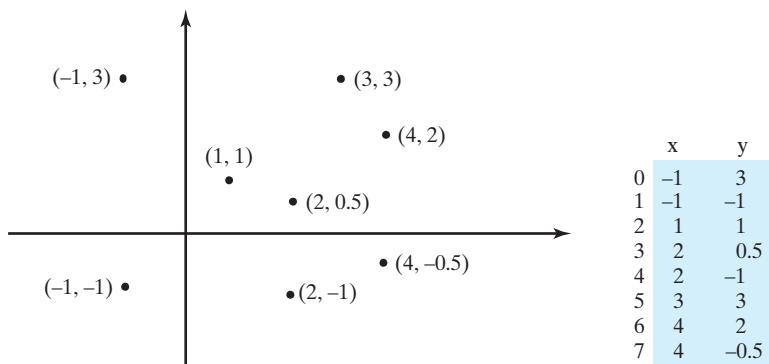


FIGURE 8.3 Points can be represented in a two-dimensional array.

LISTING 8.3 FindNearestPoints.java

```

1 import java.util.Scanner;
2
3 public class FindNearestPoints {
4     public static void main(String[] args) {
5         Scanner input = new Scanner(System.in);
6         System.out.print("Enter the number of points: ");
7         int numberOfPoints = input.nextInt();
8
9         // Create an array to store points

```

```

10  double[][] points = new double[numberOfPoints][2];
11  System.out.print("Enter " + numberOfPoints + " points: ");
12  for (int i = 0; i < points.length; i++) {
13      points[i][0] = input.nextDouble();
14      points[i][1] = input.nextDouble();
15  }
16
17  // p1 and p2 are the indices in the points' array
18  int p1 = 0, p2 = 1; // Initial two points
19  double shortestDistance = distance(points[p1][0], points[p1][1],
20      points[p2][0], points[p2][1]); // Initialize shortestDistance
21
22  // Compute distance for every two points
23  for (int i = 0; i < points.length; i++) {
24      for (int j = i + 1; j < points.length; j++) {
25          double distance = distance(points[i][0], points[i][1],
26              points[j][0], points[j][1]); // Find distance
27
28          if (shortestDistance > distance) {
29              p1 = i; // Update p1
30              p2 = j; // Update p2
31              shortestDistance = distance; // Update shortestDistance
32          }
33      }
34  }
35
36  // Display result
37  System.out.println("The closest two points are " +
38      "(" + points[p1][0] + ", " + points[p1][1] + ") and (" +
39      points[p2][0] + ", " + points[p2][1] + ")");
40 }
41
42 /** Compute the distance between two points (x1, y1) and (x2, y2)*/
43 public static double distance(
44     double x1, double y1, double x2, double y2) {
45     return Math.sqrt((x2 - x1) * (x2 - x1) + (y2 - y1) * (y2 - y1));
46 }
47 }
```

Enter the number of points: 8 ↵
 Enter 8 points: -1 3 -1 -1 1 1 2 0.5 2 -1 3 3 4 2 4 -0.5 ↵
 The closest two points are (1, 1) and (2, 0.5)



The program prompts the user to enter the number of points (lines 6–7). The points are read from the console and stored in a two-dimensional array named **points** (lines 12–15). The program uses the variable **shortestDistance** (line 19) to store the distance between the two nearest points, and the indices of these two points in the **points** array are stored in **p1** and **p2** (line 18).

For each point at index **i**, the program computes the distance between **points[i]** and **points[j]** for all **j > i** (lines 23–34). Whenever a shorter distance is found, the variable **shortestDistance** and **p1** and **p2** are updated (lines 28–32).

The distance between two points **(x₁, y₁)** and **(x₂, y₂)** can be computed using the formula $\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$ (lines 43–46).

The program assumes that the plane has at least two points. You can easily modify the program to handle the case if the plane has zero or one point.

multiple closest pairs

Note that there might be more than one closest pair of points with the same minimum distance. The program finds one such pair. You may modify the program to find all closest pairs in Programming Exercise 8.8.

input file

**Tip**

It is cumbersome to enter all points from the keyboard. You may store the input in a file, say **FindNearestPoints.txt**, and compile and run the program using the following command:

```
java FindNearestPoints < FindNearestPoints.txt
```



8.7 Case Study: Sudoku

The problem is to check whether a given Sudoku solution is correct.

VideoNote
Sudoku

fixed cells
free cells

This section presents an interesting problem of a sort that appears in the newspaper every day. It is a number-placement puzzle, commonly known as *Sudoku*. This is a very challenging problem. To make it accessible to the novice, this section presents a simplified version of the Sudoku problem, which is to verify whether a Sudoku solution is correct. The complete program for finding a Sudoku solution is presented in Supplement VI.A.

Sudoku is a 9×9 grid divided into smaller 3×3 boxes (also called *regions* or *blocks*), as shown in Figure 8.4a. Some cells, called *fixed cells*, are populated with numbers from **1** to **9**. The objective is to fill the empty cells, also called *free cells*, with the numbers **1** to **9** so that every row, every column, and every 3×3 box contains the numbers **1** to **9**, as shown in Figure 8.4b.

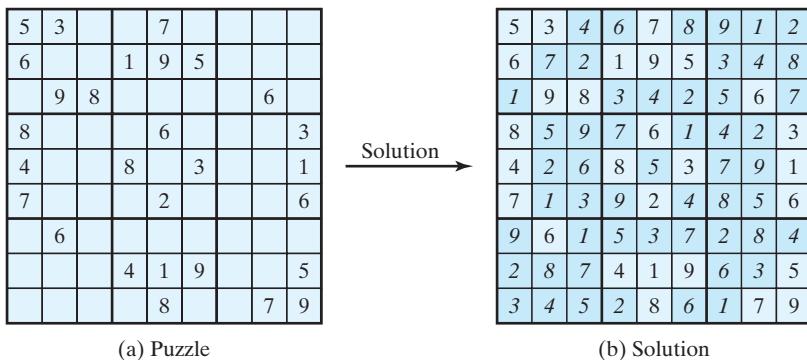


FIGURE 8.4 The Sudoku puzzle in (a) is solved in (b).

representing a grid

For convenience, we use value **0** to indicate a free cell, as shown in Figure 8.5a. The grid can be naturally represented using a two-dimensional array, as shown in Figure 8.5b.

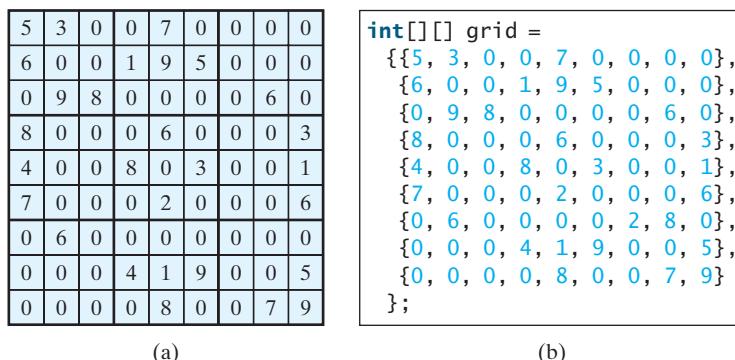


FIGURE 8.5 A grid can be represented using a two-dimensional array.

To find a solution for the puzzle, we must replace each **0** in the grid with an appropriate number from **1** to **9**. For the solution to the puzzle in Figure 8.5, the grid should be as shown in Figure 8.6.

Once a solution to a Sudoku puzzle is found, how do you verify that it is correct? Here are two approaches:

- Check if every row has numbers from **1** to **9**, every column has numbers from **1** to **9**, and every small box has numbers from **1** to **9**.
 - Check each cell. Each cell must be a number from **1** to **9** and the cell must be unique on every row, every column, and every small box.

```

A solution grid is
{{5, 3, 4, 6, 7, 8, 9, 1, 2},
 {6, 7, 2, 1, 9, 5, 3, 4, 8},
 {1, 9, 8, 3, 4, 2, 5, 6, 7},
 {8, 5, 9, 7, 6, 1, 4, 2, 3},
 {4, 2, 6, 8, 5, 3, 7, 9, 1},
 {7, 1, 3, 9, 2, 4, 8, 5, 6},
 {9, 6, 1, 5, 3, 7, 2, 8, 4},
 {2, 8, 7, 4, 1, 9, 6, 3, 5},
 {3, 4, 5, 2, 8, 6, 1, 7, 9}
}:
```

FIGURE 8.6 A solution is stored in `grid`.

The program in Listing 8.4 prompts the user to enter a solution and reports whether it is valid. We use the second approach in the program to check whether the solution is correct.

LISTING 8.4 CheckSudokuSolution.java

```
1 import java.util.Scanner;
2
3 public class CheckSudokuSolution {
4     public static void main(String[] args) {
5         // Read a Sudoku solution
6         int[][] grid = readASolution();                                read input
7
8         System.out.println(isValid(grid) ? "Valid solution" :      solution valid?
9             "Invalid solution");
10    }
11
12    /** Read a Sudoku solution from the console */
13    public static int[][] readASolution() {                           read solution
14        // Create a Scanner
15        Scanner input = new Scanner(System.in);
16
17        System.out.println("Enter a Sudoku puzzle solution:");
18        int[][] grid = new int[9][9];
19        for (int i = 0; i < 9; i++) {
20            for (int j = 0; j < 9; j++)
21                grid[i][j] = input.nextInt();
22
23        return grid;
24    }
25
26    /** Check whether a solution is valid */
27    public static boolean isValid(int[][] grid) {                   check solution
28        for (int i = 0; i < 9; i++) {
29            for (int j = 0; j < 9; j++) {
30                if (grid[i][j] < 1 || grid[i][j] > 9)
31                    return false;
32
33                int value = grid[i][j];
34                for (int k = 0; k < 9; k++) {
35                    if (k != i && grid[k][j] == value)
36                        return false;
37
38                    if (k != j && grid[i][k] == value)
39                        return false;
40
41                    if ((i / 3) * 3 + k / 3 != j / 3 * 3 + k % 3)
42                        continue;
43
44                    if (grid[(i / 3) * 3 + k / 3][j] == value)
45                        return false;
46
47                }
48            }
49        }
50
51        return true;
52    }
53}
```

```

28     for (int i = 0; i < 9; i++)
29         for (int j = 0; j < 9; j++)
30             if (grid[i][j] < 1 || grid[i][j] > 9
31                 || !isValid(i, j, grid))
32                 return false;
33     return true; // The solution is valid
34 }
35
36 /** Check whether grid[i][j] is valid in the grid */
37 public static boolean isValid(int i, int j, int[][] grid) {
38     // Check whether grid[i][j] is unique in i's row
39     for (int column = 0; column < 9; column++)
40         if (column != j && grid[i][column] == grid[i][j])
41             return false;
42
43     // Check whether grid[i][j] is unique in j's column
44     for (int row = 0; row < 9; row++)
45         if (row != i && grid[row][j] == grid[i][j])
46             return false;
47
48     // Check whether grid[i][j] is unique in the 3-by-3 box
49     for (int row = (i / 3) * 3; row < (i / 3) * 3 + 3; row++)
50         for (int col = (j / 3) * 3; col < (j / 3) * 3 + 3; col++)
51             if (row != i && col != j && grid[row][col] == grid[i][j])
52                 return false;
53
54     return true; // The current value at grid[i][j] is valid
55 }
56 }
```

check rows

check columns

check small boxes



Enter a Sudoku puzzle solution:

9	6	3	1	7	4	2	5	8
1	7	8	3	2	5	6	4	9
2	5	4	6	8	9	7	3	1
8	2	1	4	3	7	5	9	6
4	9	6	8	5	2	3	1	7
7	3	5	9	6	1	8	2	4
5	8	9	7	1	3	4	6	2
3	1	7	2	4	6	9	8	5
6	4	2	5	9	8	1	7	3

Valid solution

isValid method

overloaded isValid method

The program invokes the `readASolution()` method (line 6) to read a Sudoku solution and return a two-dimensional array representing a Sudoku grid.

The `isValid(grid)` method checks whether the values in the grid are valid by verifying that each value is between `1` and `9` and that each value is valid in the grid (lines 27–34).

The `isValid(i, j, grid)` method checks whether the value at `grid[i][j]` is valid. It checks whether `grid[i][j]` appears more than once in row `i` (lines 39–41), in column `j` (lines 44–46), and in the 3×3 box (lines 49–52).

How do you locate all the cells in the same box? For any `grid[i][j]`, the starting cell of the 3×3 box that contains it is `grid[(i / 3) * 3][(j / 3) * 3]`, as illustrated in Figure 8.7.

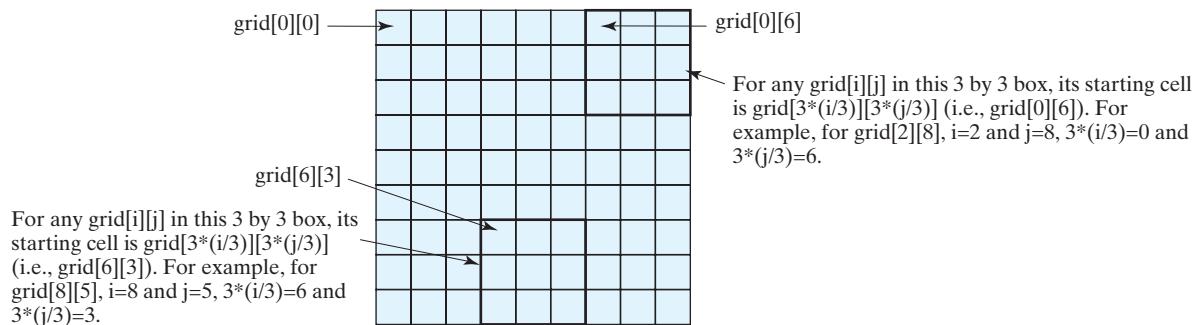


FIGURE 8.7 The location of the first cell in a 3×3 box determines the locations of other cells in the box.

With this observation, you can easily identify all the cells in the box. For instance, if `grid[r][c]` is the starting cell of a 3×3 box, the cells in the box can be traversed in a nested loop as follows:

```
// Get all cells in a 3-by-3 box starting at grid[r][c]
for (int row = r; row < r + 3; row++)
    for (int col = c; col < c + 3; col++)
        // grid[row][col] is in the box
```

It is cumbersome to enter 81 numbers from the console. When you test the program, you may store the input in a file, say `CheckSudokuSolution.txt` (see www.cs.armstrong.edu/liang/data/CheckSudokuSolution.txt), and run the program using the following command:

```
java CheckSudokuSolution < CheckSudokuSolution.txt
```

input file

8.8 Multidimensional Arrays

A two-dimensional array consists of an array of one-dimensional arrays and a three-dimensional array consists of an array of two-dimensional arrays.



In the preceding section, you used a two-dimensional array to represent a matrix or a table. Occasionally, you will need to represent n -dimensional data structures. In Java, you can create n -dimensional arrays for any integer n .

The way to declare two-dimensional array variables and create two-dimensional arrays can be generalized to declare n -dimensional array variables and create n -dimensional arrays for $n \geq 3$. For example, you may use a three-dimensional array to store exam scores for a class of six students with five exams, and each exam has two parts (multiple-choice and essay). The following syntax declares a three-dimensional array variable `scores`, creates an array, and assigns its reference to `scores`.

```
double[][][] scores = new double[6][5][2];
```

You can also use the short-hand notation to create and initialize the array as follows:

```
double[][][] scores = {
    {{7.5, 20.5}, {9.0, 22.5}, {15, 33.5}, {13, 21.5}, {15, 2.5}},
    {{4.5, 21.5}, {9.0, 22.5}, {15, 34.5}, {12, 20.5}, {14, 9.5}},
    {{6.5, 30.5}, {9.4, 10.5}, {11, 33.5}, {11, 23.5}, {10, 2.5}},
    {{6.5, 23.5}, {9.4, 32.5}, {13, 34.5}, {11, 20.5}, {16, 7.5}},
    {{8.5, 26.5}, {9.4, 52.5}, {13, 36.5}, {13, 24.5}, {16, 2.5}},
    {{9.5, 20.5}, {9.4, 42.5}, {13, 31.5}, {12, 20.5}, {16, 6.5}}};
```

`scores[0][1][0]` refers to the multiple-choice score for the first student's second exam, which is **9.0**. `scores[0][1][1]` refers to the essay score for the first student's second exam, which is **22.5**. This is depicted in the following figure:



A multidimensional array is actually an array in which each element is another array. A three-dimensional array consists of an array of two-dimensional arrays. A two-dimensional array consists of an array of one-dimensional arrays. For example, suppose `x = new int[2][2][5]`, and `x[0]` and `x[1]` are two-dimensional arrays. `x[0][0]`, `x[0][1]`, `x[1][0]`, and `x[1][1]` are one-dimensional arrays and each contains five elements. `x.length` is **2**, `x[0].length` and `x[1].length` are **2**, and `x[0][0].length`, `x[0][1].length`, `x[1][0].length`, and `x[1][1].length` are **5**.

8.8.1 Case Study: Daily Temperature and Humidity

Suppose a meteorology station records the temperature and humidity every hour of every day and stores the data for the past ten days in a text file named **Weather.txt** (see www.cs.armstrong.edu/liang/data/Weather.txt). Each line of the file consists of four numbers that indicate the day, hour, temperature, and humidity. The contents of the file may look like the one in (a).

Day	Hour	Temperature	Humidity
1	1	76.4	0.92
1	2	77.7	0.93
..			
10	23	97.7	0.71
10	24	98.7	0.74

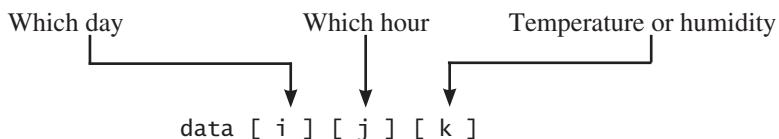
(a)

Day	Hour	Temperature	Humidity
10	24	98.7	0.74
1	2	77.7	0.93
..			
10	23	97.7	0.71
1	1	76.4	0.92

(b)

Note that the lines in the file are not necessarily in increasing order of day and hour. For example, the file may appear as shown in (b).

Your task is to write a program that calculates the average daily temperature and humidity for the **10** days. You can use the input redirection to read the file and store the data in a three-dimensional array named **data**. The first index of **data** ranges from **0** to **9** and represents **10** days, the second index ranges from **0** to **23** and represents **24** hours, and the third index ranges from **0** to **1** and represents temperature and humidity, as depicted in the following figure:



Note that the days are numbered from 1 to 10 and the hours from 1 to 24 in the file. Because the array index starts from 0, `data[0][0][0]` stores the temperature in day 1 at hour 1 and `data[9][23][1]` stores the humidity in day 10 at hour 24.

The program is given in Listing 8.5.

LISTING 8.5 Weather.java

```

1 import java.util.Scanner;
2
3 public class Weather {
4     public static void main(String[] args) {
5         final int NUMBER_OF_DAYS = 10;
6         final int NUMBER_OF_HOURS = 24;
7         double[][][] data
8             = new double[NUMBER_OF_DAYS][NUMBER_OF_HOURS][2];           three-dimensional array
9
10    Scanner input = new Scanner(System.in);
11    // Read input using input redirection from a file
12    for (int k = 0; k < NUMBER_OF_DAYS * NUMBER_OF_HOURS; k++) {
13        int day = input.nextInt();
14        int hour = input.nextInt();
15        double temperature = input.nextDouble();
16        double humidity = input.nextDouble();
17        data[day - 1][hour - 1][0] = temperature;
18        data[day - 1][hour - 1][1] = humidity;
19    }
20
21    // Find the average daily temperature and humidity
22    for (int i = 0; i < NUMBER_OF_DAYS; i++) {
23        double dailyTemperatureTotal = 0, dailyHumidityTotal = 0;
24        for (int j = 0; j < NUMBER_OF_HOURS; j++) {
25            dailyTemperatureTotal += data[i][j][0];
26            dailyHumidityTotal += data[i][j][1];
27        }
28
29        // Display result
30        System.out.println("Day " + i + "'s average temperature is "
31            + dailyTemperatureTotal / NUMBER_OF_HOURS);
32        System.out.println("Day " + i + "'s average humidity is "
33            + dailyHumidityTotal / NUMBER_OF_HOURS);
34    }
35 }
36 }
```

```

Day 0's average temperature is 77.7708
Day 0's average humidity is 0.929583
Day 1's average temperature is 77.3125
Day 1's average humidity is 0.929583
...
Day 9's average temperature is 79.3542
Day 9's average humidity is 0.9125

```



You can use the following command to run the program:

```
java Weather < Weather.txt
```

A three-dimensional array for storing temperature and humidity is created in line 8. The loop in lines 12–19 reads the input to the array. You can enter the input from the keyboard, but

doing so will be awkward. For convenience, we store the data in a file and use input redirection to read the data from the file. The loop in lines 24–27 adds all temperatures for each hour in a day to `dailyTemperatureTotal` and all humidity for each hour to `dailyHumidityTotal`. The average daily temperature and humidity are displayed in lines 30–33.

8.8.2 Case Study: Guessing Birthdays

Listing 3.3, `GuessBirthday.java`, gives a program that guesses a birthday. The program can be simplified by storing the numbers in five sets in a three-dimensional array, and it prompts the user for the answers using a loop, as shown in Listing 8.6. The sample run of the program can be the same as shown in Listing 4.3.

LISTING 8.6 `GuessBirthdayUsingArray.java`

```

1 import java.util.Scanner;
2
3 public class GuessBirthdayUsingArray {
4     public static void main(String[] args) {
5         int day = 0; // Day to be determined
6         int answer;
7
three-dimensional array
8         int[][][] dates = {
9             {{ 1,  3,  5,  7},
10            { 9, 11, 13, 15},
11            {17, 19, 21, 23},
12            {25, 27, 29, 31}},
13            {{ 2,  3,  6,  7},
14            {10, 11, 14, 15},
15            {18, 19, 22, 23},
16            {26, 27, 30, 31}},
17            {{ 4,  5,  6,  7},
18            {12, 13, 14, 15},
19            {20, 21, 22, 23},
20            {28, 29, 30, 31}},
21            {{ 8,  9, 10, 11},
22            {12, 13, 14, 15},
23            {24, 25, 26, 27},
24            {28, 29, 30, 31}},
25            {{16, 17, 18, 19},
26            {20, 21, 22, 23},
27            {24, 25, 26, 27},
28            {28, 29, 30, 31}}};
29
30 // Create a Scanner
31 Scanner input = new Scanner(System.in);
32
Set i
33 for (int i = 0; i < 5; i++) {
34     System.out.println("Is your birthday in Set" + (i + 1) + "?");
35     for (int j = 0; j < 4; j++) {
36         for (int k = 0; k < 4; k++)
37             System.out.printf("%4d", dates[i][j][k]);
38         System.out.println();
39     }
40
41     System.out.print("\nEnter 0 for No and 1 for Yes: ");
42     answer = input.nextInt();
43
44     if (answer == 1)
45         day += dates[i][0][0];

```

add to day

```

46     }
47
48     System.out.println("Your birthday is " + day);
49 }
50 }
```

A three-dimensional array **dates** is created in Lines 8–28. This array stores five sets of numbers. Each set is a 4-by-4 two-dimensional array.

The loop starting from line 33 displays the numbers in each set and prompts the user to answer whether the birthday is in the set (lines 41–42). If the day is in the set, the first number (**dates[i][0][0]**) in the set is added to variable **day** (line 45).

- 8.8** Declare an array variable for a three-dimensional array, create a $4 \times 6 \times 5$ **int** array, and assign its reference to the variable.
- 8.9** Assume **int[][][] x = new char[12][5][2]**, how many elements are in the array? What are **x.length**, **x[2].length**, and **x[0][0].length**?
- 8.10** Show the output of the following code:



```

int[][][] array = {{{1, 2}, {3, 4}}, {{5, 6}, {7, 8}}};
System.out.println(array[0][0][0]);
System.out.println(array[1][1][1]);
```

CHAPTER SUMMARY

1. A two-dimensional array can be used to store a table.
2. A variable for two-dimensional arrays can be declared using the syntax: **elementType[][] arrayVar**.
3. A two-dimensional array can be created using the syntax: **new elementType [ROW_SIZE][COLUMN_SIZE]**.
4. Each element in a two-dimensional array is represented using the syntax: **arrayVar[rowIndex][columnIndex]**.
5. You can create and initialize a two-dimensional array using an array initializer with the syntax: **elementType[][] arrayVar = {{row values}, . . . , {row values}}**.
6. You can use arrays of arrays to form multidimensional arrays. For example, a variable for three-dimensional arrays can be declared as **elementType[][][] arrayVar**, and a three-dimensional array can be created using **new elementType[size1][size2][size3]**.

Quiz

Answer the quiz for this chapter online at www.cs.armstrong.edu/liang/intro10e/quiz.html.

PROGRAMMING EXERCISES

MyProgrammingLab™

- *8.1** (*Sum elements column by column*) Write a method that returns the sum of all the elements in a specified column in a matrix using the following header:

```
public static double sumColumn(double[][] m, int columnIndex)
```

Write a test program that reads a 3-by-4 matrix and displays the sum of each column. Here is a sample run:



```
Enter a 3-by-4 matrix row by row:
1.5 2 3 4 ↵ Enter
5.5 6 7 8 ↵ Enter
9.5 1 3 1 ↵ Enter
Sum of the elements at column 0 is 16.5
Sum of the elements at column 1 is 9.0
Sum of the elements at column 2 is 13.0
Sum of the elements at column 3 is 13.0
```

***8.2**

(*Sum the major diagonal in a matrix*) Write a method that sums all the numbers in the major diagonal in an $n \times n$ matrix of **double** values using the following header:

```
public static double sumMajorDiagonal(double[][] m)
```

Write a test program that reads a 4-by-4 matrix and displays the sum of all its elements on the major diagonal. Here is a sample run:



```
Enter a 4-by-4 matrix row by row:
1 2 3 4.0 ↵ Enter
5 6.5 7 8 ↵ Enter
9 10 11 12 ↵ Enter
13 14 15 16 ↵ Enter
Sum of the elements in the major diagonal is 34.5
```

***8.3**

(*Sort students on grades*) Rewrite Listing 8.2, GradeExam.java, to display the students in increasing order of the number of correct answers.

****8.4**

(*Compute the weekly hours for each employee*) Suppose the weekly hours for all employees are stored in a two-dimensional array. Each row records an employee's seven-day work hours with seven columns. For example, the following array stores the work hours for eight employees. Write a program that displays employees and their total hours in decreasing order of the total hours.

	Su	M	T	W	Th	F	Sa
Employee 0	2	4	3	4	5	8	8
Employee 1	7	3	4	3	3	4	4
Employee 2	3	3	4	3	3	2	2
Employee 3	9	3	4	7	3	4	1
Employee 4	3	5	4	3	6	3	8
Employee 5	3	4	4	6	3	4	4
Employee 6	3	7	4	8	3	8	4
Employee 7	6	3	5	9	2	7	9

8.5

(*Algebra: add two matrices*) Write a method to add two matrices. The header of the method is as follows:

```
public static double[][] addMatrix(double[][] a, double[][] b)
```

In order to be added, the two matrices must have the same dimensions and the same or compatible types of elements. Let **c** be the resulting matrix. Each element c_{ij} is $a_{ij} + b_{ij}$. For example, for two 3×3 matrices **a** and **b**, **c** is

$$\begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} + \begin{pmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{pmatrix} = \begin{pmatrix} a_{11} + b_{11} & a_{12} + b_{12} & a_{13} + b_{13} \\ a_{21} + b_{21} & a_{22} + b_{22} & a_{23} + b_{23} \\ a_{31} + b_{31} & a_{32} + b_{32} & a_{33} + b_{33} \end{pmatrix}$$



Multiply two matrices

Write a test program that prompts the user to enter two 3×3 matrices and displays their sum. Here is a sample run:



```
Enter matrix1: 1 2 3 4 5 6 7 8 9 ↵Enter
Enter matrix2: 0 2 4 1 4.5 2.2 1.1 4.3 5.2 ↵Enter
The matrices are added as follows
1.0 2.0 3.0      0.0 2.0 4.0      1.0 4.0 7.0
4.0 5.0 6.0 +   1.0 4.5 2.2 =   5.0 9.5 8.2
7.0 8.0 9.0      1.1 4.3 5.2      8.1 12.3 14.2
```

**8.6

(Algebra: multiply two matrices) Write a method to multiply two matrices. The header of the method is:

```
public static double[][] multiplyMatrix(double[][] a, double[][] b)
```

To multiply matrix **a** by matrix **b**, the number of columns in **a** must be the same as the number of rows in **b**, and the two matrices must have elements of the same or compatible types. Let **c** be the result of the multiplication. Assume the column size of matrix **a** is **n**. Each element c_{ij} is $a_{i1} \times b_{1j} + a_{i2} \times b_{2j} + \dots + a_{in} \times b_{nj}$. For example, for two 3×3 matrices **a** and **b**, **c** is

$$\begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \times \begin{pmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{pmatrix} = \begin{pmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{pmatrix}$$

where $c_{ij} = a_{i1} \times b_{1j} + a_{i2} \times b_{2j} + a_{i3} \times b_{3j}$.

Write a test program that prompts the user to enter two 3×3 matrices and displays their product. Here is a sample run:



```
Enter matrix1: 1 2 3 4 5 6 7 8 9 ↵Enter
Enter matrix2: 0 2 4 1 4.5 2.2 1.1 4.3 5.2 ↵Enter
The multiplication of the matrices is
1 2 3      0 2.0 4.0      5.3 23.9 24
4 5 6 * 1 4.5 2.2 = 11.6 56.3 58.2
7 8 9      1.1 4.3 5.2      17.9 88.7 92.4
```

*8.7

(Points nearest to each other) Listing 8.3 gives a program that finds two points in a two-dimensional space nearest to each other. Revise the program so that it finds two points in a three-dimensional space nearest to each other. Use a two-dimensional array to represent the points. Test the program using the following points:

```
double[][] points = {{-1, 0, 3}, {-1, -1, -1}, {4, 1, 1},
{2, 0.5, 9}, {3.5, 2, -1}, {3, 1.5, 3}, {-1.5, 4, 2},
{5.5, 4, -0.5}};
```

The formula for computing the distance between two points (x_1 , y_1 , z_1) and (x_2 , y_2 , z_2) is $\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}$.

- **8.8** (All closest pairs of points) Revise Listing 8.3, FindNearestPoints.java, to display all closest pairs of points with the same minimum distance. Here is a sample run:



```
Enter the number of points: 8 ↵ Enter
Enter 8 points: 0 0 1 1 -1 -1 2 2 -2 -2 -3 -3 -4 -4 5 5 ↵ Enter
The closest two points are (0.0, 0.0) and (1.0, 1.0)
The closest two points are (0.0, 0.0) and (-1.0, -1.0)
The closest two points are (1.0, 1.0) and (2.0, 2.0)
The closest two points are (-1.0, -1.0) and (-2.0, -2.0)
The closest two points are (-2.0, -2.0) and (-3.0, -3.0)
The closest two points are (-3.0, -3.0) and (-4.0, -4.0)
Their distance is 1.4142135623730951
```

- ***8.9** (Game: play a tic-tac-toe game) In a game of tic-tac-toe, two players take turns marking an available cell in a 3×3 grid with their respective tokens (either X or O). When one player has placed three tokens in a horizontal, vertical, or diagonal row on the grid, the game is over and that player has won. A draw (no winner) occurs when all the cells on the grid have been filled with tokens and neither player has achieved a win. Create a program for playing tic-tac-toe.

The program prompts two players to enter an X token and O token alternately. Whenever a token is entered, the program redisplays the board on the console and determines the status of the game (win, draw, or continue). Here is a sample run:



```
-----
| | | |
-----
| | | |
-----
| | | |
-----
Enter a row (0, 1, or 2) for player X: 1 ↵ Enter
Enter a column (0, 1, or 2) for player X: 1 ↵ Enter
-----
| | | |
-----
| | X | |
-----
| | | |
-----
Enter a row (0, 1, or 2) for player O: 1 ↵ Enter
Enter a column (0, 1, or 2) for player O: 2 ↵ Enter
-----
| | | |
-----
| | X | O |
-----
| | | |
-----
```

Enter a row (0, 1, or 2) for player X:

. . .

	X					
	0		X		0	
			X			

X player won

*8.10

(Largest row and column) Write a program that randomly fills in 0s and 1s into a 4-by-4 matrix, prints the matrix, and finds the first row and column with the most 1s. Here is a sample run of the program:

```
0011
0011
1101
1010
The largest row index: 2
The largest column index: 2
```

**8.11

(Game: nine heads and tails) Nine coins are placed in a 3-by-3 matrix with some face up and some face down. You can represent the state of the coins using a 3-by-3 matrix with values **0** (heads) and **1** (tails). Here are some examples:

0 0 0	1 0 1	1 1 0	1 0 1	1 0 0
0 1 0	0 0 1	1 0 0	1 1 0	1 1 1
0 0 0	1 0 0	0 0 1	1 0 0	1 1 0

Each state can also be represented using a binary number. For example, the preceding matrices correspond to the numbers

000010000 101001100 110100001 101110100 100111110

There are a total of 512 possibilities, so you can use decimal numbers 0, 1, 2, 3, . . . , and 511 to represent all states of the matrix. Write a program that prompts the user to enter a number between 0 and 511 and displays the corresponding matrix with the characters **H** and **T**. Here is a sample run:

Enter a number between 0 and 511: 7

H	H	H
H	H	H
T	T	T



The user entered **7**, which corresponds to **000000111**. Since **0** stands for **H** and **1** for **T**, the output is correct.

**8.12

(Financial application: compute tax) Rewrite Listing 3.5, ComputeTax.java, using arrays. For each filing status, there are six tax rates. Each rate is applied to a certain amount of taxable income. For example, from the taxable income of \$400,000 for a single filer, \$8,350 is taxed at 10%, $(33,950 - 8,350)$ at 15%,

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$(82,250 - 33,950)$ at 25%, $(171,550 - 82,550)$ at 28%, $(372,550 - 82,250)$ at 33%, and $(400,000 - 372,950)$ at 36%. The six rates are the same for all filing statuses, which can be represented in the following array:

```
double[] rates = {0.10, 0.15, 0.25, 0.28, 0.33, 0.35};
```

The brackets for each rate for all the filing statuses can be represented in a two-dimensional array as follows:

```
int[][] brackets = {
    {8350, 33950, 82250, 171550, 372950}, // Single filer
    {16700, 67900, 137050, 20885, 372950}, // Married jointly
                                                // -or qualifying widow(er)
    {8350, 33950, 68525, 104425, 186475}, // Married separately
    {11950, 45500, 117450, 190200, 372950} // Head of household
};
```

Suppose the taxable income is \$400,000 for single filers. The tax can be computed as follows:

```
tax = brackets[0][0] * rates[0] +
      (brackets[0][1] - brackets[0][0]) * rates[1] +
      (brackets[0][2] - brackets[0][1]) * rates[2] +
      (brackets[0][3] - brackets[0][2]) * rates[3] +
      (brackets[0][4] - brackets[0][3]) * rates[4] +
      (400000 - brackets[0][4]) * rates[5]
```

- *8.13** (*Locate the largest element*) Write the following method that returns the location of the largest element in a two-dimensional array.

```
public static int[] locateLargest(double[][] a)
```

The return value is a one-dimensional array that contains two elements. These two elements indicate the row and column indices of the largest element in the two-dimensional array. Write a test program that prompts the user to enter a two-dimensional array and displays the location of the largest element in the array. Here is a sample run:



```
Enter the number of rows and columns of the array: 3 4 ↵Enter
Enter the array:
23.5 35 2 10 ↵Enter
4.5 3 45 3.5 ↵Enter
35 44 5.5 9.6 ↵Enter
The location of the largest element is at (1, 2)
```

- **8.14** (*Explore matrix*) Write a program that prompts the user to enter the length of a square matrix, randomly fills in **0**s and **1**s into the matrix, prints the matrix, and finds the rows, columns, and diagonals with all **0**s or **1**s. Here is a sample run of the program:

```
Enter the size for the matrix: 4 ↵Enter
0111
0000
0100
1111
All 0s on row 1
All 1s on row 3
No same numbers on a column
No same numbers on the major diagonal
No same numbers on the sub-diagonal
```



- *8.15** (*Geometry: same line?*) Programming Exercise 6.39 gives a method for testing whether three points are on the same line.

Write the following method to test whether all the points in the array `points` are on the same line.

```
public static boolean sameLine(double[][] points)
```

Write a program that prompts the user to enter five points and displays whether they are on the same line. Here are sample runs:

```
Enter five points: 3.4 2 6.5 9.5 2.3 2.3 5.5 5 -5 4 ↵Enter
The five points are not on the same line
```



```
Enter five points: 1 1 2 2 3 3 4 4 5 5 ↵Enter
The five points are on the same line
```



- *8.16** (*Sort two-dimensional array*) Write a method to sort a two-dimensional array using the following header:

```
public static void sort(int m[][])
```

The method performs a primary sort on rows and a secondary sort on columns. For example, the following array

```
{{{4, 2},{1, 7},{4, 5},{1, 2},{1, 1},{4, 1}}}
```

will be sorted to

```
{{{1, 1},{1, 2},{1, 7},{4, 1},{4, 2},{4, 5}}}.
```

- ***8.17** (*Financial tsunami*) Banks lend money to each other. In tough economic times, if a bank goes bankrupt, it may not be able to pay back the loan. A bank's total assets are its current balance plus its loans to other banks. The diagram in Figure 8.8 shows five banks. The banks' current balances are 25, 125, 175, 75, and 181 million dollars, respectively. The directed edge from node 1 to node 2 indicates that bank 1 lends 40 million dollars to bank 2.



FIGURE 8.8 Banks lend money to each other.

If a bank's total assets are under a certain limit, the bank is unsafe. The money it borrowed cannot be returned to the lender, and the lender cannot count the loan in its total assets. Consequently, the lender may also be unsafe, if its total assets are under the limit. Write a program to find all the unsafe banks. Your program reads the input as follows. It first reads two integers **n** and **limit**, where **n** indicates the number of banks and **limit** is the minimum total assets for keeping a bank safe. It then reads **n** lines that describe the information for **n** banks with IDs from **0** to **n-1**. The first number in the line is the bank's balance, the second number indicates the number of banks that borrowed money from the bank, and the rest are pairs of two numbers. Each pair describes a borrower. The first number in the pair is the borrower's ID and the second is the amount borrowed. For example, the input for the five banks in Figure 8.8 is as follows (note that the limit is 201):

```
5 201
25 2 1 100.5 4 320.5
125 2 2 40 3 85
175 2 0 125 3 75
75 1 0 125
181 1 2 125
```

The total assets of bank 3 are $(75 + 125)$, which is under 201, so bank 3 is unsafe. After bank 3 becomes unsafe, the total assets of bank 1 fall below $(125 + 40)$. Thus, bank 1 is also unsafe. The output of the program should be

Unsafe banks are 3 1

(Hint: Use a two-dimensional array **borrowers** to represent loans. **borrowers[i][j]** indicates the loan that bank **i** loans to bank **j**. Once bank **j** becomes unsafe, **borrowers[i][j]** should be set to **0**.)

*8.18

(*Shuffle rows*) Write a method that shuffles the rows in a two-dimensional **int** array using the following header:

```
public static void shuffle(int[][] m)
```

Write a test program that shuffles the following matrix:

```
int[][] m = {{1, 2}, {3, 4}, {5, 6}, {7, 8}, {9, 10}};
```

**8.19

(*Pattern recognition: four consecutive equal numbers*) Write the following method that tests whether a two-dimensional array has four consecutive numbers of the same value, either horizontally, vertically, or diagonally.

```
public static boolean isConsecutiveFour(int[][] values)
```

Write a test program that prompts the user to enter the number of rows and columns of a two-dimensional array and then the values in the array and displays true if the array contains four consecutive numbers with the same value. Otherwise, display false. Here are some examples of the true cases:

0	1	0	3	1	6	1
0	1	6	8	6	0	1
5	6	2	1	8	2	9
6	5	6	1	1	9	1
1	3	6	1	4	0	7
3	3	3	3	4	0	7

0	1	0	3	1	6	1
0	1	6	8	6	0	1
5	5	2	1	8	2	9
6	5	6	1	1	9	1
1	5	6	1	4	0	7
3	5	3	3	4	0	7

0	1	0	3	1	6	1
0	1	6	8	6	0	1
5	6	2	1	6	2	9
6	5	6	1	1	9	1
1	3	6	1	4	0	7
3	6	3	3	4	0	7

0	1	0	3	1	6	1
0	1	6	8	6	0	1
9	6	2	1	8	2	9
6	9	6	1	1	9	1
1	3	9	1	4	0	7
3	3	3	9	4	0	7

- ***8.20** (*Game: connect four*) Connect four is a two-player board game in which the players alternately drop colored disks into a seven-column, six-row vertically suspended grid, as shown below.



The objective of the game is to connect four same-colored disks in a row, a column, or a diagonal before your opponent can do likewise. The program prompts two players to drop a red or yellow disk alternately. In the preceding figure, the red disk is shown in a dark color and the yellow in a light color. Whenever a disk is dropped, the program redisplays the board on the console and determines the status of the game (win, draw, or continue). Here is a sample run:

```

| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |

Drop a red disk at column (0-6): 0 ↵Enter

| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| R | | | | |

```





Drop a yellow disk at column (0-6): 3 ↵ Enter

```
| | | | | | | |
| | | | | | | |
| | | | | | | |
|R| | |Y| | | |
```

. . .
. . .
. . .

Drop a yellow disk at column (0-6): 6 ↵ Enter

```
| | | | | | | | | |
| | | | | | | |
| | | |R| | | | |
| | | |Y|R|Y| | |
| | | |R|Y|Y|Y|Y| |
|R|Y|R|Y|R|R|R|
```

The yellow player won

*8.21

(Central city) Given a set of cities, the central city is the city that has the shortest total distance to all other cities. Write a program that prompts the user to enter the number of the cities and the locations of the cities (coordinates), and finds the central city and its total distance to all other cities.



Enter the number of cities: 5 ↵ Enter

Enter the coordinates of the cities:

2.5 5 5.1 3 1 9 5.4 54 5.5 2.1 ↵ Enter

The central city is at (2.5, 5.0)

The total distance to all other cities is 60.81

*8.22

(Even number of 1s) Write a program that generates a 6-by-6 two-dimensional matrix filled with 0s and 1s, displays the matrix, and checks if every row and every column have an even number of 1s.

*8.23

(Game: find the flipped cell) Suppose you are given a 6-by-6 matrix filled with 0s and 1s. All rows and all columns have an even number of 1s. Let the user flip one cell (i.e., flip from 1 to 0 or from 0 to 1) and write a program to find which cell was flipped. Your program should prompt the user to enter a 6-by-6 array with 0s and 1s and find the first row r and first column c where the even number of the 1s property is violated (i.e., the number of 1s is not even). The flipped cell is at (r, c) . Here is a sample run:



Enter a 6-by-6 matrix row by row:

1 1 1 0 1 1 ↵ Enter

1 1 1 1 0 0 ↵ Enter

0 1 0 1 1 1 ↵ Enter

1 1 1 1 1 1 ↵ Enter

0 1 1 1 1 0 ↵ Enter

1 0 0 0 0 1 ↵ Enter

The flipped cell is at (0, 1)



VideoNote

Even number of 1s

***8.24** (*Check Sudoku solution*) Listing 8.4 checks whether a solution is valid by checking whether every number is valid in the board. Rewrite the program by checking whether every row, every column, and every small box has the numbers 1 to 9.

***8.25** (*Markov matrix*) An $n \times n$ matrix is called a *positive Markov matrix* if each element is positive and the sum of the elements in each column is 1. Write the following method to check whether a matrix is a Markov matrix.

```
public static boolean isMarkovMatrix(double[][] m)
```

Write a test program that prompts the user to enter a 3×3 matrix of double values and tests whether it is a Markov matrix. Here are sample runs:



```
Enter a 3-by-3 matrix row by row:  
0.15 0.875 0.375 ↵ Enter  
0.55 0.005 0.225 ↵ Enter  
0.30 0.12 0.4 ↵ Enter  
It is a Markov matrix
```



```
Enter a 3-by-3 matrix row by row:  
0.95 -0.875 0.375 ↵ Enter  
0.65 0.005 0.225 ↵ Enter  
0.30 0.22 -0.4 ↵ Enter  
It is not a Markov matrix
```

***8.26** (*Row sorting*) Implement the following method to sort the rows in a two-dimensional array. A new array is returned and the original array is intact.

```
public static double[][] sortRows(double[][] m)
```

Write a test program that prompts the user to enter a 3×3 matrix of double values and displays a new row-sorted matrix. Here is a sample run:



```
Enter a 3-by-3 matrix row by row:  
0.15 0.875 0.375 ↵ Enter  
0.55 0.005 0.225 ↵ Enter  
0.30 0.12 0.4 ↵ Enter  
  
The row-sorted array is  
0.15 0.375 0.875  
0.005 0.225 0.55  
0.12 0.30 0.4
```

***8.27** (*Column sorting*) Implement the following method to sort the columns in a two-dimensional array. A new array is returned and the original array is intact.

```
public static double[][] sortColumns(double[][] m)
```

Write a test program that prompts the user to enter a 3×3 matrix of double values and displays a new column-sorted matrix. Here is a sample run:



Enter a 3-by-3 matrix row by row:

0.15 0.875 0.375

0.55 0.005 0.225

0.30 0.12 0.4

The column-sorted array is

0.15 0.0050 0.225

0.3 0.12 0.375

0.55 0.875 0.4

8.28

(*Strictly identical arrays*) The two-dimensional arrays `m1` and `m2` are *strictly identical* if their corresponding elements are equal. Write a method that returns `true` if `m1` and `m2` are strictly identical, using the following header:

```
public static boolean equals(int[][] m1, int[][] m2)
```

Write a test program that prompts the user to enter two 3×3 arrays of integers and displays whether the two are strictly identical. Here are the sample runs.



Enter list1: 51 22 25 6 1 4 24 54 6

Enter list2: 51 22 25 6 1 4 24 54 6

The two arrays are strictly identical



Enter list1: 51 25 22 6 1 4 24 54 6

Enter list2: 51 22 25 6 1 4 24 54 6

The two arrays are not strictly identical

8.29

(*Identical arrays*) The two-dimensional arrays `m1` and `m2` are *identical* if they have the same contents. Write a method that returns `true` if `m1` and `m2` are identical, using the following header:

```
public static boolean equals(int[][] m1, int[][] m2)
```

Write a test program that prompts the user to enter two 3×3 arrays of integers and displays whether the two are identical. Here are the sample runs.



Enter list1: 51 25 22 6 1 4 24 54 6

Enter list2: 51 22 25 6 1 4 24 54 6

The two arrays are identical



Enter list1: 51 5 22 6 1 4 24 54 6

Enter list2: 51 22 25 6 1 4 24 54 6

The two arrays are not identical

- *8.30** (*Algebra: solve linear equations*) Write a method that solves the following 2×2 system of linear equations:

$$\begin{aligned} a_{00}x + a_{01}y &= b_0 & x &= \frac{b_0a_{11} - b_1a_{01}}{a_{00}a_{11} - a_{01}a_{10}} & y &= \frac{b_1a_{00} - b_0a_{10}}{a_{00}a_{11} - a_{01}a_{10}} \\ a_{10}x + a_{11}y &= b_1 \end{aligned}$$

The method header is

```
public static double[] linearEquation(double[][] a, double[] b)
```

The method returns **null** if $a_{00}a_{11} - a_{01}a_{10}$ is **0**. Write a test program that prompts the user to enter a_{00} , a_{01} , a_{10} , a_{11} , b_0 , and b_1 , and displays the result. If $a_{00}a_{11} - a_{01}a_{10}$ is **0**, report that “The equation has no solution.” A sample run is similar to Programming Exercise 3.3.

- *8.31** (*Geometry: intersecting point*) Write a method that returns the intersecting point of two lines. The intersecting point of the two lines can be found by using the formula shown in Programming Exercise 3.25. Assume that (x_1, y_1) and (x_2, y_2) are the two points on line 1 and (x_3, y_3) and (x_4, y_4) are on line 2. The method header is

```
public static double[] getIntersectingPoint(double[][] points)
```

The points are stored in a 4-by-2 two-dimensional array **points** with **points[0][0], points[0][1]** for (x_1, y_1) . The method returns the intersecting point or **null** if the two lines are parallel. Write a program that prompts the user to enter four points and displays the intersecting point. See Programming Exercise 3.25 for a sample run.

- *8.32** (*Geometry: area of a triangle*) Write a method that returns the area of a triangle using the following header:

```
public static double getTriangleArea(double[][] points)
```

The points are stored in a 3-by-2 two-dimensional array **points** with **points[0][0], points[0][1]** for (x_1, y_1) . The triangle area can be computed using the formula in Programming Exercise 2.19. The method returns **0** if the three points are on the same line. Write a program that prompts the user to enter three points of a triangle and displays the triangle's area. Here is a sample run of the program:

Enter $x_1, y_1, x_2, y_2, x_3, y_3$: 2.5 2 5 -1.0 4.0 2.0



The area of the triangle is 2.25



Enter $x_1, y_1, x_2, y_2, x_3, y_3$: 2 2 4.5 4.5 6 6

The three points are on the same line

- *8.33** (*Geometry: polygon subareas*) A convex 4-vertex polygon is divided into four triangles, as shown in Figure 8.9.

Write a program that prompts the user to enter the coordinates of four vertices and displays the areas of the four triangles in increasing order. Here is a sample run:

Enter $x_1, y_1, x_2, y_2, x_3, y_3, x_4, y_4$:

-2.5 2 4 4 3 -2 -2 -3.5



The areas are 6.17 7.96 8.08 10.42



FIGURE 8.9 A 4-vertex polygon is defined by four vertices.

- *8.34** (*Geometry: rightmost lowest point*) In computational geometry, often you need to find the rightmost lowest point in a set of points. Write the following method that returns the rightmost lowest point in a set of points.

```
public static double[]
getRightmostLowestPoint(double[][] points)
```

Write a test program that prompts the user to enter the coordinates of six points and displays the rightmost lowest point. Here is a sample run:



```
Enter 6 points: 1.5 2.5 -3 4.5 5.6 -7 6.5 -7 8 1 10 2.5 ↵ Enter
The rightmost lowest point is (6.5, -7.0)
```

- **8.35** (*Largest block*) Given a square matrix with the elements 0 or 1, write a program to find a maximum square submatrix whose elements are all 1s. Your program should prompt the user to enter the number of rows in the matrix. The program then displays the location of the first element in the maximum square submatrix and the number of the rows in the submatrix. Here is a sample run:



```
Enter the number of rows in the matrix: 5 ↵ Enter
Enter the matrix row by row:
1 0 1 0 1 ↵ Enter
1 1 1 0 1 ↵ Enter
1 0 1 1 1 ↵ Enter
1 0 1 1 1 ↵ Enter
1 0 1 1 1 ↵ Enter
```

```
The maximum square submatrix is at (2, 2) with size 3
```

Your program should implement and use the following method to find the maximum square submatrix:

```
public static int[] findLargestBlock(int[][] m)
```

The return value is an array that consists of three values. The first two values are the row and column indices for the first element in the submatrix, and the third value is the number of the rows in the submatrix.

- **8.36** (*Latin square*) A Latin square is an n -by- n array filled with n different Latin letters, each occurring exactly once in each row and once in each column. Write a

program that prompts the user to enter the number **n** and the array of characters, as shown in the sample output, and checks if the input array is a Latin square. The characters are the first **n** characters starting from **A**.



```
Enter number n: 4 ↵Enter
Enter 4 rows of letters separated by spaces:
A B C D ↵Enter
B A D C ↵Enter
C D B A ↵Enter
D C A B ↵Enter
The input array is a Latin square
```



```
Enter number n: 3 ↵Enter
Enter 3 rows of letters separated by spaces:
A F D ↵Enter
Wrong input: the letters must be from A to C
```

- **8.37** (*Guess the capitals*) Write a program that repeatedly prompts the user to enter a capital for a state. Upon receiving the user input, the program reports whether the answer is correct. Assume that **50** states and their capitals are stored in a two-dimensional array, as shown in Figure 8.10. The program prompts the user to answer all states' capitals and displays the total correct count. The user's answer is not case-sensitive.

Alabama	Montgomery
Alaska	Juneau
Arizona	Phoenix
...	...
...	...

FIGURE 8.10 A two-dimensional array stores states and their capitals.

Here is a sample run:



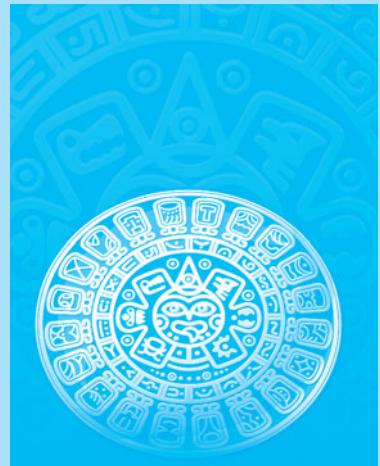
```
What is the capital of Alabama? Montogomery ↵Enter
The correct answer should be Montgomery
What is the capital of Alaska? Juneau ↵Enter
Your answer is correct
What is the capital of Arizona? ...
...
The correct count is 35
```

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OBJECTS AND CLASSES

Objectives

- To describe objects and classes, and use classes to model objects (§9.2).
- To use UML graphical notation to describe classes and objects (§9.2).
- To demonstrate how to define classes and create objects (§9.3).
- To create objects using constructors (§9.4).
- To access objects via object reference variables (§9.5).
- To define a reference variable using a reference type (§9.5.1).
- To access an object's data and methods using the object member access operator (`.`) (§9.5.2).
- To define data fields of reference types and assign default values for an object's data fields (§9.5.3).
- To distinguish between object reference variables and primitive data type variables (§9.5.4).
- To use the Java library classes `Date`, `Random`, and `Point2D` (§9.6).
- To distinguish between instance and static variables and methods (§9.7).
- To define private data fields with appropriate getter and setter methods (§9.8).
- To encapsulate data fields to make classes easy to maintain (§9.9).
- To develop methods with object arguments and differentiate between primitive-type arguments and object-type arguments (§9.10).
- To store and process objects in arrays (§9.11).
- To create immutable objects from immutable classes to protect the contents of objects (§9.12).
- To determine the scope of variables in the context of a class (§9.13).
- To use the keyword `this` to refer to the calling object itself (§9.14).



9.1 Introduction



Object-oriented programming enables you to develop large-scale software and GUIs effectively.

why OOP?

Having learned the material in the preceding chapters, you are able to solve many programming problems using selections, loops, methods, and arrays. However, these Java features are not sufficient for developing graphical user interfaces and large-scale software systems. Suppose you want to develop a graphical user interface (GUI, pronounced *goo-ee*) as shown in Figure 9.1. How would you program it?

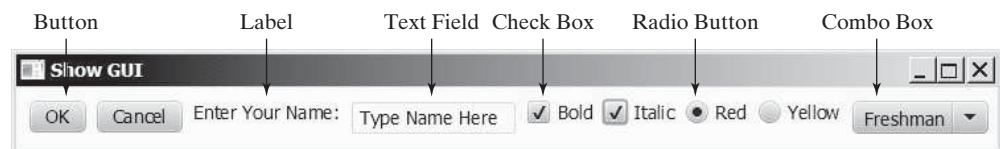


FIGURE 9.1 The GUI objects are created from classes.

This chapter introduces object-oriented programming, which you can use to develop GUI and large-scale software systems.

9.2 Defining Classes for Objects



A class defines the properties and behaviors for objects.



Define classes and objects

object
state of an object
properties
attributes
data fields
behavior
actions

class
contract

instantiation
instance

data field
method
constructors

- The *state* of an object (also known as its *properties* or *attributes*) is represented by *data fields* with their current values. A circle object, for example, has a data field **radius**, which is the property that characterizes a circle. A rectangle object has the data fields **width** and **height**, which are the properties that characterize a rectangle.
- The *behavior* of an object (also known as its *actions*) is defined by methods. To invoke a method on an object is to ask the object to perform an action. For example, you may define methods named **getArea()** and **getPerimeter()** for circle objects. A circle object may invoke **getArea()** to return its area and **getPerimeter()** to return its perimeter. You may also define the **setRadius(radius)** method. A circle object can invoke this method to change its radius.

Objects of the same type are defined using a common class. A *class* is a template, blueprint, or *contract* that defines what an object's data fields and methods will be. An object is an instance of a class. You can create many instances of a class. Creating an instance is referred to as *instantiation*. The terms *object* and *instance* are often interchangeable. The relationship between classes and objects is analogous to that between an apple-pie recipe and apple pies: You can make as many apple pies as you want from a single recipe. Figure 9.2 shows a class named **Circle** and its three objects.

A Java class uses variables to define data fields and methods to define actions. Additionally, a class provides methods of a special type, known as **constructors**, which are invoked to create a new object. A constructor can perform any action, but constructors are designed to perform initializing actions, such as initializing the data fields of objects. Figure 9.3 shows an example of defining the class for circle objects.



FIGURE 9.2 A class is a template for creating objects.

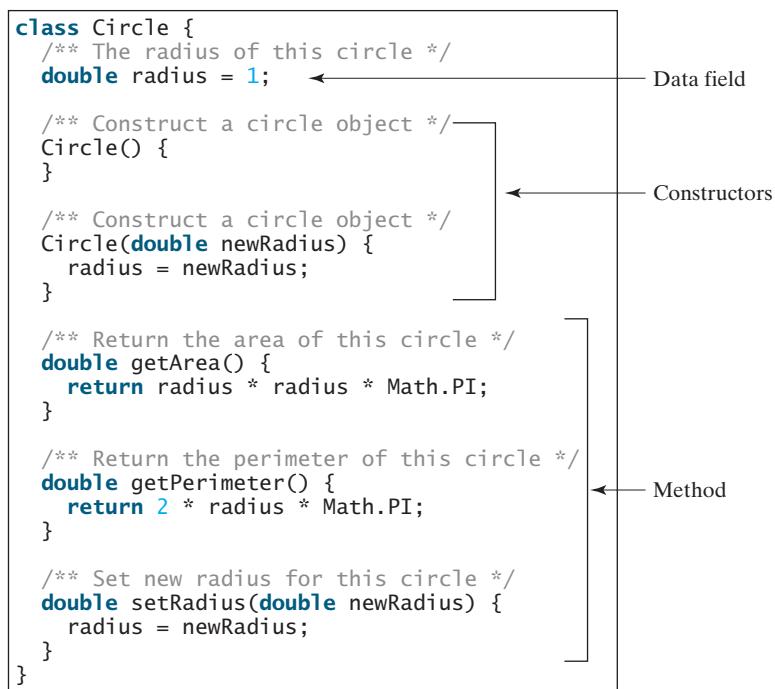


FIGURE 9.3 A class is a construct that defines objects of the same type.

The **Circle** class is different from all of the other classes you have seen thus far. It does not have a **main** method and therefore cannot be run; it is merely a definition for circle objects. The class that contains the **main** method will be referred to in this book, for convenience, as the *main class*.

The illustration of class templates and objects in Figure 9.2 can be standardized using *Unified Modeling Language (UML)* notation. This notation, as shown in Figure 9.4, is called a *UML class diagram*, or simply a *class diagram*. In the class diagram, the data field is denoted as

`dataFieldName: dataFieldType`

The constructor is denoted as

`ClassName(parameterName: parameterType)`

main class
Unified Modeling Language
(UML)
class diagram

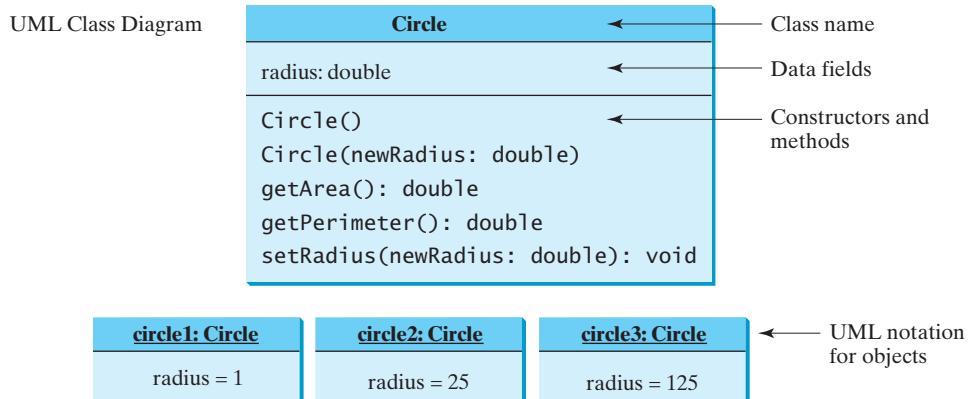


FIGURE 9.4 Classes and objects can be represented using UML notation.

The method is denoted as

```
methodName(parameterName: parameterType): returnType
```

9.3 Example: Defining Classes and Creating Objects



Classes are definitions for objects and objects are created from classes.

This section gives two examples of defining classes and uses the classes to create objects. Listing 9.1 is a program that defines the **Circle** class and uses it to create objects. The program constructs three circle objects with radius **1**, **25**, and **125** and displays the radius and area of each of the three circles. It then changes the radius of the second object to **100** and displays its new radius and area.



Note

To avoid a naming conflict with several enhanced versions of the **Circle** class introduced later in the chapter, the **Circle** class in this example is named **SimpleCircle**. For simplicity, we will still refer to the class in the text as **Circle**.

LISTING 9.1 TestSimpleCircle.java

main class	1 public class TestSimpleCircle {
main method	2 /** Main method */
create object	3 public static void main(String [] args) {
create object	4 // Create a circle with radius 1
create object	5 SimpleCircle circle1 = new SimpleCircle() ;
	6 System.out.println("The area of the circle of radius "
	7 + circle1.radius + " is " + circle1.getArea());
	8
	9 // Create a circle with radius 25
create object	10 SimpleCircle circle2 = new SimpleCircle(25) ;
	11 System.out.println("The area of the circle of radius "
	12 + circle2.radius + " is " + circle2.getArea());
	13
	14 // Create a circle with radius 125
create object	15 SimpleCircle circle3 = new SimpleCircle(125) ;
	16 System.out.println("The area of the circle of radius "
	17 + circle3.radius + " is " + circle3.getArea());
	18
	19 // Modify circle radius
	20 circle2.radius = 100 ; // or circle2.setRadius(100)
	21 System.out.println("The area of the circle of radius "
	22 + circle2.radius + " is " + circle2.getArea());

```

23     }
24 }
25
26 // Define the circle class with two constructors
27 class SimpleCircle {
28     double radius;
29
30     /** Construct a circle with radius 1 */
31     SimpleCircle() {
32         radius = 1;
33     }
34
35     /** Construct a circle with a specified radius */
36     SimpleCircle(double newRadius) {
37         radius = newRadius;
38     }
39
40     /** Return the area of this circle */
41     double getArea() {
42         return radius * radius * Math.PI;
43     }
44
45     /** Return the perimeter of this circle */
46     double getPerimeter() {
47         return 2 * radius * Math.PI;
48     }
49
50     /** Set a new radius for this circle */
51     void setRadius(double newRadius) {
52         radius = newRadius;
53     }
54 }
```

class SimpleCircle
data field

no-arg constructor

second constructor

getArea

getPerimeter

setRadius

```

The area of the circle of radius 1.0 is 3.141592653589793
The area of the circle of radius 25.0 is 1963.4954084936207
The area of the circle of radius 125.0 is 49087.385212340516
The area of the circle of radius 100.0 is 31415.926535897932
```



client

public class

The program contains two classes. The first of these, `TestSimpleCircle`, is the main class. Its sole purpose is to test the second class, `SimpleCircle`. Such a program that uses the class is often referred to as a *client* of the class. When you run the program, the Java runtime system invokes the `main` method in the main class.

You can put the two classes into one file, but only one class in the file can be a *public class*. Furthermore, the public class must have the same name as the file name. Therefore, the file name is `TestSimpleCircle.java`, since `TestSimpleCircle` is public. Each class in the source code is compiled into a `.class` file. When you compile `TestSimpleCircle.java`, two class files `TestSimpleCircle.class` and `SimpleCircle.class` are generated, as shown in Figure 9.5.

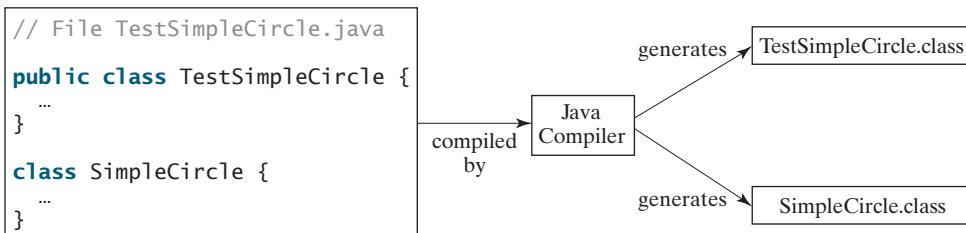


FIGURE 9.5 Each class in the source code file is compiled into a `.class` file.

The main class contains the `main` method (line 3) that creates three objects. As in creating an array, the `new` operator is used to create an object from the constructor: `new SimpleCircle()` creates an object with radius `1` (line 5), `new SimpleCircle(25)` creates an object with radius `25` (line 10), and `new SimpleCircle(125)` creates an object with radius `125` (line 15).

These three objects (referenced by `circle1`, `circle2`, and `circle3`) have different data but the same methods. Therefore, you can compute their respective areas by using the `getArea()` method. The data fields can be accessed via the reference of the object using `circle1.radius`, `circle2.radius`, and `circle3.radius`, respectively. The object can invoke its method via the reference of the object using `circle1.getArea()`, `circle2.getArea()`, and `circle3.getArea()`, respectively.

These three objects are independent. The radius of `circle2` is changed to `100` in line 20. The object's new radius and area are displayed in lines 21–22.

There are many ways to write Java programs. For instance, you can combine the two classes in the example into one, as shown in Listing 9.2.

LISTING 9.2 SimpleCircle.java

```

1  public class SimpleCircle {
2      /** Main method */
3      public static void main(String[] args) {
4          // Create a circle with radius 1
5          SimpleCircle circle1 = new SimpleCircle();
6          System.out.println("The area of the circle of radius "
7              + circle1.radius + " is " + circle1.getArea());
8
9          // Create a circle with radius 25
10         SimpleCircle circle2 = new SimpleCircle(25);
11         System.out.println("The area of the circle of radius "
12             + circle2.radius + " is " + circle2.getArea());
13
14         // Create a circle with radius 125
15         SimpleCircle circle3 = new SimpleCircle(125);
16         System.out.println("The area of the circle of radius "
17             + circle3.radius + " is " + circle3.getArea());
18
19         // Modify circle radius
20         circle2.radius = 100;
21         System.out.println("The area of the circle of radius "
22             + circle2.radius + " is " + circle2.getArea());
23     }
24
25     double radius;
26
27     /** Construct a circle with radius 1 */
28     SimpleCircle() {
29         radius = 1;
30     }
31
32     /** Construct a circle with a specified radius */
33     SimpleCircle(double newRadius) {
34         radius = newRadius;
35     }
36
37     /** Return the area of this circle */
38     double getArea() {
39         return radius * radius * Math.PI;
40     }
41

```

main method

data field

no-arg constructor

second constructor

method

```

42  /** Return the perimeter of this circle */
43  double getPerimeter() {
44      return 2 * radius * Math.PI;
45  }
46
47  /** Set a new radius for this circle */
48  void setRadius(double newRadius) {
49      radius = newRadius;
50  }
51 }
```

Since the combined class has a `main` method, it can be executed by the Java interpreter. The `main` method is the same as that in Listing 9.1. This demonstrates that you can test a class by simply adding a `main` method in the same class.

As another example, consider television sets. Each TV is an object with states (current channel, current volume level, power on or off) and behaviors (change channels, adjust volume, turn on/off). You can use a class to model TV sets. The UML diagram for the class is shown in Figure 9.6.

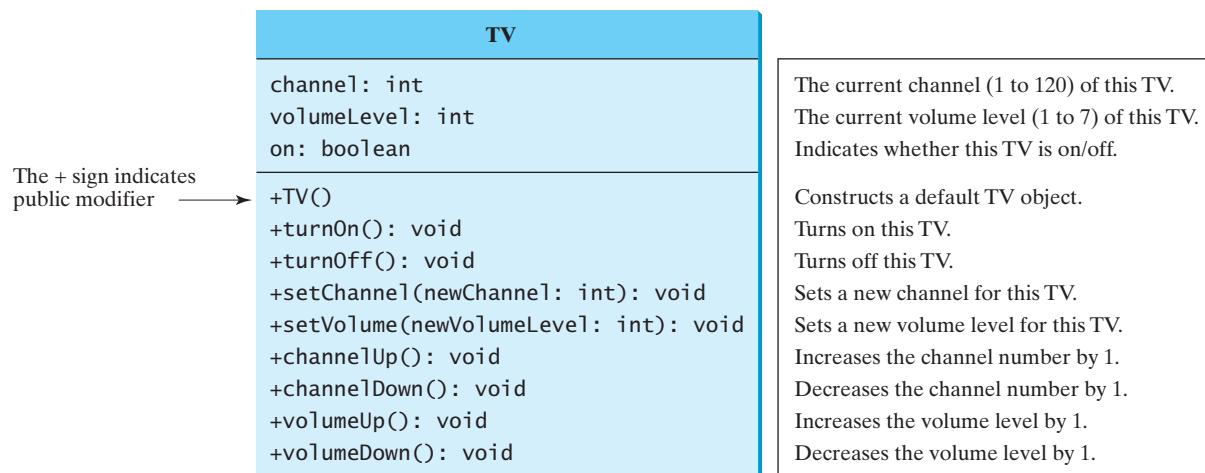


FIGURE 9.6 The TV class models TV sets.

Listing 9.3 gives a program that defines the `TV` class.

LISTING 9.3 TV.java

```

1  public class TV {
2      int channel = 1; // Default channel is 1
3      int volumeLevel = 1; // Default volume level is 1
4      boolean on = false; // TV is off
5
6      public TV() {                                         data fields
7      }
8
9      public void turnOn() {                                constructor
10     on = true;
11 }
12
13     public void turnOff() {                               turn on TV
14 }
```

turn off TV

```

14      on = false;
15  }
16
set a new channel
17  public void setChannel(int newChannel) {
18      if (on && newChannel >= 1 && newChannel <= 120)
19          channel = newChannel;
20  }
21
set a new volume
22  public void setVolume(int newVolumeLevel) {
23      if (on && newVolumeLevel >= 1 && newVolumeLevel <= 7)
24          volumeLevel = newVolumeLevel;
25  }
26
increase channel
27  public void channelUp() {
28      if (on && channel < 120)
29          channel++;
30  }
31
decrease channel
32  public void channelDown() {
33      if (on && channel > 1)
34          channel--;
35  }
36
increase volume
37  public void volumeUp() {
38      if (on && volumeLevel < 7)
39          volumeLevel++;
40  }
41
decrease volume
42  public void volumeDown() {
43      if (on && volumeLevel > 1)
44          volumeLevel--;
45  }
46 }

```

The constructor and methods in the **TV** class are defined public so they can be accessed from other classes. Note that the channel and volume level are not changed if the TV is not on. Before either of these is changed, its current value is checked to ensure that it is within the correct range.

Listing 9.4 gives a program that uses the **TV** class to create two objects.

LISTING 9.4 TestTV.java

```

main method
1  public class TestTV {
2      public static void main(String[] args) {
3          TV tv1 = new TV();
4          tv1.turnOn();
5          tv1.setChannel(30);
6          tv1.setVolume(3);
7
create a TV
8          TV tv2 = new TV();
9          tv2.turnOn();
turn on
10         tv2.channelUp();
11         tv2.channelUp();
12         tv2.volumeUp();
increase channel
13
increase volume
14         System.out.println("tv1's channel is " + tv1.channel
15             + " and volume level is " + tv1.volumeLevel);
16         System.out.println("tv2's channel is " + tv2.channel
17             + " and volume level is " + tv2.volumeLevel);
display state
18     }
19 }

```

```
tv1's channel is 30 and volume level is 3
tv2's channel is 3 and volume level is 2
```



The program creates two objects in lines 3 and 8 and invokes the methods on the objects to perform actions for setting channels and volume levels and for increasing channels and volumes. The program displays the state of the objects in lines 14–17. The methods are invoked using syntax such as `tv1.turnOn()` (line 4). The data fields are accessed using syntax such as `tv1.channel` (line 14).

These examples have given you a glimpse of classes and objects. You may have many questions regarding constructors, objects, reference variables, accessing data fields, and invoking object’s methods. The sections that follow discuss these issues in detail.

- 9.1** Describe the relationship between an object and its defining class.
- 9.2** How do you define a class?
- 9.3** How do you declare an object’s reference variable?
- 9.4** How do you create an object?



9.4 Constructing Objects Using Constructors

A constructor is invoked to create an object using the `new` operator.

Constructors are a special kind of method. They have three peculiarities:

- A constructor must have the same name as the class itself.
- Constructors do not have a return type—not even `void`.
- Constructors are invoked using the `new` operator when an object is created.
Constructors play the role of initializing objects.



constructor’s name

no return type

new operator

overloaded constructors

no void

constructing objects

no-arg constructor

default constructor



In this case, `Circle()` is a method, not a constructor.

Constructors are used to construct objects. To construct an object from a class, invoke a constructor of the class using the `new` operator, as follows:

```
new ClassName(arguments);
```

For example, `new Circle()` creates an object of the `Circle` class using the first constructor defined in the `Circle` class, and `new Circle(25)` creates an object using the second constructor defined in the `Circle` class.

A class normally provides a constructor without arguments (e.g., `Circle()`). Such a constructor is referred to as a *no-arg* or *no-argument constructor*.

A class may be defined without constructors. In this case, a public no-arg constructor with an empty body is implicitly defined in the class. This constructor, called a *default constructor*, is provided automatically *only if no constructors are explicitly defined in the class*.

- 9.5** What are the differences between constructors and methods?
- 9.6** When will a class have a default constructor?



9.5 Accessing Objects via Reference Variables

An object's data and methods can be accessed through the dot (.) operator via the object's reference variable.

Newly created objects are allocated in the memory. They can be accessed via reference variables.

9.5.1 Reference Variables and Reference Types

reference variable

Objects are accessed via the object's *reference variables*, which contain references to the objects. Such variables are declared using the following syntax:

```
ClassName objectRefVar;
```

reference type

A class is essentially a programmer-defined type. A class is a *reference type*, which means that a variable of the class type can reference an instance of the class. The following statement declares the variable `myCircle` to be of the `Circle` type:

```
Circle myCircle;
```

The variable `myCircle` can reference a `Circle` object. The next statement creates an object and assigns its reference to `myCircle`:

```
myCircle = new Circle();
```

You can write a single statement that combines the declaration of an object reference variable, the creation of an object, and the assigning of an object reference to the variable with the following syntax:

```
ClassName objectRefVar = new ClassName();
```

Here is an example:

```
Circle myCircle = new Circle();
```

The variable `myCircle` holds a reference to a `Circle` object.

object vs. object reference variable



Note

An object reference variable that appears to hold an object actually contains a reference to that object. Strictly speaking, an object reference variable and an object are different, but most of the time the distinction can be ignored. Therefore, it is fine, for simplicity, to say that `myCircle` is a `Circle` object rather than use the longer-winded description that `myCircle` is a variable that contains a reference to a `Circle` object.

array object



Note

Arrays are treated as objects in Java. Arrays are created using the `new` operator. An array variable is actually a variable that contains a reference to an array.

9.5.2 Accessing an Object's Data and Methods

In OOP terminology, an object's member refers to its data fields and methods. After an object is created, its data can be accessed and its methods can be invoked using the *dot operator* (.), also known as the *object member access operator*:

- `objectRefVar.dataField` references a data field in the object.
- `objectRefVar.method(arguments)` invokes a method on the object.

For example, `myCircle.radius` references the radius in `myCircle`, and `myCircle.getArea()` invokes the `getArea` method on `myCircle`. Methods are invoked as operations on objects.

The data field `radius` is referred to as an *instance variable*, because it is dependent on a specific instance. For the same reason, the method `getArea` is referred to as an *instance method*, because you can invoke it only on a specific instance. The object on which an instance method is invoked is called a *calling object*.

instance variable
instance method
calling object



Caution

Recall that you use `Math.methodName(arguments)` (e.g., `Math.pow(3, 2.5)`) to invoke a method in the `Math` class. Can you invoke `getArea()` using `Circle.getArea()`? The answer is no. All the methods in the `Math` class are static methods, which are defined using the `static` keyword. However, `getArea()` is an instance method, and thus nonstatic. It must be invoked from an object using `objectRefVar.methodName(arguments)` (e.g., `myCircle.getArea()`). Further explanation is given in Section 9.7, Static Variables, Constants, and Methods.

invoking methods



Note

Usually you create an object and assign it to a variable, and then later you can use the variable to reference the object. Occasionally an object does not need to be referenced later. In this case, you can create an object without explicitly assigning it to a variable using the syntax:

```
new Circle();
```

or

```
System.out.println("Area is " + new Circle(5).getArea());
```

The former statement creates a `Circle` object. The latter creates a `Circle` object and invokes its `getArea` method to return its area. An object created in this way is known as an *anonymous object*.

anonymous object

9.5.3 Reference Data Fields and the `null` Value

The data fields can be of reference types. For example, the following `Student` class contains a data field `name` of the `String` type. `String` is a predefined Java class.

reference data fields

```
class Student {
    String name; // name has the default value null
    int age; // age has the default value 0
    boolean isScienceMajor; // isScienceMajor has default value false
    char gender; // gender has default value '\u0000'
}
```

If a data field of a reference type does not reference any object, the data field holds a special Java value, `null`. `null` is a literal just like `true` and `false`. While `true` and `false` are Boolean literals, `null` is a literal for a reference type.

null value

The default value of a data field is `null` for a reference type, `0` for a numeric type, `false` for a `boolean` type, and `\u0000` for a `char` type. However, Java assigns no default value to a local variable inside a method. The following code displays the default values of the data fields `name`, `age`, `isScienceMajor`, and `gender` for a `Student` object:

default field values

```
class Test {
    public static void main(String[] args) {
        Student student = new Student();
        System.out.println("name? " + student.name);
```

```

        System.out.println("age? " + student.age);
        System.out.println("isScienceMajor? " + student.isScienceMajor);
        System.out.println("gender? " + student.gender);
    }
}

```

The following code has a compile error, because the local variables **x** and **y** are not initialized:

```

class Test {
    public static void main(String[] args) {
        int x; // x has no default value
        String y; // y has no default value
        System.out.println("x is " + x);
        System.out.println("y is " + y);
    }
}

```

NullPointerException



Caution

NullPointerException is a common runtime error. It occurs when you invoke a method on a reference variable with a **null** value. Make sure you assign an object reference to the variable before invoking the method through the reference variable (See Checkpoint Question 9.11c).

9.5.4 Differences between Variables of Primitive Types and Reference Types

Every variable represents a memory location that holds a value. When you declare a variable, you are telling the compiler what type of value the variable can hold. For a variable of a primitive type, the value is of the primitive type. For a variable of a reference type, the value is a reference to where an object is located. For example, as shown in Figure 9.7, the value of **int** variable **i** is **int** value **1**, and the value of **Circle** object **c** holds a reference to where the contents of the **Circle** object are stored in memory.

When you assign one variable to another, the other variable is set to the same value. For a variable of a primitive type, the real value of one variable is assigned to the other variable. For a variable of a reference type, the reference of one variable is assigned to the other variable. As shown in Figure 9.8, the assignment statement **i = j** copies the contents of **j** into **i**.

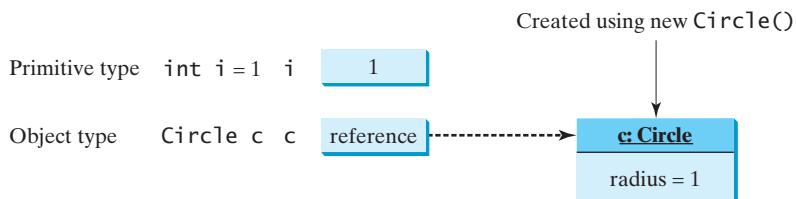


FIGURE 9.7 A variable of a primitive type holds a value of the primitive type, and a variable of a reference type holds a reference to where an object is stored in memory.

Primitive type assignment **i = j**

Before: After:

i	1	i	2
j	2	j	2

FIGURE 9.8 Primitive variable **j** is copied to variable **i**.

for primitive variables. As shown in Figure 9.9, the assignment statement `c1 = c2` copies the reference of `c2` into `c1` for reference variables. After the assignment, variables `c1` and `c2` refer to the same object.

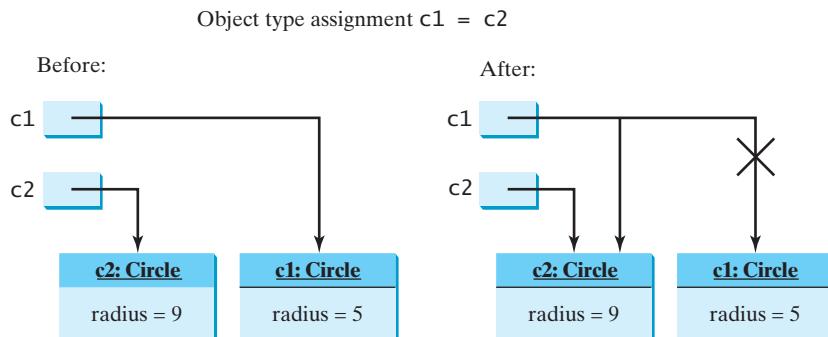


FIGURE 9.9 Reference variable `c2` is copied to variable `c1`.



Note

As illustrated in Figure 9.9, after the assignment statement `c1 = c2`, `c1` points to the same object referenced by `c2`. The object previously referenced by `c1` is no longer useful and therefore is now known as *garbage*. Garbage occupies memory space, so the Java runtime system detects garbage and automatically reclaims the space it occupies. This process is called *garbage collection*.

garbage

garbage collection



Tip

If you know that an object is no longer needed, you can explicitly assign `null` to a reference variable for the object. The JVM will automatically collect the space if the object is not referenced by any reference variable.



9.7 Which operator is used to access a data field or invoke a method from an object?

9.8 What is an anonymous object?

9.9 What is `NullPointerException`?

9.10 Is an array an object or a primitive type value? Can an array contain elements of an object type? Describe the default value for the elements of an array.

9.11 What is wrong with each of the following programs?

```
1 public class ShowErrors {
2     public static void main(String[] args) {
3         ShowErrors t = new ShowErrors(5);
4     }
5 }
```

(a)

```
1 public class ShowErrors {
2     public static void main(String[] args) {
3         ShowErrors t = new ShowErrors();
4         t.x();
5     }
6 }
```

(b)

```
1 public class ShowErrors {
2     public void method1() {
3         Circle c;
4         System.out.println("What is radius "
5             + c.getRadius());
6         c = new Circle();
7     }
8 }
```

(c)

```
1 public class ShowErrors {
2     public static void main(String[] args) {
3         C c = new C(5.0);
4         System.out.println(c.value);
5     }
6 }
7
8 class C {
9     int value = 2;
10 }
```

(d)

9.12 What is wrong in the following code?

```

1  class Test {
2      public static void main(String[] args) {
3          A a = new A();
4          a.print();
5      }
6  }
7
8  class A {
9      String s;
10
11     A(String newS) {
12         s = newS;
13     }
14
15     public void print() {
16         System.out.print(s);
17     }
18 }
```

9.13 What is the output of the following code?

```

public class A {
    boolean x;

    public static void main(String[] args) {
        A a = new A();
        System.out.println(a.x);
    }
}
```

9.6 Using Classes from the Java Library



The Java API contains a rich set of classes for developing Java programs.

Listing 9.1 defined the `SimpleCircle` class and created objects from the class. You will frequently use the classes in the Java library to develop programs. This section gives some examples of the classes in the Java library.



VideoNote
Use classes

java.util.Date class

9.6.1 The Date Class

In Listing 2.7, `ShowCurrentTime.java`, you learned how to obtain the current time using `System.currentTimeMillis()`. You used the division and remainder operators to extract the current second, minute, and hour. Java provides a system-independent encapsulation of date and time in the `java.util.Date` class, as shown in Figure 9.10.

java.util.Date	
+ <code>Date()</code>	Constructs a Date object for the current time.
+ <code>Date(elapseTime: long)</code>	Constructs a Date object for a given time in milliseconds elapsed since January 1, 1970, GMT.
+ <code>toString(): String</code>	Returns a string representing the date and time.
+ <code>getTime(): long</code>	Returns the number of milliseconds since January 1, 1970, GMT.
+ <code>setTime(elapseTime: long): void</code>	Sets a new elapse time in the object.

FIGURE 9.10 A `Date` object represents a specific date and time.

You can use the no-arg constructor in the **Date** class to create an instance for the current date and time, the **getTime()** method to return the elapsed time since January 1, 1970, GMT, and the **toString()** method to return the date and time as a string. For example, the following code

```
java.util.Date date = new java.util.Date();
System.out.println("The elapsed time since Jan 1, 1970 is " +
    date.getTime() + " milliseconds");
System.out.println(date.toString());
```

create object
get elapsed time
invoke **toString**

displays the output like this:

```
The elapsed time since Jan 1, 1970 is 1324903419651 milliseconds
Mon Dec 26 07:43:39 EST 2011
```

The **Date** class has another constructor, **Date(long elapsedTime)**, which can be used to construct a **Date** object for a given time in milliseconds elapsed since January 1, 1970, GMT.

9.6.2 The Random Class

You have used **Math.random()** to obtain a random **double** value between **0.0** and **1.0** (excluding **1.0**). Another way to generate random numbers is to use the **java.util.Random** class, as shown in Figure 9.11, which can generate a random **int**, **long**, **double**, **float**, and **boolean** value.

java.util.Random	
+Random()	Constructs a Random object with the current time as its seed.
+Random(seed: long)	Constructs a Random object with a specified seed .
+nextInt(): int	Returns a random int value.
+nextInt(n: int): int	Returns a random int value between 0 and n (excluding n).
+nextLong(): long	Returns a random long value.
+nextDouble(): double	Returns a random double value between 0.0 and 1.0 (excluding 1.0).
+nextFloat(): float	Returns a random float value between 0.0F and 1.0F (excluding 1.0F).
+nextBoolean(): boolean	Returns a random boolean value.

FIGURE 9.11 A **Random** object can be used to generate random values.

When you create a **Random** object, you have to specify a seed or use the default seed. A seed is a number used to initialize a random number generator. The no-arg constructor creates a **Random** object using the current elapsed time as its seed. If two **Random** objects have the same seed, they will generate identical sequences of numbers. For example, the following code creates two **Random** objects with the same seed, 3.

```
Random random1 = new Random(3);
System.out.print("From random1: ");
for (int i = 0; i < 10; i++)
    System.out.print(random1.nextInt(1000) + " ");

Random random2 = new Random(3);
System.out.print("\nFrom random2: ");
for (int i = 0; i < 10; i++)
    System.out.print(random2.nextInt(1000) + " ");
```

The code generates the same sequence of random `int` values:

```
From random1: 734 660 210 581 128 202 549 564 459 961
From random2: 734 660 210 581 128 202 549 564 459 961
```

same sequence



Note

The ability to generate the same sequence of random values is useful in software testing and many other applications. In software testing, often you need to reproduce the test cases from a fixed sequence of random numbers.

9.6.3 The `Point2D` Class

Java API has a convenient `Point2D` class in the `javafx.geometry` package for representing a point in a two-dimensional plane. The UML diagram for the class is shown in Figure 9.12.

javafx.geometry.Point2D	
+ <code>Point2D(x: double, y: double)</code>	Constructs a <code>Point2D</code> object with the specified x- and y-coordinates.
+ <code>distance(x: double, y: double): double</code>	Returns the distance between this point and the specified point (x,y).
+ <code>distance(p: Point2D): double</code>	Returns the distance between this point and the specified point p.
+ <code>getX(): double</code>	Returns the x-coordinate from this point.
+ <code>getY(): double</code>	Returns the y-coordinate from this point.
+ <code>toString(): String</code>	Returns a string representation for the point.

FIGURE 9.12 A `Point2D` object represents a point with x- and y-coordinates.

You can create a `Point2D` object for a point with the specified x- and y-coordinates, use the `distance` method to compute the distance from this point to another point, and use the `toString()` method to return a string representation of the point. Listing 9.5 gives an example of using this class.

LISTING 9.5 TestPoint2D.java

```

1 import java.util.Scanner;
2 import javafx.geometry.Point2D;
3
4 public class TestPoint2D {
5     public static void main(String[] args) {
6         Scanner input = new Scanner(System.in);
7
8         System.out.print("Enter point1's x-, y-coordinates: ");
9         double x1 = input.nextDouble();
10        double y1 = input.nextDouble();
11        System.out.print("Enter point2's x-, y-coordinates: ");
12        double x2 = input.nextDouble();
13        double y2 = input.nextDouble();
14
15        Point2D p1 = new Point2D(x1, y1);
16        Point2D p2 = new Point2D(x2, y2);
17        System.out.println("p1 is " + p1.toString());
18        System.out.println("p2 is " + p2.toString());
19        System.out.println("The distance between p1 and p2 is " +
20                           p1.distance(p2));
21    }
22 }
```

create an object

invoke `toString()`

get distance



```
Enter point1's x-, y-coordinates: 1.5 5.5 ↵ Enter
Enter point2's x-, y-coordinates: -5.3 -4.4 ↵ Enter
p1 is Point2D [x = 1.5, y = 5.5]
p2 is Point2D [x = -5.3, y = -4.4]
The distance between p1 and p2 is 12.010412149464313
```

This program creates two objects of the `Point2D` class (lines 15–16). The `toString()` method returns a string that describes the object (lines 17–18). Invoking `p1.distance(p2)` returns the distance between the two points (line 20).

- 9.14 How do you create a `Date` for the current time? How do you display the current time?
- 9.15 How do you create a `Point2D`? Suppose `p1` and `p2` are two instances of `Point2D`? How do you obtain the distance between the two points?
- 9.16 Which packages contain the classes `Date`, `Random`, `Point2D`, `System`, and `Math`?



9.7 Static Variables, Constants, and Methods

A static variable is shared by all objects of the class. A static method cannot access instance members of the class.



The data field `radius` in the `circle` class is known as an *instance variable*. An instance variable is tied to a specific instance of the class; it is not shared among objects of the same class. For example, suppose that you create the following objects:

Static vs. instance
instance variable

```
Circle circle1 = new Circle();
Circle circle2 = new Circle(5);
```



The `radius` in `circle1` is independent of the `radius` in `circle2` and is stored in a different memory location. Changes made to `circle1`'s `radius` do not affect `circle2`'s `radius`, and vice versa.

Static vs. instance
instance variable

If you want all the instances of a class to share data, use *static variables*, also known as *class variables*. Static variables store values for the variables in a common memory location. Because of this common location, if one object changes the value of a static variable, all objects of the same class are affected. Java supports static methods as well as static variables. *Static methods* can be called without creating an instance of the class.

static variable

Let's modify the `Circle` class by adding a static variable `numberOfObjects` to count the number of circle objects created. When the first object of this class is created, `numberOfObjects` is **1**. When the second object is created, `numberOfObjects` becomes **2**. The UML of the new `circle` class is shown in Figure 9.13. The `Circle` class defines the instance variable `radius` and the static variable `numberOfObjects`, the instance methods `getRadius`, `setRadius`, and `getArea`, and the static method `getNumberOfObjects`. (Note that static variables and methods are underlined in the UML class diagram.)

static method

To declare a static variable or define a static method, put the modifier `static` in the variable or method declaration. The static variable `numberOfObjects` and the static method `getNumberOfObjects()` can be declared as follows:

```
static int numberOfObjects;

static int getNumberOfObjects() {
    return numberOfObjects;
}
```

declare static variable

define static method

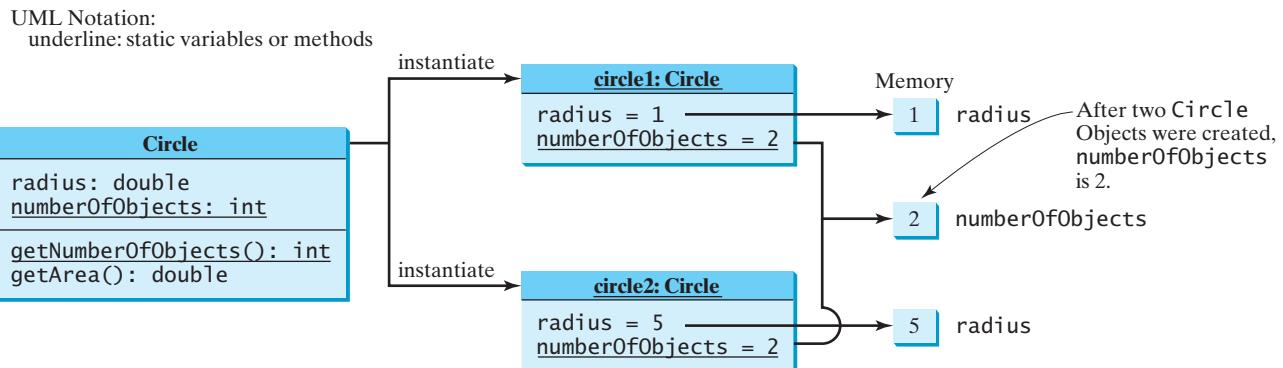


FIGURE 9.13 Instance variables belong to the instances and have memory storage independent of one another. Static variables are shared by all the instances of the same class.

declare constant

Constants in a class are shared by all objects of the class. Thus, constants should be declared as `final static`. For example, the constant `PI` in the `Math` class is defined as:

```
final static double PI = 3.14159265358979323846;
```

The new circle class, named `CircleWithStaticMembers`, is defined in Listing 9.6:

LISTING 9.6 CircleWithStaticMembers.java

static variable

increase by 1

increase by 1

static method

```

1 public class CircleWithStaticMembers {
2     /** The radius of the circle */
3     double radius;
4
5     /** The number of objects created */
6     static int numberofObjects = 0;
7
8     /** Construct a circle with radius 1 */
9     CircleWithStaticMembers() {
10         radius = 1;
11         numberofObjects++;
12     }
13
14     /** Construct a circle with a specified radius */
15     CircleWithStaticMembers(double newRadius) {
16         radius = newRadius;
17         numberofObjects++;
18     }
19
20     /** Return numberofObjects */
21     static int getNumberOfObjects() {
22         return numberofObjects;
23     }
24
25     /** Return the area of this circle */
26     double getArea() {
27         return radius * radius * Math.PI;
28     }
29 }
```

Method `getNumberOfObjects()` in `CircleWithStaticMembers` is a static method. All the methods in the `Math` class are static. The `main` method is static, too.

Instance methods (e.g., `getArea()`) and instance data (e.g., `radius`) belong to instances and can be used only after the instances are created. They are accessed via a reference variable. Static methods (e.g., `getNumberOfObjects()`) and static data (e.g., `numberOfObjects`) can be accessed from a reference variable or from their class name.

The program in Listing 9.7 demonstrates how to use instance and static variables and methods and illustrates the effects of using them.

LISTING 9.7 TestCircleWithStaticMembers.java

```

1  public class TestCircleWithStaticMembers {
2      /** Main method */
3      public static void main(String[] args) {
4          System.out.println("Before creating objects");
5          System.out.println("The number of Circle objects is " +
6              CircleWithStaticMembers.numberOfObjects);           static variable
7
8          // Create c1
9          CircleWithStaticMembers c1 = new CircleWithStaticMembers();
10
11         // Display c1 BEFORE c2 is created
12         System.out.println("\nAfter creating c1");
13         System.out.println("c1: radius (" + c1.radius +           instance variable
14             ") and number of Circle objects (" +
15             c1.numberOfObjects + ")");                      static variable
16
17         // Create c2
18         CircleWithStaticMembers c2 = new CircleWithStaticMembers(5);
19
20         // Modify c1
21         c1.radius = 9;                                     instance variable
22
23         // Display c1 and c2 AFTER c2 was created
24         System.out.println("\nAfter creating c2 and modifying c1");
25         System.out.println("c1: radius (" + c1.radius +           static variable
26             ") and number of Circle objects (" +
27             c1.numberOfObjects + ")");
28         System.out.println("c2: radius (" + c2.radius +           static variable
29             ") and number of Circle objects (" +
30             c2.numberOfObjects + ")");
31     }
32 }
```

```

Before creating objects
The number of Circle objects is 0
After creating c1
c1: radius (1.0) and number of Circle objects (1)
After creating c2 and modifying c1
c1: radius (9.0) and number of Circle objects (2)
c2: radius (5.0) and number of Circle objects (2)
```



When you compile `TestCircleWithStaticMembers.java`, the Java compiler automatically compiles `CircleWithStaticMembers.java` if it has not been compiled since the last change.

Static variables and methods can be accessed without creating objects. Line 6 displays the number of objects, which is 0, since no objects have been created.

The `main` method creates two circles, `c1` and `c2` (lines 9, 18). The instance variable `radius` in `c1` is modified to become `9` (line 21). This change does not affect the instance variable `radius` in `c2`, since these two instance variables are independent. The static variable `numberOfObjects` becomes `1` after `c1` is created (line 9), and it becomes `2` after `c2` is created (line 18).

Note that `PI` is a constant defined in `Math`, and `Math.PI` references the constant. `c1.numberOfObjects` (line 27) and `c2.numberOfObjects` (line 30) are better replaced by `CircleWithStaticMembers.numberOfObjects`. This improves readability, because other programmers can easily recognize the static variable. You can also replace `CircleWithStaticMembers.numberOfObjects` with `CircleWithStaticMembers.getNumberOfObjects()`.

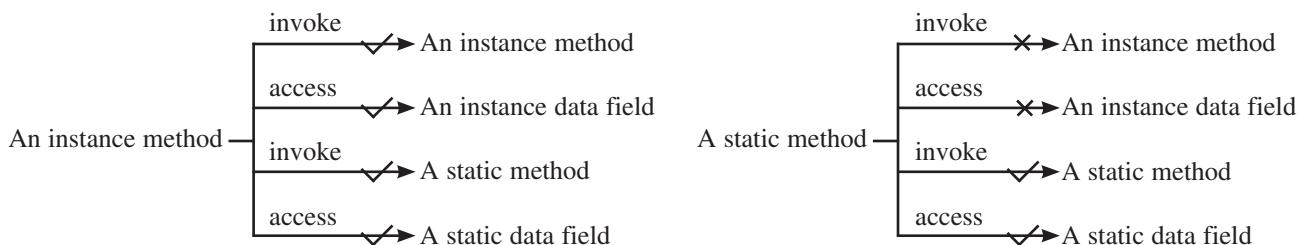


use class name

Tip

Use `ClassName.methodName(arguments)` to invoke a static method and `ClassName.staticVariable` to access a static variable. This improves readability, because this makes the static method and data easy to spot.

An instance method can invoke an instance or static method and access an instance or static data field. A static method can invoke a static method and access a static data field. However, a static method cannot invoke an instance method or access an instance data field, since static methods and static data fields don't belong to a particular object. The relationship between static and instance members is summarized in the following diagram:



For example, the following code is wrong.

```

1  public class A {
2      int i = 5;
3      static int k = 2;
4
5      public static void main(String[] args) {
6          int j = i; // Wrong because i is an instance variable
7          m1(); // Wrong because m1() is an instance method
8      }
9
10     public void m1() {
11         // Correct since instance and static variables and methods
12         // can be used in an instance method
13         i = i + m2(i, k);
14     }
15
16     public static int m2(int i, int j) {
17         return (int)(Math.pow(i, j));
18     }
19 }

```

Note that if you replace the preceding code with the following new code, the program would be fine, because the instance data field `i` and method `m1` are now accessed from an object `a` (lines 7–8):

```

1 public class A {
2     int i = 5;
3     static int k = 2;
4
5     public static void main(String[] args) {
6         A a = new A();
7         int j = a.i; // OK, a.i accesses the object's instance variable
8         a.m1(); // OK. a.m1() invokes the object's instance method
9     }
10
11    public void m1() {
12        i = i + k + m2(i, k);
13    }
14
15    public static int m2(int i, int j) {
16        return (int)(Math.pow(i, j));
17    }
18 }
```



Design Guide

How do you decide whether a variable or a method should be an instance one or a static one? A variable or a method that is dependent on a specific instance of the class should be an instance variable or method. A variable or a method that is not dependent on a specific instance of the class should be a static variable or method. For example, every circle has its own radius, so the radius is dependent on a specific circle. Therefore, `radius` is an instance variable of the `Circle` class. Since the `getArea` method is dependent on a specific circle, it is an instance method. None of the methods in the `Math` class, such as `random`, `pow`, `sin`, and `cos`, is dependent on a specific instance. Therefore, these methods are static methods. The `main` method is static and can be invoked directly from a class.

instance or static?



Caution

It is a common design error to define an instance method that should have been defined as static. For example, the method `factorial(int n)` should be defined as static, as shown next, because it is independent of any specific instance.

common design error

```

public class Test {
    public int factorial(int n) {
        int result = 1;
        for (int i = 1; i <= n; i++)
            result *= i;

        return result;
    }
}
```

(a) Wrong design

```

public class Test {
    public static int factorial(int n) {
        int result = 1;
        for (int i = 1; i <= n; i++)
            result *= i;

        return result;
    }
}
```

(b) Correct design

- 9.17** Suppose that the class `F` is defined in (a). Let `f` be an instance of `F`. Which of the statements in (b) are correct?



```
public class F {
    int i;
    static String s;

    void imethod() {
    }

    static void smethod() {
    }
}
```

(a)

```
System.out.println(f.i);
System.out.println(f.s);
f.imethod();
f.smethod();
System.out.println(F.i);
System.out.println(F.s);
F.imethod();
F.smethod();
```

(b)

- 9.18** Add the **static** keyword in the place of ? if appropriate.

```
public class Test {
    int count;

    public ? void main(String[] args) {
        ..

        public ? int getCount() {
            return count;
        }

        public ? int factorial(int n) {
            int result = 1;
            for (int i = 1; i <= n; i++)
                result *= i;

            return result;
        }
    }
}
```

- 9.19** Can you invoke an instance method or reference an instance variable from a static method? Can you invoke a static method or reference a static variable from an instance method? What is wrong in the following code?

```
1 public class C {
2     public static void main(String[] args) {
3         method1();
4     }
5
6     public void method1() {
7         method2();
8     }
9
10    public static void method2() {
11        System.out.println("What is radius " + c.getRadius());
12    }
13
14    Circle c = new Circle();
15 }
```

9.8 Visibility Modifiers



Visibility modifiers can be used to specify the visibility of a class and its members.

You can use the **public** visibility modifier for classes, methods, and data fields to denote that they can be accessed from any other classes. If no visibility modifier is used, then by default the classes, methods, and data fields are accessible by any class in the same package. This is known as *package-private* or *package-access*.

**Note**

Packages can be used to organize classes. To do so, you need to add the following line as the first noncomment and nonblank statement in the program:

using packages

```
package packageName;
```

If a class is defined without the package statement, it is said to be placed in the *default package*.

Java recommends that you place classes into packages rather than using a default package. For simplicity, however, this book uses default packages. For more information on packages, see Supplement III.E, Packages.

In addition to the **public** and default visibility modifiers, Java provides the **private** and **protected** modifiers for class members. This section introduces the **private** modifier. The **protected** modifier will be introduced in Section 11.14, The **protected** Data and Methods.

The **private** modifier makes methods and data fields accessible only from within its own class. Figure 9.14 illustrates how a public, default, and private data field or method in class **C1** can be accessed from a class **C2** in the same package and from a class **C3** in a different package.

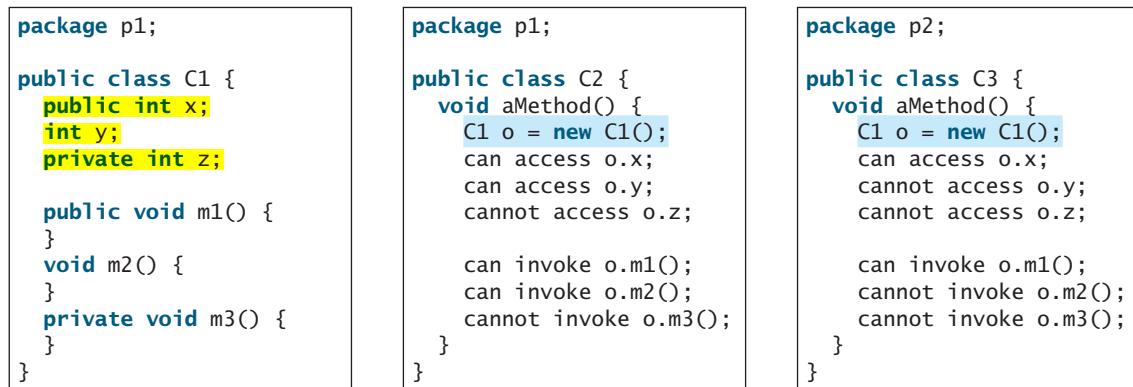


FIGURE 9.14 The private modifier restricts access to its defining class, the default modifier restricts access to a package, and the public modifier enables unrestricted access.

If a class is not defined as public, it can be accessed only within the same package. As shown in Figure 9.15, **C1** can be accessed from **C2** but not from **C3**.

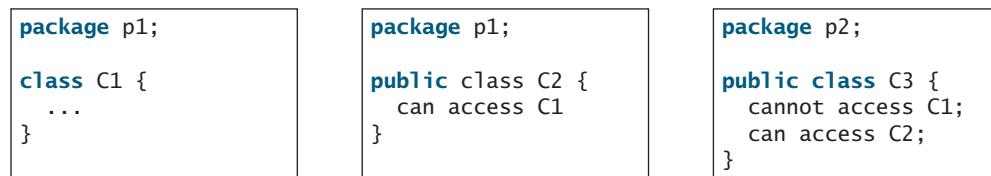


FIGURE 9.15 A nonpublic class has package-access.

A visibility modifier specifies how data fields and methods in a class can be accessed from outside the class. There is no restriction on accessing data fields and methods from inside the class. As shown in Figure 9.16b, an object **c** of class **C** cannot access its private members, because **c** is in the **Test** class. As shown in Figure 9.16a, an object **c** of class **C** can access its private members, because **c** is defined inside its own class.

inside access

```
public class C {
    private boolean x;

    public static void main(String[] args) {
        C c = new C();
        System.out.println(c.x);
        System.out.println(c.convert());
    }

    private int convert() {
        return x ? 1 : -1;
    }
}
```

(a) This is okay because object `c` is used inside the class `C`.

```
public class Test {
    public static void main(String[] args) {
        C c = new C();
        System.out.println(c.x);
        System.out.println(c.convert());
    }
}
```



(b) This is wrong because `x` and `convert` are private in class `C`.

FIGURE 9.16 An object can access its private members if it is defined in its own class.



Caution

The `private` modifier applies only to the members of a class. The `public` modifier can apply to a class or members of a class. Using the modifiers `public` and `private` on local variables would cause a compile error.



Note

In most cases, the constructor should be public. However, if you want to prohibit the user from creating an instance of a class, use a *private constructor*. For example, there is no reason to create an instance from the `Math` class, because all of its data fields and methods are static. To prevent the user from creating objects from the `Math` class, the constructor in `java.lang.Math` is defined as follows:

```
private Math() { }
```

private constructor



9.9 Data Field Encapsulation

Making data fields private protects data and makes the class easy to maintain.

Data field encapsulation



Video Note

Data field encapsulation

- First, data may be tampered with. For example, `numberOfObjects` is to count the number of objects created, but it may be mistakenly set to an arbitrary value (e.g., `CircleWithStaticMembers.numberOfObjects = 10`).
- Second, the class becomes difficult to maintain and vulnerable to bugs. Suppose you want to modify the `CircleWithStaticMembers` class to ensure that the radius is nonnegative after other programs have already used the class. You have to change not only the `CircleWithStaticMembers` class but also the programs that use it, because the clients may have modified the radius directly (e.g., `c1.radius = -5`).

To prevent direct modifications of data fields, you should declare the data fields `private`, using the `private` modifier. This is known as *data field encapsulation*.

data field encapsulation

A private data field cannot be accessed by an object from outside the class that defines the private field. However, a client often needs to retrieve and modify a data field. To make a private data field accessible, provide a *getter* method to return its value. To enable a private data field to be updated, provide a *setter* method to set a new value. A getter method is also referred to as an *accessor* and a setter to a *mutator*.

getter (or accessor)
setter (or mutator)

A getter method has the following signature:

```
public returnType getPropertyname()
```

If the **returnType** is **boolean**, the getter method should be defined as follows by convention: boolean accessor

```
public boolean isPropertyName()
```

A setter method has the following signature:

```
public void setPropertyName(datatype propertyName)
```

Let's create a new circle class with a private data-field radius and its associated accessor and mutator methods. The class diagram is shown in Figure 9.17. The new circle class, named **CircleWithPrivateDataFields**, is defined in Listing 9.8:

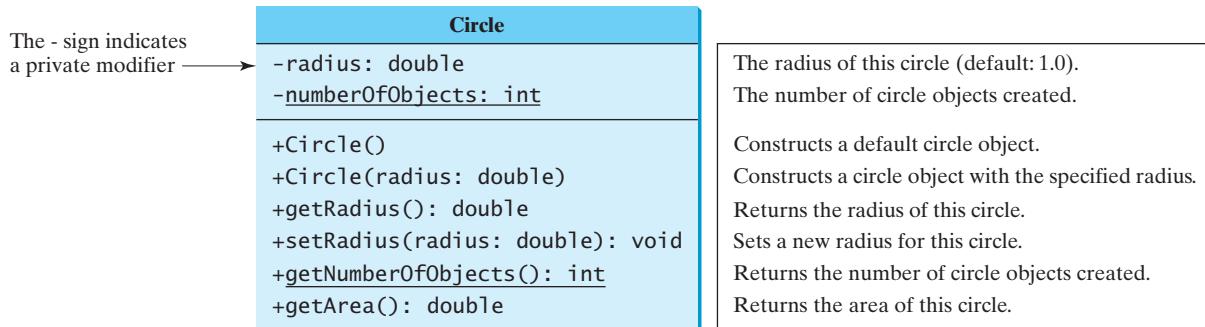


FIGURE 9.17 The **Circle** class encapsulates circle properties and provides getter/setter and other methods.

LISTING 9.8 CircleWithPrivateDataFields.java

```

1 public class CircleWithPrivateDataFields {
2     /** The radius of the circle */
3     private double radius = 1;
4
5     /** The number of objects created */
6     private static int numberofObjects = 0;
7
8     /** Construct a circle with radius 1 */
9     public CircleWithPrivateDataFields() {
10         numberofObjects++;
11     }
12
13     /** Construct a circle with a specified radius */
14     public CircleWithPrivateDataFields(double newRadius) {
15         radius = newRadius;
16         numberofObjects++;
    }
```

encapsulate radius

encapsulate numberofObjects

```

17    }
18
19    /** Return radius */
20    public double getRadius() {
21        return radius;
22    }
23
24    /** Set a new radius */
25    public void setRadius(double newRadius) {
26        radius = (newRadius >= 0) ? newRadius : 0;
27    }
28
29    /** Return numberOfObjects */
30    public static int getNumberOfObjects() {
31        return numberOfObjects;
32    }
33
34    /** Return the area of this circle */
35    public double getArea() {
36        return radius * radius * Math.PI;
37    }
38 }

```

accessor method

mutator method

accessor method

The `getRadius()` method (lines 20–22) returns the radius, and the `setRadius(newRadius)` method (line 25–27) sets a new radius for the object. If the new radius is negative, `0` is set as the radius for the object. Since these methods are the only ways to read and modify the radius, you have total control over how the `radius` property is accessed. If you have to change the implementation of these methods, you don't need to change the client programs. This makes the class easy to maintain.

Listing 9.9 gives a client program that uses the `Circle` class to create a `Circle` object and modifies the radius using the `setRadius` method.

LISTING 9.9 TestCircleWithPrivateDataFields.java

invoke public method

invoke public method

invoke public method

```

1 public class TestCircleWithPrivateDataFields {
2     /* Main method */
3     public static void main(String[] args) {
4         // Create a circle with radius 5.0
5         CircleWithPrivateDataFields myCircle =
6             new CircleWithPrivateDataFields(5.0);
7         System.out.println("The area of the circle of radius "
8             + myCircle.getRadius() + " is " + myCircle.getArea());
9
10        // Increase myCircle's radius by 10%
11        myCircle.setRadius(myCircle.getRadius() * 1.1);
12        System.out.println("The area of the circle of radius "
13            + myCircle.getRadius() + " is " + myCircle.getArea());
14
15        System.out.println("The number of objects created is "
16            + CircleWithPrivateDataFields.getNumberOfObjects());
17    }
18 }

```

The data field `radius` is declared private. Private data can be accessed only within their defining class, so you cannot use `myCircle.radius` in the client program. A compile error would occur if you attempted to access private data from a client.

Since `numberOfObjects` is private, it cannot be modified. This prevents tampering. For example, the user cannot set `numberOfObjects` to `100`. The only way to make it `100` is to create `100` objects of the `Circle` class.

Suppose you combined `TestCircleWithPrivateDataFields` and `Circle` into one class by moving the `main` method in `TestCircleWithPrivateDataFields` into `Circle`. Could you use `myCircle.radius` in the `main` method? See Checkpoint Question 9.22 for the answer.



Design Guide

To prevent data from being tampered with and to make the class easy to maintain, declare data fields private.

- 9.20** What is an accessor method? What is a mutator method? What are the naming conventions for accessor methods and mutator methods?



- 9.21** What are the benefits of data field encapsulation?

- 9.22** In the following code, `radius` is private in the `Circle` class, and `myCircle` is an object of the `Circle` class. Does the highlighted code cause any problems? If so, explain why.

```
public class Circle {
    private double radius = 1;

    /** Find the area of this circle */
    public double getArea() {
        return radius * radius * Math.PI;
    }

    public static void main(String[] args) {
        Circle myCircle = new Circle();
        System.out.println("Radius is " + myCircle.radius);
    }
}
```

9.10 Passing Objects to Methods

Passing an object to a method is to pass the reference of the object.



You can pass objects to methods. Like passing an array, passing an object is actually passing the reference of the object. The following code passes the `myCircle` object as an argument to the `printCircle` method:

```
1 public class Test {
2     public static void main(String[] args) {
3         // CircleWithPrivateDataFields is defined in Listing 9.8
4         CircleWithPrivateDataFields myCircle = new
5             CircleWithPrivateDataFields(5.0);
6         printCircle(myCircle);                                pass an object
7     }
8
9     public static void printCircle(CircleWithPrivateDataFields c) {
10        System.out.println("The area of the circle of radius "
11            + c.getRadius() + " is " + c.getArea());
12    }
13 }
```

Java uses exactly one mode of passing arguments: pass-by-value. In the preceding code, the value of `myCircle` is passed to the `printCircle` method. This value is a reference to a `Circle` object.

The program in Listing 9.10 demonstrates the difference between passing a primitive type value and passing a reference value.

LISTING 9.10 TestPassObject.java

```

1  public class TestPassObject {
2      /** Main method */
3      public static void main(String[] args) {
4          // Create a Circle object with radius 1
5          CircleWithPrivateDataFields myCircle =
6              new CircleWithPrivateDataFields(1);
7
8          // Print areas for radius 1, 2, 3, 4, and 5.
9          int n = 5;
10         printAreas(myCircle, n);
11
12         // See myCircle.radius and times
13         System.out.println("\n" + "Radius is " + myCircle.getRadius());
14         System.out.println("n is " + n);
15     }
16
17     /** Print a table of areas for radius */
18     public static void printAreas(
19         CircleWithPrivateDataFields c, int times) {
20         System.out.println("Radius \t\tArea");
21         while (times >= 1) {
22             System.out.println(c.getRadius() + "\t\t" + c.getArea());
23             c.setRadius(c.getRadius() + 1);
24             times--;
25         }
26     }
27 }
```



Radius	Area
1.0	3.141592653589793
2.0	12.566370614359172
3.0	29.274333882308138
4.0	50.26548245743669
5.0	79.53981633974483
Radius is 6.0	
n is 5	

pass-by-sharing

The `CircleWithPrivateDataFields` class is defined in Listing 9.8. The program passes a `CircleWithPrivateDataFields` object `myCircle` and an integer value from `n` to invoke `printAreas(myCircle, n)` (line 10), which prints a table of areas for radii `1, 2, 3, 4, 5`, as shown in the sample output.

Figure 9.18 shows the call stack for executing the methods in the program. Note that the objects are stored in a heap (see Section 7.6).

When passing an argument of a primitive data type, the value of the argument is passed. In this case, the value of `n` (5) is passed to `times`. Inside the `printAreas` method, the content of `times` is changed; this does not affect the content of `n`.

When passing an argument of a reference type, the reference of the object is passed. In this case, `c` contains a reference for the object that is also referenced via `myCircle`. Therefore, changing the properties of the object through `c` inside the `printAreas` method has the same effect as doing so outside the method through the variable `myCircle`. Pass-by-value on references can be best described semantically as *pass-by-sharing*; that is, the object referenced in the method is the same as the object being passed.

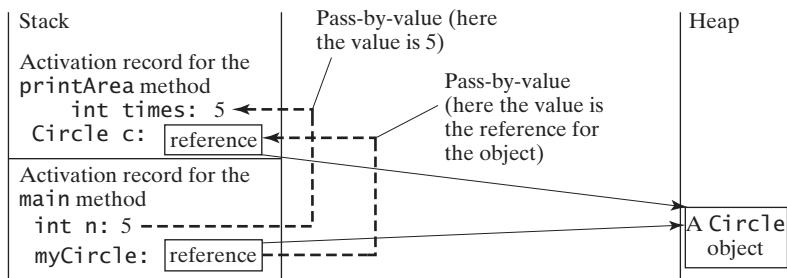


FIGURE 9.18 The value of `n` is passed to `times`, and the reference to `myCircle` is passed to `c` in the `printAreas` method.

- 9.23** Describe the difference between passing a parameter of a primitive type and passing a parameter of a reference type. Show the output of the following programs:



```
public class Test {
    public static void main(String[] args) {
        Count myCount = new Count();
        int times = 0;

        for (int i = 0; i < 100; i++)
            increment(myCount, times);

        System.out.println("count is " + myCount.count);
        System.out.println("times is " + times);
    }

    public static void increment(Count c, int times) {
        c.count++;
        times++;
    }
}
```

```
public class Count {
    public int count;

    public Count(int c) {
        count = c;
    }

    public Count() {
        count = 1;
    }
}
```

- 9.24** Show the output of the following program:

```
public class Test {
    public static void main(String[] args) {
        Circle circle1 = new Circle(1);
        Circle circle2 = new Circle(2);

        swap1(circle1, circle2);
        System.out.println("After swap1: circle1 = " +
                           circle1.radius + " circle2 = " + circle2.radius);

        swap2(circle1, circle2);
        System.out.println("After swap2: circle1 = " +
                           circle1.radius + " circle2 = " + circle2.radius);
    }

    public static void swap1(Circle x, Circle y) {
        Circle temp = x;
        x = y;
        y = temp;
    }
}
```

```

public static void swap2(Circle x, Circle y) {
    double temp = x.radius;
    x.radius = y.radius;
    y.radius = temp;
}
}

class Circle {
    double radius;

    Circle(double newRadius) {
        radius = newRadius;
    }
}

```

9.25 Show the output of the following code:

```

public class Test {
    public static void main(String[] args) {
        int[] a = {1, 2};
        swap(a[0], a[1]);
        System.out.println("a[0] = " + a[0]
            + " a[1] = " + a[1]);
    }

    public static void swap(int n1, int n2) {
        int temp = n1;
        n1 = n2;
        n2 = temp;
    }
}

```

(a)

```

public class Test {
    public static void main(String[] args) {
        int[] a = {1, 2};
        swap(a);
        System.out.println("a[0] = " + a[0]
            + " a[1] = " + a[1]);
    }

    public static void swap(int[] a) {
        int temp = a[0];
        a[0] = a[1];
        a[1] = temp;
    }
}

```

(b)

```

public class Test {
    public static void main(String[] args) {
        T t = new T();
        swap(t);
        System.out.println("e1 = " + t.e1
            + " e2 = " + t.e2);
    }

    public static void swap(T t) {
        int temp = t.e1;
        t.e1 = t.e2;
        t.e2 = temp;
    }

    class T {
        int e1 = 1;
        int e2 = 2;
    }
}

```

(c)

```

public class Test {
    public static void main(String[] args) {
        T t1 = new T();
        T t2 = new T();
        System.out.println("t1's i = " +
            t1.i + " and j = " + t1.j);
        System.out.println("t2's i = " +
            t2.i + " and j = " + t2.j);
    }

    class T {
        static int i = 0;
        int j = 0;

        T() {
            i++;
            j = 1;
        }
    }
}

```

(d)

9.26 What is the output of the following programs?

```
import java.util.Date;

public class Test {
    public static void main(String[] args) {
        Date date = null;
        m1(date);
        System.out.println(date);
    }

    public static void m1(Date date) {
        date = new Date();
    }
}
```

(a)

```
import java.util.Date;

public class Test {
    public static void main(String[] args) {
        Date date = new Date(1234567);
        m1(date);
        System.out.println(date.getTime());
    }

    public static void m1(Date date) {
        date = new Date(7654321);
    }
}
```

(b)

```
import java.util.Date;

public class Test {
    public static void main(String[] args) {
        Date date = new Date(1234567);
        m1(date);
        System.out.println(date.getTime());
    }

    public static void m1(Date date) {
        date.setTime(7654321);
    }
}
```

(c)

```
import java.util.Date;

public class Test {
    public static void main(String[] args) {
        Date date = new Date(1234567);
        m1(date);
        System.out.println(date.getTime());
    }

    public static void m1(Date date) {
        date = null;
    }
}
```

(d)

9.11 Array of Objects

An array can hold objects as well as primitive type values.

Chapter 7, Single-Dimensional Arrays, described how to create arrays of primitive type elements. You can also create arrays of objects. For example, the following statement declares and creates an array of ten `Circle` objects:

```
Circle[] circleArray = new Circle[10];
```

To initialize `circleArray`, you can use a `for` loop like this one:

```
for (int i = 0; i < circleArray.length; i++) {
    circleArray[i] = new Circle();
}
```

An array of objects is actually an *array of reference variables*. So, invoking `circleArray[1].getArea()` involves two levels of referencing, as shown in Figure 9.19. `circleArray` references the entire array; `circleArray[1]` references a `Circle` object.



Note

When an array of objects is created using the `new` operator, each element in the array is a reference variable with a default value of `null`.

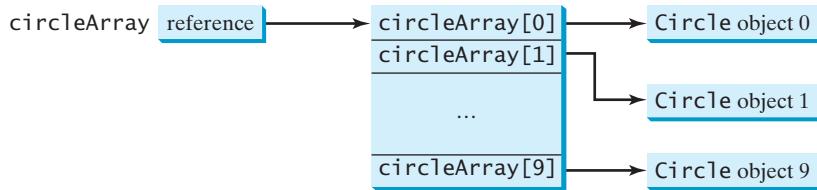


FIGURE 9.19 In an array of objects, an element of the array contains a reference to an object.

Listing 9.11 gives an example that demonstrates how to use an array of objects. The program summarizes the areas of an array of circles. The program creates `circleArray`, an array composed of five `Circle` objects; it then initializes circle radii with random values and displays the total area of the circles in the array.

LISTING 9.11 TotalArea.java

```

1  public class TotalArea {
2      /** Main method */
3      public static void main(String[] args) {
4          // Declare circleArray
5          CircleWithPrivateDataFields[] circleArray;
6
7          // Create circleArray
8          circleArray = createCircleArray();
9
10         // Print circleArray and total areas of the circles
11         printCircleArray(circleArray);
12     }
13
14     /** Create an array of Circle objects */
15     public static CircleWithPrivateDataFields[] createCircleArray() {
16         CircleWithPrivateDataFields[] circleArray =
17             new CircleWithPrivateDataFields[5];
18
19         for (int i = 0; i < circleArray.length; i++) {
20             circleArray[i] =
21                 new CircleWithPrivateDataFields(Math.random() * 100);
22         }
23
24         // Return Circle array
25         return circleArray;
26     }
27
28     /** Print an array of circles and their total area */
29     public static void printCircleArray(
30         CircleWithPrivateDataFields[] circleArray) {
31         System.out.printf("%-30s%-15s\n", "Radius", "Area");
32         for (int i = 0; i < circleArray.length; i++) {
33             System.out.printf("%-30F%-15F\n", circleArray[i].getRadius(),
34                             circleArray[i].getArea());
35         }
36
37         System.out.println("-----");
38
39         // Compute and display the result
40         System.out.printf("%-30s%-15F\n", "The total area of circles is",
41                         sum(circleArray));
42     }
  
```

array of objects

return array of objects

pass array of objects

```

43  /** Add circle areas */
44  public static double sum(CircleWithPrivateDataFields[] circleArray) {    pass array of objects
45      // Initialize sum
46      double sum = 0;
47
48      // Add areas to sum
49      for (int i = 0; i < circleArray.length; i++)
50          sum += circleArray[i].getArea();
51
52      return sum;
53  }
54
55 }
```

Radius	Area
70.577708	15649.941866
44.152266	6124.291736
24.867853	1942.792644
5.680718	101.380949
36.734246	4239.280350

The total area of circles is 28056.687544



The program invokes `createCircleArray()` (line 8) to create an array of five circle objects. Several circle classes were introduced in this chapter. This example uses the `CircleWithPrivateDataFields` class introduced in Section 9.9, Data Field Encapsulation.

The circle radii are randomly generated using the `Math.random()` method (line 21). The `createCircleArray` method returns an array of `CircleWithPrivateDataFields` objects (line 25). The array is passed to the `printCircleArray` method, which displays the radius and area of each circle and the total area of the circles.

The sum of the circle areas is computed by invoking the `sum` method (line 41), which takes the array of `CircleWithPrivateDataFields` objects as the argument and returns a `double` value for the total area.

9.27 What is wrong in the following code?

```

1 public class Test {
2     public static void main(String[] args) {
3         java.util.Date[] dates = new java.util.Date[10];
4         System.out.println(dates[0]);
5         System.out.println(dates[0].toString());
6     }
7 }
```



9.12 Immutable Objects and Classes

You can define immutable classes to create immutable objects. The contents of immutable objects cannot be changed.

Normally, you create an object and allow its contents to be changed later. However, occasionally it is desirable to create an object whose contents cannot be changed once the object has been created. We call such an object as *immutable object* and its class as *immutable class*. The `String` class, for example, is immutable. If you deleted the setter method in the `CircleWithPrivateDataFields` class in Listing 9.9, the class would be immutable, because radius is private and cannot be changed without a setter method.



immutable object
immutable class

Student class

If a class is immutable, then all its data fields must be private and it cannot contain public setter methods for any data fields. A class with all private data fields and no mutators is not necessarily immutable. For example, the following **Student** class has all private data fields and no setter methods, but it is not an immutable class.

```

1  public class Student {
2      private int id;
3      private String name;
4      private java.util.Date dateCreated;
5
6      public Student(int ssn, String newName) {
7          id = ssn;
8          name = newName;
9          dateCreated = new java.util.Date();
10     }
11
12     public int getId() {
13         return id;
14     }
15
16     public String getName() {
17         return name;
18     }
19
20     public java.util.Date getDateCreated() {
21         return dateCreated;
22     }
23 }
```

As shown in the following code, the data field **dateCreated** is returned using the **getDateCreated()** method. This is a reference to a **Date** object. Through this reference, the content for **dateCreated** can be changed.

```

public class Test {
    public static void main(String[] args) {
        Student student = new Student(111223333, "John");
        java.util.Date dateCreated = student.getDateCreated();
        dateCreated.setTime(200000); // Now dateCreated field is changed!
    }
}
```

For a class to be immutable, it must meet the following requirements:

- All data fields must be private.
- There can't be any mutator methods for data fields.
- No accessor methods can return a reference to a data field that is mutable.

Interested readers may refer to Supplement III.U for an extended discussion on immutable objects.



- 9.28** If a class contains only private data fields and no setter methods, is the class immutable?
- 9.29** If all the data fields in a class are private and of primitive types, and the class doesn't contain any setter methods, is the class immutable?
- 9.30** Is the following class immutable?

```

public class A {
    private int[] values;

    public int[] getValues() {
```

```

    return values;
}
}

```

9.13 The Scope of Variables

The scope of instance and static variables is the entire class, regardless of where the variables are declared.



Section 6.9 discussed local variables and their scope rules. Local variables are declared and used inside a method locally. This section discusses the scope rules of all the variables in the context of a class.

Instance and static variables in a class are referred to as the *class's variables* or *data fields*. A variable defined inside a method is referred to as a *local variable*. The scope of a class's variables is the entire class, regardless of where the variables are declared. A class's variables and methods can appear in any order in the class, as shown in Figure 9.20a. The exception is when a data field is initialized based on a reference to another data field. In such cases, the other data field must be declared first, as shown in Figure 9.20b. For consistency, this book declares data fields at the beginning of the class.

```

public class Circle {
    public double findArea() {
        return radius * radius * Math.PI;
    }

    private double radius = 1;
}

```

(a) The variable `radius` and method `findArea()` can be declared in any order.

```

public class F {
    private int i ;
    private int j = i + 1;
}

```

(b) `i` has to be declared before `j` because `j`'s initial value is dependent on `i`.

FIGURE 9.20 Members of a class can be declared in any order, with one exception.

You can declare a class's variable only once, but you can declare the same variable name in a method many times in different nonnesting blocks.

If a local variable has the same name as a class's variable, the local variable takes precedence and the class's variable with the same name is *hidden*. For example, in the following program, `x` is defined both as an instance variable and as a local variable in the method.

hidden variables

```

public class F {
    private int x = 0; // Instance variable
    private int y = 0;

    public F() {
    }

    public void p() {
        int x = 1; // Local variable
        System.out.println("x = " + x);
        System.out.println("y = " + y);
    }
}

```

What is the output for `f.p()`, where `f` is an instance of `F`? The output for `f.p()` is `1` for `x` and `0` for `y`. Here is why:

- `x` is declared as a data field with the initial value of `0` in the class, but it is also declared in the method `p()` with an initial value of `1`. The latter `x` is referenced in the `System.out.println` statement.
- `y` is declared outside the method `p()`, but `y` is accessible inside the method.

**Tip**

To avoid confusion and mistakes, do not use the names of instance or static variables as local variable names, except for method parameters.

9.31 What is the output of the following program?

```
public class Test {
    private static int i = 0;
    private static int j = 0;

    public static void main(String[] args) {
        int i = 2;
        int k = 3;

        {
            int j = 3;
            System.out.println("i + j is " + i + j);
        }

        k = i + j;
        System.out.println("k is " + k);
        System.out.println("j is " + j);
    }
}
```

**9.14 The this Reference**

The keyword **this** refers to the object itself. It can also be used inside a constructor to invoke another constructor of the same class.

this keyword

The **this** keyword is the name of a reference that an object can use to refer to itself. You can use the **this** keyword to reference the object's instance members. For example, the following code in (a) uses **this** to reference the object's **radius** and invokes its **getArea()** method explicitly. The **this** reference is normally omitted, as shown in (b). However, the **this** reference is needed to reference hidden data fields or invoke an overloaded constructor.

```
public class Circle {
    private double radius;

    ...

    public double getArea() {
        return this.radius * this.radius * Math.PI;
    }

    public String toString() {
        return "radius: " + this.radius
            + "area: " + this.getArea();
    }
}
```

(a)

Equivalent

```
public class Circle {
    private double radius;

    ...

    public double getArea() {
        return radius * radius * Math.PI;
    }

    public String toString() {
        return "radius: " + radius
            + "area: " + getArea();
    }
}
```

(b)

9.14.1 Using this to Reference Hidden Data Fields

hidden data fields

The **this** keyword can be used to reference a class's *hidden data fields*. For example, a data-field name is often used as the parameter name in a setter method for the data field. In this case, the data field is hidden in the setter method. You need to reference the hidden data-field name in the method in order to set a new value to it. A hidden static variable can be accessed

simply by using the **ClassName.staticVariable** reference. A hidden instance variable can be accessed by using the keyword **this**, as shown in Figure 9.21a.

```
public class F {
    private int i = 5;
    private static double k = 0;

    public void setI(int i) {
        this.i = i;
    }

    public static void setK(double k) {
        F.k = k;
    }

    // Other methods omitted
}
```

(a)

Suppose that f1 and f2 are two objects of F.
Invoking f1.setI(10) is to execute
this.i = 10, where **this** refers f1
Invoking f2.setI(45) is to execute
this.i = 45, where **this** refers f2
Invoking F.setK(33) is to execute
F.k = 33. setK is a static method

(b)

FIGURE 9.21 The keyword **this** refers to the calling object that invokes the method.

The **this** keyword gives us a way to reference the object that invokes an instance method. To invoke **f1.setI(10)**, **this.i = i** is executed, which assigns the value of parameter **i** to the data field **i** of this calling object **f1**. The keyword **this** refers to the object that invokes the instance method **setI**, as shown in Figure 9.21b. The line **F.k = k** means that the value in parameter **k** is assigned to the static data field **k** of the class, which is shared by all the objects of the class.

9.14.2 Using **this** to Invoke a Constructor

The **this** keyword can be used to invoke another constructor of the same class. For example, you can rewrite the **Circle** class as follows:

```
public class Circle {
    private double radius;

    public Circle(double radius) {
        this.radius = radius;
    }

    public Circle() {
        this(1.0);
    }

    ...
}
```

The **this** keyword is used to reference the hidden data field **radius** of the object being constructed.

The **this** keyword is used to invoke another constructor.

The line **this(1.0)** in the second constructor invokes the first constructor with a **double** value argument.



Note

Java requires that the **this(arg-list)** statement appear first in the constructor before any other executable statements.



Tip

If a class has multiple constructors, it is better to implement them using **this(arg-list)** as much as possible. In general, a constructor with no or fewer arguments can invoke a constructor with more arguments using **this(arg-list)**. This syntax often simplifies coding and makes the class easier to read and to maintain.



- 9.32** Describe the role of the `this` keyword.
9.33 What is wrong in the following code?

```

1  public class C {
2    private int p;
3
4    public C() {
5      System.out.println("C's no-arg constructor invoked");
6      this(0);
7    }
8
9    public C(int p) {
10   p = p;
11 }
12
13  public void setP(int p) {
14   p = p;
15 }
16 }
```

- 9.34** What is wrong in the following code?

```

public class Test {
  private int id;

  public void m1() {
    this.id = 45;
  }

  public void m2() {
    Test.id = 45;
  }
}
```

KEY TERMS

- | | |
|------------------------------|---|
| action 322 | immutable object 353 |
| anonymous object 331 | no-arg constructor 329 |
| attribute 322 | null value 331 |
| behavior 322 | object 322 |
| class 322 | object-oriented programming (OOP) 322 |
| class's variable 355 | package-private (or package-access) 342 |
| client 325 | private constructor 344 |
| constructor 322 | property 322 |
| data field 322 | public class 325 |
| data field encapsulation 344 | reference type 330 |
| default constructor 329 | reference variable 330 |
| dot operator (.) 330 | setter (or mutator) 345 |
| getter (or accessor) 345 | state 322 |
| instance 322 | static method 337 |
| instance method 331 | static variable 337 |
| instance variable 331 | this keyword 356 |
| instantiation 322 | Unified Modeling Language (UML) 323 |
| immutable class 353 | |

CHAPTER SUMMARY

1. A *class* is a template for *objects*. It defines the *properties* of objects and provides *constructors* for creating objects and methods for manipulating them.
2. A class is also a data type. You can use it to declare object *reference variables*. An object reference variable that appears to hold an object actually contains a reference to that object. Strictly speaking, an object reference variable and an object are different, but most of the time the distinction can be ignored.
3. An object is an *instance* of a class. You use the **new** operator to create an object, and the *dot operator* (`.`) to access members of that object through its reference variable.
4. An *instance variable* or *method* belongs to an instance of a class. Its use is associated with individual instances. A *static variable* is a variable shared by all instances of the same class. A *static method* is a method that can be invoked without using instances.
5. Every instance of a class can access the class's static variables and methods. For clarity, however, it is better to invoke static variables and methods using **ClassName.variable** and **ClassName.method**.
6. Visibility modifiers specify how the class, method, and data are accessed. A **public** class, method, or data is accessible to all clients. A **private** method or data is accessible only inside the class.
7. You can provide a getter (accessor) method or a setter (mutator) method to enable clients to see or modify the data.
8. A getter method has the signature **public returnType getPropertyname()**. If the **returnType** is **boolean**, the **get** method should be defined as **public boolean isPropertyName()**. A setter method has the signature **public void setPropertyName(dataType propertyName)**.
9. All parameters are passed to methods using pass-by-value. For a parameter of a primitive type, the actual value is passed; for a parameter of a *reference type*, the reference for the object is passed.
10. A Java array is an object that can contain primitive type values or object type values. When an array of objects is created, its elements are assigned the default value of **null**.
11. Once it is created, an *immutable object* cannot be modified. To prevent users from modifying an object, you can define *immutable classes*.
12. The scope of instance and static variables is the entire class, regardless of where the variables are declared. Instance and static variables can be declared anywhere in the class. For consistency, they are declared at the beginning of the class in this book.
13. The keyword **this** can be used to refer to the calling object. It can also be used inside a constructor to invoke another constructor of the same class.

Quiz

Answer the quiz for this chapter online at www.cs.armstrong.edu/liang/intro10e/quiz.html.

three objectives

**Pedagogical Note**

The exercises in Chapters 9–13 help you achieve three objectives:

- Design classes and draw UML class diagrams.
- Implement classes from the UML.
- Use classes to develop applications.

Students can download solutions for the UML diagrams for the even-numbered exercises from the Companion Website, and instructors can download all solutions from the same site.

Sections 9.2–9.5

- 9.1** (*The Rectangle class*) Following the example of the **Circle** class in Section 9.2, design a class named **Rectangle** to represent a rectangle. The class contains:

- Two **double** data fields named **width** and **height** that specify the width and height of the rectangle. The default values are **1** for both **width** and **height**.
- A no-arg constructor that creates a default rectangle.
- A constructor that creates a rectangle with the specified **width** and **height**.
- A method named **getArea()** that returns the area of this rectangle.
- A method named **getPerimeter()** that returns the perimeter.

Draw the UML diagram for the class and then implement the class. Write a test program that creates two **Rectangle** objects—one with width **4** and height **40** and the other with width **3.5** and height **35.9**. Display the width, height, area, and perimeter of each rectangle in this order.

- 9.2** (*The Stock class*) Following the example of the **Circle** class in Section 9.2, design a class named **Stock** that contains:

- A string data field named **symbol** for the stock's symbol.
- A string data field named **name** for the stock's name.
- A **double** data field named **previousClosingPrice** that stores the stock price for the previous day.
- A **double** data field named **currentPrice** that stores the stock price for the current time.
- A constructor that creates a stock with the specified symbol and name.
- A method named **getChangePercent()** that returns the percentage changed from **previousClosingPrice** to **currentPrice**.

Draw the UML diagram for the class and then implement the class. Write a test program that creates a **Stock** object with the stock symbol **ORCL**, the name **Oracle Corporation**, and the previous closing price of **34.5**. Set a new current price to **34.35** and display the price-change percentage.

Section 9.6

- *9.3** (*Use the Date class*) Write a program that creates a **Date** object, sets its elapsed time to **10000**, **100000**, **1000000**, **10000000**, **100000000**, **1000000000**, **10000000000**, and **100000000000**, and displays the date and time using the **toString()** method, respectively.

- *9.4** (*Use the Random class*) Write a program that creates a **Random** object with seed **1000** and displays the first 50 random integers between **0** and **100** using the **nextInt(100)** method.

***9.5** (*Use the GregorianCalendar class*) Java API has the **GregorianCalendar** class in the **java.util** package, which you can use to obtain the year, month, and day of a date. The no-arg constructor constructs an instance for the current date, and the methods `get(GregorianCalendar.YEAR)`, `get(GregorianCalendar.MONTH)`, and `get(GregorianCalendar.DAY_OF_MONTH)` return the year, month, and day. Write a program to perform two tasks:

- Display the current year, month, and day.
- The **GregorianCalendar** class has the `setTimeInMillis(long)`, which can be used to set a specified elapsed time since January 1, 1970. Set the value to **1234567898765L** and display the year, month, and day.

Sections 9.7–9.9

***9.6** (*Stopwatch*) Design a class named **StopWatch**. The class contains:

- Private data fields `startTime` and `endTime` with getter methods.
- A no-arg constructor that initializes `startTime` with the current time.
- A method named `start()` that resets the `startTime` to the current time.
- A method named `stop()` that sets the `endTime` to the current time.
- A method named `getElapsedTime()` that returns the elapsed time for the stopwatch in milliseconds.

Draw the UML diagram for the class and then implement the class. Write a test program that measures the execution time of sorting 100,000 numbers using selection sort.

9.7 (*The Account class*) Design a class named **Account** that contains:

- A private **int** data field named `id` for the account (default **0**).
- A private **double** data field named `balance` for the account (default **0**).
- A private **double** data field named `annualInterestRate` that stores the current interest rate (default **0**). Assume all accounts have the same interest rate.
- A private **Date** data field named `dateCreated` that stores the date when the account was created.
- A no-arg constructor that creates a default account.
- A constructor that creates an account with the specified id and initial balance.
- The accessor and mutator methods for `id`, `balance`, and `annualInterestRate`.
- The accessor method for `dateCreated`.
- A method named `getMonthlyInterestRate()` that returns the monthly interest rate.
- A method named `getMonthlyInterest()` that returns the monthly interest.
- A method named `withdraw` that withdraws a specified amount from the account.
- A method named `deposit` that deposits a specified amount to the account.

Draw the UML diagram for the class and then implement the class. (*Hint:* The method `getMonthlyInterest()` is to return monthly interest, not the interest rate. Monthly interest is `balance * monthlyInterestRate`. `monthlyInterestRate` is `annualInterestRate / 12`. Note that `annualInterestRate` is a percentage, e.g., like 4.5%. You need to divide it by 100.)

Write a test program that creates an **Account** object with an account ID of 1122, a balance of \$20,000, and an annual interest rate of 4.5%. Use the `withdraw` method to withdraw \$2,500, use the `deposit` method to deposit \$3,000, and print the balance, the monthly interest, and the date when this account was created.

**9.8** (*The Fan class*) Design a class named `Fan` to represent a fan. The class contains:

- Three constants named `SLOW`, `MEDIUM`, and `FAST` with the values `1`, `2`, and `3` to denote the fan speed.
- A private `int` data field named `speed` that specifies the speed of the fan (the default is `SLOW`).
- A private `boolean` data field named `on` that specifies whether the fan is on (the default is `false`).
- A private `double` data field named `radius` that specifies the radius of the fan (the default is `5`).
- A string data field named `color` that specifies the color of the fan (the default is `blue`).
- The accessor and mutator methods for all four data fields.
- A no-arg constructor that creates a default fan.
- A method named `toString()` that returns a string description for the fan. If the fan is on, the method returns the fan speed, color, and radius in one combined string. If the fan is not on, the method returns the fan color and radius along with the string “fan is off” in one combined string.

Draw the UML diagram for the class and then implement the class. Write a test program that creates two `Fan` objects. Assign maximum speed, radius `10`, color `yellow`, and turn it on to the first object. Assign medium speed, radius `5`, color `blue`, and turn it off to the second object. Display the objects by invoking their `toString` method.

****9.9**

(*Geometry: n-sided regular polygon*) In an *n*-sided regular polygon, all sides have the same length and all angles have the same degree (i.e., the polygon is both equilateral and equiangular). Design a class named `RegularPolygon` that contains:

- A private `int` data field named `n` that defines the number of sides in the polygon with default value `3`.
- A private `double` data field named `side` that stores the length of the side with default value `1`.
- A private `double` data field named `x` that defines the *x*-coordinate of the polygon’s center with default value `0`.
- A private `double` data field named `y` that defines the *y*-coordinate of the polygon’s center with default value `0`.
- A no-arg constructor that creates a regular polygon with default values.
- A constructor that creates a regular polygon with the specified number of sides and length of side, centered at `(0, 0)`.
- A constructor that creates a regular polygon with the specified number of sides, length of side, and *x*- and *y*-coordinates.
- The accessor and mutator methods for all data fields.
- The method `getPerimeter()` that returns the perimeter of the polygon.
- The method `getArea()` that returns the area of the polygon. The formula for

$$\text{computing the area of a regular polygon is } Area = \frac{n \times s^2}{4 \times \tan\left(\frac{\pi}{n}\right)}.$$

Draw the UML diagram for the class and then implement the class. Write a test program that creates three `RegularPolygon` objects, created using the no-arg constructor, using `RegularPolygon(6, 4)`, and using `RegularPolygon(10, 4, 5.6, 7.8)`. For each object, display its perimeter and area.

- *9.10** (*Algebra: quadratic equations*) Design a class named **QuadraticEquation** for a quadratic equation $ax^2 + bx + c = 0$. The class contains:

- Private data fields **a**, **b**, and **c** that represent three coefficients.
- A constructor for the arguments for **a**, **b**, and **c**.
- Three getter methods for **a**, **b**, and **c**.
- A method named **getDiscriminant()** that returns the discriminant, which is $b^2 - 4ac$.
- The methods named **getRoot1()** and **getRoot2()** for returning two roots of the equation

$$r_1 = \frac{-b + \sqrt{b^2 - 4ac}}{2a} \quad \text{and} \quad r_2 = \frac{-b - \sqrt{b^2 - 4ac}}{2a}$$

These methods are useful only if the discriminant is nonnegative. Let these methods return **0** if the discriminant is negative.

Draw the UML diagram for the class and then implement the class. Write a test program that prompts the user to enter values for a , b , and c and displays the result based on the discriminant. If the discriminant is positive, display the two roots. If the discriminant is 0, display the one root. Otherwise, display “The equation has no roots.” See Programming Exercise 3.1 for sample runs.

- *9.11** (*Algebra: 2×2 linear equations*) Design a class named **LinearEquation** for a 2×2 system of linear equations:

$$\begin{aligned} ax + by &= e \\ cx + dy &= f \end{aligned} \quad x = \frac{ed - bf}{ad - bc} \quad y = \frac{af - ec}{ad - bc}$$

The class contains:

- Private data fields **a**, **b**, **c**, **d**, **e**, and **f**.
- A constructor with the arguments for **a**, **b**, **c**, **d**, **e**, and **f**.
- Six getter methods for **a**, **b**, **c**, **d**, **e**, and **f**.
- A method named **isSolvable()** that returns true if $ad - bc$ is not 0.
- Methods **getX()** and **getY()** that return the solution for the equation.

Draw the UML diagram for the class and then implement the class. Write a test program that prompts the user to enter **a**, **b**, **c**, **d**, **e**, and **f** and displays the result. If $ad - bc$ is 0, report that “The equation has no solution.” See Programming Exercise 3.3 for sample runs.

- **9.12** (*Geometry: intersecting point*) Suppose two line segments intersect. The two endpoints for the first line segment are (x_1, y_1) and (x_2, y_2) and for the second line segment are (x_3, y_3) and (x_4, y_4) . Write a program that prompts the user to enter these four endpoints and displays the intersecting point. As discussed in Programming Exercise 3.25, the intersecting point can be found by solving a linear equation. Use the **LinearEquation** class in Programming Exercise 9.11 to solve this equation. See Programming Exercise 3.25 for sample runs.

- **9.13** (*The **Location** class*) Design a class named **Location** for locating a maximal value and its location in a two-dimensional array. The class contains public data fields **row**, **column**, and **maxValue** that store the maximal value and its indices in a two-dimensional array with **row** and **column** as **int** types and **maxValue** as a **double** type.

Write the following method that returns the location of the largest element in a two-dimensional array:

```
public static Location locateLargest(double[][] a)
```

The return value is an instance of [Location](#). Write a test program that prompts the user to enter a two-dimensional array and displays the location of the largest element in the array. Here is a sample run:



```
Enter the number of rows and columns in the array: 3 4 ↵Enter
Enter the array:
23.5 35 2 10 ↵Enter
4.5 3 45 3.5 ↵Enter
35 44 5.5 9.6 ↵Enter
The location of the largest element is 45 at (1, 2)
```

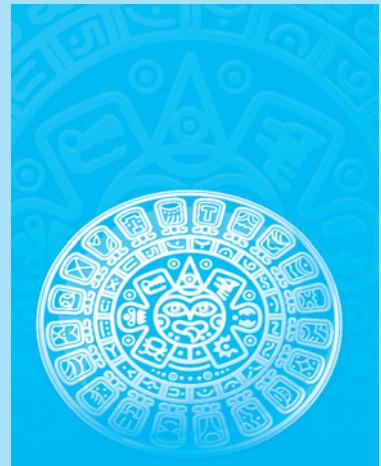
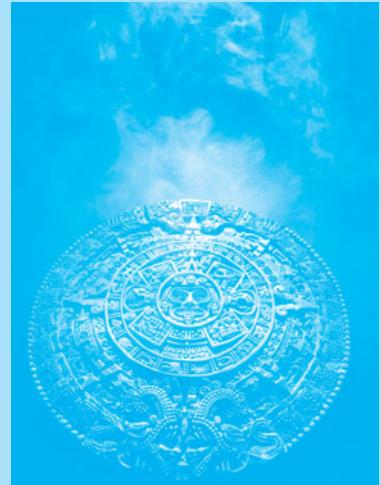
CHAPTER

10

OBJECT-ORIENTED THINKING

Objectives

- To apply class abstraction to develop software (§10.2).
- To explore the differences between the procedural paradigm and object-oriented paradigm (§10.3).
- To discover the relationships between classes (§10.4).
- To design programs using the object-oriented paradigm (§§10.5–10.6).
- To create objects for primitive values using the wrapper classes (**Byte**, **Short**, **Integer**, **Long**, **Float**, **Double**, **Character**, and **Boolean**) (§10.7).
- To simplify programming using automatic conversion between primitive types and wrapper class types (§10.8).
- To use the **BigInteger** and **BigDecimal** classes for computing very large numbers with arbitrary precisions (§10.9).
- To use the **String** class to process immutable strings (§10.10).
- To use the **StringBuilder** and **StringBuffer** classes to process mutable strings (§10.11).



10.1 Introduction



The focus of this chapter is on class design and explores the differences between procedural programming and object-oriented programming.

The preceding chapter introduced objects and classes. You learned how to define classes, create objects, and use objects from several classes in the Java API (e.g., **Circle**, **Date**, **Random**, and **Point2D**). This book’s approach is to teach problem solving and fundamental programming techniques before object-oriented programming. This chapter shows how procedural and object-oriented programming differ. You will see the benefits of object-oriented programming and learn to use it effectively.

Our focus here is on class design. We will use several examples to illustrate the advantages of the object-oriented approach. The examples involve designing new classes and using them in applications and introducing new classes in the Java API.

10.2 Class Abstraction and Encapsulation



Class abstraction is the separation of class implementation from the use of a class. The details of implementation are encapsulated and hidden from the user. This is known as class encapsulation.

class abstraction

class's contract

class encapsulation

abstract data type

In Chapter 6, you learned about method abstraction and used it in stepwise refinement. Java provides many levels of abstraction, and *class abstraction* separates class implementation from how the class is used. The creator of a class describes the functions of the class and lets the user know how the class can be used. The collection of methods and fields that are accessible from outside the class, together with the description of how these members are expected to behave, serves as the *class's contract*. As shown in Figure 10.1, the user of the class does not need to know how the class is implemented. The details of implementation are encapsulated and hidden from the user. This is called *class encapsulation*. For example, you can create a **Circle** object and find the area of the circle without knowing how the area is computed. For this reason, a class is also known as an *abstract data type* (ADT).

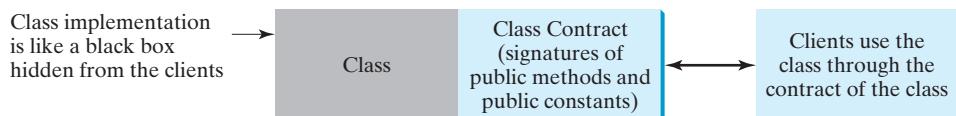


FIGURE 10.1 Class abstraction separates class implementation from the use of the class.

Class abstraction and encapsulation are two sides of the same coin. Many real-life examples illustrate the concept of class abstraction. Consider, for instance, building a computer system. Your personal computer has many components—a CPU, memory, disk, motherboard, fan, and so on. Each component can be viewed as an object that has properties and methods. To get the components to work together, you need to know only how each component is used and how it interacts with the others. You don’t need to know how the components work internally. The internal implementation is encapsulated and hidden from you. You can build a computer without knowing how a component is implemented.

The computer-system analogy precisely mirrors the object-oriented approach. Each component can be viewed as an object of the class for the component. For example, you might have a class that models all kinds of fans for use in a computer, with properties such as fan size and speed and methods such as start and stop. A specific fan is an instance of this class with specific property values.

As another example, consider getting a loan. A specific loan can be viewed as an object of a **Loan** class. The interest rate, loan amount, and loan period are its data properties, and

computing the monthly payment and total payment are its methods. When you buy a car, a loan object is created by instantiating the class with your loan interest rate, loan amount, and loan period. You can then use the methods to find the monthly payment and total payment of your loan. As a user of the **Loan** class, you don't need to know how these methods are implemented.



Listing 2.9, ComputeLoan.java, presented a program for computing loan payments. That program cannot be reused in other programs because the code for computing the payments is in the **main** method. One way to fix this problem is to define static methods for computing the monthly payment and total payment. However, this solution has limitations. Suppose you wish to associate a date with the loan. There is no good way to tie a date with a loan without using objects. The traditional procedural programming paradigm is action-driven, and data are separated from actions. The object-oriented programming paradigm focuses on objects, and actions are defined along with the data in objects. To tie a date with a loan, you can define a loan class with a date along with the loan's other properties as data fields. A loan object now contains data and actions for manipulating and processing data, and the loan data and actions are integrated in one object. Figure 10.2 shows the UML class diagram for the **Loan** class.

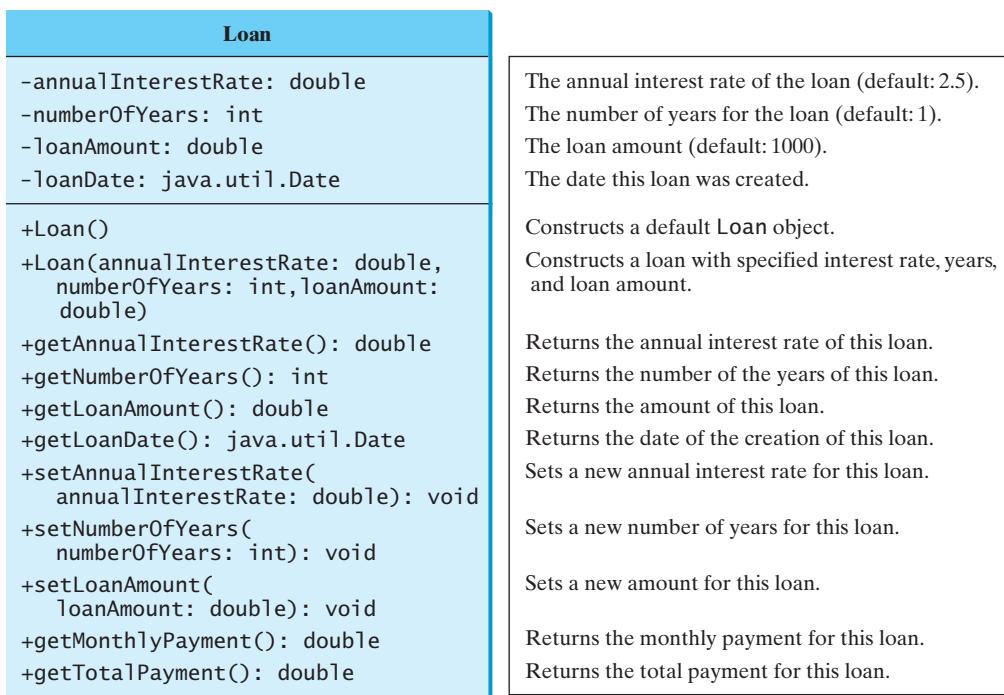


FIGURE 10.2 The **Loan** class models the properties and behaviors of loans.

The UML diagram in Figure 10.2 serves as the contract for the **Loan** class. Throughout this book, you will play the roles of both class user and class developer. Remember that a class user can use the class without knowing how the class is implemented.

Assume that the **Loan** class is available. The program in Listing 10.1 uses that class.

LISTING 10.1 TestLoanClass.java

```

1 import java.util.Scanner;
2
3 public class TestLoanClass {
4     /** Main method */
5     public static void main(String[] args) {

```

```

6      // Create a Scanner
7      Scanner input = new Scanner(System.in);
8
9      // Enter annual interest rate
10     System.out.print(
11         "Enter annual interest rate, for example, 8.25: ");
12     double annualInterestRate = input.nextDouble();
13
14     // Enter number of years
15     System.out.print("Enter number of years as an integer: ");
16     int numberOfYears = input.nextInt();
17
18     // Enter loan amount
19     System.out.print("Enter loan amount, for example, 120000.95: ");
20     double loanAmount = input.nextDouble();
21
22     // Create a Loan object
23     Loan loan =
24         new Loan(annualInterestRate, numberOfYears, loanAmount);
25
26     // Display loan date, monthly payment, and total payment
27     System.out.printf("The loan was created on %s\n" +
28         "The monthly payment is %.2f\nThe total payment is %.2f\n",
29         loan.getLoanDate().toString(), loan.getMonthlyPayment(),
30         loan.getTotalPayment());
31 }
32 }
```

create Loan object

invoke instance method

invoke instance method



```

Enter annual interest rate, for example, 8.25: 2.5 ↵Enter
Enter number of years as an integer: 5 ↵Enter
Enter loan amount, for example, 120000.95: 1000 ↵Enter
The loan was created on Sat Jun 16 21:12:50 EDT 2012
The monthly payment is 17.75
The total payment is 1064.84
```

The `main` method reads the interest rate, the payment period (in years), and the loan amount; creates a `Loan` object; and then obtains the monthly payment (line 29) and the total payment (line 30) using the instance methods in the `Loan` class.

The `Loan` class can be implemented as in Listing 10.2.

LISTING 10.2 `Loan.java`

no-arg constructor

```

1  public class Loan {
2      private double annualInterestRate;
3      private int numberOfYears;
4      private double loanAmount;
5      private java.util.Date loanDate;
6
7      /** Default constructor */
8      public Loan() {
9          this(2.5, 1, 1000);
10     }
11
12     /** Construct a Loan with specified annual interest rate,
```

```

13     number of years, and loan amount
14     */
15 public Loan(double annualInterestRate, int numberOfYears,
16     double loanAmount) {                                         constructor
17     this.annualInterestRate = annualInterestRate;
18     this.numberOfYears = numberOfYears;
19     this.loanAmount = loanAmount;
20     loanDate = new java.util.Date();
21 }
22
23 /** Return annualInterestRate */
24 public double getAnnualInterestRate() {
25     return annualInterestRate;
26 }
27
28 /** Set a new annualInterestRate */
29 public void setAnnualInterestRate(double annualInterestRate) {
30     this.annualInterestRate = annualInterestRate;
31 }
32
33 /** Return numberOfYears */
34 public int getNumberOfYears() {
35     return numberOfYears;
36 }
37
38 /** Set a new numberOfYears */
39 public void setNumberOfYears(int numberOfYears) {
40     this.numberOfYears = numberOfYears;
41 }
42
43 /** Return loanAmount */
44 public double getLoanAmount() {
45     return loanAmount;
46 }
47
48 /** Set a new loanAmount */
49 public void setLoanAmount(double loanAmount) {
50     this.loanAmount = loanAmount;
51 }
52
53 /** Find monthly payment */
54 public double getMonthlyPayment() {
55     double monthlyInterestRate = annualInterestRate / 1200;
56     double monthlyPayment = loanAmount * monthlyInterestRate / (1 -
57         (1 / Math.pow(1 + monthlyInterestRate, numberOfYears * 12)));
58     return monthlyPayment;
59 }
60
61 /** Find total payment */
62 public double getTotalPayment() {
63     double totalPayment = getMonthlyPayment() * numberOfYears * 12;
64     return totalPayment;
65 }
66
67 /** Return loan date */
68 public java.util.Date getLoanDate() {
69     return loanDate;
70 }
71 }
```

From a class developer's perspective, a class is designed for use by many different customers. In order to be useful in a wide range of applications, a class should provide a variety of ways for customization through constructors, properties, and methods.

The `Loan` class contains two constructors, four getter methods, three setter methods, and the methods for finding the monthly payment and the total payment. You can construct a `Loan` object by using the no-arg constructor or the constructor with three parameters: annual interest rate, number of years, and loan amount. When a loan object is created, its date is stored in the `loanDate` field. The `getLoanDate` method returns the date. The methods—`getAnnualInterest`, `getNumberOfYears`, and `getLoanAmount`—return the annual interest rate, payment years, and loan amount, respectively. All the data properties and methods in this class are tied to a specific instance of the `Loan` class. Therefore, they are instance variables and methods.



Important Pedagogical Tip

Use the UML diagram for the `Loan` class shown in Figure 10.2 to write a test program that uses the `Loan` class even though you don't know how the `Loan` class is implemented. This has three benefits:

- It demonstrates that developing a class and using a class are two separate tasks.
- It enables you to skip the complex implementation of certain classes without interrupting the sequence of this book.
- It is easier to learn how to implement a class if you are familiar with it by using the class.

For all the class examples from now on, create an object from the class and try using its methods before turning your attention to its implementation.



- 10.1** If you redefine the `Loan` class in Listing 10.2 without setter methods, is the class immutable?



10.3 Thinking in Objects

The procedural paradigm focuses on designing methods. The object-oriented paradigm couples data and methods together into objects. Software design using the object-oriented paradigm focuses on objects and operations on objects.

Chapters 1–8 introduced fundamental programming techniques for problem solving using loops, methods, and arrays. Knowing these techniques lays a solid foundation for object-oriented programming. Classes provide more flexibility and modularity for building reusable software. This section improves the solution for a problem introduced in Chapter 3 using the object-oriented approach. From these improvements, you will gain insight into the differences between procedural and object-oriented programming and see the benefits of developing reusable code using objects and classes.

Listing 3.4, `ComputeAndInterpretBMI.java`, presented a program for computing body mass index. The code cannot be reused in other programs, because the code is in the `main` method. To make it reusable, define a static method to compute body mass index as follows:

```
public static double getBMI(double weight, double height)
```

This method is useful for computing body mass index for a specified weight and height. However, it has limitations. Suppose you need to associate the weight and height with a person's name and birth date. You could declare separate variables to store these values, but these values would not be tightly coupled. The ideal way to couple them is to create an object that contains them all. Since these values are tied to individual objects, they should be stored in instance data fields. You can define a class named `BMI` as shown in Figure 10.3.





FIGURE 10.3 The **BMI** class encapsulates BMI information.

Assume that the **BMI** class is available. Listing 10.3 gives a test program that uses this class.

LISTING 10.3 UseBMIClass.java

```

1  public class UseBMIClass {
2    public static void main(String[] args) {
3      BMI bmi1 = new BMI("Kim Yang", 18, 145, 70);
4      System.out.println("The BMI for " + bmi1.getName() + " is "
5        + bmi1.getBMI() + " " + bmi1.getStatus());
6
7      BMI bmi2 = new BMI("Susan King", 215, 70);
8      System.out.println("The BMI for " + bmi2.getName() + " is "
9        + bmi2.getBMI() + " " + bmi2.getStatus());
10     }
11   }
  
```

create an object
invoke instance method

create an object
invoke instance method

The BMI for Kim Yang is 20.81 Normal
The BMI for Susan King is 30.85 Obese



Line 3 creates the object **bmi1** for **Kim Yang** and line 7 creates the object **bmi2** for **Susan King**. You can use the instance methods **getName()**, **getBMI()**, and **getStatus()** to return the BMI information in a **BMI** object.

The **BMI** class can be implemented as in Listing 10.4.

LISTING 10.4 BMI.java

```

1  public class BMI {
2    private String name;
3    private int age;
4    private double weight; // in pounds
5    private double height; // in inches
6    public static final double KILOGRAMS_PER_POUND = 0.45359237;
7    public static final double METERS_PER_INCH = 0.0254;
8
9    public BMI(String name, int age, double weight, double height) { constructor
10      this.name = name;
  
```

```

11     this.age = age;
12     this.weight = weight;
13     this.height = height;
14 }
15
constructor 16 public BMI(String name, double weight, double height) {
17     this(name, 20, weight, height);
18 }
19
getBMI 20 public double getBMI() {
21     double bmi = weight * KILOGRAMS_PER_POUND /
22         ((height * METERS_PER_INCH) * (height * METERS_PER_INCH));
23     return Math.round(bmi * 100) / 100.0;
24 }
25
getStatus 26 public String getStatus() {
27     double bmi = getBMI();
28     if (bmi < 18.5)
29         return "Underweight";
30     else if (bmi < 25)
31         return "Normal";
32     else if (bmi < 30)
33         return "Overweight";
34     else
35         return "Obese";
36 }
37
38 public String getName() {
39     return name;
40 }
41
42 public int getAge() {
43     return age;
44 }
45
46 public double getWeight() {
47     return weight;
48 }
49
50 public double getHeight() {
51     return height;
52 }
53 }

```

procedural vs. object-oriented paradigms

The mathematical formula for computing the BMI using weight and height is given in Section 3.8. The instance method `getBMI()` returns the BMI. Since the weight and height are instance data fields in the object, the `getBMI()` method can use these properties to compute the BMI for the object.

The instance method `getStatus()` returns a string that interprets the BMI. The interpretation is also given in Section 3.8.

This example demonstrates the advantages of the object-oriented paradigm over the procedural paradigm. The procedural paradigm focuses on designing methods. The object-oriented paradigm couples data and methods together into objects. Software design using the object-oriented paradigm focuses on objects and operations on objects. The object-oriented approach combines the power of the procedural paradigm with an added dimension that integrates data with operations into objects.

In procedural programming, data and operations on the data are separate, and this methodology requires passing data to methods. Object-oriented programming places data and

the operations that pertain to them in an object. This approach solves many of the problems inherent in procedural programming. The object-oriented programming approach organizes programs in a way that mirrors the real world, in which all objects are associated with both attributes and activities. Using objects improves software reusability and makes programs easier to develop and easier to maintain. Programming in Java involves thinking in terms of objects; a Java program can be viewed as a collection of cooperating objects.

10.2 Is the **BMI** class defined in Listing 10.4 immutable?



10.4 Class Relationships

To design classes, you need to explore the relationships among classes. The common relationships among classes are association, aggregation, composition, and inheritance.



This section explores association, aggregation, and composition. The inheritance relationship will be introduced in the next chapter.

10.4.1 Association

Association is a general binary relationship that describes an activity between two classes. For example, a student taking a course is an association between the **Student** class and the **Course** class, and a faculty member teaching a course is an association between the **Faculty** class and the **Course** class. These associations can be represented in UML graphical notation, as shown in Figure 10.4.

association



FIGURE 10.4 This UML diagram shows that a student may take any number of courses, a faculty member may teach at most three courses, a course may have from five to sixty students, and a course is taught by only one faculty member.

An association is illustrated by a solid line between two classes with an optional label that describes the relationship. In Figure 10.4, the labels are *Take* and *Teach*. Each relationship may have an optional small black triangle that indicates the direction of the relationship. In this figure, the direction indicates that a student takes a course (as opposed to a course taking a student).

Each class involved in the relationship may have a role name that describes the role it plays in the relationship. In Figure 10.4, *teacher* is the role name for **Faculty**.

Each class involved in an association may specify a *multiplicity*, which is placed at the side of the class to specify how many of the class's objects are involved in the relationship in UML. A multiplicity could be a number or an interval that specifies how many of the class's objects are involved in the relationship. The character * means an unlimited number of objects, and the interval **m..n** indicates that the number of objects is between **m** and **n**, inclusively. In Figure 10.4, each student may take any number of courses, and each course must have at least five and at most sixty students. Each course is taught by only one faculty member, and a faculty member may teach from zero to three courses per semester.

multiplicity

In Java code, you can implement associations by using data fields and methods. For example, the relationships in Figure 10.4 may be implemented using the classes in Figure 10.5. The

relation “a student takes a course” is implemented using the `addCourse` method in the `Student` class and the `addStuent` method in the `Course` class. The relation “a faculty teaches a course” is implemented using the `addCourse` method in the `Faculty` class and the `setFaculty` method in the `Course` class. The `Student` class may use a list to store the courses that the student is taking, the `Faculty` class may use a list to store the courses that the faculty is teaching, and the `Course` class may use a list to store students enrolled in the course and a data field to store the instructor who teaches the course.

```
public class Student {
    private Course[] courseList;

    public void addCourse(
        Course s) { ... }
}

public class Course {
    private Student[] classList;
    private Faculty faculty;

    public void addStudent(
        Student s) { ... }

    public void setFaculty(
        Faculty faculty) { ... }
}

public class Faculty {
    private Course[] courseList;

    public void addCourse(
        Course c) { ... }
}
```

FIGURE 10.5 The association relations are implemented using data fields and methods in classes.

many possible implementations



Note

There are many possible ways to implement relationships. For example, the student and faculty information in the `Course` class can be omitted, since they are already in the `Student` and `Faculty` class. Likewise, if you don't need to know the courses a student takes or a faculty member teaches, the data field `courseList` and the `addCourse` method in `Student` or `Faculty` can be omitted.

aggregation
aggregating object
aggregated object
aggregated class
aggregating class

composition

10.4.2 Aggregation and Composition

Aggregation is a special form of association that represents an ownership relationship between two objects. Aggregation models *has-a* relationships. The owner object is called an *aggregating object*, and its class is called an *aggregating class*. The subject object is called an *aggregated object*, and its class is called an *aggregated class*.

An object can be owned by several other aggregating objects. If an object is exclusively owned by an aggregating object, the relationship between the object and its aggregating object is referred to as a *composition*. For example, “a student has a name” is a composition relationship between the `Student` class and the `Name` class, whereas “a student has an address” is an aggregation relationship between the `Student` class and the `Address` class, since an address can be shared by several students. In UML, a filled diamond is attached to an aggregating class (in this case, `Student`) to denote the composition relationship with an aggregated class (`Name`), and an empty diamond is attached to an aggregating class (`Student`) to denote the aggregation relationship with an aggregated class (`Address`), as shown in Figure 10.6.

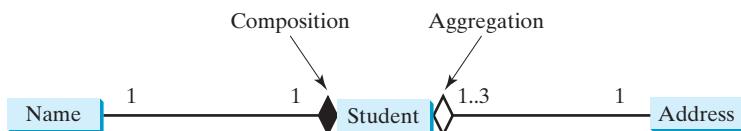


FIGURE 10.6 Each student has a name and an address.

In Figure 10.6, each student has only one multiplicity—address—and each address can be shared by up to 3 students. Each student has one name, and a name is unique for each student.

An aggregation relationship is usually represented as a data field in the aggregating class. For example, the relationships in Figure 10.6 may be implemented using the classes in Figure 10.7. The relation “a student has a name” and “a student has an address” are implemented in the data field **name** and **address** in the **Student** class.



FIGURE 10.7 The composition relations are implemented using data fields in classes.

Aggregation may exist between objects of the same class. For example, a person may have a supervisor. This is illustrated in Figure 10.8.

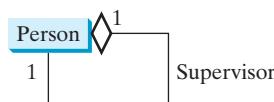


FIGURE 10.8 A person may have a supervisor.

In the relationship “a person has a supervisor,” a supervisor can be represented as a data field in the [Person](#) class, as follows:

```
public class Person {  
    // The type for the data is the class itself  
    private Person supervisor;  
  
    ...  
}
```

If a person can have several supervisors, as shown in Figure 10.9a, you may use an array to store supervisors, as shown in Figure 10.9b.

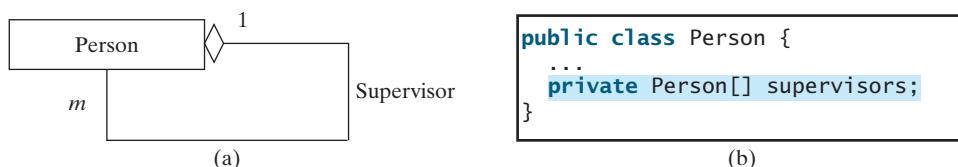


FIGURE 10.9 A person can have several supervisors.



Note

Since aggregation and composition relationships are represented using classes in the same way, we will not differentiate them and call both compositions for simplicity.

aggregation or composition

- 10.3** What are common relationships among classes?
 - 10.4** What is association? What is aggregation? What is composition?
 - 10.5** What is UML notation of aggregation and composition?
 - 10.6** Why both aggregation and composition are together referred to as composition?





10.5 Case Study: Designing the Course Class

This section designs a class for modeling courses.

This book's philosophy is *teaching by example and learning by doing*. The book provides a wide variety of examples to demonstrate object-oriented programming. This section and the next offer additional examples on designing classes.

Suppose you need to process course information. Each course has a name and has students enrolled. You should be able to add/drop a student to/from the course. You can use a class to model the courses, as shown in Figure 10.10.

Course	
-courseName: String	The name of the course.
-students: String[]	An array to store the students for the course.
-numberOfStudents: int	The number of students (default: 0).
+Course(courseName: String)	Creates a course with the specified name.
+getCourseName(): String	Returns the course name.
+addStudent(student: String): void	Adds a new student to the course.
+dropStudent(student: String): void	Drops a student from the course.
+getStudents(): String[]	Returns the students for the course.
+getNumberOfStudents(): int	Returns the number of students for the course.

FIGURE 10.10 The `Course` class models the courses.

A `Course` object can be created using the constructor `Course(String name)` by passing a course name. You can add students to the course using the `addStudent(String student)` method, drop a student from the course using the `dropStudent(String student)` method, and return all the students in the course using the `getStudents()` method. Suppose the `Course` class is available; Listing 10.5 gives a test class that creates two courses and adds students to them.

LISTING 10.5 TestCourse.java

create a course

add a student

number of students
return students

```

1  public class TestCourse {
2      public static void main(String[] args) {
3          Course course1 = new Course("Data Structures");
4          Course course2 = new Course("Database Systems");
5
6          course1.addStudent("Peter Jones");
7          course1.addStudent("Kim Smith");
8          course1.addStudent("Anne Kennedy");
9
10         course2.addStudent("Peter Jones");
11         course2.addStudent("Steve Smith");
12
13         System.out.println("Number of students in course1: "
14             + course1.getNumberOfStudents());
15         String[] students = course1.getStudents();
16         for (int i = 0; i < course1.getNumberOfStudents(); i++)
17             System.out.print(students[i] + ", ");
18
19         System.out.println();
20         System.out.print("Number of students in course2: "
21             + course2.getNumberOfStudents());
22     }
23 }
```

```
Number of students in course1: 3
Peter Jones, Kim Smith, Anne Kennedy,
Number of students in course2: 2
```



The **Course** class is implemented in Listing 10.6. It uses an array to store the students in the course. For simplicity, assume that the maximum course enrollment is **100**. The array is created using **new String[100]** in line 3. The **addStudent** method (line 10) adds a student to the array. Whenever a new student is added to the course, **numberOfStudents** is increased (line 12). The **getStudents** method returns the array. The **dropStudent** method (line 27) is left as an exercise.

LISTING 10.6 Course.java

```

1  public class Course {
2      private String courseName;
3      private String[] students = new String[100];
4      private int numberOfStudents;
5
6      public Course(String courseName) {
7          this.courseName = courseName;
8      }
9
10     public void addStudent(String student) {
11         students[numberOfStudents] = student;
12         numberOfStudents++;
13     }
14
15     public String[] getStudents() {
16         return students;
17     }
18
19     public int getNumberOfStudents() {
20         return numberOfStudents;
21     }
22
23     public String getCourseName() {
24         return courseName;
25     }
26
27     public void dropStudent(String student) {
28         // Left as an exercise in Programming Exercise 10.9
29     }
30 }
```

create students
add a course
return students
number of students

The array size is fixed to be **100** (line 3), so you cannot have more than 100 students in the course. You can improve the class by automatically increasing the array size in Programming Exercise 10.9.

When you create a **Course** object, an array object is created. A **Course** object contains a reference to the array. For simplicity, you can say that the **Course** object contains the array.

The user can create a **Course** object and manipulate it through the public methods **addStudent**, **dropStudent**, **getNumberOfStudents**, and **getStudents**. However, the user doesn't need to know how these methods are implemented. The **Course** class encapsulates the internal implementation. This example uses an array to store students, but you could use a different data structure to store **students**. The program that uses **Course** does not need to change as long as the contract of the public methods remains unchanged.

stack



10.6 Case Study: Designing a Class for Stacks

This section designs a class for modeling stacks.

Recall that a *stack* is a data structure that holds data in a last-in, first-out fashion, as shown in Figure 10.11.



FIGURE 10.11 A stack holds data in a last-in, first-out fashion.

Stacks have many applications. For example, the compiler uses a stack to process method invocations. When a method is invoked, its parameters and local variables are pushed into a stack. When a method calls another method, the new method's parameters and local variables are pushed into the stack. When a method finishes its work and returns to its caller, its associated space is released from the stack.

You can define a class to model stacks. For simplicity, assume the stack holds the `int` values. So name the stack class `StackOfIntegers`. The UML diagram for the class is shown in Figure 10.12.



VideoNote

The `StackOfIntegers` class

StackOfIntegers	
-elements: <code>int[]</code>	An array to store integers in the stack.
-size: <code>int</code>	The number of integers in the stack.
+StackOfIntegers()	Constructs an empty stack with a default capacity of 16.
+StackOfIntegers(<code>capacity: int</code>)	Constructs an empty stack with a specified capacity.
+empty(): <code>boolean</code>	Returns true if the stack is empty.
+peek(): <code>int</code>	Returns the integer at the top of the stack without removing it from the stack.
+push(<code>value: int</code>): <code>void</code>	Stores an integer into the top of the stack.
+pop(): <code>int</code>	Removes the integer at the top of the stack and returns it.
+getSize(): <code>int</code>	Returns the number of elements in the stack.

FIGURE 10.12 The `StackOfIntegers` class encapsulates the stack storage and provides the operations for manipulating the stack.

Suppose that the class is available. The test program in Listing 10.7 uses the class to create a stack (line 3), store ten integers `0, 1, 2, ..., 9` (line 6), and displays them in reverse order (line 9).

LISTING 10.7 TestStackOfIntegers.java

```

1  public class TestStackOfIntegers {
2      public static void main(String[] args) {
3          StackOfIntegers stack = new StackOfIntegers();

```

create a stack

```

4
5     for (int i = 0; i < 10; i++)
6         stack.push(i);                                push to stack
7
8     while (!stack.empty())
9         System.out.print(stack.pop() + " ");
10    }
11 }
```

9 8 7 6 5 4 3 2 1 0



How do you implement the `StackOfIntegers` class? The elements in the stack are stored in an array named `elements`. When you create a stack, the array is also created. The no-arg constructor creates an array with the default capacity of **16**. The variable `size` counts the number of elements in the stack, and `size - 1` is the index of the element at the top of the stack, as shown in Figure 10.13. For an empty stack, `size` is **0**.



FIGURE 10.13 The `StackOfIntegers` class encapsulates the stack storage and provides the operations for manipulating the stack.

The `StackOfIntegers` class is implemented in Listing 10.8. The methods `empty()`, `peek()`, `pop()`, and `getSize()` are easy to implement. To implement `push(int value)`, assign `value` to `elements[size]` if `size < capacity` (line 24). If the stack is full (i.e., `size >= capacity`), create a new array of twice the current capacity (line 19), copy the contents of the current array to the new array (line 20), and assign the reference of the new array to the current array in the stack (line 21). Now you can add the new value to the array (line 24).

LISTING 10.8 StackOfIntegers.java

```

1  public class StackOfIntegers {
2      private int[] elements;
3      private int size;
4      public static final int DEFAULT_CAPACITY = 16;                      max capacity 16
5
6      /** Construct a stack with the default capacity 16 */
7      public StackOfIntegers() {
8          this(DEFAULT_CAPACITY);
9      }
10
11     /** Construct a stack with the specified maximum capacity */
12     public StackOfIntegers(int capacity) {
13         elements = new int[capacity];
14     }
15 }
```

double the capacity

```

16  /** Push a new integer to the top of the stack */
17  public void push(int value) {
18      if (size >= elements.length) {
19          int[] temp = new int[elements.length * 2];
20          System.arraycopy(elements, 0, temp, 0, elements.length);
21          elements = temp;
22      }
23
24      elements[size++] = value;
25  }
26
27  /** Return and remove the top element from the stack */
28  public int pop() {
29      return elements[--size];
30  }
31
32  /** Return the top element from the stack */
33  public int peek() {
34      return elements[size - 1];
35  }
36
37  /** Test whether the stack is empty */
38  public boolean empty() {
39      return size == 0;
40  }
41
42  /** Return the number of elements in the stack */
43  public int getSize() {
44      return size;
45  }
46 }
```

add to stack

10.7 Processing Primitive Data Type Values as Objects



A primitive type value is not an object, but it can be wrapped in an object using a wrapper class in the Java API.

why wrapper class?

Owing to performance considerations, primitive data type values are not objects in Java. Because of the overhead of processing objects, the language's performance would be adversely affected if primitive data type values were treated as objects. However, many Java methods require the use of objects as arguments. Java offers a convenient way to incorporate, or wrap, a primitive data type into an object (e.g., wrapping **int** into the **Integer** class, wrapping **double** into the **Double** class, and wrapping **char** into the **Character** class.). By using a wrapper class, you can process primitive data type values as objects. Java provides **Boolean**, **Character**, **Double**, **Float**, **Byte**, **Short**, **Integer**, and **Long** wrapper classes in the **java.lang** package for primitive data types. The **Boolean** class wraps a Boolean value **true** or **false**. This section uses **Integer** and **Double** as examples to introduce the numeric wrapper classes.

naming convention



Note

Most wrapper class names for a primitive type are the same as the primitive data type name with the first letter capitalized. The exceptions are **Integer** and **Character**.

Numeric wrapper classes are very similar to each other. Each contains the methods **doubleValue()**, **floatValue()**, **intValue()**, **longValue()**, **shortValue()**, and **byteValue()**. These methods “convert” objects into primitive type values. The key features of **Integer** and **Double** are shown in Figure 10.14.

java.lang.Integer	java.lang.Double
<u>-value: int</u> <u>+MAX_VALUE: int</u> <u>+MIN_VALUE: int</u> <u>+Integer(value: int)</u> <u>+Integer(s: String)</u> <u>+byteValue(): byte</u> <u>+shortValue(): short</u> <u>+intValue(): int</u> <u>+longValue(): long</u> <u>+floatValue(): float</u> <u>+doubleValue(): double</u> <u>+compareTo(o: Integer): int</u> <u>+toString(): String</u> <u>+valueOf(s: String): Integer</u> <u>+valueOf(s: String, radix: int): Integer</u> <u>+parseInt(s: String): int</u> <u>+parseInt(s: String, radix: int): int</u>	<u>-value: double</u> <u>+MAX_VALUE: double</u> <u>+MIN_VALUE: double</u> <u>+Double(value: double)</u> <u>+Double(s: String)</u> <u>+byteValue(): byte</u> <u>+shortValue(): short</u> <u>+intValue(): int</u> <u>+longValue(): long</u> <u>+floatValue(): float</u> <u>+doubleValue(): double</u> <u>+compareTo(o: Double): int</u> <u>+toString(): String</u> <u>+valueOf(s: String): Double</u> <u>+valueOf(s: String, radix: int): Double</u> <u>+parseDouble(s: String): double</u> <u>+parseDouble(s: String, radix: int): double</u>

FIGURE 10.14 The wrapper classes provide constructors, constants, and conversion methods for manipulating various data types.

You can construct a wrapper object either from a primitive data type value or from a string representing the numeric value—for example, `new Double(5.0)`, `new Double("5.0")`, `new Integer(5)`, and `new Integer("5")`.

The wrapper classes do not have no-arg constructors. The instances of all wrapper classes are immutable; this means that, once the objects are created, their internal values cannot be changed.

Each numeric wrapper class has the constants `MAX_VALUE` and `MIN_VALUE`. `MAX_VALUE` represents the maximum value of the corresponding primitive data type. For `Byte`, `Short`, `Integer`, and `Long`, `MIN_VALUE` represents the minimum `byte`, `short`, `int`, and `long` values. For `Float` and `Double`, `MIN_VALUE` represents the minimum *positive* `float` and `double` values. The following statements display the maximum integer (2,147,483,647), the minimum positive float (1.4E-45), and the maximum double floating-point number (1.79769313486231570e + 308d).

```
System.out.println("The maximum integer is " + Integer.MAX_VALUE);
System.out.println("The minimum positive float is " +
    Float.MIN_VALUE);
System.out.println(
    "The maximum double-precision floating-point number is " +
    Double.MAX_VALUE);
```

Each numeric wrapper class contains the methods `doubleValue()`, `floatValue()`, `intValue()`, `longValue()`, and `shortValue()` for returning a `double`, `float`, `int`, `long`, or `short` value for the wrapper object. For example,

```
new Double(12.4).intValue() returns 12;
new Integer(12).doubleValue() returns 12.0;
```

Recall that the `String` class contains the `compareTo` method for comparing two strings. The numeric wrapper classes contain the `compareTo` method for comparing two numbers

and returns **1**, **0**, or **-1**, if this number is greater than, equal to, or less than the other number. For example,

```
new Double(12.4).compareTo(new Double(12.3)) returns 1;
new Double(12.3).compareTo(new Double(12.3)) returns 0;
new Double(12.3).compareTo(new Double(12.51)) returns -1;
```

static valueOf methods

The numeric wrapper classes have a useful static method, **valueOf (String s)**. This method creates a new object initialized to the value represented by the specified string. For example,

```
Double doubleObject = Double.valueOf("12.4");
Integer integerObject = Integer.valueOf("12");
```

static parsing methods

You have used the **parseInt** method in the **Integer** class to parse a numeric string into an **int** value and the **parseDouble** method in the **Double** class to parse a numeric string into a **double** value. Each numeric wrapper class has two overloaded parsing methods to parse a numeric string into an appropriate numeric value based on **10** (decimal) or any specified radix (e.g., **2** for binary, **8** for octal, and **16** for hexadecimal).

```
// These two methods are in the Byte class
public static byte parseByte(String s)
public static byte parseByte(String s, int radix)

// These two methods are in the Short class
public static short parseShort(String s)
public static short parseShort(String s, int radix)

// These two methods are in the Integer class
public static int parseInt(String s)
public static int parseInt(String s, int radix)

// These two methods are in the Long class
public static long parseLong(String s)
public static long parseLong(String s, int radix)

// These two methods are in the Float class
public static float parseFloat(String s)
public static float parseFloat(String s, int radix)

// These two methods are in the Double class
public static double parseDouble(String s)
public static double parseDouble(String s, int radix)
```

For example,

```
Integer.parseInt("11", 2) returns 3;
Integer.parseInt("12", 8) returns 10;
Integer.parseInt("13", 10) returns 13;
Integer.parseInt("1A", 16) returns 26;
```

Integer.parseInt("12", 2) would raise a runtime exception because **12** is not a binary number.

Note that you can convert a decimal number into a hex number using the **format** method. For example,

```
String.format("%x", 26) returns 1A;
```

converting decimal to hex

10.7 Describe primitive-type wrapper classes.**10.8** Can each of the following statements be compiled?

- a. Integer i = **new** Integer("23");
- b. Integer i = **new** Integer(23);
- c. Integer i = Integer.valueOf("23");
- d. Integer i = Integer.parseInt("23", 8);
- e. Double d = **new** Double();
- f. Double d = Double.valueOf("23.45");
- g. **int** i = (Integer.valueOf("23")).intValue();
- h. **double** d = (Double.valueOf("23.4")).doubleValue();
- i. **int** i = (Double.valueOf("23.4")).intValue();
- j. String s = (Double.valueOf("23.4")).toString();

10.9 How do you convert an integer into a string? How do you convert a numeric string into an integer? How do you convert a double number into a string? How do you convert a numeric string into a double value?**10.10** Show the output of the following code.

```
public class Test {
    public static void main(String[] args) {
        Integer x = new Integer(3);
        System.out.println(x.intValue());
        System.out.println(x.compareTo(new Integer(4)));
    }
}
```

10.11 What is the output of the following code?

```
public class Test {
    public static void main(String[] args) {
        System.out.println(Integer.parseInt("10"));
        System.out.println(Integer.parseInt("10", 10));
        System.out.println(Integer.parseInt("10", 16));
        System.out.println(Integer.parseInt("11"));
        System.out.println(Integer.parseInt("11", 10));
        System.out.println(Integer.parseInt("11", 16));
    }
}
```

10.8 Automatic Conversion between Primitive Types and Wrapper Class Types

A primitive type value can be automatically converted to an object using a wrapper class, and vice versa, depending on the context.

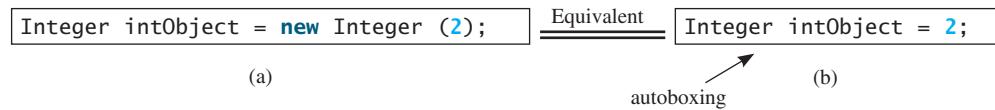


Converting a primitive value to a wrapper object is called *boxing*. The reverse conversion is called *unboxing*. Java allows primitive types and wrapper classes to be converted automatically. The compiler will automatically box a primitive value that appears in a context requiring an object, and will unbox an object that appears in a context requiring a primitive value. This is called *autoboxing* and *autounboxing*.

boxing
unboxing

autoboxing
autounboxing

For instance, the following statement in (a) can be simplified as in (b) due to autoboxing.



Consider the following example:

```
1 Integer[] intArray = {1, 2, 3};
2 System.out.println(intArray[0] + intArray[1] + intArray[2]);
```

In line 1, the primitive values 1, 2, and 3 are automatically boxed into objects `new Integer(1)`, `new Integer(2)`, and `new Integer(3)`. In line 2, the objects `intArray[0]`, `intArray[1]`, and `intArray[2]` are automatically unboxed into `int` values that are added together.



10.12 What are autoboxing and autounboxing? Are the following statements correct?

- Integer x = 3 + new Integer(5);
- Integer x = 3;
- Double x = 3;
- Double x = 3.0;
- int x = new Integer(3);
- int x = new Integer(3) + new Integer(4);

10.13 Show the output of the following code?

```
public class Test {
    public static void main(String[] args) {
        Double x = 3.5;
        System.out.println(x.intValue());
        System.out.println(x.compareTo(4.5));
    }
}
```

10.9 The BigInteger and BigDecimal Classes



The `BigInteger` and `BigDecimal` classes can be used to represent integers or decimal numbers of any size and precision.

immutable

If you need to compute with very large integers or high-precision floating-point values, you can use the `BigInteger` and `BigDecimal` classes in the `java.math` package. Both are *immutable*. The largest integer of the `long` type is `Long.MAX_VALUE` (i.e., `9223372036854775807`). An instance of `BigInteger` can represent an integer of any size. You can use `new BigInteger(String)` and `new BigDecimal(String)` to create an instance of `BigInteger` and `BigDecimal`, use the `add`, `subtract`, `multiply`, `divide`, and `remainder` methods to perform arithmetic operations, and use the `compareTo` method to compare two big numbers. For example, the following code creates two `BigInteger` objects and multiplies them.

```
BigInteger a = new BigInteger("9223372036854775807");
BigInteger b = new BigInteger("2");
BigInteger c = a.multiply(b); // 9223372036854775807 * 2
System.out.println(c);
```



Process large numbers

The output is **18446744073709551614**.

There is no limit to the precision of a `BigDecimal` object. The `divide` method may throw an `ArithException` if the result cannot be terminated. However, you can use the overloaded `divide(BigDecimal d, int scale, int roundingMode)` method to specify a scale and a rounding mode to avoid this exception, where `scale` is the maximum number of digits after the decimal point. For example, the following code creates two `BigDecimal` objects and performs division with scale `20` and rounding mode `BigDecimal.ROUND_UP`.

```
BigDecimal a = new BigDecimal(1.0);
BigDecimal b = new BigDecimal(3);
BigDecimal c = a.divide(b, 20, BigDecimal.ROUND_UP);
System.out.println(c);
```

The output is **0.3333333333333334**.

Note that the factorial of an integer can be very large. Listing 10.9 gives a method that can return the factorial of any integer.

LISTING 10.9 LargeFactorial.java

```
1 import java.math.*;
2
3 public class LargeFactorial {
4     public static void main(String[] args) {
5         System.out.println("50! is \n" + factorial(50));
6     }
7
8     public static BigInteger factorial(long n) {
9         BigInteger result = BigInteger.ONE;
10        for (int i = 1; i <= n; i++)
11            result = result.multiply(new BigInteger(i + ""));
12
13        return result;
14    }
15 }
```

50! is
3041409320171337804361260816606476884437764156896051200000000000000



`BigInteger.ONE` (line 9) is a constant defined in the `BigInteger` class. `BigInteger.ONE` is the same as `new BigInteger("1")`.

A new result is obtained by invoking the `multiply` method (line 11).

10.14 What is the output of the following code?

Check Point

```
public class Test {  
    public static void main(String[] args) {  
        java.math.BigInteger x = new java.math.BigInteger("3");  
        java.math.BigInteger y = new java.math.BigInteger("7");  
        java.math.BigInteger z = x.add(y);  
        System.out.println("x is " + x);  
        System.out.println("y is " + y);  
        System.out.println("z is " + z);  
    }  
}
```

10.10 The String Class



A **String** object is immutable: Its content cannot be changed once the string is created.



VideoNote

The String class

Strings were introduced in Section 4.4. You know strings are objects. You can invoke the **charAt(index)** method to obtain a character at the specified index from a string, the **length()** method to return the size of a string, the **substring** method to return a substring in a string, and the **indexOf** and **lastIndexOf** methods to return the first or last index of a matching character or a substring. We will take a closer look at strings in this section.

The **String** class has 13 constructors and more than 40 methods for manipulating strings. Not only is it very useful in programming, but it is also a good example for learning classes and objects.

10.10.1 Constructing a String

You can create a string object from a string literal or from an array of characters. To create a string from a string literal, use the syntax:

```
String newString = new String(stringLiteral);
```

The argument **stringLiteral** is a sequence of characters enclosed inside double quotes. The following statement creates a **String** object **message** for the string literal "Welcome to Java":

```
String message = new String("Welcome to Java");
```

string literal object

Java treats a string literal as a **String** object. Thus, the following statement is valid:

```
String message = "Welcome to Java";
```

You can also create a string from an array of characters. For example, the following statements create the string "Good Day":

```
char[] charArray = {'G', 'o', 'o', 'd', ' ', 'D', 'a', 'y'};
String message = new String(charArray);
```



Note

A **String** variable holds a reference to a **String** object that stores a string value. Strictly speaking, the terms **String variable**, **String object**, and **string value** are different, but most of the time the distinctions between them can be ignored. For simplicity, the term **string** will often be used to refer to **String variable**, **String object**, and **string value**.

String variable, String object, string value

immutable

10.10.2 Immutable Strings and Interned Strings

A **String** object is immutable; its contents cannot be changed. Does the following code change the contents of the string?

```
String s = "Java";
s = "HTML";
```

The answer is no. The first statement creates a **String** object with the content "Java" and assigns its reference to **s**. The second statement creates a new **String** object with the content "HTML" and assigns its reference to **s**. The first **String** object still exists after the assignment, but it can no longer be accessed, because variable **s** now points to the new object, as shown in Figure 10.15.

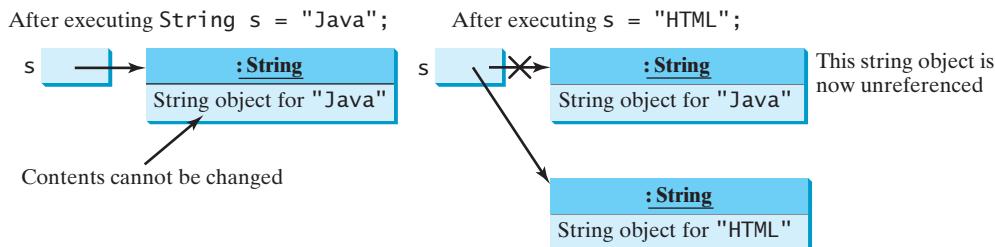
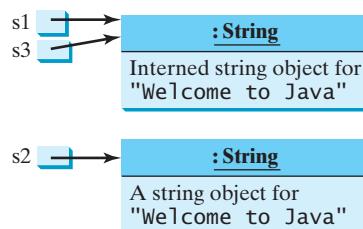


FIGURE 10.15 Strings are immutable; once created, their contents cannot be changed.

Because strings are immutable and are ubiquitous in programming, the JVM uses a unique instance for string literals with the same character sequence in order to improve efficiency and save memory. Such an instance is called an *interned string*. For example, the following statements:

```
String s1 = "Welcome to Java";
String s2 = new String("Welcome to Java");
String s3 = "Welcome to Java";
System.out.println("s1 == s2 is " + (s1 == s2));
System.out.println("s1 == s3 is " + (s1 == s3));
```



display

```
s1 == s2 is false
s1 == s3 is true
```

In the preceding statements, `s1` and `s3` refer to the same interned string—"Welcome to Java"—so `s1 == s3` is `true`. However, `s1 == s2` is `false`, because `s1` and `s2` are two different string objects, even though they have the same contents.

10.10.3 Replacing and Splitting Strings

The **String** class provides the methods for replacing and splitting strings, as shown in Figure 10.16.

java.lang.String	
<code>+replace(oldChar: char, newChar: char): String</code>	Returns a new string that replaces all matching characters in this string with the new character.
<code>+replaceFirst(oldString: String, newString: String): String</code>	Returns a new string that replaces the first matching substring in this string with the new substring.
<code>+replaceAll(oldString: String, newString: String): String</code>	Returns a new string that replaces all matching substrings in this string with the new substring.
<code>+split(delimiter: String): String[]</code>	Returns an array of strings consisting of the substrings split by the delimiter.

FIGURE 10.16 The **String** class contains the methods for replacing and splitting strings.

Once a string is created, its contents cannot be changed. The methods `replace`, `replaceFirst`, and `replaceAll` return a new string derived from the original string (without changing the original string!). Several versions of the `replace` methods are provided to replace a character or a substring in the string with a new character or a new substring.

For example,

```
replace "Welcome".replace('e', 'A') returns a new string, WALcomA.
replaceFirst "Welcome".replaceFirst("e", "AB") returns a new string, WABlcome.
replace "Welcome".replace("e", "AB") returns a new string, WABlcomAB.
replace "Welcome".replace("el", "AB") returns a new string, WABcome.
```

`split`

The `split` method can be used to extract tokens from a string with the specified delimiters. For example, the following code

```
String[] tokens = "Java#HTML#Perl".split("#");
for (int i = 0; i < tokens.length; i++)
    System.out.print(tokens[i] + " ")
```

displays

Java HTML Perl

10.10.4 Matching, Replacing and Splitting by Patterns

why regular expression?

Often you will need to write code that validates user input, such as to check whether the input is a number, a string with all lowercase letters, or a Social Security number. How do you write this type of code? A simple and effective way to accomplish this task is to use the regular expression.

regular expression
regex

A *regular expression* (abbreviated *regex*) is a string that describes a pattern for matching a set of strings. You can match, replace, or split a string by specifying a pattern. This is an extremely useful and powerful feature.

`matches(regex)`

Let us begin with the `matches` method in the `String` class. At first glance, the `matches` method is very similar to the `equals` method. For example, the following two statements both evaluate to `true`.

```
"Java".matches("Java");
"Java".equals("Java");
```

However, the `matches` method is more powerful. It can match not only a fixed string, but also a set of strings that follow a pattern. For example, the following statements all evaluate to `true`:

```
"Java is fun".matches("Java.*")
"Java is cool".matches("Java.*")
"Java is powerful".matches("Java.*")
```

`Java.*` in the preceding statements is a regular expression. It describes a string pattern that begins with Java followed by *any* zero or more characters. Here, the substring matches any zero or more characters.

The following statement evaluates to `true`.

```
"440-02-4534".matches("\d{3}-\d{2}-\d{4}")
```

Here `\d` represents a single digit, and `\d{3}` represents three digits.

The **replaceAll**, **replaceFirst**, and **split** methods can be used with a regular expression. For example, the following statement returns a new string that replaces \$, +, or # in **a+b\$#c** with the string **NNN**.

```
String s = "a+b$#c".replaceAll("[+$#]", "NNN"); replaceAll(regex)
System.out.println(s);
```

Here the regular expression **[+\$#]** specifies a pattern that matches \$, +, or #. So, the output is **aNNNbNNNNNNc**.

The following statement splits the string into an array of strings delimited by punctuation marks.

```
String[] tokens = "Java,C?C#,C++".split("[.,;:]"); split(regex)
for (int i = 0; i < tokens.length; i++)
    System.out.println(tokens[i]);
```

In this example, the regular expression **[.,;:]** specifies a pattern that matches ., , :, :, or ?. Each of these characters is a delimiter for splitting the string. Thus, the string is split into **Java**, **C**, **C#**, and **C++**, which are stored in array **tokens**.

further studies

Regular expression patterns are complex for beginning students to understand. For this reason, simple patterns are introduced in this section. Please refer to Appendix H, Regular Expressions, to learn more about these patterns.

10.10.5 Conversion between Strings and Arrays

Strings are not arrays, but a string can be converted into an array, and vice versa. To convert a string into an array of characters, use the **toCharArray** method. For example, the following statement converts the string **Java** to an array.

toCharArray

```
char[] chars = "Java".toCharArray();
```

Thus, **chars[0]** is **J**, **chars[1]** is **a**, **chars[2]** is **v**, and **chars[3]** is **a**.

You can also use the **getChars(int srcBegin, int srcEnd, char[] dst, int dstBegin)** method to copy a substring of the string from index **srcBegin** to index **srcEnd-1** into a character array **dst** starting from index **dstBegin**. For example, the following code copies a substring "3720" in "CS3720" from index 2 to index 6-1 into the character array **dst** starting from index 4.

```
char[] dst = {'J', 'A', 'V', 'A', '1', '3', '0', '1'};
"CS3720".getChars(2, 6, dst, 4); getChars
```

Thus, **dst** becomes **{'J', 'A', 'V', 'A', '3', '7', '2', '0'}**.

To convert an array of characters into a string, use the **String(char[])** constructor or the **valueOf(char[])** method. For example, the following statement constructs a string from an array using the **String** constructor.

```
String str = new String(new char[]{'J', 'a', 'v', 'a'});
```

The next statement constructs a string from an array using the **valueOf** method.

valueOf

```
String str = String.valueOf(new char[]{'J', 'a', 'v', 'a'});
```

10.10.6 Converting Characters and Numeric Values to Strings

Recall that you can use **Double.parseDouble(str)** or **Integer.parseInt(str)** to convert a string to a **double** value or an **int** value and you can convert a character or a number into a string by using the string concatenating operator. Another way of converting a

overloaded `valueOf`

number into a string is to use the overloaded static `valueOf` method. This method can also be used to convert a character or an array of characters into a string, as shown in Figure 10.17.

<code>java.lang.String</code>	
<code>+valueOf(c: char): String</code>	Returns a string consisting of the character <code>c</code> .
<code>+valueOf(data: char[]): String</code>	Returns a string consisting of the characters in the array.
<code>+valueOf(d: double): String</code>	Returns a string representing the <code>double</code> value.
<code>+valueOf(f: float): String</code>	Returns a string representing the <code>float</code> value.
<code>+valueOf(i: int): String</code>	Returns a string representing the <code>int</code> value.
<code>+valueOf(l: long): String</code>	Returns a string representing the <code>long</code> value.
<code>+valueOf(b: boolean): String</code>	Returns a string representing the <code>boolean</code> value.

FIGURE 10.17 The `String` class contains the static methods for creating strings from primitive type values.

For example, to convert a `double` value `5.44` to a string, use `String.valueOf(5.44)`. The return value is a string consisting of the characters '`5`', '`.`', '`4`', and '`4`'.

10.10.7 Formatting Strings

The `String` class contains the static `format` method to return a formatted string. The syntax to invoke this method is:

```
String.format(format, item1, item2, ..., itemk)
```

This method is similar to the `printf` method except that the `format` method returns a formatted string, whereas the `printf` method displays a formatted string. For example,

```
String s = String.format("%7.2f%6d%-4s", 45.556, 14, "AB");  
System.out.println(s);
```

displays

```
□□45.56□□□14AB□□
```

Note that

```
System.out.printf(format, item1, item2, ..., itemk);
```

is equivalent to

```
System.out.print(  
    String.format(format, item1, item2, ..., itemk));
```

where the square box (`□`) denotes a blank space.

10.15 Suppose that `s1`, `s2`, `s3`, and `s4` are four strings, given as follows:

```
String s1 = "Welcome to Java";  
String s2 = s1;  
String s3 = new String("Welcome to Java");  
String s4 = "Welcome to Java";
```

What are the results of the following expressions?

- a. `s1 == s2`
- b. `s1 == s3`



c. `s1 == s4`
 d. `s1.equals(s3)`
 e. `s1.equals(s4)`
 f. `"Welcome to Java".replace("Java", "HTML")`
 g. `s1.replace('o', 'T')`
 h. `s1.replaceAll("o", "T")`
 i. `s1.replaceFirst("o", "T")`
 j. `s1.toCharArray()`

- 10.16** To create the string `Welcome to Java`, you may use a statement like this:

```
String s = "Welcome to Java";
```

or:

```
String s = new String("Welcome to Java");
```

Which one is better? Why?

- 10.17** What is the output of the following code?

```
String s1 = "Welcome to Java";
String s2 = s1.replace("o", "abc");
System.out.println(s1);
System.out.println(s2);
```

- 10.18** Let `s1` be `"Welcome"` and `s2` be `"welcome"`. Write the code for the following statements:

- Replace all occurrences of the character `e` with `E` in `s1` and assign the new string to `s2`.
- Split `Welcome to Java and HTML` into an array `tokens` delimited by a space and assign the first two tokens into `s1` and `s2`.

- 10.19** Does any method in the **String** class change the contents of the string?

- 10.20** Suppose string `s` is created using `new String()`; what is `s.length()`?

- 10.21** How do you convert a `char`, an array of characters, or a number to a string?

- 10.22** Why does the following code cause a `NullPointerException`?

```
1 public class Test {
2     private String text;
3
4     public Test(String s) {
5         String text = s;
6     }
7
8     public static void main(String[] args) {
9         Test test = new Test("ABC");
10        System.out.println(test.text.toLowerCase());
11    }
12 }
```

- 10.23** What is wrong in the following program?

```
1 public class Test {
2     String text;
3 }
```

```

4  public void Test(String s) {
5      text = s;
6  }
7
8  public static void main(String[] args) {
9      Test test = new Test("ABC");
10     System.out.println(test);
11 }
12 }
```

10.24 Show the output of the following code.

```

public class Test {
    public static void main(String[] args) {
        System.out.println("Hi, ABC, good".matches("ABC "));
        System.out.println("Hi, ABC, good".matches(".*ABC.*"));
        System.out.println("A,B;C".replaceAll(", ;", "#"));
        System.out.println("A,B;C".replaceAll("[, ;]", "#"));

        String[] tokens = "A,B;C".split("[, ;]");
        for (int i = 0; i < tokens.length; i++)
            System.out.print(tokens[i] + " ");
    }
}
```

10.25 Show the output of the following code.

```

public class Test {
    public static void main(String[] args) {
        String s = "Hi, Good Morning";
        System.out.println(m(s));
    }

    public static int m(String s) {
        int count = 0;
        for (int i = 0; i < s.length(); i++)
            if (Character.isUpperCase(s.charAt(i)))
                count++;

        return count;
    }
}
```

10.11 The **StringBuilder** and **StringBuffer** Classes



*The **StringBuilder** and **StringBuffer** classes are similar to the **String** class except that the **String** class is immutable.*

In general, the **StringBuilder** and **StringBuffer** classes can be used wherever a string is used. **StringBuilder** and **StringBuffer** are more flexible than **String**. You can add, insert, or append new contents into **StringBuilder** and **StringBuffer** objects, whereas the value of a **String** object is fixed once the string is created.

StringBuilder

The **StringBuilder** class is similar to **StringBuffer** except that the methods for modifying the buffer in **StringBuffer** are *synchronized*, which means that only one task is allowed to execute the methods. Use **StringBuffer** if the class might be accessed by multiple tasks concurrently, because synchronization is needed in this case to prevent corruptions to

StringBuffer. Concurrent programming will be introduced in Chapter 30. Using **String-Builder** is more efficient if it is accessed by just a single task, because no synchronization is needed in this case. The constructors and methods in **StringBuffer** and **StringBuilder** are almost the same. This section covers **StringBuilder**. You can replace **StringBuilder** in all occurrences in this section by **StringBuffer**. The program can compile and run without any other changes.

The **StringBuilder** class has three constructors and more than 30 methods for managing the builder and modifying strings in the builder. You can create an empty string builder or a string builder from a string using the constructors, as shown in Figure 10.18.

StringBuilder constructors

java.lang.StringBuilder
+StringBuilder()
+StringBuilder(capacity: int)
+StringBuilder(s: String)

Constructs an empty string builder with capacity 16.
 Constructs a string builder with the specified capacity.
 Constructs a string builder with the specified string.

FIGURE 10.18 The **StringBuilder** class contains the constructors for creating instances of **StringBuilder**.

10.11.1 Modifying Strings in the **StringBuilder**

You can append new contents at the end of a string builder, insert new contents at a specified position in a string builder, and delete or replace characters in a string builder, using the methods listed in Figure 10.19.

java.lang.StringBuilder
+append(data: char[]): StringBuilder
+append(data: char[], offset: int, len: int): StringBuilder
+append(v: aPrimitiveType): StringBuilder
+append(s: String): StringBuilder
+delete(startIndex: int, endIndex: int): StringBuilder
+deleteCharAt(index: int): StringBuilder
+insert(index: int, data: char[], offset: int, len: int): StringBuilder
+insert(offset: int, data: char[]): StringBuilder
+insert(offset: int, b: aPrimitiveType): StringBuilder
+insert(offset: int, s: String): StringBuilder
+replace(startIndex: int, endIndex: int, s: String): StringBuilder
+reverse(): StringBuilder
+setCharAt(index: int, ch: char): void

Appends a **char** array into this string builder.
 Appends a subarray in **data** into this string builder.

 Appends a primitive type value as a string to this builder.
 Appends a string to this string builder.
 Deletes characters from **startIndex** to **endIndex-1**.

 Deletes a character at the specified index.
 Inserts a subarray of the data in the array into the builder at the specified index.
 Inserts data into this builder at the position offset.

 Inserts a value converted to a string into this builder.

 Inserts a string into this builder at the position offset.
 Replaces the characters in this builder from **startIndex** to **endIndex-1** with the specified string.
 Reverses the characters in the builder.
 Sets a new character at the specified index in this builder.

FIGURE 10.19 The **StringBuilder** class contains the methods for modifying string builders.

The `StringBuilder` class provides several overloaded methods to append `boolean`, `char`, `char[]`, `double`, `float`, `int`, `long`, and `String` into a string builder. For example, the following code appends strings and characters into `stringBuilder` to form a new string, `Welcome to Java`.

append

```
StringBuilder stringBuilder = new StringBuilder();
stringBuilder.append("Welcome");
stringBuilder.append(' ');
stringBuilder.append("to");
stringBuilder.append(' ');
stringBuilder.append("Java");
```

The `StringBuilder` class also contains overloaded methods to insert `boolean`, `char`, `char array`, `double`, `float`, `int`, `long`, and `String` into a string builder. Consider the following code:

insert

```
stringBuilder.insert(11, "HTML and ");
```

Suppose `stringBuilder` contains `Welcome to Java` before the `insert` method is applied. This code inserts `"HTML and "` at position 11 in `stringBuilder` (just before the `J`). The new `stringBuilder` is `Welcome to HTML and Java`.

You can also delete characters from a string in the builder using the two `delete` methods, reverse the string using the `reverse` method, replace characters using the `replace` method, or set a new character in a string using the `setCharAt` method.

For example, suppose `stringBuilder` contains `Welcome to Java` before each of the following methods is applied:

delete
deleteCharAt
reverse
replace
setCharAt

```
stringBuilder.delete(8, 11) changes the builder to Welcome Java.
stringBuilder.deleteCharAt(8) changes the builder to Welcome o Java.
stringBuilder.reverse() changes the builder to avaJ ot emocleW.
stringBuilder.replace(11, 15, "HTML") changes the builder to Welcome to HTML.
stringBuilder.setCharAt(0, 'w') sets the builder to welcome to Java.
```

All these modification methods except `setCharAt` do two things:

- Change the contents of the string builder
- Return the reference of the string builder

ignore return value

For example, the following statement

```
StringBuilder stringBuilder1 = stringBuilder.reverse();
```

reverses the string in the builder and assigns the builder's reference to `stringBuilder1`. Thus, `stringBuilder` and `stringBuilder1` both point to the same `StringBuilder` object. Recall that a value-returning method can be invoked as a statement, if you are not interested in the return value of the method. In this case, the return value is simply ignored. For example, in the following statement

```
stringBuilder.reverse();
```

the return value is ignored.

String or StringBuilder?



Tip

If a string does not require any change, use `String` rather than `StringBuilder`. Java can perform some optimizations for `String`, such as sharing interned strings.

10.11.2 The **toString**, **capacity**, **length**, **setLength**, and **charAt** Methods

The **StringBuilder** class provides the additional methods for manipulating a string builder and obtaining its properties, as shown in Figure 10.20.

java.lang.StringBuilder	
<code>+toString(): String</code>	Returns a string object from the string builder.
<code>+capacity(): int</code>	Returns the capacity of this string builder.
<code>+charAt(index: int): char</code>	Returns the character at the specified index.
<code>+length(): int</code>	Returns the number of characters in this builder.
<code>+setLength(newLength: int): void</code>	Sets a new length in this builder.
<code>+substring(startIndex: int): String</code>	Returns a substring starting at <code>startIndex</code> .
<code>+substring(startIndex: int, endIndex: int): String</code>	Returns a substring from <code>startIndex</code> to <code>endIndex-1</code> .
<code>+trimToSize(): void</code>	Reduces the storage size used for the string builder.

FIGURE 10.20 The **StringBuilder** class contains the methods for modifying string builders.

The **capacity()** method returns the current capacity of the string builder. The capacity is the number of characters the string builder is able to store without having to increase its size.

`capacity()`

The **length()** method returns the number of characters actually stored in the string builder. The **setLength(newLength)** method sets the length of the string builder. If the **newLength** argument is less than the current length of the string builder, the string builder is truncated to contain exactly the number of characters given by the **newLength** argument. If the **newLength** argument is greater than or equal to the current length, sufficient null characters (`\u0000`) are appended to the string builder so that **length** becomes the **newLength** argument. The **newLength** argument must be greater than or equal to **0**.

`length()`
`setLength(int)`

The **charAt(index)** method returns the character at a specific **index** in the string builder. The index is **0** based. The first character of a string builder is at index **0**, the next at index **1**, and so on. The **index** argument must be greater than or equal to **0**, and less than the length of the string builder.

`charAt(int)`



Note

The length of the string is always less than or equal to the capacity of the builder. The length is the actual size of the string stored in the builder, and the capacity is the current size of the builder. The builder's capacity is automatically increased if more characters are added to exceed its capacity. Internally, a string builder is an array of characters, so the builder's capacity is the size of the array. If the builder's capacity is exceeded, the array is replaced by a new array. The new array size is **2 * (the previous array size + 1)**.

`length` and `capacity`



Tip

You can use **new StringBuilder(initialCapacity)** to create a **StringBuilder** with a specified initial capacity. By carefully choosing the initial capacity, you can make your program more efficient. If the capacity is always larger than the actual length of the builder, the JVM will never need to reallocate memory for the builder. On the other hand, if the capacity is too large, you will waste memory space. You can use the **trimToSize()** method to reduce the capacity to the actual size.

`initial capacity`

`trimToSize()`

10.11.3 Case Study: Ignoring Nonalphanumeric Characters When Checking Palindromes

Listing 5.14, `Palindrome.java`, considered all the characters in a string to check whether it is a palindrome. Write a new program that ignores nonalphanumeric characters in checking whether a string is a palindrome.

Here are the steps to solve the problem:

1. Filter the string by removing the nonalphanumeric characters. This can be done by creating an empty string builder, adding each alphanumeric character in the string to a string builder, and returning the string from the string builder. You can use the `isLetterOrDigit(ch)` method in the `Character` class to check whether character `ch` is a letter or a digit.
 2. Obtain a new string that is the reversal of the filtered string. Compare the reversed string with the filtered string using the `equals` method.

The complete program is shown in Listing 10.10.

LISTING 10.10 `PalindromeIgnoreNonAlphanumeric.java`

```
1 import java.util.Scanner;
2
3 public class PalindromeIgnoreNonAlphanumeric {
4     /** Main method */
5     public static void main(String[] args) {
6         // Create a Scanner
7         Scanner input = new Scanner(System.in);
8
9         // Prompt the user to enter a string
10        System.out.print("Enter a string: ");
11        String s = input.nextLine();
12
13        // Display result
14        System.out.println("Ignoring nonalphanumeric characters, \nis " +
15            + s + " a palindrome? " + isPalindrome(s));
16    }
17
18    /** Return true if a string is a palindrome */
19    public static boolean isPalindrome(String s) {
20        // Create a new string by eliminating nonalphanumeric chars
21        String s1 = filter(s);
22
23        // Create a new string that is the reversal of s1
24        String s2 = reverse(s1);
25
26        // Check if the reversal is the same as the original string
27        return s2.equals(s1);
28    }
29
30    /** Create a new string by eliminating nonalphanumeric chars */
31    public static String filter(String s) {
32        // Create a string builder
33        StringBuilder stringBuilder = new StringBuilder();
34
35        // Examine each char in the string to skip alphanumeric char
36        for (int i = 0; i < s.length(); i++) {
37            if (Character.isLetterOrDigit(s.charAt(i))) {
38                stringBuilder.append(s.charAt(i));
39            }
40        }
41
42        return stringBuilder.toString();
43    }
44
45    // Reverse a string
46    private static String reverse(String s) {
47        int len = s.length();
48        char[] arr = s.toCharArray();
49
50        for (int i = 0, j = len - 1; i < j; i++, j--) {
51            char temp = arr[i];
52            arr[i] = arr[j];
53            arr[j] = temp;
54        }
55
56        return new String(arr);
57    }
58}
```

```

40     }
41
42     // Return a new filtered string
43     return stringBuilder.toString();
44 }
45
46 /** Create a new string by reversing a specified string */
47 public static String reverse(String s) {
48     StringBuilder stringBuilder = new StringBuilder(s);
49     stringBuilder.reverse(); // Invoke reverse in StringBuilder
50     return stringBuilder.toString();
51 }
52 }
```

Enter a string: ab<c>cb?a ↵ Enter
 Ignoring nonalphanumeric characters,
 is ab<c>cb?a a palindrome? true



Enter a string: abcc><?cab ↵ Enter
 Ignoring nonalphanumeric characters,
 is abcc><?cab a palindrome? false



The **filter(String s)** method (lines 31–44) examines each character in string **s** and copies it to a string builder if the character is a letter or a numeric character. The **filter** method returns the string in the builder. The **reverse(String s)** method (lines 47–51) creates a new string that reverses the specified string **s**. The **filter** and **reverse** methods both return a new string. The original string is not changed.

The program in Listing 5.14 checks whether a string is a palindrome by comparing pairs of characters from both ends of the string. Listing 10.10 uses the **reverse** method in the **StringBuilder** class to reverse the string, then compares whether the two strings are equal to determine whether the original string is a palindrome.

10.26 What is the difference between **StringBuilder** and **StringBuffer**?

10.27 How do you create a string builder from a string? How do you return a string from a string builder?



10.28 Write three statements to reverse a string **s** using the **reverse** method in the **StringBuilder** class.

10.29 Write three statements to delete a substring from a string **s** of 20 characters, starting at index 4 and ending with index 10. Use the **delete** method in the **StringBuilder** class.

10.30 What is the internal storage for characters in a string and a string builder?

10.31 Suppose that **s1** and **s2** are given as follows:

```
StringBuilder s1 = new StringBuilder("Java");
StringBuilder s2 = new StringBuilder("HTML");
```

Show the value of **s1** after each of the following statements. Assume that the statements are independent.

- s1.append(" is fun");**
- s1.append(s2);**

- c. `s1.insert(2, "is fun");`
- d. `s1.insert(1, s2);`
- e. `s1.charAt(2);`
- f. `s1.length();`
- g. `s1.deleteCharAt(3);`
- h. `s1.delete(1, 3);`
- i. `s1.reverse();`
- j. `s1.replace(1, 3, "Computer");`
- k. `s1.substring(1, 3);`
- l. `s1.substring(2);`

10.32 Show the output of the following program:

```
public class Test {
    public static void main(String[] args) {
        String s = "Java";
        StringBuilder builder = new StringBuilder(s);
        change(s, builder);

        System.out.println(s);
        System.out.println(builder);
    }

    private static void change(String s, StringBuilder builder) {
        s = s + " and HTML";
        builder.append(" and HTML");
    }
}
```

KEY TERMS

abstract data type (ADT)	366	composition	374
aggregation	374	has-a relationship	374
boxing	383	multiplicity	373
class abstraction	366	stack	378
class encapsulation	366	unboxing	383
class's contract	366		

CHAPTER SUMMARY

- 1.** The procedural paradigm focuses on designing methods. The object-oriented paradigm couples data and methods together into objects. Software design using the object-oriented paradigm focuses on objects and operations on objects. The object-oriented approach combines the power of the procedural paradigm with an added dimension that integrates data with operations into objects.
- 2.** Many Java methods require the use of objects as arguments. Java offers a convenient way to incorporate, or wrap, a primitive data type into an object (e.g., wrapping `int` into the `Integer` class, and wrapping `double` into the `Double` class).

3. Java can automatically convert a primitive type value to its corresponding wrapper object in the context and vice versa.
4. The **BigInteger** class is useful for computing and processing integers of any size. The **BigDecimal** class can be used to compute and process floating-point numbers with any arbitrary precision.
5. A **String** object is immutable; its contents cannot be changed. To improve efficiency and save memory, the JVM stores two literal strings that have the same character sequence in a unique object. This unique object is called an *interned string object*.
6. A *regular expression* (abbreviated *regex*) is a string that describes a pattern for matching a set of strings. You can match, replace, or split a string by specifying a pattern.
7. The **StringBuilder** and **StringBuffer** classes can be used to replace the **String** class. The **String** object is immutable, but you can add, insert, or append new contents into **StringBuilder** and **StringBuffer** objects. Use **String** if the string contents do not require any change, and use **StringBuilder** or **StringBuffer** if they might change.

Quiz

Answer the quiz for this chapter online at www.cs.armstrong.edu/liang/intro10e/quiz.html.

PROGRAMMING EXERCISES

MyProgrammingLab™

Sections 10.2–10.3

*10.1 (*The Time class*) Design a class named **Time**. The class contains:

- The data fields **hour**, **minute**, and **second** that represent a time.
- A no-arg constructor that creates a **Time** object for the current time. (The values of the data fields will represent the current time.)
- A constructor that constructs a **Time** object with a specified elapsed time since midnight, January 1, 1970, in milliseconds. (The values of the data fields will represent this time.)
- A constructor that constructs a **Time** object with the specified hour, minute, and second.
- Three getter methods for the data fields **hour**, **minute**, and **second**, respectively.
- A method named **setTime(long elapsedTime)** that sets a new time for the object using the elapsed time. For example, if the elapsed time is **555550000** milliseconds, the hour is **10**, the minute is **19**, and the second is **10**.

Draw the UML diagram for the class and then implement the class. Write a test program that creates two **Time** objects (using **new Time()** and **new Time(555550000)**) and displays their hour, minute, and second in the format hour:minute:second.

(Hint: The first two constructors will extract the hour, minute, and second from the elapsed time. For the no-arg constructor, the current time can be obtained using **System.currentTimeMillis()**, as shown in Listing 2.7, ShowCurrentTime.java.)

10.2 (*The BMI class*) Add the following new constructor in the **BMI** class:

```
/** Construct a BMI with the specified name, age, weight,
 * feet, and inches
 */
public BMI(String name, int age, double weight, double feet,
           double inches)
```

10.3 (*The MyInteger class*) Design a class named **MyInteger**. The class contains:

- An **int** data field named **value** that stores the **int** value represented by this object.
- A constructor that creates a **MyInteger** object for the specified **int** value.
- A getter method that returns the **int** value.
- The methods **isEven()**, **isOdd()**, and **isPrime()** that return **true** if the value in this object is even, odd, or prime, respectively.
- The static methods **isEven(int)**, **isOdd(int)**, and **isPrime(int)** that return **true** if the specified value is even, odd, or prime, respectively.
- The static methods **isEven(MyInteger)**, **isOdd(MyInteger)**, and **isPrime(MyInteger)** that return **true** if the specified value is even, odd, or prime, respectively.
- The methods **equals(int)** and **equals(MyInteger)** that return **true** if the value in this object is equal to the specified value.
- A static method **parseInt(char[])** that converts an array of numeric characters to an **int** value.
- A static method **parseInt(String)** that converts a string into an **int** value.

Draw the UML diagram for the class and then implement the class. Write a client program that tests all methods in the class.

10.4 (*The MyPoint class*) Design a class named **MyPoint** to represent a point with **x**- and **y**-coordinates. The class contains:

- The data fields **x** and **y** that represent the coordinates with getter methods.
- A no-arg constructor that creates a point **(0, 0)**.
- A constructor that constructs a point with specified coordinates.
- A method named **distance** that returns the distance from this point to a specified point of the **MyPoint** type.
- A method named **distance** that returns the distance from this point to another point with specified **x**- and **y**-coordinates.

Draw the UML diagram for the class and then implement the class. Write a test program that creates the two points **(0, 0)** and **(10, 30.5)** and displays the distance between them.



VideoNote

The MyPoint class

Sections 10.4–10.8

***10.5** (*Displaying the prime factors*) Write a program that prompts the user to enter a positive integer and displays all its smallest factors in decreasing order. For example, if the integer is **120**, the smallest factors are displayed as **5, 3, 2, 2, 2**. Use the **StackOfIntegers** class to store the factors (e.g., **2, 2, 2, 3, 5**) and retrieve and display them in reverse order.

***10.6** (*Displaying the prime numbers*) Write a program that displays all the prime numbers less than **120** in decreasing order. Use the **StackOfIntegers** class to store the prime numbers (e.g., **2, 3, 5, ...**) and retrieve and display them in reverse order.

****10.7** (*Game: ATM machine*) Use the **Account** class created in Programming Exercise 9.7 to simulate an ATM machine. Create ten accounts in an array with id **0, 1, . . . , 9**, and initial balance \$100. The system prompts the user to enter an id. If the id is entered incorrectly, ask the user to enter a correct id. Once an id is accepted, the main menu is displayed as shown in the sample run. You can enter a choice **1** for viewing the current balance, **2** for withdrawing money, **3** for depositing money, and **4** for exiting the main menu. Once you exit, the system will prompt for an id again. Thus, once the system starts, it will not stop.



```

Enter an id: 4 ↵Enter
Main menu
1: check balance
2: withdraw
3: deposit
4: exit
Enter a choice: 1 ↵Enter
The balance is 100.0

Main menu
1: check balance
2: withdraw
3: deposit
4: exit
Enter a choice: 2 ↵Enter
Enter an amount to withdraw: 3 ↵Enter

Main menu
1: check balance
2: withdraw
3: deposit
4: exit
Enter a choice: 1 ↵Enter
The balance is 97.0

Main menu
1: check balance
2: withdraw
3: deposit
4: exit
Enter a choice: 3 ↵Enter
Enter an amount to deposit: 10 ↵Enter

Main menu
1: check balance
2: withdraw
3: deposit
4: exit
Enter a choice: 1 ↵Enter
The balance is 107.0

Main menu
1: check balance
2: withdraw
3: deposit
4: exit
Enter a choice: 4 ↵Enter

Enter an id:

```

*****10.8** (*Financial: the Tax class*) Programming Exercise 8.12 writes a program for computing taxes using arrays. Design a class named `Tax` to contain the following instance data fields:

- `int filingStatus`: One of the four tax-filing statuses: `0`—single filer, `1`—married filing jointly or qualifying widow(er), `2`—married filing separately, and `3`—head of household. Use the public static constants `SINGLE_FILER(0)`, `MARRIED_JOINTLY_OR_QUALIFYING_WIDOW(ER)(1)`, `MARRIED_SEPARATELY(2)`, `HEAD_OF_HOUSEHOLD(3)` to represent the statuses.
- `int[][] brackets`: Stores the tax brackets for each filing status.
- `double[] rates`: Stores the tax rates for each bracket.
- `double taxableIncome`: Stores the taxable income.

Provide the getter and setter methods for each data field and the `getTax()` method that returns the tax. Also provide a no-arg constructor and the constructor `Tax(filingStatus, brackets, rates, taxableIncome)`.

Draw the UML diagram for the class and then implement the class. Write a test program that uses the `Tax` class to print the 2001 and 2009 tax tables for taxable income from \$50,000 to \$60,000 with intervals of \$1,000 for all four statuses. The tax rates for the year 2009 were given in Table 3.2. The tax rates for 2001 are shown in Table 10.1.

TABLE 10.1 2001 United States Federal Personal Tax Rates

Tax rate	Single filers	Married filing jointly or qualifying widow(er)	Married filing separately	Head of household
15%	Up to \$27,050	Up to \$45,200	Up to \$22,600	Up to \$36,250
27.5%	\$27,051–\$65,550	\$45,201–\$109,250	\$22,601–\$54,625	\$36,251–\$93,650
30.5%	\$65,551–\$136,750	\$109,251–\$166,500	\$54,626–\$83,250	\$93,651–\$151,650
35.5%	\$136,751–\$297,350	\$166,501–\$297,350	\$83,251–\$148,675	\$151,651–\$297,350
39.1%	\$297,351 or more	\$297,351 or more	\$ 148,676 or more	\$297,351 or more

****10.9** (*The Course class*) Revise the `Course` class as follows:

- The array size is fixed in Listing 10.6. Improve it to automatically increase the array size by creating a new larger array and copying the contents of the current array to it.
- Implement the `dropStudent` method.
- Add a new method named `clear()` that removes all students from the course.

Write a test program that creates a course, adds three students, removes one, and displays the students in the course.

***10.10** (*The Queue class*) Section 10.6 gives a class for `Stack`. Design a class named `Queue` for storing integers. Like a stack, a queue holds elements. In a stack, the elements are retrieved in a last-in first-out fashion. In a queue, the elements are retrieved in a first-in first-out fashion. The class contains:

- An `int[]` data field named `elements` that stores the `int` values in the queue.
- A data field named `size` that stores the number of elements in the queue.
- A constructor that creates a `Queue` object with default capacity `8`.
- The method `enqueue(int v)` that adds `v` into the queue.

- The method `dequeue()` that removes and returns the element from the queue.
- The method `empty()` that returns true if the queue is empty.
- The method `getSize()` that returns the size of the queue.

Draw an UML diagram for the class. Implement the class with the initial array size set to 8. The array size will be doubled once the number of the elements exceeds the size. After an element is removed from the beginning of the array, you need to shift all elements in the array one position to the left. Write a test program that adds 20 numbers from 1 to 20 into the queue and removes these numbers and displays them.

***10.11** (*Geometry: the Circle2D class*) Define the `Circle2D` class that contains:

- Two `double` data fields named `x` and `y` that specify the center of the circle with getter methods.
- A data field `radius` with a getter method.
- A no-arg constructor that creates a default circle with `(0, 0)` for `(x, y)` and `1` for `radius`.
- A constructor that creates a circle with the specified `x`, `y`, and `radius`.
- A method `getArea()` that returns the area of the circle.
- A method `getPerimeter()` that returns the perimeter of the circle.
- A method `contains(double x, double y)` that returns `true` if the specified point `(x, y)` is inside this circle (see Figure 10.21a).
- A method `contains(Circle2D circle)` that returns `true` if the specified circle is inside this circle (see Figure 10.21b).
- A method `overlaps(Circle2D circle)` that returns `true` if the specified circle overlaps with this circle (see Figure 10.21c).

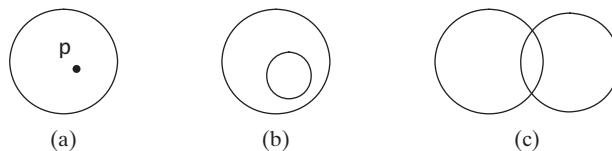


FIGURE 10.21 (a) A point is inside the circle. (b) A circle is inside another circle. (c) A circle overlaps another circle.

Draw the UML diagram for the class and then implement the class. Write a test program that creates a `Circle2D` object `c1(new Circle2D(2, 2, 5.5))`, displays its area and perimeter, and displays the result of `c1.contains(3, 3)`, `c1.contains(new Circle2D(4, 5, 10.5))`, and `c1.overlaps(new Circle2D(3, 5, 2.3))`.

*****10.12** (*Geometry: the Triangle2D class*) Define the `Triangle2D` class that contains:

- Three points named `p1`, `p2`, and `p3` of the type `MyPoint` with getter and setter methods. `MyPoint` is defined in Programming Exercise 10.4.
- A no-arg constructor that creates a default triangle with the points `(0, 0)`, `(1, 1)`, and `(2, 5)`.
- A constructor that creates a triangle with the specified points.
- A method `getArea()` that returns the area of the triangle.
- A method `getPerimeter()` that returns the perimeter of the triangle.
- A method `contains(MyPoint p)` that returns `true` if the specified point `p` is inside this triangle (see Figure 10.22a).

- A method `contains(Triangle2D t)` that returns `true` if the specified triangle is inside this triangle (see Figure 10.22b).
- A method `overlaps(Triangle2D t)` that returns `true` if the specified triangle overlaps with this triangle (see Figure 10.22c).

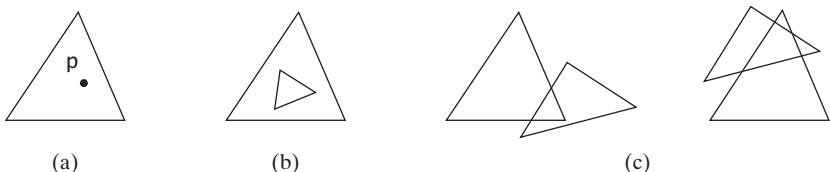


FIGURE 10.22 (a) A point is inside the triangle. (b) A triangle is inside another triangle.
 (c) A triangle overlaps another triangle.

Draw the UML diagram for the class and then implement the class. Write a test program that creates a `Triangle2D` objects `t1` using the constructor `new Triangle2D(new MyPoint(2.5, 2), new MyPoint(4.2, 3), new MyPoint(5, 3.5))`, displays its area and perimeter, and displays the result of `t1.contains(3, 3)`, `r1.contains(new Triangle2D(new MyPoint(2.9, 2), new MyPoint(4, 1), MyPoint(1, 3.4)))`, and `t1.overlaps(new Triangle2D(new MyPoint(2, 5.5), new MyPoint(4, -3), MyPoint(2, 6.5)))`.

(Hint: For the formula to compute the area of a triangle, see Programming Exercise 2.19. To detect whether a point is inside a triangle, draw three dashed lines, as shown in Figure 10.23. If the point is inside a triangle, each dashed line should intersect a side only once. If a dashed line intersects a side twice, then the point must be outside the triangle. For the algorithm of finding the intersecting point of two lines, see Programming Exercise 3.25.)

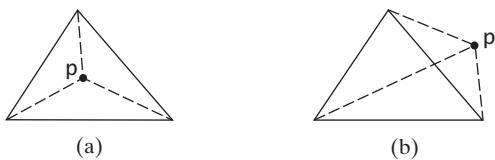


FIGURE 10.23 (a) A point is inside the triangle. (b) A point is outside the triangle.

***10.13** (*Geometry: the MyRectangle2D class*) Define the `MyRectangle2D` class that contains:

- Two `double` data fields named `x` and `y` that specify the center of the rectangle with getter and setter methods. (Assume that the rectangle sides are parallel to `x-` or `y-` axes.)
- The data fields `width` and `height` with getter and setter methods.
- A no-arg constructor that creates a default rectangle with `(0, 0)` for `(x, y)` and `1` for both `width` and `height`.
- A constructor that creates a rectangle with the specified `x`, `y`, `width`, and `height`.

- A method `getArea()` that returns the area of the rectangle.
- A method `getPerimeter()` that returns the perimeter of the rectangle.
- A method `contains(double x, double y)` that returns `true` if the specified point `(x, y)` is inside this rectangle (see Figure 10.24a).
- A method `contains(MyRectangle2D r)` that returns `true` if the specified rectangle is inside this rectangle (see Figure 10.24b).
- A method `overlaps(MyRectangle2D r)` that returns `true` if the specified rectangle overlaps with this rectangle (see Figure 10.24c).



FIGURE 10.24 A point is inside the rectangle. (b) A rectangle is inside another rectangle.
 (c) A rectangle overlaps another rectangle. (d) Points are enclosed inside a rectangle.

Draw the UML diagram for the class and then implement the class. Write a test program that creates a `MyRectangle2D` object `r1(new MyRectangle2D(2, 2, 5.5, 4.9))`, displays its area and perimeter, and displays the result of `r1.contains(3, 3), r1.contains(new MyRectangle2D(4, 5, 10.5, 3.2))`, and `r1.overlaps(new MyRectangle2D(3, 5, 2.3, 5.4))`.

*10.14 (The `MyDate` class) Design a class named `MyDate`. The class contains:

- The data fields `year`, `month`, and `day` that represent a date. `month` is 0-based, i.e., 0 is for January.
- A no-arg constructor that creates a `MyDate` object for the current date.
- A constructor that constructs a `MyDate` object with a specified elapsed time since midnight, January 1, 1970, in milliseconds.
- A constructor that constructs a `MyDate` object with the specified year, month, and day.
- Three getter methods for the data fields `year`, `month`, and `day`, respectively.
- A method named `setDate(long elapsedTime)` that sets a new date for the object using the elapsed time.

Draw the UML diagram for the class and then implement the class. Write a test program that creates two `MyDate` objects (using `new MyDate()` and `new MyDate(34355555133101L)`) and displays their year, month, and day.

(Hint: The first two constructors will extract the year, month, and day from the elapsed time. For example, if the elapsed time is `561555550000` milliseconds, the year is `1987`, the month is `9`, and the day is `18`. You may use the `GregorianCalendar` class discussed in Programming Exercise 9.5 to simplify coding.)

*10.15 (Geometry: the bounding rectangle) A bounding rectangle is the minimum rectangle that encloses a set of points in a two-dimensional plane, as shown in Figure 10.24d. Write a method that returns a bounding rectangle for a set of points in a two-dimensional plane, as follows:

```
public static MyRectangle2D getRectangle(double[][] points)
```

The `Rectangle2D` class is defined in Programming Exercise 10.13. Write a test program that prompts the user to enter five points and displays the bounding rectangle's center, width, and height. Here is a sample run:



Enter five points: 1.0 2.5 3 4 5 6 7 8 9 10 The bounding rectangle's center (5.0, 6.25), width 8.0, height 7.5

Section 10.9

- *10.16 (*Divisible by 2 or 3*) Find the first ten numbers with **50** decimal digits that are divisible by **2** or **3**.
- *10.17 (*Square numbers*) Find the first ten square numbers that are greater than `Long.MAX_VALUE`. A square number is a number in the form of n^2 . For example, 4, 9, and 16 are square numbers. Find an efficient approach to run your program fast.
- *10.18 (*Large prime numbers*) Write a program that finds five prime numbers larger than `Long.MAX_VALUE`.
- *10.19 (*Mersenne prime*) A prime number is called a *Mersenne prime* if it can be written in the form $2^p - 1$ for some positive integer p . Write a program that finds all Mersenne primes with $p \leq 100$ and displays the output as shown below. (*Hint*: You have to use `BigInteger` to store the number, because it is too big to be stored in `Long`. Your program may take several hours to run.)

$$p \quad 2^p - 1$$

2	3
3	7
5	31

...

- *10.20 (*Approximate e*) Programming Exercise 5.26 approximates e using the following series:

$$e = 1 + \frac{1}{1!} + \frac{1}{2!} + \frac{1}{3!} + \frac{1}{4!} + \dots + \frac{1}{i!}$$

In order to get better precision, use `BigDecimal` with **25** digits of precision in the computation. Write a program that displays the `e` value for $i = 100, 200, \dots$, and **1000**.

- 10.21 (*Divisible by 5 or 6*) Find the first ten numbers greater than `Long.MAX_VALUE` that are divisible by **5** or **6**.

Sections 10.10–10.11

- **10.22 (*Implement the `String` class*) The `String` class is provided in the Java library. Provide your own implementation for the following methods (name the new class `MyString1`):

```
public MyString1(char[] chars);
public char charAt(int index);
public int length();
public MyString1 substring(int begin, int end);
public MyString1 toLowerCase();
public boolean equals(MyString1 s);
public static MyString1 valueOf(int i);
```

- ** 10.23** (*Implement the **String** class*) The **String** class is provided in the Java library. Provide your own implementation for the following methods (name the new class **MyString2**):

```
public MyString2(String s);
public int compare(String s);
public MyString2 substring(int begin);
public MyString2 toUpperCase();
public char[] toChars();
public static MyString2 valueOf(boolean b);
```

- 10.24** (*Implement the **Character** class*) The **Character** class is provided in the Java library. Provide your own implementation for this class. Name the new class **MyCharacter**.
- ** 10.25** (*New string **split** method*) The **split** method in the **String** class returns an array of strings consisting of the substrings split by the delimiters. However, the delimiters are not returned. Implement the following new method that returns an array of strings consisting of the substrings split by the matching delimiters, including the matching delimiters.

```
public static String[] split(String s, String regex)
```

For example, `split("ab#12#453", "#")` returns `ab, #, 12, #, 453` in an array of **String**, and `split("a?b?gf#e", "[?#]")` returns `a, b, ?, b, gf, #, and e` in an array of **String**.

- * 10.26** (*Calculator*) Revise Listing 7.9, Calculator.java, to accept an expression as a string in which the operands and operator are separated by zero or more spaces. For example, `3+4` and `3 + 4` are acceptable expressions. Here is a sample run:

```
c:\>Administrator: Command Prompt
c:\>exercise>java Exercise10_26 "4+5"
4 + 5 = 9
c:\>exercise>java Exercise10_26 "4 + 5"
4 + 5 = 9
c:\>exercise>java Exercise10_26 "4 + 5"
4 + 5 = 9
c:\>exercise>java Exercise10_26 "4 * 5"
4 * 5 = 20
c:\>exercise>
```

- ** 10.27** (*Implement the **StringBuilder** class*) The **StringBuilder** class is provided in the Java library. Provide your own implementation for the following methods (name the new class **MyStringBuilder1**):

```
public MyStringBuilder1(String s);
public MyStringBuilder1 append(MyStringBuilder1 s);
public MyStringBuilder1 append(int i);
public int length();
public char charAt(int index);
public MyStringBuilder1 toLowerCase();
public MyStringBuilder1 substring(int begin, int end);
public String toString();
```

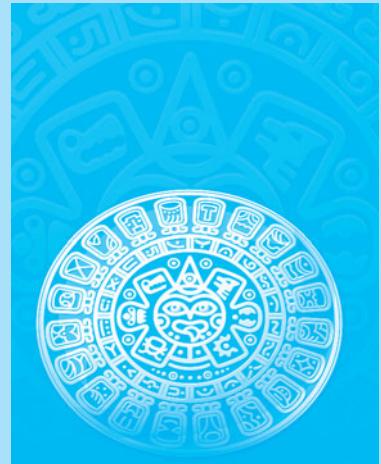
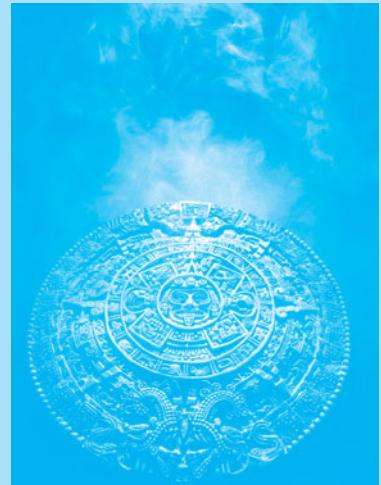
**** 10.28** (*Implement the `StringBuilder` class*) The `StringBuilder` class is provided in the Java library. Provide your own implementation for the following methods (name the new class `MyStringBuilder2`):

```
public MyStringBuilder2();
public MyStringBuilder2(char[] chars);
public MyStringBuilder2(String s);
public MyStringBuilder2 insert(int offset, MyStringBuilder2 s);
public MyStringBuilder2 reverse();
public MyStringBuilder2 substring(int begin);
public MyStringBuilder2 toUpperCase();
```

INHERITANCE AND POLYMORPHISM

Objectives

- To define a subclass from a superclass through inheritance (§11.2).
- To invoke the superclass's constructors and methods using the `super` keyword (§11.3).
- To override instance methods in the subclass (§11.4).
- To distinguish differences between overriding and overloading (§11.5).
- To explore the `toString()` method in the `Object` class (§11.6).
- To discover polymorphism and dynamic binding (§§11.7–11.8).
- To describe casting and explain why explicit downcasting is necessary (§11.9).
- To explore the `equals` method in the `Object` class (§11.10).
- To store, retrieve, and manipulate objects in an `ArrayList` (§11.11).
- To construct an array list from an array, to sort and shuffle a list, and to obtain max and min element from a list (§11.12).
- To implement a `Stack` class using `ArrayList` (§11.13).
- To enable data and methods in a superclass accessible from subclasses using the `protected` visibility modifier (§11.14).
- To prevent class extending and method overriding using the `final` modifier (§11.15).



11.1 Introduction



Object-oriented programming allows you to define new classes from existing classes. This is called inheritance.

inheritance

As discussed earlier in the book, the procedural paradigm focuses on designing methods and the object-oriented paradigm couples data and methods together into objects. Software design using the object-oriented paradigm focuses on objects and operations on objects. The object-oriented approach combines the power of the procedural paradigm with an added dimension that integrates data with operations into objects.

why inheritance?

Inheritance is an important and powerful feature for reusing software. Suppose you need to define classes to model circles, rectangles, and triangles. These classes have many common features. What is the best way to design these classes so as to avoid redundancy and make the system easy to comprehend and easy to maintain? The answer is to use inheritance.

11.2 Superclasses and Subclasses



Inheritance enables you to define a general class (i.e., a superclass) and later extend it to more specialized classes (i.e., subclasses).



VideoNote

Geometric class hierarchy

You use a class to model objects of the same type. Different classes may have some common properties and behaviors, which can be generalized in a class that can be shared by other classes. You can define a specialized class that extends the generalized class. The specialized classes inherit the properties and methods from the general class.

Consider geometric objects. Suppose you want to design the classes to model geometric objects such as circles and rectangles. Geometric objects have many common properties and behaviors. They can be drawn in a certain color and be filled or unfilled. Thus a general class **GeometricObject** can be used to model all geometric objects. This class contains the properties **color** and **filled** and their appropriate getter and setter methods. Assume that this class also contains the **dateCreated** property and the **getDateCreated()** and **toString()** methods. The **toString()** method returns a string representation of the object. Since a circle is a special type of geometric object, it shares common properties and methods with other geometric objects. Thus it makes sense to define the **Circle** class that extends the **GeometricObject** class. Likewise, **Rectangle** can also be defined as a subclass of **GeometricObject**. Figure 11.1 shows the relationship among these classes. A triangular arrow pointing to the superclass is used to denote the inheritance relationship between the two classes involved.

subclass
superclass

In Java terminology, a class **C1** extended from another class **C2** is called a *subclass*, and **C2** is called a *superclass*. A superclass is also referred to as a *parent class* or a *base class*, and a subclass as a *child class*, an *extended class*, or a *derived class*. A subclass inherits accessible data fields and methods from its superclass and may also add new data fields and methods.

The **Circle** class inherits all accessible data fields and methods from the **GeometricObject** class. In addition, it has a new data field, **radius**, and its associated getter and setter methods. The **Circle** class also contains the **getArea()**, **getPerimeter()**, and **getDiameter()** methods for returning the area, perimeter, and diameter of the circle.

The **Rectangle** class inherits all accessible data fields and methods from the **GeometricObject** class. In addition, it has the data fields **width** and **height** and their associated getter and setter methods. It also contains the **getArea()** and **getPerimeter()** methods for returning the area and perimeter of the rectangle.

The **GeometricObject**, **Circle**, and **Rectangle** classes are shown in Listings 11.1, 11.2, and 11.3.

avoid naming conflicts



Note

To avoid a naming conflict with the improved **GeometricObject**, **Circle**, and **Rectangle** classes introduced in Chapter 13, we'll name these classes



FIGURE 11.1 The **GeometricObject** class is the superclass for **Circle** and **Rectangle**.

SimpleGeometricObject, **CircleFromSimpleGeometricObject**, and **RectangleFromSimpleGeometricObject** in this chapter. For simplicity, we will still refer to them in the text as **GeometricObject**, **Circle**, and **Rectangle** classes. The best way to avoid naming conflicts is to place these classes in different packages. However, for simplicity and consistency, all classes in this book are placed in the default package.

LISTING 11.1 SimpleGeometricObject.java

```

1 public class SimpleGeometricObject {
2     private String color = "white";
3     private boolean filled;
4     private java.util.Date dateCreated;
5
6     /** Construct a default geometric object */
7     public SimpleGeometricObject() {
8         dateCreated = new java.util.Date();
9     }

```

data fields

constructor
date constructed

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```
10  /**
11   * Construct a geometric object with the specified color
12   * and filled value */
13  public SimpleGeometricObject(String color, boolean filled) {
14      dateCreated = new java.util.Date();
15      this.color = color;
16      this.filled = filled;
17  }
18
19  /**
20   * Return color */
21  public String getColor() {
22      return color;
23  }
24
25  /**
26   * Set a new color */
27  public void setColor(String color) {
28      this.color = color;
29  }
30
31  /**
32   * Return filled. Since filled is boolean,
33   * its getter method is named isFilled */
34  public boolean isFilled() {
35      return filled;
36  }
37
38  /**
39   * Set a new filled */
40  public void setFilled(boolean filled) {
41      this.filled = filled;
42  }
43
44  /**
45   * Get dateCreated */
46  public java.util.Date getDateCreated() {
47      return dateCreated;
48  }
49
50 }
```

LISTING 11.2 CircleFromSimpleGeometricObject.java

```
1  public class CircleFromSimpleGeometricObject
2      extends SimpleGeometricObject
3      private double radius;
4
5  public CircleFromSimpleGeometricObject() {
6  }
7
8  public CircleFromSimpleGeometricObject(double radius) {
9      this.radius = radius;
10 }
11
12 public CircleFromSimpleGeometricObject(double radius,
13     String color, boolean filled) {
14     this.radius = radius;
15     setColor(color);
16     setFilled(filled);
```

extends superclass
data fields

constructor

```

17 }
18
19 /** Return radius */
20 public double getRadius() {
21     return radius;
22 }
23
24 /** Set a new radius */
25 public void setRadius(double radius) {
26     this.radius = radius;
27 }
28
29 /** Return area */
30 public double getArea() {
31     return radius * radius * Math.PI;
32 }
33
34 /** Return diameter */
35 public double getDiameter() {
36     return 2 * radius;
37 }
38
39 /** Return perimeter */
40 public double getPerimeter() {
41     return 2 * radius * Math.PI;
42 }
43
44 /** Print the circle info */
45 public void printCircle() {
46     System.out.println("The circle is created " + getDateCreated() +
47         " and the radius is " + radius);
48 }
49 }
```

The **Circle** class (Listing 11.2) extends the **GeometricObject** class (Listing 11.1) using the following syntax:



The keyword **extends** (lines 1–2) tells the compiler that the **Circle** class extends the **GeometricObject** class, thus inheriting the methods **getColor**, **setColor**, **isFilled**, **setFilled**, and **toString**.

The overloaded constructor **Circle(double radius, String color, boolean filled)** is implemented by invoking the **setColor** and **setFilled** methods to set the **color** and **filled** properties (lines 12–17). These two public methods are defined in the superclass **GeometricObject** and are inherited in **Circle**, so they can be used in the **Circle** class.

You might attempt to use the data fields **color** and **filled** directly in the constructor as follows:

```

public CircleFromSimpleGeometricObject(
    double radius, String color, boolean filled) {
    this.radius = radius;
    this.color = color; // Illegal
    this.filled = filled; // Illegal
}
```

This is wrong, because the private data fields `color` and `filled` in the `GeometricObject` class cannot be accessed in any class other than in the `GeometricObject` class itself. The only way to read and modify `color` and `filled` is through their getter and setter methods.

The `Rectangle` class (Listing 11.3) extends the `GeometricObject` class (Listing 11.1) using the following syntax:



The keyword `extends` (lines 1–2) tells the compiler that the `Rectangle` class extends the `GeometricObject` class, thus inheriting the methods `getColor`, `setColor`, `isFilled`, `setFilled`, and `toString`.

LISTING 11.3 RectangleFromSimpleGeometricObject.java

```

1  public class RectangleFromSimpleGeometricObject
2      extends SimpleGeometricObject {
3          private double width;
4          private double height;
5
6          public RectangleFromSimpleGeometricObject() {
7      }
8
9          public RectangleFromSimpleGeometricObject(
10              double width, double height) {
11              this.width = width;
12              this.height = height;
13          }
14
15         public RectangleFromSimpleGeometricObject(
16             double width, double height, String color, boolean filled) {
17             this.width = width;
18             this.height = height;
19             setColor(color);
20             setFilled(filled);
21         }
22
23         /** Return width */
24         public double getWidth() {
25             return width;
26         }
27
28         /** Set a new width */
29         public void setWidth(double width) {
30             this.width = width;
31         }
32
33         /** Return height */
34         public double getHeight() {
35             return height;
36         }
37
38         /** Set a new height */
39         public void setHeight(double height) {
40             this.height = height;
41         }
  
```

extends superclass
data fields

constructor

methods

```

42 	/** Return area */
43 	public double getArea() {
44 		return width * height;
45 	}
46
47 	/** Return perimeter */
48 	public double getPerimeter() {
49 		return 2 * (width + height);
50 	}
51 }
52 }
```

The code in Listing 11.4 creates objects of `Circle` and `Rectangle` and invokes the methods on these objects. The `toString()` method is inherited from the `GeometricObject` class and is invoked from a `Circle` object (line 5) and a `Rectangle` object (line 13).

LISTING 11.4 TestCircleRectangle.java

```

1  public class TestCircleRectangle {
2  public static void main(String[] args) {
3  	CircleFromSimpleGeometricObject circle =
4  	new CircleFromSimpleGeometricObject(1);
5  	System.out.println("A circle " + circle.toString());
6  	System.out.println("The color is " + circle.getColor());
7  	System.out.println("The radius is " + circle.getRadius());
8  	System.out.println("The area is " + circle.getArea());
9  	System.out.println("The diameter is " + circle.getDiameter());
10
11 	RectangleFromSimpleGeometricObject rectangle =
12 	new RectangleFromSimpleGeometricObject(2, 4);
13 	System.out.println("\nA rectangle " + rectangle.toString());
14 	System.out.println("The area is " + rectangle.getArea());
15 	System.out.println("The perimeter is " +
16 	rectangle.getPerimeter());
17 }
18 }
```

Circle object
invoke `toString`
invoke `getColor`

Rectangle object
invoke `toString`

```

A circle created on Thu Feb 10 19:54:25 EST 2011
color: white and filled: false
The color is white
The radius is 1.0
The area is 3.141592653589793
The diameter is 2.0
A rectangle created on Thu Feb 10 19:54:25 EST 2011
color: white and filled: false
The area is 8.0
The perimeter is 12.0
```



Note the following points regarding inheritance:

- Contrary to the conventional interpretation, a subclass is not a subset of its superclass.
In fact, a subclass usually contains more information and methods than its superclass. more in subclass
- Private data fields in a superclass are not accessible outside the class. Therefore, they cannot be used directly in a subclass. They can, however, be accessed/mutated through public accessors/mutators if defined in the superclass. private data fields

nonextensible is-a

- Not all is-a relationships should be modeled using inheritance. For example, a square is a rectangle, but you should not extend a **Square** class from a **Rectangle** class, because the **width** and **height** properties are not appropriate for a square. Instead, you should define a **Square** class to extend the **GeometricObject** class and define the **side** property for the side of a square.

no blind extension

- Inheritance is used to model the is-a relationship. Do not blindly extend a class just for the sake of reusing methods. For example, it makes no sense for a **Tree** class to extend a **Person** class, even though they share common properties such as height and weight. A subclass and its superclass must have the is-a relationship.

multiple inheritance

- Some programming languages allow you to derive a subclass from several classes. This capability is known as *multiple inheritance*. Java, however, does not allow multiple inheritance. A Java class may inherit directly from only one superclass. This restriction is known as *single inheritance*. If you use the **extends** keyword to define a subclass, it allows only one parent class. Nevertheless, multiple inheritance can be achieved through interfaces, which will be introduced in Section 13.4.



11.1 True or false? A subclass is a subset of a superclass.

11.2 What keyword do you use to define a subclass?

11.3 What is single inheritance? What is multiple inheritance? Does Java support multiple inheritance?



11.3 Using the **super** Keyword

*The keyword **super** refers to the superclass and can be used to invoke the superclass's methods and constructors.*

A subclass inherits accessible data fields and methods from its superclass. Does it inherit constructors? Can the superclass's constructors be invoked from a subclass? This section addresses these questions and their ramifications.

Section 9.14, The **this** Reference, introduced the use of the keyword **this** to reference the calling object. The keyword **super** refers to the superclass of the class in which **super** appears. It can be used in two ways:

- To call a superclass constructor.
- To call a superclass method.

11.3.1 Calling Superclass Constructors

A constructor is used to construct an instance of a class. Unlike properties and methods, the constructors of a superclass are not inherited by a subclass. They can only be invoked from the constructors of the subclasses using the keyword **super**.

The syntax to call a superclass's constructor is:

super(), or **super(parameters)**;

The statement **super()** invokes the no-arg constructor of its superclass, and the statement **super(arguments)** invokes the superclass constructor that matches the **arguments**. The statement **super()** or **super(arguments)** must be the first statement of the subclass's constructor; this is the only way to explicitly invoke a superclass constructor. For example, the constructor in lines 12–17 in Listing 11.2 can be replaced by the following code:

```
public CircleFromSimpleGeometricObject(
    double radius, String color, boolean filled) {
```

```

super(color, filled);
this.radius = radius;
}

```

**Caution**

You must use the keyword **super** to call the superclass constructor, and the call must be the first statement in the constructor. Invoking a superclass constructor's name in a subclass causes a syntax error.

11.3.2 Constructor Chaining

A constructor may invoke an overloaded constructor or its superclass constructor. If neither is invoked explicitly, the compiler automatically puts **super()** as the first statement in the constructor. For example:

```

public ClassName() {
    // some statements
}

```

Equivalent

```

public ClassName() {
    super();
    // some statements
}

```

```

public ClassName(double d) {
    // some statements
}

```

Equivalent

```

public ClassName(double d) {
    super();
    // some statements
}

```

In any case, constructing an instance of a class invokes the constructors of all the superclasses along the inheritance chain. When constructing an object of a subclass, the subclass constructor first invokes its superclass constructor before performing its own tasks. If the superclass is derived from another class, the superclass constructor invokes its parent-class constructor before performing its own tasks. This process continues until the last constructor along the inheritance hierarchy is called. This is called *constructor chaining*.

constructor chaining

Consider the following code:

```

1 public class Faculty extends Employee {
2     public static void main(String[] args) {
3         new Faculty();
4     }
5
6     public Faculty() {
7         System.out.println("(4) Performs Faculty's tasks");
8     }
9 }
10
11 class Employee extends Person {
12     public Employee() {
13         this("(2) Invoke Employee's overloaded constructor");
14         System.out.println("(3) Performs Employee's tasks ");
15     }
16
17     public Employee(String s) {
18         System.out.println(s);
19     }
20 }
21
22 class Person {

```

invoke overloaded
constructor

```

23     public Person() {
24         System.out.println("(1) Performs Person's tasks");
25     }
26 }
```



- (1) Performs Person's tasks
 (2) Invoke Employee's overloaded constructor
 (3) Performs Employee's tasks
 (4) Performs Faculty's tasks

The program produces the preceding output. Why? Let us discuss the reason. In line 3, `new Faculty()` invokes `Faculty`'s no-arg constructor. Since `Faculty` is a subclass of `Employee`, `Employee`'s no-arg constructor is invoked before any statements in `Faculty`'s constructor are executed. `Employee`'s no-arg constructor invokes `Employee`'s second constructor (line 13). Since `Employee` is a subclass of `Person`, `Person`'s no-arg constructor is invoked before any statements in `Employee`'s second constructor are executed. This process is illustrated in the following figure.



no-arg constructor



Caution

If a class is designed to be extended, it is better to provide a no-arg constructor to avoid programming errors. Consider the following code:

```

1 public class Apple extends Fruit {
2 }
3
4 class Fruit {
5     public Fruit(String name) {
6         System.out.println("Fruit's constructor is invoked");
7     }
8 }
```

Since no constructor is explicitly defined in `Apple`, `Apple`'s default no-arg constructor is defined implicitly. Since `Apple` is a subclass of `Fruit`, `Apple`'s default constructor automatically invokes `Fruit`'s no-arg constructor. However, `Fruit` does not have a no-arg constructor, because `Fruit` has an explicit constructor defined. Therefore, the program cannot be compiled.

no-arg constructor



Design Guide

If possible, you should provide a no-arg constructor for every class to make the class easy to extend and to avoid errors.

11.3.3 Calling Superclass Methods

The keyword `super` can also be used to reference a method other than the constructor in the superclass. The syntax is:

`super.method(parameters);`

You could rewrite the `printCircle()` method in the `Circle` class as follows:

```
public void printCircle() {
    System.out.println("The circle is created " +
        super.getDateCreated() + " and the radius is " + radius);
}
```

It is not necessary to put `super` before `getDateCreated()` in this case, however, because `getDateCreated` is a method in the `GeometricObject` class and is inherited by the `Circle` class. Nevertheless, in some cases, as shown in the next section, the keyword `super` is needed.

- 11.4 What is the output of running the class C in (a)? What problem arises in compiling the program in (b)?



```
class A {
    public A() {
        System.out.println(
            "A's no-arg constructor is invoked");
    }
}

class B extends A {
}

public class C {
    public static void main(String[] args) {
        B b = new B();
    }
}
```

(a)

```
class A {
    public A(int x) {
    }
}

class B extends A {
    public B() {
    }
}

public class C {
    public static void main(String[] args) {
        B b = new B();
    }
}
```

(b)

- 11.5 How does a subclass invoke its superclass's constructor?

- 11.6 True or false? When invoking a constructor from a subclass, its superclass's no-arg constructor is always invoked.

11.4 Overriding Methods

To override a method, the method must be defined in the subclass using the same signature and the same return type as in its superclass.



A subclass inherits methods from a superclass. Sometimes it is necessary for the subclass to modify the implementation of a method defined in the superclass. This is referred to as *method overriding*.

method overriding

The `toString` method in the `GeometricObject` class (lines 46–49 in Listing 11.1) returns the string representation of a geometric object. This method can be overridden to return the string representation of a circle. To override it, add the following new method in the `Circle` class in Listing 11.2.

```
1 public class CircleFromSimpleGeometricObject
2     extends SimpleGeometricObject {
3     // Other methods are omitted
4
5     // Override the toString method defined in the superclass
6     public String toString() {
7         return super.toString() + "\nradius is " + radius;
8     }
9 }
```

toString in superclass

The `toString()` method is defined in the `GeometricObject` class and modified in the `Circle` class. Both methods can be used in the `Circle` class. To invoke the `toString` method defined in the `GeometricObject` class from the `Circle` class, use `super.toString()` (line 7).

`no super.super.methodName()`

Can a subclass of `Circle` access the `toString` method defined in the `GeometricObject` class using syntax such as `super.super.toString()`? No. This is a syntax error.

Several points are worth noting:

override accessible instance method

- An instance method can be overridden only if it is accessible. Thus a private method cannot be overridden, because it is not accessible outside its own class. If a method defined in a subclass is private in its superclass, the two methods are completely unrelated.

cannot override static method

- Like an instance method, a static method can be inherited. However, a static method cannot be overridden. If a static method defined in the superclass is redefined in a subclass, the method defined in the superclass is hidden. The hidden static methods can be invoked using the syntax `SuperClassName.staticMethodName`.



11.7 True or false? You can override a private method defined in a superclass.

11.8 True or false? You can override a static method defined in a superclass.

11.9 How do you explicitly invoke a superclass's constructor from a subclass?

11.10 How do you invoke an overridden superclass method from a subclass?



11.5 Overriding vs. Overloading

Overloading means to define multiple methods with the same name but different signatures. Overriding means to provide a new implementation for a method in the subclass.

You learned about overloading methods in Section 6.8. To override a method, the method must be defined in the subclass using the same signature and the same return type.

Let us use an example to show the differences between overriding and overloading. In (a) below, the method `p(double i)` in class `A` overrides the same method defined in class `B`. In (b), however, the class `A` has two overloaded methods: `p(double i)` and `p(int i)`. The method `p(double i)` is inherited from `B`.

```
public class Test {
    public static void main(String[] args) {
        A a = new A();
        a.p(10);
        a.p(10.0);
    }
}

class B {
    public void p(double i) {
        System.out.println(i * 2);
    }
}

class A extends B {
    // This method overrides the method in B
    public void p(double i) {
        System.out.println(i);
    }
}
```

```
public class Test {
    public static void main(String[] args) {
        A a = new A();
        a.p(10);
        a.p(10.0);
    }
}

class B {
    public void p(double i) {
        System.out.println(i * 2);
    }
}

class A extends B {
    // This method overloads the method in B
    public void p(int i) {
        System.out.println(i);
    }
}
```

(a)

(b)

When you run the **Test** class in (a), both **a.p(10)** and **a.p(10.0)** invoke the **p(double i)** method defined in class **A** to display **10.0**. When you run the **Test** class in (b), **a.p(10)** invokes the **p(int i)** method defined in class **A** to display **10**, and **a.p(10.0)** invokes the **p(double i)** method defined in class **B** to display **20.0**.

Note the following:

- Overridden methods are in different classes related by inheritance; overloaded methods can be either in the same class or different classes related by inheritance.
- Overridden methods have the same signature and return type; overloaded methods have the same name but a different parameter list.

To avoid mistakes, you can use a special Java syntax, called *override annotation*, to place **@Override** before the method in the subclass. For example:

```

1 public class CircleFromSimpleGeometricObject
2     extends SimpleGeometricObject {
3     // Other methods are omitted
4
5     @Override
6     public String toString() {
7         return super.toString() + "\nradius is " + radius;
8     }
9 }
```

toString in superclass

This annotation denotes that the annotated method is required to override a method in the superclass. If a method with this annotation does not override its superclass's method, the compiler will report an error. For example, if **toString** is mistyped as **tostring**, a compile error is reported. If the override annotation isn't used, the compile won't report an error. Using annotation avoids mistakes.

11.11 Identify the problems in the following code:

```

1 public class Circle {
2     private double radius;
3
4     public Circle(double radius) {
5         radius = radius;
6     }
7
8     public double getRadius() {
9         return radius;
10    }
11
12    public double getArea() {
13        return radius * radius * Math.PI;
14    }
15 }
16
17 class B extends Circle {
18     private double length;
19
20     B(double radius, double length) {
21         Circle(radius);
22         length = length;
23     }
24
25     @Override
```



Check
Point

```

26     public double getArea() {
27         return getArea() * length;
28     }
29 }
```

- 11.12** Explain the difference between method overloading and method overriding.
- 11.13** If a method in a subclass has the same signature as a method in its superclass with the same return type, is the method overridden or overloaded?
- 11.14** If a method in a subclass has the same signature as a method in its superclass with a different return type, will this be a problem?
- 11.15** If a method in a subclass has the same name as a method in its superclass with different parameter types, is the method overridden or overloaded?
- 11.16** What is the benefit of using the `@Override` annotation?



11.6 The Object Class and Its `toString()` Method

Every class in Java is descended from the `java.lang.Object` class.

If no inheritance is specified when a class is defined, the superclass of the class is `Object` by default. For example, the following two class definitions are the same:

<pre>public class ClassName { ... }</pre>	\equiv Equivalent	<pre>public class ClassName extends Object { ... }</pre>
---	------------------------	--

Classes such as `String`, `StringBuilder`, `Loan`, and `GeometricObject` are implicitly subclasses of `Object` (as are all the main classes you have seen in this book so far). It is important to be familiar with the methods provided by the `Object` class so that you can use them in your classes. This section introduces the `toString` method in the `Object` class.

toString()

The signature of the `toString()` method is:

```
public String toString()
```

string representation

Invoking `toString()` on an object returns a string that describes the object. By default, it returns a string consisting of a class name of which the object is an instance, an at sign (@), and the object's memory address in hexadecimal. For example, consider the following code for the `Loan` class defined in Listing 10.2:

```
Loan loan = new Loan();  
System.out.println(loan.toString());
```

The output for this code displays something like `Loan@15037e5`. This message is not very helpful or informative. Usually you should override the `toString` method so that it returns a descriptive string representation of the object. For example, the `toString` method in the `Object` class was overridden in the `GeometricObject` class in lines 46–49 in Listing 11.1 as follows:

```
public String toString() {  
    return "created on " + dateCreated + "\ncolor: " + color +  
        " and filled: " + filled;  
}
```

**Note**

You can also pass an object to invoke `System.out.println(object)` or `System.out.print(object)`. This is equivalent to invoking `System.out.println(object.toString())` or `System.out.print(object.toString())`. Thus, you could replace `System.out.println(loan.toString())` with `System.out.println(loan)`.

print object



subtype
supertype

11.7 Polymorphism

Polymorphism means that a variable of a supertype can refer to a subtype object.

The three pillars of object-oriented programming are encapsulation, inheritance, and polymorphism. You have already learned the first two. This section introduces polymorphism.

First, let us define two useful terms: subtype and supertype. A class defines a type. A type defined by a subclass is called a *subtype*, and a type defined by its superclass is called a *supertype*. Therefore, you can say that `Circle` is a subtype of `GeometricObject` and `GeometricObject` is a supertype for `Circle`.

The inheritance relationship enables a subclass to inherit features from its superclass with additional new features. A subclass is a specialization of its superclass; every instance of a subclass is also an instance of its superclass, but not vice versa. For example, every circle is a geometric object, but not every geometric object is a circle. Therefore, you can always pass an instance of a subclass to a parameter of its superclass type. Consider the code in Listing 11.5.

LISTING 11.5 PolymorphismDemo.java

```

1  public class PolymorphismDemo {
2      /** Main method */
3      public static void main(String[] args) {
4          // Display circle and rectangle properties
5          displayObject(new CircleFromSimpleGeometricObject
6              (1, "red", false));
7          displayObject(new RectangleFromSimpleGeometricObject
8              (1, 1, "black", true));
9      }
10
11     /** Display geometric object properties */
12     public static void displayObject(SimpleGeometricObject object) {
13         System.out.println("Created on " + object.getDateCreated() +
14             ". Color is " + object.getColor());
15     }
16 }
```

polymorphic call
polymorphic call

Created on Mon Mar 09 19:25:20 EDT 2011. Color is red
Created on Mon Mar 09 19:25:20 EDT 2011. Color is black



The method `displayObject` (line 12) takes a parameter of the `GeometricObject` type. You can invoke `displayObject` by passing any instance of `GeometricObject` (e.g., `new CircleFromSimpleGeometricObject(1, "red", false)` and `new RectangleFromSimpleGeometricObject(1, 1, "black", false)` in lines 5–8). An object of a subclass can be used wherever its superclass object is used. This is commonly known as *polymorphism* (from a Greek word meaning “many forms”). In simple terms, polymorphism means that a variable of a supertype can refer to a subtype object.

what is polymorphism?

11.8 Dynamic Binding



A method can be implemented in several classes along the inheritance chain. The JVM decides which method is invoked at runtime.

A method can be defined in a superclass and overridden in its subclass. For example, the `toString()` method is defined in the `Object` class and overridden in `GeometricObject`. Consider the following code:

```
Object o = new GeometricObject();
System.out.println(o.toString());
```

declared type

actual type

dynamic binding

Which `toString()` method is invoked by `o`? To answer this question, we first introduce two terms: declared type and actual type. A variable must be declared a type. The type that declares a variable is called the variable's *declared type*. Here `o`'s declared type is `Object`. A variable of a reference type can hold a `null` value or a reference to an instance of the declared type. The *actual type* of the variable is the actual class for the object referenced by the variable. Here `o`'s actual type is `GeometricObject`, because `o` references an object created using `new GeometricObject()`. Which `toString()` method is invoked by `o` is determined by `o`'s actual type. This is known as *dynamic binding*.

Dynamic binding works as follows: Suppose an object `o` is an instance of classes `C1`, `C2`, ..., `Cn-1`, and `Cn`, where `C1` is a subclass of `C2`, `C2` is a subclass of `C3`, ..., and `Cn-1` is a subclass of `Cn`, as shown in Figure 11.2. That is, `Cn` is the most general class, and `C1` is the most specific class. In Java, `Cn` is the `Object` class. If `o` invokes a method `p`, the JVM searches for the implementation of the method `p` in `C1`, `C2`, ..., `Cn-1`, and `Cn`, in this order, until it is found. Once an implementation is found, the search stops and the first-found implementation is invoked.

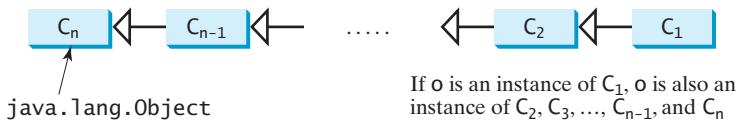


FIGURE 11.2 The method to be invoked is dynamically bound at runtime.



VideoNote

Polymorphism and dynamic binding demo

polymorphic call

dynamic binding

override `toString()`

Listing 11.6 gives an example to demonstrate dynamic binding.

LISTING 11.6 DynamicBindingDemo.java

```
1  public class DynamicBindingDemo {
2      public static void main(String[] args) {
3          m(new GraduateStudent());
4          m(new Student());
5          m(new Person());
6          m(new Object());
7      }
8
9      public static void m(Object x) {
10         System.out.println(x.toString());
11     }
12 }
13
14 class GraduateStudent extends Student {
15 }
16
17 class Student extends Person {
18     @Override
19     public String toString() {
```

```

20     return "Student" ;
21 }
22 }
23
24 class Person extends Object {
25     @Override
26     public String toString() {
27         return "Person" ;
28     }
29 }
```

override `toString()`

```

Student
Student
Person
java.lang.Object@130c19b
```



Method `m` (line 9) takes a parameter of the `Object` type. You can invoke `m` with any object (e.g., `new GraduateStudent()`, `new Student()`, `new Person()`, and `new Object()`) in lines 3–6).

When the method `m(Object x)` is executed, the argument `x`'s `toString` method is invoked. `x` may be an instance of `GraduateStudent`, `Student`, `Person`, or `Object`. The classes `GraduateStudent`, `Student`, `Person`, and `Object` have their own implementations of the `toString` method. Which implementation is used will be determined by `x`'s actual type at runtime. Invoking `m(new GraduateStudent())` (line 3) causes the `toString` method defined in the `Student` class to be invoked.

Invoking `m(new Student())` (line 4) causes the `toString` method defined in the `Student` class to be invoked; invoking `m(new Person())` (line 5) causes the `toString` method defined in the `Person` class to be invoked; and invoking `m(new Object())` (line 6) causes the `toString` method defined in the `Object` class to be invoked.

Matching a method signature and binding a method implementation are two separate issues. The *declared type* of the reference variable decides which method to match at compile time. The compiler finds a matching method according to the parameter type, number of parameters, and order of the parameters at compile time. A method may be implemented in several classes along the inheritance chain. The JVM dynamically binds the implementation of the method at runtime, decided by the actual type of the variable.

matching vs. binding

11.17 What is polymorphism? What is dynamic binding?



11.18 Describe the difference between method matching and method binding.

11.19 Can you assign `new int[50]`, `new Integer[50]`, `new String[50]`, or `new Object[50]`, into a variable of `Object[]` type?

11.20 What is wrong in the following code?

```

1  public class Test {
2      public static void main(String[] args) {
3          Integer[] list1 = {12, 24, 55, 1};
4          Double[] list2 = {12.4, 24.0, 55.2, 1.0};
5          int[] list3 = {1, 2, 3};
6          printArray(list1);
7          printArray(list2);
8          printArray(list3);
9      }
10
11     public static void printArray(Object[] list) {
12         for (Object o: list)
```

```

13         System.out.print(o + " ");
14         System.out.println();
15     }
16 }
```

11.21 Show the output of the following code:

```

public class Test {
    public static void main(String[] args) {
        new Person().printPerson();
        new Student().printPerson();
    }
}

class Student extends Person {
    @Override
    public String getInfo() {
        return "Student";
    }
}

class Person {
    public String getInfo() {
        return "Person";
    }

    public void printPerson() {
        System.out.println(getInfo());
    }
}
```

(a)

```

public class Test {
    public static void main(String[] args) {
        new Person().printPerson();
        new Student().printPerson();
    }
}

class Student extends Person {
    private String getInfo() {
        return "Student";
    }
}

class Person {
    private String getInfo() {
        return "Person";
    }

    public void printPerson() {
        System.out.println(getInfo());
    }
}
```

(b)

11.22 Show the output of following program:

```

1  public class Test {
2      public static void main(String[] args) {
3          A a = new A(3);
4      }
5  }
6
7  class A extends B {
8      public A(int t) {
9          System.out.println("A's constructor is invoked");
10     }
11 }
12
13 class B {
14     public B() {
15         System.out.println("B's constructor is invoked");
16     }
17 }
```

Is the no-arg constructor of **Object** invoked when **new A(3)** is invoked?

11.23 Show the output of following program:

```

public class Test {
    public static void main(String[] args) {
        new A();
        new B();
    }
}
```

```

class A {
    int i = 7;

    public A() {
        setI(20);
        System.out.println("i from A is " + i);
    }

    public void setI(int i) {
        this.i = 2 * i;
    }
}

class B extends A {
    public B() {
        System.out.println("i from B is " + i);
    }

    public void setI(int i) {
        this.i = 3 * i;
    }
}

```

11.9 Casting Objects and the `instanceof` Operator

One object reference can be typecast into another object reference. This is called casting object.

In the preceding section, the statement

```
m(new Student());
```

assigns the object `new Student()` to a parameter of the `Object` type. This statement is equivalent to

```
Object o = new Student(); // Implicit casting
m(o);
```

The statement `Object o = new Student()`, known as *implicit casting*, is legal because an instance of `Student` is an instance of `Object`. implicit casting

Suppose you want to assign the object reference `o` to a variable of the `Student` type using the following statement:

```
Student b = o;
```

In this case a compile error would occur. Why does the statement `Object o = new Student()` work but `Student b = o` doesn't? The reason is that a `Student` object is always an instance of `Object`, but an `Object` is not necessarily an instance of `Student`. Even though you can see that `o` is really a `Student` object, the compiler is not clever enough to know it. To tell the compiler that `o` is a `Student` object, use *explicit casting*. The syntax is similar to the one used for casting among primitive data types. Enclose the target object type in parentheses and place it before the object to be cast, as follows:

```
Student b = (Student)o; // Explicit casting
```

It is always possible to cast an instance of a subclass to a variable of a superclass (known as *upcasting*), because an instance of a subclass is *always* an instance of its superclass. When casting an instance of a superclass to a variable of its subclass (known as *downcasting*), explicit



casting object

explicit casting

upcasting
downcasting

ClassCastException

instanceof

casting must be used to confirm your intention to the compiler with the **(SubClassName)** cast notation. For the casting to be successful, you must make sure that the object to be cast is an instance of the subclass. If the superclass object is not an instance of the subclass, a runtime **ClassCastException** occurs. For example, if an object is not an instance of **Student**, it cannot be cast into a variable of **Student**. It is a good practice, therefore, to ensure that the object is an instance of another object before attempting a casting. This can be accomplished by using the **instanceof** operator. Consider the following code:

```
Object myObject = new Circle();
... // Some lines of code
/** Perform casting if myObject is an instance of Circle */
if (myObject instanceof Circle) {
    System.out.println("The circle diameter is " +
        ((Circle)myObject).getDiameter());
...
}
```

You may be wondering why casting is necessary. The variable **myObject** is declared **Object**. The *declared type* decides which method to match at compile time. Using **myObject.getDiameter()** would cause a compile error, because the **Object** class does not have the **getDiameter** method. The compiler cannot find a match for **myObject.getDiameter()**. Therefore, it is necessary to cast **myObject** into the **Circle** type to tell the compiler that **myObject** is also an instance of **Circle**.

Why not define **myObject** as a **Circle** type in the first place? To enable generic programming, it is a good practice to define a variable with a supertype, which can accept an object of any subtype.

lowercase keywords

**Note**

instanceof is a Java keyword. Every letter in a Java keyword is in lowercase.

casting analogy

**Tip**

To help understand casting, you may also consider the analogy of fruit, apple, and orange, with the **Fruit** class as the superclass for **Apple** and **Orange**. An apple is a fruit, so you can always safely assign an instance of **Apple** to a variable for **Fruit**. However, a fruit is not necessarily an apple, so you have to use explicit casting to assign an instance of **Fruit** to a variable of **Apple**.

Listing 11.7 demonstrates polymorphism and casting. The program creates two objects (lines 5–6), a circle and a rectangle, and invokes the **displayObject** method to display them (lines 9–10). The **displayObject** method displays the area and diameter if the object is a circle (line 15), and the area if the object is a rectangle (lines 21–22).

LISTING 11.7 CastingDemo.java

```
1 public class CastingDemo {
2     /** Main method */
3     public static void main(String[] args) {
4         // Create and initialize two objects
5         Object object1 = new CircleFromSimpleGeometricObject(1);
6         Object object2 = new RectangleFromSimpleGeometricObject(1, 1);
7
8         // Display circle and rectangle
9         displayObject(object1);
10        displayObject(object2);
11    }
12}
```

```

13  /** A method for displaying an object */
14  public static void displayObject(Object object) {
15      if (object instanceof CircleFromSimpleGeometricObject) {
16          System.out.println("The circle area is " +
17              ((CircleFromSimpleGeometricObject)object).getArea());           polymorphic call
18          System.out.println("The circle diameter is " +
19              ((CircleFromSimpleGeometricObject)object).getDiameter());
20      }
21      else if (object instanceof
22              RectangleFromSimpleGeometricObject) {
23          System.out.println("The rectangle area is " +
24              ((RectangleFromSimpleGeometricObject)object).getArea());       polymorphic call
25      }
26  }
27 }
```

The circle area is 3.141592653589793
 The circle diameter is 2.0
 The rectangle area is 1.0



The `displayObject(Object object)` method is an example of generic programming. It can be invoked by passing any instance of `Object`.

The program uses implicit casting to assign a `Circle` object to `object1` and a `Rectangle` object to `object2` (lines 5–6), then invokes the `displayObject` method to display the information on these objects (lines 9–10).

In the `displayObject` method (lines 14–26), explicit casting is used to cast the object to `Circle` if the object is an instance of `Circle`, and the methods `getArea` and `getDiameter` are used to display the area and diameter of the circle.

Casting can be done only when the source object is an instance of the target class. The program uses the `instanceof` operator to ensure that the source object is an instance of the target class before performing a casting (line 15).

Explicit casting to `Circle` (lines 17, 19) and to `Rectangle` (line 24) is necessary because the `getArea` and `getDiameter` methods are not available in the `Object` class.



Caution

The object member access operator (`.`) precedes the casting operator. Use parentheses to ensure that casting is done before the `.` operator, as in

```
((Circle)object).getArea();
```

precedes casting

Casting a primitive type value is different from casting an object reference. Casting a primitive type value returns a new value. For example:

```
int age = 45;
byte newAge = (byte)age; // A new value is assigned to newAge
```

However, casting an object reference does not create a new object. For example:

```
Object o = new Circle();
Circle c = (Circle)o; // No new object is created
```

Now reference variables `o` and `c` point to the same object.

**11.24** Indicate true or false for the following statements:

- You can always successfully cast an instance of a subclass to a superclass.
- You can always successfully cast an instance of a superclass to a subclass.

11.25 For the **GeometricObject** and **Circle** classes in Listings 11.1 and 11.2, answer the following questions:

- a. Assume are **circle** and **object** created as follows:

```
Circle circle = new Circle(1);
GeometricObject object = new GeometricObject();
```

Are the following Boolean expressions true or false?

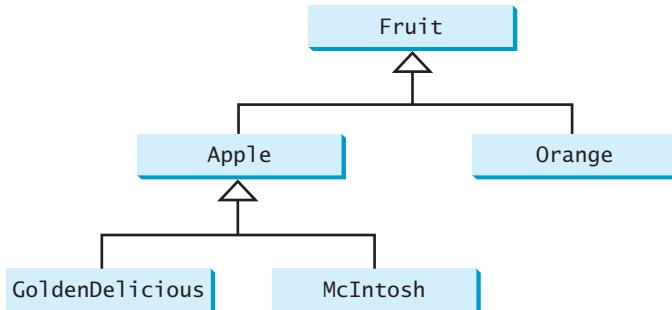
```
(circle instanceof GeometricObject)
(object instanceof GeometricObject)
(circle instanceof Circle)
(object instanceof Circle)
```

- b. Can the following statements be compiled?

```
Circle circle = new Circle(5);
GeometricObject object = circle;
```

- c. Can the following statements be compiled?

```
GeometricObject object = new GeometricObject();
Circle circle = (Circle)object;
```

11.26 Suppose that **Fruit**, **Apple**, **Orange**, **GoldenDelicious**, and **McIntosh** are defined in the following inheritance hierarchy:

Assume that the following code is given:

```
Fruit fruit = new GoldenDelicious();
Orange orange = new Orange();
```

Answer the following questions:

- a. Is **fruit instanceof Fruit**?
- b. Is **fruit instanceof Orange**?
- c. Is **fruit instanceof Apple**?
- d. Is **fruit instanceof GoldenDelicious**?
- e. Is **fruit instanceof McIntosh**?
- f. Is **orange instanceof Orange**?

- g. Is **orange instanceof Fruit**?
- h. Is **orange instanceof Apple**?
- i. Suppose the method **makeAppleCider** is defined in the **Apple** class. Can **fruit** invoke this method? Can **orange** invoke this method?
- j. Suppose the method **makeOrangeJuice** is defined in the **Orange** class. Can **orange** invoke this method? Can **fruit** invoke this method?
- k. Is the statement **Orange p = new Apple()** legal?
- l. Is the statement **McIntosh p = new Apple()** legal?
- m. Is the statement **Apple p = new McIntosh()** legal?

11.27 What is wrong in the following code?

```

1 public class Test {
2     public static void main(String[] args) {
3         Object fruit = new Fruit();
4         Object apple = (Apple)fruit;
5     }
6 }
7
8 class Apple extends Fruit {
9 }
10
11 class Fruit {
12 }
```

11.10 The **Object**'s **equals** Method

*Like the **toString()** method, the **equals(Object)** method is another useful method defined in the **Object** class.*



Another method defined in the **Object** class that is often used is the **equals** method. Its signature is

```
public boolean equals(Object o)
```

This method tests whether two objects are equal. The syntax for invoking it is:

```
object1.equals(object2);
```

The default implementation of the **equals** method in the **Object** class is:

```
public boolean equals(Object obj) {
    return (this == obj);
}
```

This implementation checks whether two reference variables point to the same object using the **==** operator. You should override this method in your custom class to test whether two distinct objects have the same content.

The **equals** method is overridden in many classes in the Java API, such as **java.lang.String** and **java.util.Date**, to compare whether the contents of two objects are equal. You have already used the **equals** method to compare two strings in Section 4.4.7, The **String** Class. The **equals** method in the **String** class is inherited from the **Object** class and is overridden in the **String** class to test whether two strings are identical in content.

You can override the `equals` method in the `Circle` class to compare whether two circles are equal based on their radius as follows:

```
public boolean equals(Object o) {
    if (o instanceof Circle)
        return radius == ((Circle)o).radius;
    else
        return this == o;
}
```

`==` vs. `equals`



Note

The `==` comparison operator is used for comparing two primitive data type values or for determining whether two objects have the same references. The `equals` method is intended to test whether two objects have the same contents, provided that the method is overridden in the defining class of the objects. The `==` operator is stronger than the `equals` method, in that the `==` operator checks whether the two reference variables refer to the same object.

`equals(Object)`



Caution

Using the signature `equals(SomeClassName obj)` (e.g., `equals(Circle c)`) to override the `equals` method in a subclass is a common mistake. You should use `equals(Object obj)`. See CheckPoint Question 11.29.



11.28 Does every object have a `toString` method and an `equals` method? Where do they come from? How are they used? Is it appropriate to override these methods?

11.29 When overriding the `equals` method, a common mistake is mistyping its signature in the subclass. For example, the `equals` method is incorrectly written as `equals(Circle circle)`, as shown in (a) in following the code; instead, it should be `equals(Object circle)`, as shown in (b). Show the output of running class `Test` with the `Circle` class in (a) and in (b), respectively.

```
public class Test {
    public static void main(String[] args) {
        Object circle1 = new Circle();
        Object circle2 = new Circle();
        System.out.println(circle1.equals(circle2));
    }
}
```

```
class Circle {
    double radius;

    public boolean equals(Circle circle) {
        return this.radius == circle.radius;
    }
}
```

(a)

```
class Circle {
    double radius;

    public boolean equals(Object circle) {
        return this.radius ==
            ((Circle)circle).radius;
    }
}
```

(b)

If `Object` is replaced by `Circle` in the `Test` class, what would be the output to run `Test` using the `Circle` class in (a) and (b), respectively?

11.11 The `ArrayList` Class

class, which can be used to store an unlimited number of objects. Figure 11.3 shows some methods in `ArrayList`.

java.util.ArrayList<E>	
<code>+ArrayList()</code>	Creates an empty list.
<code>+add(o: E): void</code>	Appends a new element o at the end of this list.
<code>+add(index: int, o: E): void</code>	Adds a new element o at the specified index in this list.
<code>+clear(): void</code>	Removes all the elements from this list.
<code>+contains(o: Object): boolean</code>	Returns true if this list contains the element o.
<code>+get(index: int): E</code>	Returns the element from this list at the specified index.
<code>+indexOf(o: Object): int</code>	Returns the index of the first matching element in this list.
<code>+isEmpty(): boolean</code>	Returns true if this list contains no elements.
<code>+lastIndexOf(o: Object): int</code>	Returns the index of the last matching element in this list.
<code>+remove(o: Object): boolean</code>	Removes the first element o from this list. Returns true if an element is removed.
<code>+size(): int</code>	Returns the number of elements in this list.
<code>+remove(index: int): boolean</code>	Removes the element at the specified index. Returns true if an element is removed.
<code>+set(index: int, o: E): E</code>	Sets the element at the specified index.

FIGURE 11.3 An `ArrayList` stores an unlimited number of objects.

`ArrayList` is known as a generic class with a generic type `E`. You can specify a concrete type to replace `E` when creating an `ArrayList`. For example, the following statement creates an `ArrayList` and assigns its reference to variable `cities`. This `ArrayList` object can be used to store strings.

```
ArrayList<String> cities = new ArrayList<String>();
```

The following statement creates an `ArrayList` and assigns its reference to variable `dates`. This `ArrayList` object can be used to store dates.

```
ArrayList<java.util.Date> dates = new ArrayList<java.util.Date>();
```



Note

Since JDK 7, the statement

```
ArrayList<AConcreteType> list = new ArrayList<AConcreteType>();
```

can be simplified by

```
ArrayList<AConcreteType> list = new ArrayList<>();
```

The concrete type is no longer required in the constructor thanks to a feature called *type inference*. The compiler is able to infer the type from the variable declaration. More discussions on generics including how to define custom generic classes and methods will be introduced in Chapter 19, Generics.

type inference

Listing 11.8 gives an example of using `ArrayList` to store objects.

LISTING 11.8 TestArrayList.java

```
1 import java.util.ArrayList;
2
```

```
import ArrayList
```

```

3  public class TestArrayList {
4      public static void main(String[] args) {
5          // Create a list to store cities
6          ArrayList<String> cityList = new ArrayList<>();
7
8          // Add some cities in the list
9          cityList.add("London");
10         // cityList now contains [London]
11         cityList.add("Denver");
12         // cityList now contains [London, Denver]
13         cityList.add("Paris");
14         // cityList now contains [London, Denver, Paris]
15         cityList.add("Miami");
16         // cityList now contains [London, Denver, Paris, Miami]
17         cityList.add("Seoul");
18         // Contains [London, Denver, Paris, Miami, Seoul]
19         cityList.add("Tokyo");
20         // Contains [London, Denver, Paris, Miami, Seoul, Tokyo]
21
22         System.out.println("List size? " + cityList.size());
23         System.out.println("Is Miami in the list? " +
24             cityList.contains("Miami"));
25         System.out.println("The location of Denver in the list? " +
26             + cityList.indexOf("Denver"));
27         System.out.println("Is the list empty? " +
28             cityList.isEmpty()); // Print false
29
30         // Insert a new city at index 2
31         cityList.add(2, "Xian");
32         // Contains [London, Denver, Xian, Paris, Miami, Seoul, Tokyo]
33
34         // Remove a city from the list
35         cityList.remove("Miami");
36         // Contains [London, Denver, Xian, Paris, Seoul, Tokyo]
37
38         // Remove a city at index 1
39         cityList.remove(1);
40         // Contains [London, Xian, Paris, Seoul, Tokyo]
41
42         // Display the contents in the list
43         System.out.println(cityList.toString());
44
45         // Display the contents in the list in reverse order
46         for (int i = cityList.size() - 1; i >= 0; i--)
47             System.out.print(cityList.get(i) + " ");
48         System.out.println();
49
50         // Create a list to store two circles
51         ArrayList<CircleFromSimpleGeometricObject> list
52             = new ArrayList<>();
53
54         // Add two circles
55         list.add(new CircleFromSimpleGeometricObject(2));
56         list.add(new CircleFromSimpleGeometricObject(3));
57
58         // Display the area of the first circle in the list
59         System.out.println("The area of the circle? " +
60             list.get(0).getArea());
61     }
62 }
```



```
List size? 6
Is Miami in the list? True
The location of Denver in the list? 1
Is the list empty? false
[London, Xian, Paris, Seoul, Tokyo]
Tokyo Seoul Paris Xian London
The area of the circle? 12.566370614359172
```

Since the `ArrayList` is in the `java.util` package, it is imported in line 1. The program creates an `ArrayList` of strings using its no-arg constructor and assigns the reference to `cityList` (line 6). The `add` method (lines 9–19) adds strings to the end of list. So, after `cityList.add("London")` (line 9), the list contains

[London]

After `cityList.add("Denver")` (line 11), the list contains

[London, Denver]

After adding `Paris`, `Miami`, `Seoul`, and `Tokyo` (lines 13–19), the list contains

[London, Denver, Paris, Miami, Seoul, Tokyo]

Invoking `size()` (line 22) returns the size of the list, which is currently **6**. Invoking `contains("Miami")` (line 24) checks whether the object is in the list. In this case, it returns `true`, since `Miami` is in the list. Invoking `indexOf("Denver")` (line 26) returns the index of `Denver` in the list, which is **1**. If `Denver` were not in the list, it would return **-1**. The `isEmpty()` method (line 28) checks whether the list is empty. It returns `false`, since the list is not empty.

The statement `cityList.add(2, "Xian")` (line 31) inserts an object into the list at the specified index. After this statement, the list becomes

[London, Denver, Xian, Paris, Miami, Seoul, Tokyo]

The statement `cityList.remove("Miami")` (line 35) removes the object from the list. After this statement, the list becomes

[London, Denver, Xian, Paris, Seoul, Tokyo]

The statement `cityList.remove(1)` (line 39) removes the object at the specified index from the list. After this statement, the list becomes

[London, Xian, Paris, Seoul, Tokyo]

The statement in line 43 is same as

```
System.out.println(cityList);
```

The `toString()` method returns a string representation of the list in the form of `[e0.toString(), e1.toString(), ..., ek.toString()]`, where `e0`, `e1`, ..., and `ek` are the elements in the list.

`toString()`

The `get(index)` method (line 47) returns the object at the specified index.

`get(index)`

`ArrayList` objects can be used like arrays, but there are many differences. Table 11.1 lists their similarities and differences.

array vs. `ArrayList`

Once an array is created, its size is fixed. You can access an array element using the square-bracket notation (e.g., `a[index]`). When an `ArrayList` is created, its size is **0**.

TABLE 11.1 Differences and Similarities between Arrays and `ArrayList`

<i>Operation</i>	<i>Array</i>	<i>ArrayList</i>
Creating an array/ArrayList	<code>String[] a = new String[10]</code>	<code>ArrayList<String> list = new ArrayList<>();</code>
Accessing an element	<code>a[index]</code>	<code>list.get(index);</code>
Updating an element	<code>a[index] = "London";</code>	<code>list.set(index, "London");</code>
Returning size	<code>a.length</code>	<code>list.size();</code>
Adding a new element		<code>list.add("London");</code>
Inserting a new element		<code>list.add(index, "London");</code>
Removing an element		<code>list.remove(index);</code>
Removing an element		<code>list.remove(Object);</code>
Removing all elements		<code>list.clear();</code>

You cannot use the `get(index)` and `set(index, element)` methods if the element is not in the list. It is easy to add, insert, and remove elements in a list, but it is rather complex to add, insert, and remove elements in an array. You have to write code to manipulate the array in order to perform these operations. Note that you can sort an array using the `java.util.Arrays.sort(array)` method. To sort an array list, use the `java.util.Collections.sort(arraylist)` method.

Suppose you want to create an `ArrayList` for storing integers. Can you use the following code to create a list?

```
ArrayList<int> list = new ArrayList<>();
```

No. This will not work because the elements stored in an `ArrayList` must be of an object type. You cannot use a primitive data type such as `int` to replace a generic type. However, you can create an `ArrayList` for storing `Integer` objects as follows:

```
ArrayList<Integer> list = new ArrayList<>();
```

Listing 11.9 gives a program that prompts the user to enter a sequence of numbers and displays the distinct numbers in the sequence. Assume that the input ends with `0` and `0` is not counted as a number in the sequence.

LISTING 11.9 DistinctNumbers.java

```

1 import java.util.ArrayList;
2 import java.util.Scanner;
3
4 public class DistinctNumbers {
5     public static void main(String[] args) {
6         ArrayList<Integer> list = new ArrayList<>();
7
8         Scanner input = new Scanner(System.in);
9         System.out.print("Enter integers (input ends with 0): ");
10        int value;
11
12        do {
13            value = input.nextInt(); // Read a value from the input
14
15            if (!list.contains(value) && value != 0)
16                list.add(value); // Add the value if it is not in the list
17        } while (value != 0);
    
```

create an array list
contained in list?
add to list

```

18
19     // Display the distinct numbers
20     for (int i = 0; i < list.size(); i++)
21         System.out.print(list.get(i) + " ");
22     }
23 }
```

Enter numbers (input ends with 0): 1 2 3 2 1 6 3 4 5 4 5 1 2 3 0
The distinct numbers are: 1 2 3 6 4 5



The program creates an `ArrayList` for `Integer` objects (line 6) and repeatedly reads a value in the loop (lines 12–17). For each value, if it is not in the list (line 15), add it to the list (line 16). You can rewrite this program using an array to store the elements rather than using an `ArrayList`. However, it is simpler to implement this program using an `ArrayList` for two reasons.

- First, the size of an `ArrayList` is flexible so you don't have to specify its size in advance. When creating an array, its size must be specified.
- Second, `ArrayList` contains many useful methods. For example, you can test whether an element is in the list using the `contains` method. If you use an array, you have to write additional code to implement this method.

You can traverse the elements in an array using a foreach loop. The elements in an array list can also be traversed using a foreach loop using the following syntax:

```

for (elementType element: arrayList) {
    // Process the element
}
```

For example, you can replace the code in lines 20–21 using the following code:

```

for (int number: list)
    System.out.print(number + " ");
```



11.30 How do you do the following?

- a. Create an `ArrayList` for storing double values?
- b. Append an object to a list?
- c. Insert an object at the beginning of a list?
- d. Find the number of objects in a list?
- e. Remove a given object from a list?
- f. Remove the last object from the list?
- g. Check whether a given object is in a list?
- h. Retrieve an object at a specified index from a list?

11.31 Identify the errors in the following code.

```

ArrayList<String> list = new ArrayList<>();
list.add("Denver");
list.add("Austin");
list.add(new java.util.Date());
String city = list.get(0);
list.set(3, "Dallas");
System.out.println(list.get(3));
```

- 11.32** Suppose the `ArrayList` `list` contains `{"Dallas", "Dallas", "Houston", "Dallas"}`. What is the list after invoking `list.remove("Dallas")` one time? Does the following code correctly remove all elements with value `"Dallas"` from the list? If not, correct the code.

```
for (int i = 0; i < list.size(); i++)
    list.remove("Dallas");
```

- 11.33** Explain why the following code displays `[1, 3]` rather than `[2, 3]`.

```
ArrayList<Integer> list = new ArrayList<>();
list.add(1);
list.add(2);
list.add(3);
list.remove(1);
System.out.println(list);
```

- 11.34** Explain why the following code is wrong.

```
ArrayList<Double> list = new ArrayList<>();
list.add(1);
```

11.12 Useful Methods for Lists



array to array list

Java provides the methods for creating a list from an array, for sorting a list, and finding maximum and minimum element in a list, and for shuffling a list.

Often you need to create an array list from an array of objects or vice versa. You can write the code using a loop to accomplish this, but an easy way is to use the methods in the Java API. Here is an example to create an array list from an array:

```
String[] array = {"red", "green", "blue"};
ArrayList<String> list = new ArrayList<>(Arrays.asList(array));
```

array list to array

The static method `asList` in the `Arrays` class returns a list that is passed to the `ArrayList` constructor for creating an `ArrayList`. Conversely, you can use the following code to create an array of objects from an array list.

```
String[] array1 = new String[list.size()];
list.toArray(array1);
```

Invoking `list.toArray(array1)` copies the contents from `list` to `array1`.

sort a list

If the elements in a list are comparable such as integers, double, or strings, you can use the static `sort` method in the `java.util.Collections` class to sort the elements. Here are examples:

```
Integer[] array = {3, 5, 95, 4, 15, 34, 3, 6, 5};
ArrayList<Integer> list = new ArrayList<>(Arrays.asList(array));
java.util.Collections.sort(list);
System.out.println(list);
```

max and min methods

You can use the static `max` and `min` in the `java.util.Collections` class to return the maximum and minimal element in a list. Here are examples:

```
Integer[] array = {3, 5, 95, 4, 15, 34, 3, 6, 5};
ArrayList<Integer> list = new ArrayList<>(Arrays.asList(array));
System.out.println(java.util.Collections.max(list));
System.out.println(java.util.Collections.min(list));
```

You can use the static `shuffle` method in the `java.util.Collections` class to perform a random shuffle for the elements in a list. Here are examples:

```
Integer[] array = {3, 5, 95, 4, 15, 34, 3, 6, 5};
ArrayList<Integer> list = new ArrayList<>(Arrays.asList(array));
java.util.Collections.shuffle(list);
System.out.println(list);
```



11.35 Correct errors in the following statements:

```
int[] array = {3, 5, 95, 4, 15, 34, 3, 6, 5};
ArrayList<Integer> list = new ArrayList<>(Arrays.asList(array));
```

11.36 Correct errors in the following statements:

```
int[] array = {3, 5, 95, 4, 15, 34, 3, 6, 5};
System.out.println(java.util.Collections.max(array));
```



11.13 Case Study: A Custom Stack Class

This section designs a stack class for holding objects.

Section 10.6 presented a stack class for storing `int` values. This section introduces a stack class to store objects. You can use an `ArrayList` to implement `Stack`, as shown in Listing 11.10. The UML diagram for the class is shown in Figure 11.4.



VideoNote

The MyStack class

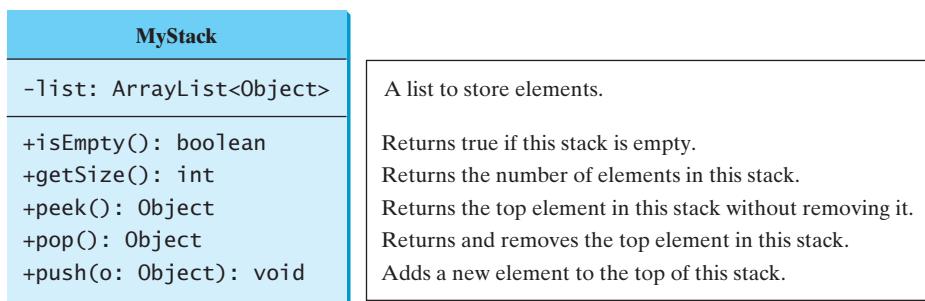


FIGURE 11.4 The `MyStack` class encapsulates the stack storage and provides the operations for manipulating the stack.

LISTING 11.10 MyStack.java

```
1 import java.util.ArrayList;
2
3 public class MyStack {
4     private ArrayList<Object> list = new ArrayList<>();
5
6     public boolean isEmpty() {
7         return list.isEmpty();
8     }
9
10    public int getSize() {
11        return list.size();
12    }
13
14    public Object peek() {
15        return list.get(getSize() - 1);
16    }
```

array list

stack empty?

get stack size

peek stack

```

remove
17
18  public Object pop() {
19      Object o = list.get(getSize() - 1);
20      list.remove(getSize() - 1);
21      return o;
22  }
23
push
24  public void push(Object o) {
25      list.add(o);
26  }
27
28  @Override
29  public String toString() {
30      return "stack: " + list.toString();
31  }
32 }
```

An array list is created to store the elements in the stack (line 4). The `isEmpty()` method (lines 6–8) returns `list.isEmpty()`. The `getSize()` method (lines 10–12) returns `list.size()`. The `peek()` method (lines 14–16) retrieves the element at the top of the stack without removing it. The end of the list is the top of the stack. The `pop()` method (lines 18–22) removes the top element from the stack and returns it. The `push(Object element)` method (lines 24–26) adds the specified element to the stack. The `toString()` method (lines 28–31) defined in the `Object` class is overridden to display the contents of the stack by invoking `list.toString()`. The `toString()` method implemented in `ArrayList` returns a string representation of all the elements in an array list.



Design Guide

In Listing 11.10, `MyStack` contains `ArrayList`. The relationship between `MyStack` and `ArrayList` is composition. While inheritance models an *is-a* relationship, composition models a *has-a* relationship. You could also implement `MyStack` as a subclass of `ArrayList` (see Programming Exercise 11.10). Using composition is better, however, because it enables you to define a completely new stack class without inheriting the unnecessary and inappropriate methods from `ArrayList`.

composition
is-a
has-a



11.14 The `protected` Data and Methods

A protected member of a class can be accessed from a subclass.

why protected?

So far you have used the `private` and `public` keywords to specify whether data fields and methods can be accessed from outside of the class. Private members can be accessed only from inside of the class, and public members can be accessed from any other classes.

Often it is desirable to allow subclasses to access data fields or methods defined in the superclass, but not to allow nonsubclasses to access these data fields and methods. To accomplish this, you can use the `protected` keyword. This way you can access protected data fields or methods in a superclass from its subclasses.

The modifiers `private`, `protected`, and `public` are known as *visibility* or *accessibility modifiers* because they specify how classes and class members are accessed. The visibility of these modifiers increases in this order:

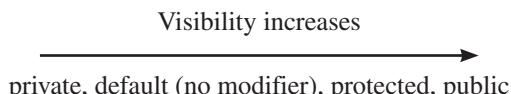


Table 11.2 summarizes the accessibility of the members in a class. Figure 11.5 illustrates how a public, protected, default, and private datum or method in class `C1` can be accessed from a class `C2` in the same package, from a subclass `C3` in the same package, from a subclass `C4` in a different package, and from a class `C5` in a different package.

Use the **private** modifier to hide the members of the class completely so that they cannot be accessed directly from outside the class. Use no modifiers (the default) in order to allow the members of the class to be accessed directly from any class within the same package but not from other packages. Use the **protected** modifier to enable the members of the class to be accessed by the subclasses in any package or classes in the same package. Use the **public** modifier to enable the members of the class to be accessed by any class.

TABLE 11.2 Data and Methods Visibility

Modifier on members in a class	Accessed from the same class	Accessed from the same package	Accessed from a subclass in a different package	Accessed from a different package
public	✓	✓	✓	✓
protected	✓	✓	✓	—
default (no modifier)	✓	✓	—	—
private	✓	—	—	—

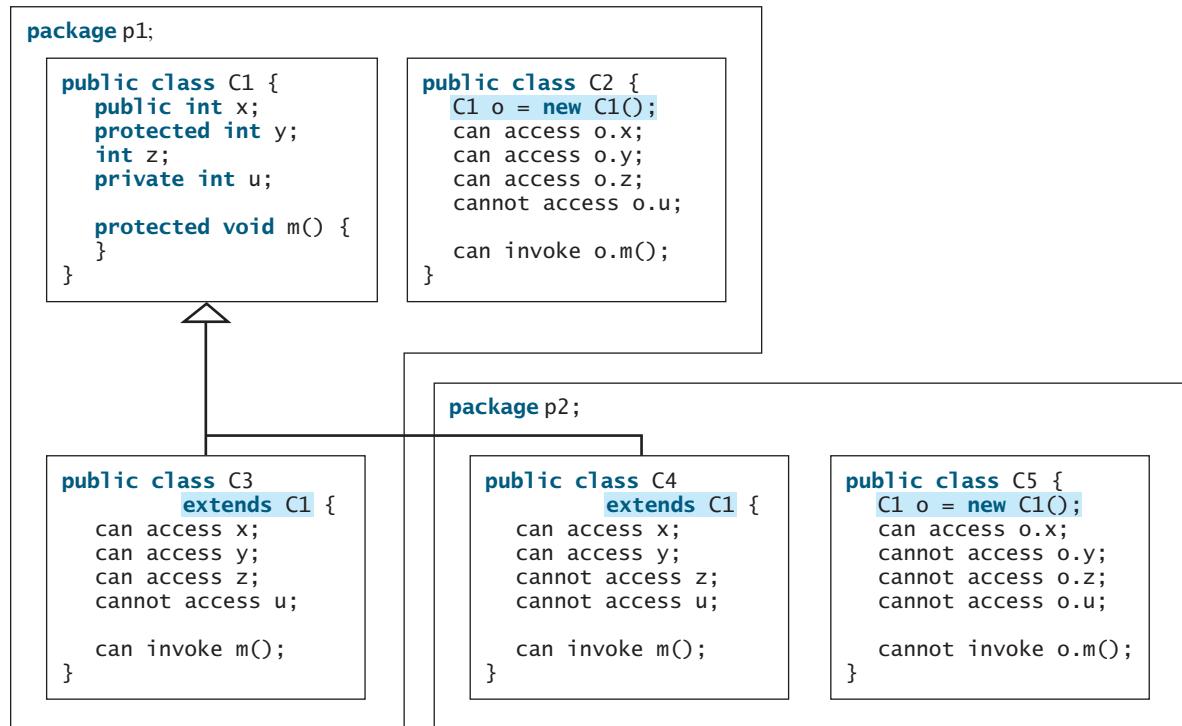


FIGURE 11.5 Visibility modifiers are used to control how data and methods are accessed.

Your class can be used in two ways: (1) for creating instances of the class and (2) for defining subclasses by extending the class. Make the members **private** if they are not intended for use from outside the class. Make the members **public** if they are intended for the users of the class. Make the fields or methods **protected** if they are intended for the extenders of the class but not for the users of the class.

The **private** and **protected** modifiers can be used only for members of the class. The **public** modifier and the default modifier (i.e., no modifier) can be used on members of the class as well as on the class. A class with no modifier (i.e., not a public class) is not accessible by classes from other packages.

change visibility

**Note**

A subclass may override a protected method defined in its superclass and change its visibility to public. However, a subclass cannot weaken the accessibility of a method defined in the superclass. For example, if a method is defined as public in the superclass, it must be defined as public in the subclass.



- 11.37** What modifier should you use on a class so that a class in the same package can access it, but a class in a different package cannot access it?
- 11.38** What modifier should you use so that a class in a different package cannot access the class, but its subclasses in any package can access it?
- 11.39** In the following code, the classes **A** and **B** are in the same package. If the question marks in (a) are replaced by blanks, can class **B** be compiled? If the question marks are replaced by **private**, can class **B** be compiled? If the question marks are replaced by **protected**, can class **B** be compiled?

```
package p1;

public class A {
    ? int i;
    ? void m() {
        ...
    }
}
```

(a)

```
package p1;

public class B extends A {
    public void m1(String[] args) {
        System.out.println(i);
        m();
    }
}
```

(b)

- 11.40** In the following code, the classes **A** and **B** are in different packages. If the question marks in (a) are replaced by blanks, can class **B** be compiled? If the question marks are replaced by **private**, can class **B** be compiled? If the question marks are replaced by **protected**, can class **B** be compiled?

```
package p1;

public class A {
    ? int i;
    ? void m() {
        ...
    }
}
```

(a)

```
package p2;

public class B extends A {
    public void m1(String[] args) {
        System.out.println(i);
        m();
    }
}
```

(b)

11.15 Preventing Extending and Overriding



Neither a final class nor a final method can be extended. A final data field is a constant.

You may occasionally want to prevent classes from being extended. In such cases, use the **final** modifier to indicate that a class is final and cannot be a parent class. The **Math** class is a final class. The **String**, **StringBuilder**, and **StringBuffer** classes are also final classes. For example, the following class **A** is final and cannot be extended:

```
public final class A {
    // Data fields, constructors, and methods omitted
}
```

You also can define a method to be final; a final method cannot be overridden by its subclasses.

For example, the following method `m` is final and cannot be overridden:

```
public class Test {
    // Data fields, constructors, and methods omitted

    public final void m() {
        // Do something
    }
}
```



Note

The modifiers `public`, `protected`, `private`, `static`, `abstract`, and `final` are used on classes and class members (data and methods), except that the `final` modifier can also be used on local variables in a method. A `final` local variable is a constant inside a method.

- 11.41** How do you prevent a class from being extended? How do you prevent a method from being overridden?



- 11.42** Indicate true or false for the following statements:

- A protected datum or method can be accessed by any class in the same package.
- A protected datum or method can be accessed by any class in different packages.
- A protected datum or method can be accessed by its subclasses in any package.
- A final class can have instances.
- A final class can be extended.
- A final method can be overridden.

Key Terms

actual type	424	override	000
casting objects	427	polymorphism	423
constructor chaining	417	protected	440
declared type	424	single inheritance	416
dynamic binding	424	subclass	410
inheritance	410	subtype	423
<code>instanceof</code>	428	superclass	410
is-a relationship	440	supertype	423
method overriding	419	type inference	433
multiple inheritance	416		

CHAPTER SUMMARY

1. You can define a new class from an existing class. This is known as class *inheritance*. The new class is called a *subclass*, *child class*, or *extended class*. The existing class is called a *superclass*, *parent class*, or *base class*.
2. A constructor is used to construct an instance of a class. Unlike properties and methods, the constructors of a superclass are not inherited in the subclass. They can be invoked only from the constructors of the subclasses, using the keyword `super`.

3. A constructor may invoke an overloaded constructor or its superclass's constructor. The call must be the first statement in the constructor. If none of them is invoked explicitly, the compiler puts `super()` as the first statement in the constructor, which invokes the superclass's no-arg constructor.
4. To *override* a method, the method must be defined in the subclass using the same signature and the same return type as in its superclass.
5. An instance method can be overridden only if it is accessible. Thus, a private method cannot be overridden because it is not accessible outside its own class. If a method defined in a subclass is private in its superclass, the two methods are completely unrelated.
6. Like an instance method, a static method can be inherited. However, a static method cannot be overridden. If a static method defined in the superclass is redefined in a subclass, the method defined in the superclass is hidden.
7. Every class in Java is descended from the `java.lang.Object` class. If no superclass is specified when a class is defined, its superclass is `Object`.
8. If a method's parameter type is a superclass (e.g., `Object`), you may pass an object to this method of any of the parameter's subclasses (e.g., `Circle` or `String`). This is known as polymorphism.
9. It is always possible to cast an instance of a subclass to a variable of a superclass, because an instance of a subclass is *always* an instance of its superclass. When casting an instance of a superclass to a variable of its subclass, explicit casting must be used to confirm your intention to the compiler with the (`SubClassName`) cast notation.
10. A class defines a type. A type defined by a subclass is called a *subtype* and a type defined by its superclass is called a *supertype*.
11. When invoking an instance method from a reference variable, the *actual type* of the variable decides which implementation of the method is used *at runtime*. This is known as dynamic binding.
12. You can use `obj instanceof AClass` to test whether an object is an instance of a class.
13. You can use the `ArrayList` class to create an object to store a list of objects.
14. You can use the `protected` modifier to prevent the data and methods from being accessed by nonsubclasses from a different package.
15. You can use the `final` modifier to indicate that a class is final and cannot be extended and to indicate that a method is final and cannot be overridden.

Quiz

Answer the quiz for this chapter online at www.cs.armstrong.edu/liang/intro10e/quiz.html.

PROGRAMMING EXERCISES

Sections 11.2–11.4

- 11.1** (*The Triangle class*) Design a class named **Triangle** that extends **GeometricObject**. The class contains:

- Three **double** data fields named **side1**, **side2**, and **side3** with default values **1.0** to denote three sides of the triangle.
- A no-arg constructor that creates a default triangle.
- A constructor that creates a triangle with the specified **side1**, **side2**, and **side3**.
- The accessor methods for all three data fields.
- A method named **getArea()** that returns the area of this triangle.
- A method named **getPerimeter()** that returns the perimeter of this triangle.
- A method named **toString()** that returns a string description for the triangle.

For the formula to compute the area of a triangle, see Programming Exercise 2.19.

The **toString()** method is implemented as follows:

```
return "Triangle: side1 = " + side1 + " side2 = " + side2 +
    " side3 = " + side3;
```

Draw the UML diagrams for the classes **Triangle** and **GeometricObject** and implement the classes. Write a test program that prompts the user to enter three sides of the triangle, a color, and a Boolean value to indicate whether the triangle is filled. The program should create a **Triangle** object with these sides and set the **color** and **filled** properties using the input. The program should display the area, perimeter, color, and true or false to indicate whether it is filled or not.

Sections 11.5–11.14

- 11.2** (*The Person, Student, Employee, Faculty, and Staff classes*) Design a class named **Person** and its two subclasses named **Student** and **Employee**. Make **Faculty** and **Staff** subclasses of **Employee**. A person has a name, address, phone number, and email address. A student has a class status (freshman, sophomore, junior, or senior). Define the status as a constant. An employee has an office, salary, and date hired. Use the **MyDate** class defined in Programming Exercise 10.14 to create an object for date hired. A faculty member has office hours and a rank. A staff member has a title. Override the **toString** method in each class to display the class name and the person's name.

Draw the UML diagram for the classes and implement them. Write a test program that creates a **Person**, **Student**, **Employee**, **Faculty**, and **Staff**, and invokes their **toString()** methods.

- 11.3** (*Subclasses of Account*) In Programming Exercise 9.7, the **Account** class was defined to model a bank account. An account has the properties account number, balance, annual interest rate, and date created, and methods to deposit and withdraw funds. Create two subclasses for checking and saving accounts. A checking account has an overdraft limit, but a savings account cannot be overdrawn.

Draw the UML diagram for the classes and then implement them. Write a test program that creates objects of **Account**, **SavingsAccount**, and **CheckingAccount** and invokes their **toString()** methods.

- 11.4** (*Maximum element in ArrayList*) Write the following method that returns the maximum value in an **ArrayList** of integers. The method returns **null** if the list is **null** or the list size is **0**.

```
public static Integer max(ArrayList<Integer> list)
```

Write a test program that prompts the user to enter a sequence of numbers ending with **0**, and invokes this method to return the largest number in the input.

- 11.5** (*The Course class*) Rewrite the **Course** class in Listing 10.6. Use an **ArrayList** to replace an array to store students. Draw the new UML diagram for the class. You should not change the original contract of the **Course** class (i.e., the definition of the constructors and methods should not be changed, but the private members may be changed.)
- 11.6** (*Use ArrayList*) Write a program that creates an **ArrayList** and adds a **Loan** object, a **Date** object, a string, and a **Circle** object to the list, and use a loop to display all the elements in the list by invoking the object's **toString()** method.
- 11.7** (*Shuffle ArrayList*) Write the following method that shuffles the elements in an **ArrayList** of integers.

```
public static void shuffle(ArrayList<Integer> list)
```



VideoNote

New Account class

****11.8**

(*New Account class*) An **Account** class was specified in Programming Exercise 9.7. Design a new **Account** class as follows:

- Add a new data field **name** of the **String** type to store the name of the customer.
- Add a new constructor that constructs an account with the specified name, id, and balance.
- Add a new data field named **transactions** whose type is **ArrayList** that stores the transaction for the accounts. Each transaction is an instance of the **Transaction** class. The **Transaction** class is defined as shown in Figure 11.6.

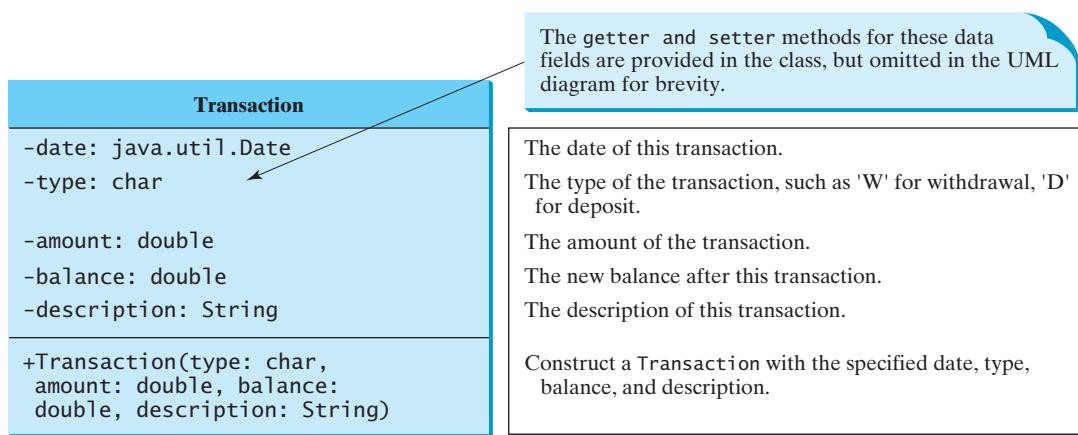


FIGURE 11.6 The **Transaction** class describes a transaction for a bank account.

- Modify the **withdraw** and **deposit** methods to add a transaction to the **transactions** array list.
- All other properties and methods are the same as in Programming Exercise 9.7.

Write a test program that creates an **Account** with annual interest rate **1.5%**, balance **1000**, id **1122**, and name **George**. Deposit \$30, \$40, and \$50 to the account and withdraw \$5, \$4, and \$2 from the account. Print an account summary that shows account holder name, interest rate, balance, and all transactions.

- *11.9** (*Largest rows and columns*) Write a program that randomly fills in 0s and 1s into an n-by-n matrix, prints the matrix, and finds the rows and columns with the most 1s. (*Hint:* Use two `ArrayList`s to store the row and column indices with the most 1s.) Here is a sample run of the program:

```
Enter the array size n: 4
The random array is
0011
0011
1101
1010
The largest row index: 2
The largest column index: 2, 3
```



- 11.10** (*Implement `MyStack` using inheritance*) In Listing 11.10, `MyStack` is implemented using composition. Define a new stack class that extends `ArrayList`. Draw the UML diagram for the classes and then implement `MyStack`. Write a test program that prompts the user to enter five strings and displays them in reverse order.

- 11.11** (*Sort `ArrayList`*) Write the following method that sorts an `ArrayList` of numbers:

```
public static void sort(ArrayList<Integer> list)
```

Write a test program that prompts the user to enter 5 numbers, stores them in an array list, and displays them in increasing order.

- 11.12** (*Sum `ArrayList`*) Write the following method that returns the sum of all numbers in an `ArrayList`:

```
public static double sum(ArrayList<Double> list)
```

Write a test program that prompts the user to enter 5 numbers, stores them in an array list, and displays their sum.

- *11.13** (*Remove duplicates*) Write a method that removes the duplicate elements from an array list of integers using the following header:

```
public static void removeDuplicate(ArrayList<Integer> list)
```

Write a test program that prompts the user to enter 10 integers to a list and displays the distinct integers separated by exactly one space. Here is a sample run:

```
Enter ten integers: 34 5 3 5 6 4 33 2 2 4
The distinct integers are 34 5 3 6 4 33 2
```



- 11.14** (*Combine two lists*) Write a method that returns the union of two array lists of integers using the following header:

```
public static ArrayList<Integer> union(
    ArrayList<Integer> list1, ArrayList<Integer> list2)
```

For example, the union of two array lists $\{2, 3, 1, 5\}$ and $\{3, 4, 6\}$ is $\{2, 3, 1, 5, 3, 4, 6\}$. Write a test program that prompts the user to enter two lists, each with five integers, and displays their union. The numbers are separated by exactly one space in the output. Here is a sample run:



```
Enter five integers for list1: 3 5 45 4 3 ↵
Enter five integers for list2: 33 51 5 4 13 ↵
The combined list is 3 5 45 4 3 33 51 5 4 13
```

- *11.15** (*Area of a convex polygon*) A polygon is convex if it contains any line segments that connects two points of the polygon. Write a program that prompts the user to enter the number of points in a convex polygon, then enter the points clockwise, and display the area of the polygon. Here is a sample run of the program:



```
Enter the number of the points: 7 ↵
Enter the coordinates of the points:
-12 0 -8.5 10 0 11.4 5.5 7.8 6 -5.5 0 -7 -3.5 -3.5 ↵
The total area is 250.075
```

- **11.16** (*Addition quiz*) Rewrite Listing 5.1 RepeatAdditionQuiz.java to alert the user if an answer is entered again. *Hint: use an array list to store answers.* Here is a sample run:



```
What is 5 + 9? 12 ↵
Wrong answer. Try again. What is 5 + 9? 34 ↵
Wrong answer. Try again. What is 5 + 9? 12 ↵
You already entered 12
Wrong answer. Try again. What is 5 + 9? 14 ↵
You got it!
```

- **11.17** (*Algebra: perfect square*) Write a program that prompts the user to enter an integer m and find the smallest integer n such that $m * n$ is a perfect square. (*Hint: Store all smallest factors of m into an array list. n is the product of the factors that appear an odd number of times in the array list.* For example, consider $m = 90$, store the factors 2, 3, 3, 5 in an array list. 2 and 5 appear an odd number of times in the array list. So, n is 10.) Here are sample runs:



```
Enter an integer m: 1500 ↵
The smallest number n for m * n to be a perfect square is 15
m * n is 22500
```



```
Enter an integer m: 63 ↵
The smalle
st number n for m * n to be a perfect square is 7
m * n is 441
```

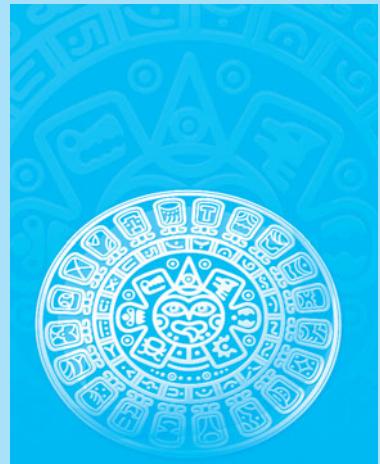
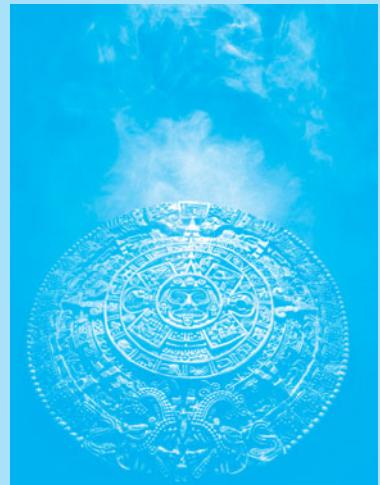
CHAPTER

12

EXCEPTION HANDLING AND TEXT I/O

Objectives

- To get an overview of exceptions and exception handling (§12.2).
- To explore the advantages of using exception handling (§12.2).
- To distinguish exception types: **Error** (fatal) vs. **Exception** (nonfatal) and checked vs. unchecked (§12.3).
- To declare exceptions in a method header (§12.4.1).
- To throw exceptions in a method (§12.4.2).
- To write a **try-catch** block to handle exceptions (§12.4.3).
- To explain how an exception is propagated (§12.4.3).
- To obtain information from an exception object (§12.4.4).
- To develop applications with exception handling (§12.4.5).
- To use the **finally** clause in a **try-catch** block (§12.5).
- To use exceptions only for unexpected errors (§12.6).
- To rethrow exceptions in a **catch** block (§12.7).
- To create chained exceptions (§12.8).
- To define custom exception classes (§12.9).
- To discover file/directory properties, to delete and rename files/directories, and to create directories using the **File** class (§12.10).
- To write data to a file using the **PrintWriter** class (§12.11.1).
- To use try-with-resources to ensure that the resources are closed automatically (§12.11.2).
- To read data from a file using the **Scanner** class (§12.11.3).
- To understand how data is read using a **Scanner** (§12.11.4).
- To develop a program that replaces text in a file (§12.11.5).
- To read data from the Web (§12.12).
- To develop a Web crawler (§12.13).



12.1 Introduction



Exception handling enables a program to deal with exceptional situations and continue its normal execution.

Runtime errors occur while a program is running if the JVM detects an operation that is impossible to carry out. For example, if you access an array using an index that is out of bounds, you will get a runtime error with an `ArrayIndexOutOfBoundsException`. If you enter a `double` value when your program expects an integer, you will get a runtime error with an `InputMismatchException`.

exception

In Java, runtime errors are thrown as exceptions. An *exception* is an object that represents an error or a condition that prevents execution from proceeding normally. If the exception is not handled, the program will terminate abnormally. How can you handle the exception so that the program can continue to run or else terminate gracefully? This chapter introduces this subject and text input and output.

12.2 Exception-Handling Overview



Exceptions are thrown from a method. The caller of the method can catch and handle the exception.



Exception-handling
advantages

read two integers

integer division

To demonstrate exception handling, including how an exception object is created and thrown, let's begin with the example in Listing 12.1, which reads in two integers and displays their quotient.

LISTING 12.1 Quotient.java

```

1 import java.util.Scanner;
2
3 public class Quotient {
4     public static void main(String[] args) {
5         Scanner input = new Scanner(System.in);
6
7         // Prompt the user to enter two integers
8         System.out.print("Enter two integers: ");
9         int number1 = input.nextInt();
10        int number2 = input.nextInt();
11
12        System.out.println(number1 + " / " + number2 + " is " +
13                            (number1 / number2));
14    }
15 }
```



Enter two integers: 5 2 ↵
5 / 2 is 2



Enter two integers: 3 0 ↵
Exception in thread "main" java.lang.ArithmaticException: / by zero
at Quotient.main(Quotient.java:11)

If you entered `0` for the second number, a runtime error would occur, because you cannot divide an integer by `0`. (*Note that a floating-point number divided by `0` does not raise an exception.*) A simple way to fix this error is to add an `if` statement to test the second number, as shown in Listing 12.2.

LISTING 12.2 QuotientWithIf.java

```

1 import java.util.Scanner;
2
3 public class QuotientWithIf {
4     public static void main(String[] args) {
5         Scanner input = new Scanner(System.in);
6
7         // Prompt the user to enter two integers
8         System.out.print("Enter two integers: ");
9         int number1 = input.nextInt();           read two integers
10        int number2 = input.nextInt();
11
12        if (number2 != 0)                      test number2
13            System.out.println(number1 + " / " + number2
14            + " is " + (number1 / number2));
15        else
16            System.out.println("Divisor cannot be zero");
17    }
18 }
```

Enter two integers: 5 0



Before introducing exception handling, let us rewrite Listing 12.2 to compute a quotient using a method, as shown in Listing 12.3.

LISTING 12.3 QuotientWithMethod.java

```

1 import java.util.Scanner;
2
3 public class QuotientWithMethod {
4     public static int quotient(int number1, int number2) {           quotient method
5         if (number2 == 0) {
6             System.out.println("Divisor cannot be zero");
7             System.exit(1);          terminate the program
8         }
9
10        return number1 / number2;
11    }
12
13    public static void main(String[] args) {
14        Scanner input = new Scanner(System.in);
15
16        // Prompt the user to enter two integers
17        System.out.print("Enter two integers: ");
18        int number1 = input.nextInt();           read two integers
19        int number2 = input.nextInt();
20
21        int result = quotient(number1, number2);   invoke method
22        System.out.println(number1 + " / " + number2 + " is "
23        + result);
24    }
25 }
```



Enter two integers: 5 3 ↵Enter
5 / 3 is 1



Enter two integers: 5 0 ↵Enter
Divisor cannot be zero

The method **quotient** (lines 4–11) returns the quotient of two integers. If **number2** is **0**, it cannot return a value, so the program is terminated in line 7. This is clearly a problem. You should not let the method terminate the program—the *caller* should decide whether to terminate the program.

How can a method notify its caller an exception has occurred? Java enables a method to throw an exception that can be caught and handled by the caller. Listing 12.3 can be rewritten, as shown in Listing 12.4.

LISTING 12.4 QuotientWithException.java

quotient method
throw exception

read two integers

try block
invoke method

catch block

```

1 import java.util.Scanner;
2
3 public class QuotientWithException {
4     public static int quotient(int number1, int number2) {
5         if (number2 == 0)
6             throw new ArithmeticException("Divisor cannot be zero");
7
8         return number1 / number2;
9     }
10
11    public static void main(String[] args) {
12        Scanner input = new Scanner(System.in);
13
14        // Prompt the user to enter two integers
15        System.out.print("Enter two integers: ");
16        int number1 = input.nextInt();
17        int number2 = input.nextInt();
18
19        try {
20            int result = quotient(number1, number2);
21            if an
22            System.out.println(number1 + " / " + number2 + " is "
23            occurs
24        } catch (ArithmeticException ex) {
25            System.out.println("Exception: an integer " +
26                "cannot be divided by zero ");
27        }
28
29        System.out.println("Execution continues ...");
30    }
31 }
```



Enter two integers: 5 3 ↵Enter
5 / 3 is 1
Execution continues ...

```
Enter two integers: 5 0 ↵Enter
Exception: an integer cannot be divided by zero
Execution continues ...
```



If `number2` is 0, the method throws an exception (line 6) by executing

```
throw new ArithmeticException("Divisor cannot be zero");
```

throw statement

The value thrown, in this case `new ArithmeticException("Divisor cannot be zero")`, is called an *exception*. The execution of a `throw` statement is called *throwing an exception*. The exception is an object created from an exception class. In this case, the exception class is `java.lang.ArithmaticException`. The constructor `ArithmaticException(str)` is invoked to construct an exception object, where `str` is a message that describes the exception.

When an exception is thrown, the normal execution flow is interrupted. As the name suggests, to “throw an exception” is to pass the exception from one place to another. The statement for invoking the method is contained in a `try` block and a `catch` block. The `try` block (lines 19–23) contains the code that is executed in normal circumstances. The exception is caught by the `catch` block. The code in the `catch` block is executed to *handle the exception*. Afterward, the statement (line 29) after the `catch` block is executed.

The `throw` statement is analogous to a method call, but instead of calling a method, it calls a `catch` block. In this sense, a `catch` block is like a method definition with a parameter that matches the type of the value being thrown. Unlike a method, however, after the `catch` block is executed, the program control does not return to the `throw` statement; instead, it executes the next statement after the `catch` block.

The identifier `ex` in the `catch`-block header

```
catch (ArithmaticException ex)
```

handle exception

acts very much like a parameter in a method. Thus, this parameter is referred to as a `catch`-block parameter. The type (e.g., `ArithmaticException`) preceding `ex` specifies what kind of exception the `catch` block can catch. Once the exception is caught, you can access the thrown value from this parameter in the body of a `catch` block.

catch-block parameter

In summary, a template for a `try-throw-catch` block may look like this:

```
try {
    Code to run;
    A statement or a method that may throw an exception;
    More code to run;
}
catch (type ex) {
    Code to process the exception;
}
```

An exception may be thrown directly by using a `throw` statement in a `try` block, or by invoking a method that may throw an exception.

The main method invokes `quotient` (line 20). If the `quotient` method executes normally, it returns a value to the caller. If the `quotient` method encounters an exception, it throws the exception back to its caller. The caller’s `catch` block handles the exception.

Now you can see the *advantage* of using exception handling: It enables a method to throw an exception to its caller, enabling the caller to handle the exception. Without this capability, the called method itself must handle the exception or terminate the program. Often the called method does not know what to do in case of error. This is typically the case for the library methods. The library method can detect the error, but only the caller knows what needs to be

advantage

done when an error occurs. The key benefit of exception handling is separating the detection of an error (done in a called method) from the handling of an error (done in the calling method).

Many library methods throw exceptions. Listing 12.5 gives an example that handles an `InputMismatchException` when reading an input.

LISTING 12.5 InputMismatchExceptionDemo.java

create a Scanner

try block

catch block

```

1 import java.util.*;
2
3 public class InputMismatchExceptionDemo {
4     public static void main(String[] args) {
5         Scanner input = new Scanner(System.in);
6         boolean continueInput = true;
7
8         do {
9             try {
10                 System.out.print("Enter an integer: ");
11                 int number = input.nextInt();
12
13                 // If an
14                 // InputMismatch
15                 // Exception
16                 // occurs
17                 // Display the result
18                 // System.out.println(
19                 //     "The number entered is " + number);
20
21                 continueInput = false;
22             } catch (InputMismatchException ex) {
23                 System.out.println("Try again. (" +
24                     "Incorrect input: an integer is required)");
25                 input.nextLine(); // Discard input
26             }
27         } while (continueInput);
28     }
29 }
```



```

Enter an integer: 3.5 ↵ Enter
Try again. (Incorrect input: an integer is required)
Enter an integer: 4 ↵ Enter
The number entered is 4

```

When executing `input.nextInt()` (line 11), an `InputMismatchException` occurs if the input entered is not an integer. Suppose 3.5 is entered. An `InputMismatchException` occurs and the control is transferred to the `catch` block. The statements in the `catch` block are now executed. The statement `input.nextLine()` in line 22 discards the current input line so that the user can enter a new line of input. The variable `continueInput` controls the loop. Its initial value is `true` (line 6), and it is changed to `false` (line 17) when a valid input is received. Once a valid input is received, there is no need to continue the input.



I2.1 What is the advantage of using exception handling?

I2.2 Which of the following statements will throw an exception?

```

System.out.println(1 / 0);
System.out.println(1.0 / 0);

```

12.3 Point out the problem in the following code. Does the code throw any exceptions?

```
long value = Long.MAX_VALUE + 1;
System.out.println(value);
```

12.4 What does the JVM do when an exception occurs? How do you catch an exception?

12.5 What is the output of the following code?

```
public class Test {
    public static void main(String[] args) {
        try {
            int value = 30;
            if (value < 40)
                throw new Exception("value is too small");
        }
        catch (Exception ex) {
            System.out.println(ex.getMessage());
        }
        System.out.println("Continue after the catch block");
    }
}
```

What would be the output if the line

```
int value = 30;
```

were changed to

```
int value = 50;
```

12.6 Show the output of the following code.

```
public class Test {
    public static void main(String[] args) {
        for (int i = 0; i < 2; i++) {
            System.out.print(i + " ");
            try {
                System.out.println(1 / 0);
            }
            catch (Exception ex) {
            }
        }
    }
}
```

(a)

```
public class Test {
    public static void main(String[] args) {
        try {
            for (int i = 0; i < 2; i++) {
                System.out.print(i + " ");
                System.out.println(1 / 0);
            }
        }
        catch (Exception ex) {
        }
    }
}
```

(b)

12.3 Exception Types

Exceptions are objects, and objects are defined using classes. The root class for exceptions is `java.lang.Throwable`.



The preceding section used the classes `ArithmaticException` and `InputMismatchException`. Are there any other types of exceptions you can use? Can you define your own exception classes? Yes. There are many predefined exception classes in the Java API. Figure 12.1 shows some of them, and in Section 12.9 you will learn how to define your own exception classes.

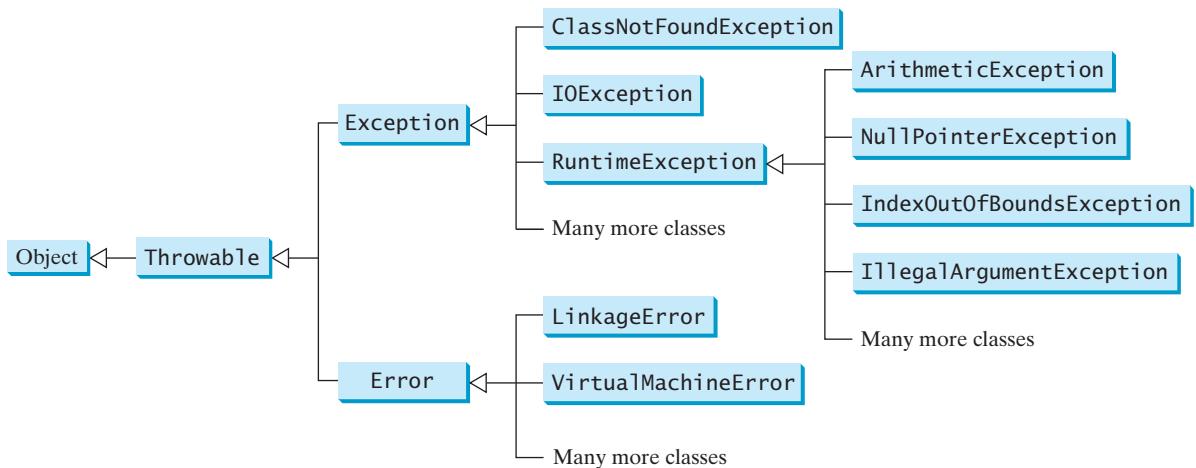


FIGURE 12.1 Exceptions thrown are instances of the classes shown in this diagram, or of subclasses of one of these classes.



Note

The class names **Error**, **Exception**, and **RuntimeException** are somewhat confusing. All three of these classes are exceptions, and all of the errors occur at runtime.

The **Throwable** class is the root of exception classes. All Java exception classes inherit directly or indirectly from **Throwable**. You can create your own exception classes by extending **Exception** or a subclass of **Exception**.

The exception classes can be classified into three major types: system errors, exceptions, and runtime exceptions.

system error

- *System errors* are thrown by the JVM and are represented in the **Error** class. The **Error** class describes internal system errors, though such errors rarely occur. If one does, there is little you can do beyond notifying the user and trying to terminate the program gracefully. Examples of subclasses of **Error** are listed in Table 12.1.

TABLE 12.1 Examples of Subclasses of Error

Class	Reasons for Exception
LinkageError	A class has some dependency on another class, but the latter class has changed incompatibly after the compilation of the former class.
VirtualMachineError	The JVM is broken or has run out of the resources it needs in order to continue operating.

exception

- *Exceptions* are represented in the **Exception** class, which describes errors caused by your program and by external circumstances. These errors can be caught and handled by your program. Examples of subclasses of **Exception** are listed in Table 12.2.

TABLE 12.2 Examples of Subclasses of Exception

Class	Reasons for Exception
ClassNotFoundException	Attempt to use a class that does not exist. This exception would occur, for example, if you tried to run a nonexistent class using the java command, or if your program were composed of, say, three class files, only two of which could be found.
IOException	Related to input/output operations, such as invalid input, reading past the end of a file, and opening a nonexistent file. Examples of subclasses of IOException are InterruptedException , EOFException (EOF is short for End of File), and FileNotFoundException .

- *Runtime exceptions* are represented in the **RuntimeException** class, which describes programming errors, such as bad casting, accessing an out-of-bounds array, and numeric errors. Runtime exceptions are generally thrown by the JVM. Examples of subclasses are listed in Table 12.3.

TABLE 12.3 Examples of Subclasses of **RuntimeException**

Class	Reasons for Exception	
ArithmaticException	Dividing an integer by zero. Note that floating-point arithmetic does not throw exceptions (see Appendix E, Special Floating-Point Values).	runtime exception
NullPointerException	Attempt to access an object through a null reference variable.	
IndexOutOfBoundsException	Index to an array is out of range.	
IllegalArgumentException	A method is passed an argument that is illegal or inappropriate.	

RuntimeException, **Error**, and their subclasses are known as *unchecked exceptions*. All other exceptions are known as *checked exceptions*, meaning that the compiler forces the programmer to check and deal with them in a **try-catch** block or declare it in the method header. Declaring an exception in the method header will be covered in Section 12.4.

In most cases, unchecked exceptions reflect programming logic errors that are unrecoverable. For example, a **NullPointerException** is thrown if you access an object through a reference variable before an object is assigned to it; an **IndexOutOfBoundsException** is thrown if you access an element in an array outside the bounds of the array. These are logic errors that should be corrected in the program. Unchecked exceptions can occur anywhere in a program. To avoid cumbersome overuse of **try-catch** blocks, Java does not mandate that you write code to catch or declare unchecked exceptions.

12.7 Describe the Java **Throwable** class, its subclasses, and the types of exceptions.

12.8 What **RuntimeException** will the following programs throw, if any?



```
public class Test {
    public static void main(String[] args) {
        System.out.println(1 / 0);
    }
}
```

(a)

```
public class Test {
    public static void main(String[] args) {
        int[] list = new int[5];
        System.out.println(list[5]);
    }
}
```

(b)

```
public class Test {
    public static void main(String[] args) {
        String s = "abc";
        System.out.println(s.charAt(3));
    }
}
```

(c)

```
public class Test {
    public static void main(String[] args) {
        Object o = new Object();
        String d = (String)o;
    }
}
```

(d)

```
public class Test {
    public static void main(String[] args) {
        Object o = null;
        System.out.println(o.toString());
    }
}
```

(e)

```
public class Test {
    public static void main(String[] args) {
        System.out.println(1.0 / 0);
    }
}
```

(f)

12.4 More on Exception Handling



A handler for an exception is found by propagating the exception backward through a chain of method calls, starting from the current method.

The preceding sections gave you an overview of exception handling and introduced several predefined exception types. This section provides an in-depth discussion of exception handling.

Java's exception-handling model is based on three operations: *declaring an exception*, *throwing an exception*, and *catching an exception*, as shown in Figure 12.2.

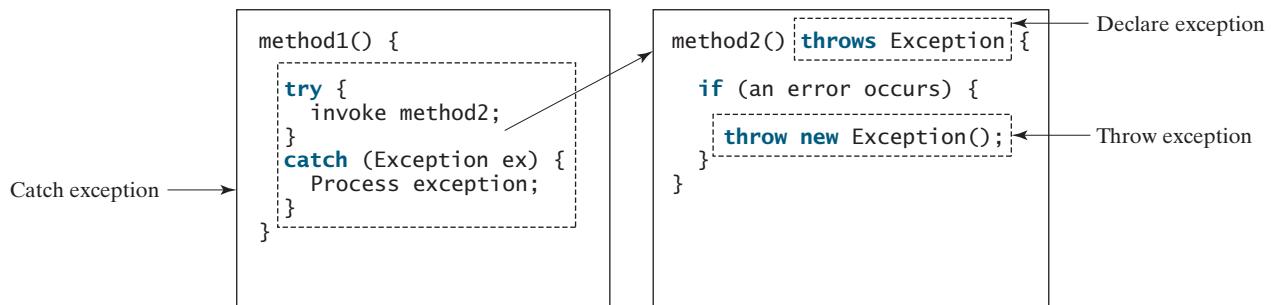


FIGURE 12.2 Exception handling in Java consists of declaring exceptions, throwing exceptions, and catching and processing exceptions.

12.4.1 Declaring Exceptions

declare exception

In Java, the statement currently being executed belongs to a method. The Java interpreter invokes the `main` method to start executing a program. Every method must state the types of checked exceptions it might throw. This is known as *declaring exceptions*. Because system errors and runtime errors can happen to any code, Java does not require that you declare `Error` and `RuntimeException` (unchecked exceptions) explicitly in the method. However, all other exceptions thrown by the method must be explicitly declared in the method header so that the caller of the method is informed of the exception.

To declare an exception in a method, use the `throws` keyword in the method header, as in this example:

```
public void myMethod() throws IOException
```

The `throws` keyword indicates that `myMethod` might throw an `IOException`. If the method might throw multiple exceptions, add a list of the exceptions, separated by commas, after `throws`:

```
public void myMethod()
    throws Exception1, Exception2, ..., ExceptionN
```



Note

If a method does not declare exceptions in the superclass, you cannot override it to declare exceptions in the subclass.

throw exception

12.4.2 Throwing Exceptions

A program that detects an error can create an instance of an appropriate exception type and throw it. This is known as *throwing an exception*. Here is an example: Suppose the program detects that an argument passed to the method violates the method contract (e.g., the argument

must be nonnegative, but a negative argument is passed); the program can create an instance of **IllegalArgumentException** and throw it, as follows:

```
IllegalArgumentException ex =
    new IllegalArgumentException("Wrong Argument");
throw ex;
```

Or, if you prefer, you can use the following:

```
throw new IllegalArgumentException("Wrong Argument");
```



Note

IllegalArgumentException is an exception class in the Java API. In general, each exception class in the Java API has at least two constructors: a no-arg constructor, and a constructor with a **String** argument that describes the exception. This argument is called the *exception message*, which can be obtained using **getMessage()**.

exception message



Tip

The keyword to declare an exception is **throws**, and the keyword to throw an exception is **throw**.

throws vs. throw

catch exception

12.4.3 Catching Exceptions

You now know how to declare an exception and how to throw an exception. When an exception is thrown, it can be caught and handled in a **try-catch** block, as follows:

```
try {
    statements; // Statements that may throw exceptions
}
catch (Exception1 exVar1) {
    handler for exception1;
}
catch (Exception2 exVar2) {
    handler for exception2;
}
...
catch (ExceptionN exVarN) {
    handler for exceptionN;
}
```

If no exceptions arise during the execution of the **try** block, the **catch** blocks are skipped.

If one of the statements inside the **try** block throws an exception, Java skips the remaining statements in the **try** block and starts the process of finding the code to handle the exception. The code that handles the exception is called the *exception handler*; it is found by *propagating the exception* backward through a chain of method calls, starting from the current method. Each **catch** block is examined in turn, from first to last, to see whether the type of the exception object is an instance of the exception class in the **catch** block. If so, the exception object is assigned to the variable declared, and the code in the **catch** block is executed. If no handler is found, Java exits this method, passes the exception to the method that invoked the method, and continues the same process to find a handler. If no handler is found in the chain of methods being invoked, the program terminates and prints an error message on the console. The process of finding a handler is called *catching an exception*.

exception handler
exception propagation

Suppose the `main` method invokes `method1`, `method1` invokes `method2`, `method2` invokes `method3`, and `method3` throws an exception, as shown in Figure 12.3. Consider the following scenario:

- If the exception type is `Exception3`, it is caught by the `catch` block for handling exception `ex3` in `method2`. `statement5` is skipped, and `statement6` is executed.
- If the exception type is `Exception2`, `method2` is aborted, the control is returned to `method1`, and the exception is caught by the `catch` block for handling exception `ex2` in `method1`. `statement3` is skipped, and `statement4` is executed.
- If the exception type is `Exception1`, `method1` is aborted, the control is returned to the `main` method, and the exception is caught by the `catch` block for handling exception `ex1` in the `main` method. `statement1` is skipped, and `statement2` is executed.
- If the exception type is not caught in `method2`, `method1`, or `main`, the program terminates, and `statement1` and `statement2` are not executed.

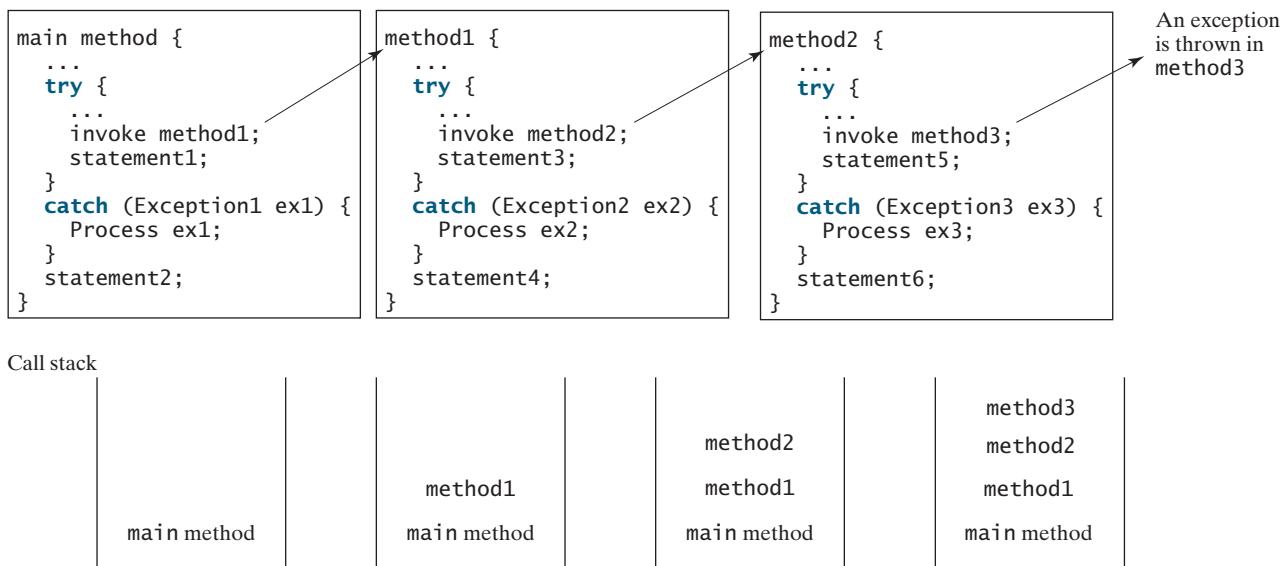


FIGURE 12.3 If an exception is not caught in the current method, it is passed to its caller. The process is repeated until the exception is caught or passed to the `main` method.

catch block

order of exception handlers



Note

Various exception classes can be derived from a common superclass. If a `catch` block catches exception objects of a superclass, it can catch all the exception objects of the subclasses of that superclass.



Note

The order in which exceptions are specified in `catch` blocks is important. A compile error will result if a catch block for a superclass type appears before a catch block for a subclass type. For example, the ordering in (a) on the next page is erroneous, because `RuntimeException` is a subclass of `Exception`. The correct ordering should be as shown in (b).

```
try {
    ...
} catch (Exception ex) {
    ...
} catch (RuntimeException ex) {
    ...
}
```

(a) Wrong order

```
try {
    ...
} catch (RuntimeException ex) {
    ...
} catch (Exception ex) {
    ...
}
```

(b) Correct order

**Note**

Java forces you to deal with checked exceptions. If a method declares a checked exception (i.e., an exception other than `Error` or `RuntimeException`), you must invoke it in a `try-catch` block or declare to throw the exception in the calling method. For example, suppose that method `p1` invokes method `p2`, and `p2` may throw a checked exception (e.g., `IOException`); you have to write the code as shown in (a) or (b) below.

catch or declare checked exceptions

```
void p1() {
    try {
        p2();
    } catch (IOException ex) {
        ...
    }
}
```

(a) Catch exception

```
void p1() throws IOException {
    p2();
}
```

(b) Throw exception

**Note**

You can use the new JDK 7 multi-catch feature to simplify coding for the exceptions with the same handling code. The syntax is:

JDK 7 multi-catch

```
catch (Exception1 | Exception2 | ... | Exceptionn ex) {
    // Same code for handling these exceptions
}
```

Each exception type is separated from the next with a vertical bar (`|`). If one of the exceptions is caught, the handling code is executed.

12.4.4 Getting Information from Exceptions

An exception object contains valuable information about the exception. You may use the following instance methods in the `java.lang.Throwable` class to get information regarding the exception, as shown in Figure 12.4. The `printStackTrace()` method prints stack trace

methods in `Throwable`

<code>java.lang.Throwable</code>	
<code>+getMessage(): String</code>	Returns the message that describes this exception object.
<code>+toString(): String</code>	Returns the concatenation of three strings: (1) the full name of the exception class; (2) ":" (a colon and a space); (3) the <code>getMessage()</code> method.
<code>+printStackTrace(): void</code>	Prints the <code>Throwable</code> object and its call stack trace information on the console.
<code>+getStackTrace(): StackTraceElement[]</code>	Returns an array of stack trace elements representing the stack trace pertaining to this exception object.

FIGURE 12.4 `Throwable` is the root class for all exception objects.

information on the console. The `getStackTrace()` method provides programmatic access to the stack trace information printed by `printStackTrace()`.

Listing 12.6 gives an example that uses the methods in `Throwable` to display exception information. Line 4 invokes the `sum` method to return the sum of all the elements in the array. There is an error in line 23 that causes the `ArrayIndexOutOfBoundsException`, a subclass of `IndexOutOfBoundsException`. This exception is caught in the `try-catch` block. Lines 7, 8, and 9 display the stack trace, exception message, and exception object and message using the `printStackTrace()`, `getMessage()`, and `toString()` methods, as shown in Figure 12.5. Line 12 brings stack trace elements into an array. Each element represents a method call. You can obtain the method (line 14), class name (line 15), and exception line number (line 16) for each element.

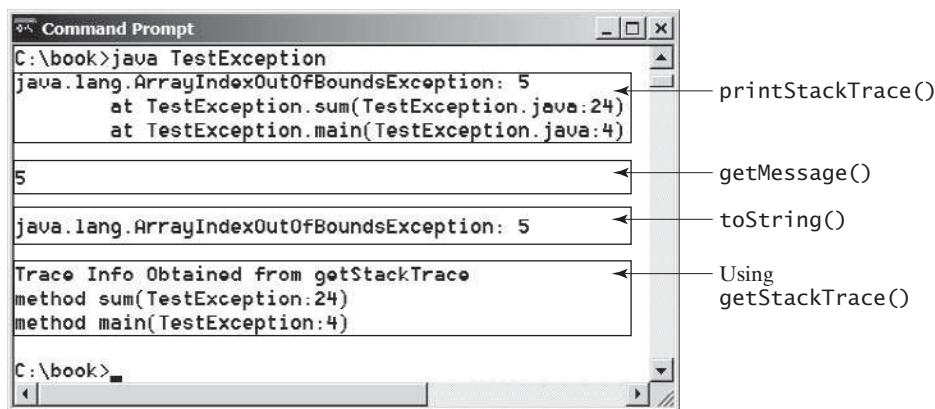


FIGURE 12.5 You can use the `printStackTrace()`, `getMessage()`, `toString()`, and `getStackTrace()` methods to obtain information from exception objects.

LISTING 12.6 TestException.java

```

invoke sum
1  public class TestException {
2      public static void main(String[] args) {
3          try {
4              System.out.println(sum(new int[] {1, 2, 3, 4, 5}));
5          }
6          catch (Exception ex) {
7              ex.printStackTrace();
8              System.out.println("\n" + ex.getMessage());
9              System.out.println("\n" + ex.toString());
10
11         System.out.println("\nTrace Info Obtained from getStackTrace");
12         StackTraceElement[] traceElements = ex.getStackTrace();
13         for (int i = 0; i < traceElements.length; i++) {
14             System.out.print("method " + traceElements[i].getMethodName());
15             System.out.print("(" + traceElements[i].getClassName() + ":");
16             System.out.println(traceElements[i].getLineNumber() + ")");
17         }
18     }
19 }
20
21 private static int sum(int[] list) {
22     int result = 0;
23     for (int i = 0; i <= list.length; i++)
cause an exception

```

```

24     result += list[i];
25 }
26 }
27 }
```

12.4.5 Example: Declaring, Throwing, and Catching Exceptions

This example demonstrates declaring, throwing, and catching exceptions by modifying the `setRadius` method in the `Circle` class in Listing 9.8, `CircleWithPrivateDataFields.java`. The new `setRadius` method throws an exception if the radius is negative.

Listing 12.7 defines a new circle class named `CircleWithException`, which is the same as `CircleWithPrivateDataFields` except that the `setRadius(double newRadius)` method throws an `IllegalArgumentException` if the argument `newRadius` is negative.

LISTING 12.7 CircleWithException.java

```

1  public class CircleWithException {
2      /** The radius of the circle */
3      private double radius;
4
5      /** The number of the objects created */
6      private static int numberOfObjects = 0;
7
8      /** Construct a circle with radius 1 */
9      public CircleWithException() {
10         this(1.0);
11     }
12
13     /** Construct a circle with a specified radius */
14     public CircleWithException(double newRadius) {
15         setRadius(newRadius);
16         number_of_objects++;
17     }
18
19     /** Return radius */
20     public double getRadius() {
21         return radius;
22     }
23
24     /** Set a new radius */
25     public void setRadius(double newRadius)
26         throws IllegalArgumentException { declare exception
27         if (newRadius >= 0)
28             radius = newRadius;
29         else
30             throw new IllegalArgumentException(
31                 "Radius cannot be negative"); throw exception
32     }
33
34     /** Return numberOfObjects */
35     public static int getNumberOfObjects() {
36         return number_of_objects;
37     }
38
39     /** Return the area of this circle */
40     public double findArea() {
41         return radius * radius * 3.14159;
42     }
43 }
```

A test program that uses the new `Circle` class is given in Listing 12.8.

LISTING 12.8 TestCircleWithException.java

```

try
1  public class TestCircleWithException {
2    public static void main(String[] args) {
3      try {
4        CircleWithException c1 = new CircleWithException(5);
5        CircleWithException c2 = new CircleWithException(-5);
6        CircleWithException c3 = new CircleWithException(0);
7      }
8      catch (IllegalArgumentException ex) {
9        System.out.println(ex);
10     }
11     System.out.println("Number of objects created: " +
12       CircleWithException.getNumberOfObjects());
13   }
14 }
15 }
```

 java.lang.IllegalArgumentException: Radius cannot be negative
Number of objects created: 1

The original `Circle` class remains intact except that the class name is changed to `CircleWithException`, a new constructor `CircleWithException(newRadius)` is added, and the `setRadius` method now declares an exception and throws it if the radius is negative.

The `setRadius` method declares to throw `IllegalArgumentException` in the method header (lines 25–32 in `CircleWithException.java`). The `CircleWithException` class would still compile if the `throws IllegalArgumentException` clause (line 26) were removed from the method declaration, since it is a subclass of `RuntimeException` and every method can throw `RuntimeException` (an unchecked exception) regardless of whether it is declared in the method header.

The test program creates three `CircleWithException` objects—`c1`, `c2`, and `c3`—to test how to handle exceptions. Invoking `new CircleWithException(-5)` (line 5 in Listing 12.8) causes the `setRadius` method to be invoked, which throws an `IllegalArgumentException`, because the radius is negative. In the `catch` block, the type of the object `ex` is `IllegalArgumentException`, which matches the exception object thrown by the `setRadius` method, so this exception is caught by the `catch` block.

The exception handler prints a short message, `ex.toString()` (line 9 in Listing 12.8), about the exception, using `System.out.println(ex)`.

Note that the execution continues in the event of the exception. If the handlers had not caught the exception, the program would have abruptly terminated.

The test program would still compile if the `try` statement were not used, because the method throws an instance of `IllegalArgumentException`, a subclass of `RuntimeException` (an unchecked exception). If a method throws an exception other than `RuntimeException` or `Error`, the method must be invoked within a `try-catch` block.



- 12.9** What is the purpose of declaring exceptions? How do you declare an exception, and where? Can you declare multiple exceptions in a method header?
- 12.10** What is a checked exception, and what is an unchecked exception?
- 12.11** How do you throw an exception? Can you throw multiple exceptions in one `throw` statement?
- 12.12** What is the keyword `throw` used for? What is the keyword `throws` used for?

12.13 Suppose that **statement2** causes an exception in the following **try-catch** block:

```
try {
    statement1;
    statement2;
    statement3;
}
catch (Exception1 ex1) {
}
catch (Exception2 ex2) {
}

statement4;
```

Answer the following questions:

- Will **statement3** be executed?
- If the exception is not caught, will **statement4** be executed?
- If the exception is caught in the **catch** block, will **statement4** be executed?

12.14 What is displayed when the following program is run?

```
public class Test {
    public static void main(String[] args) {
        try {
            int[] list = new int[10];
            System.out.println("list[10] is " + list[10]);
        }
        catch (ArithmaticException ex) {
            System.out.println("ArithmaticException");
        }
        catch (RuntimeException ex) {
            System.out.println("RuntimeException");
        }
        catch (Exception ex) {
            System.out.println("Exception");
        }
    }
}
```

12.15 What is displayed when the following program is run?

```
public class Test {
    public static void main(String[] args) {
        try {
            method();
            System.out.println("After the method call");
        }
        catch (ArithmaticException ex) {
            System.out.println("ArithmaticException");
        }
        catch (RuntimeException ex) {
            System.out.println("RuntimeException");
        }
        catch (Exception e) {
            System.out.println("Exception");
        }
    }

    static void method() throws Exception {
```

```

        System.out.println(1 / 0);
    }
}

```

12.16 What is displayed when the following program is run?

```

public class Test {
    public static void main(String[] args) {
        try {
            method();
            System.out.println("After the method call");
        }
        catch (RuntimeException ex) {
            System.out.println("RuntimeException in main");
        }
        catch (Exception ex) {
            System.out.println("Exception in main");
        }
    }

    static void method() throws Exception {
        try {
            String s = "abc";
            System.out.println(s.charAt(3));
        }
        catch (RuntimeException ex) {
            System.out.println("RuntimeException in method()");
        }
        catch (Exception ex) {
            System.out.println("Exception in method()");
        }
    }
}

```

12.17 What does the method `getMessage()` do?

12.18 What does the method `printStackTrace()` do?

12.19 Does the presence of a `try-catch` block impose overhead when no exception occurs?

12.20 Correct a compile error in the following code:

```

public void m(int value) {
    if (value < 40)
        throw new Exception("value is too small");
}

```

12.5 The `finally` Clause



The `finally` clause is always executed regardless whether an exception occurred or not.

Occasionally, you may want some code to be executed regardless of whether an exception occurs or is caught. Java has a `finally` clause that can be used to accomplish this objective. The syntax for the `finally` clause might look like this:

```

try {
    statements;
}
catch (TheException ex) {
    handling ex;
}

```

```
finally {
    finalStatements;
}
```

The code in the **finally** block is executed under all circumstances, regardless of whether an exception occurs in the **try** block or is caught. Consider three possible cases:

- If no exception arises in the **try** block, **finalStatements** is executed, and the next statement after the **try** statement is executed.
- If a statement causes an exception in the **try** block that is caught in a **catch** block, the rest of the statements in the **try** block are skipped, the **catch** block is executed, and the **finally** clause is executed. The next statement after the **try** statement is executed.
- If one of the statements causes an exception that is not caught in any **catch** block, the other statements in the **try** block are skipped, the **finally** clause is executed, and the exception is passed to the caller of this method.

The **finally** block executes even if there is a **return** statement prior to reaching the **finally** block.



Note

The **catch** block may be omitted when the **finally** clause is used.

omit catch block



Check Point

12.21 Suppose that **statement2** causes an exception in the following statement:

```
try {
    statement1;
    statement2;
    statement3;
}
catch (Exception1 ex1) {
}
finally {
    statement4;
}
statement5;
```

Answer the following questions:

- If no exception occurs, will **statement4** be executed, and will **statement5** be executed?
- If the exception is of type **Exception1**, will **statement4** be executed, and will **statement5** be executed?
- If the exception is not of type **Exception1**, will **statement4** be executed, and will **statement5** be executed?

12.6 When to Use Exceptions

A method should throw an exception if the error needs to be handled by its caller.



The **try** block contains the code that is executed in normal circumstances. The **catch** block contains the code that is executed in exceptional circumstances. Exception handling separates error-handling code from normal programming tasks, thus making programs easier to read and to modify. Be aware, however, that exception handling usually requires more time and resources, because it requires instantiating a new exception object, rolling back the call stack, and propagating the exception through the chain of methods invoked to search for the handler.

An exception occurs in a method. If you want the exception to be processed by its caller, you should create an exception object and throw it. If you can handle the exception in the method where it occurs, there is no need to throw or use exceptions.

In general, common exceptions that may occur in multiple classes in a project are candidates for exception classes. Simple errors that may occur in individual methods are best handled without throwing exceptions. This can be done by using **if** statements to check for errors.

When should you use a **try-catch** block in the code? Use it when you have to deal with unexpected error conditions. Do not use a **try-catch** block to deal with simple, expected situations. For example, the following code

```
try {
    System.out.println(refVar.toString());
}
catch (NullPointerException ex) {
    System.out.println("refVar is null");
}
```

is better replaced by

```
if (refVar != null)
    System.out.println(refVar.toString());
else
    System.out.println("refVar is null");
```

Which situations are exceptional and which are expected is sometimes difficult to decide. The point is not to abuse exception handling as a way to deal with a simple logic test.



12.22 The following method checks whether a string is a numeric string:

```
public static boolean isNumeric(String token) {
    try {
        Double.parseDouble(token);
        return true;
    }
    catch (java.lang.NumberFormatException ex) {
        return false;
    }
}
```

Is it correct? Rewrite it without using exceptions.



12.7 Rethrowing Exceptions

Java allows an exception handler to rethrow the exception if the handler cannot process the exception or simply wants to let its caller be notified of the exception.

The syntax for rethrowing an exception may look like this:

```
try {
    statements;
}
catch (TheException ex) {
    perform operations before exits;
    throw ex;
}
```

The statement **throw ex** rethrows the exception to the caller so that other handlers in the caller get a chance to process the exception **ex**.

12.23 Suppose that **statement2** causes an exception in the following statement:



```

try {
    statement1;
    statement2;
    statement3;
}
catch (Exception1 ex1) {
}
catch (Exception2 ex2) {
    throw ex2;
}
finally {
    statement4;
}
statement5;

```

Answer the following questions:

- If no exception occurs, will **statement4** be executed, and will **statement5** be executed?
- If the exception is of type **Exception1**, will **statement4** be executed, and will **statement5** be executed?
- If the exception is of type **Exception2**, will **statement4** be executed, and will **statement5** be executed?
- If the exception is not **Exception1** nor **Exception2**, will **statement4** be executed, and will **statement5** be executed?

12.8 Chained Exceptions

Throwing an exception along with another exception forms a chained exception.

In the preceding section, the **catch** block rethrows the original exception. Sometimes, you may need to throw a new exception (with additional information) along with the original exception. This is called *chained exceptions*. Listing 12.9 illustrates how to create and throw chained exceptions.



chained exception

LISTING 12.9 ChainedExceptionDemo.java

```

1 public class ChainedExceptionDemo {
2     public static void main(String[] args) {
3         try {
4             method1();
5         }
6         catch (Exception ex) {
7             ex.printStackTrace();
8         }
9     }
10
11    public static void method1() throws Exception {
12        try {
13            method2();
14        }
15        catch (Exception ex) {
16            throw new Exception("New info from method1", ex);
17        }
18    }

```

stack trace

chained exception

throw exception

```

19
20  public static void method2() throws Exception {
21      throw new Exception("New info from method2");
22  }
23 }
```



```

java.lang.Exception: New info from method1
    at ChainedExceptionDemo.method1(ChainedExceptionDemo.java:16)
    at ChainedExceptionDemo.main(ChainedExceptionDemo.java:4)
Caused by: java.lang.Exception: New info from method2
    at ChainedExceptionDemo.method2(ChainedExceptionDemo.java:21)
    at ChainedExceptionDemo.method1(ChainedExceptionDemo.java:13)
    ... 1 more
```

The `main` method invokes `method1` (line 4), `method1` invokes `method2` (line 13), and `method2` throws an exception (line 21). This exception is caught in the `catch` block in `method1` and is wrapped in a new exception in line 16. The new exception is thrown and caught in the catch block in the `main` method in line 6. The sample output shows the output from the `printStackTrace()` method in line 7. The new exception thrown from `method1` is displayed first, followed by the original exception thrown from `method2`.



12.24 What would be the output if line 16 is replaced by the following line?

```
throw new Exception("New info from method1");
```



12.9 Defining Custom Exception Classes

You can define a custom exception class by extending the `java.lang.Exception` class.



VideoNote

Create custom exception classes

extends `Exception`

Java provides quite a few exception classes. Use them whenever possible instead of defining your own exception classes. However, if you run into a problem that cannot be adequately described by the predefined exception classes, you can create your own exception class, derived from `Exception` or from a subclass of `Exception`, such as `IOException`.

In Listing 12.7, `CircleWithException.java`, the `setRadius` method throws an exception if the radius is negative. Suppose you wish to pass the radius to the handler. In that case, you can define a custom exception class, as shown in Listing 12.10.

LISTING 12.10 InvalidRadiusException.java

```

1  public class InvalidRadiusException extends Exception {
2      private double radius;
3
4      /** Construct an exception */
5      public InvalidRadiusException(double radius) {
6          super("Invalid radius " + radius);
7          this.radius = radius;
8      }
9
10     /** Return the radius */
11     public double getRadius() {
12         return radius;
13     }
14 }
```

This custom exception class extends `java.lang.Exception` (line 1). The `Exception` class extends `java.lang.Throwable`. All the methods (e.g., `getMessage()`, `toString()`, and

`printStackTrace()` in `Exception` are inherited from `Throwable`. The `Exception` class contains four constructors. Among them, the following two constructors are often used:

java.lang.Exception	
+Exception()	Constructs an exception with no message.
+Exception(message: String)	Constructs an exception with the specified message.

Line 6 invokes the superclass's constructor with a message. This message will be set in the exception object and can be obtained by invoking `getMessage()` on the object.



Tip

Most exception classes in the Java API contain two constructors: a no-arg constructor and a constructor with a message parameter.

To create an `InvalidRadiusException`, you have to pass a radius. Therefore, the `setRadius` method in Listing 12.7 can be modified as shown in Listing 12.11.

LISTING 12.11 TestCircleWithCustomException.java

```

1  public class TestCircleWithCustomException {
2      public static void main(String[] args) {
3          try {
4              new CircleWithCustomException(5);
5              new CircleWithCustomException(-5);
6              new CircleWithCustomException(0);
7          }
8          catch (InvalidRadiusException ex) {
9              System.out.println(ex);
10         }
11
12         System.out.println("Number of objects created: " +
13             CircleWithCustomException.getNumber0fObjects());
14     }
15 }
16
17 class CircleWithCustomException {
18     /** The radius of the circle */
19     private double radius;
20
21     /** The number of objects created */
22     private static int number0fObjects = 0;
23
24     /** Construct a circle with radius 1 */
25     public CircleWithCustomException() throws InvalidRadiusException { declare exception
26         this(1.0);
27     }
28
29     /** Construct a circle with a specified radius */
30     public CircleWithCustomException(double newRadius)
31         throws InvalidRadiusException {
32         setRadius(newRadius);
33         number0fObjects++;
34     }
35
36     /** Return radius */
37     public double getRadius() {

```

```

38     return radius;
39 }
40
41 /** Set a new radius */
42 public void setRadius(double newRadius)
43     throws InvalidRadiusException {
44     if (newRadius >= 0)
45         radius = newRadius;
46     else
47         throw new InvalidRadiusException(newRadius);
48 }
49
50 /** Return numberOfObjects */
51 public static int getNumberOfObjects() {
52     return numberOfObjects;
53 }
54
55 /** Return the area of this circle */
56 public double findArea() {
57     return radius * radius * 3.14159;
58 }
59 }
```

throw exception



```
InvalidRadiusException: Invalid radius -5.0
Number of objects created: 1
```

The `setRadius` method in `CircleWithCustomException` throws an `InvalidRadiusException` when radius is negative (line 47). Since `InvalidRadiusException` is a checked exception, the `setRadius` method must declare it in the method header (line 43). Since the constructors for `CircleWithCustomException` invoke the `setRadius` method to a set a new radius and it may throw an `InvalidRadiusException`, the constructors are declared to throw `InvalidRadiusException` (lines 25, 31).

Invoking `new CircleWithCustomException(-5)` (line 5) throws an `InvalidRadiusException`, which is caught by the handler. The handler displays the radius in the exception object `ex`.

checked custom exception

**Tip**

Can you define a custom exception class by extending `RuntimeException`? Yes, but it is not a good way to go, because it makes your custom exception unchecked. It is better to make a custom exception checked, so that the compiler can force these exceptions to be caught in your program.



12.25 How do you define a custom exception class?

12.26 Suppose the `setRadius` method throws the `InvalidRadiusException` defined in Listing 12.10. What is displayed when the following program is run?

```
public class Test {
    public static void main(String[] args) {
        try {
            method();
            System.out.println("After the method call");
        }
        catch (RuntimeException ex) {
            System.out.println("RuntimeException in main");
        }
    }
}
```

```

catch (Exception ex) {
    System.out.println("Exception in main");
}
}

static void method() throws Exception {
    try {
        Circle c1 = new Circle(1);
        c1.setRadius(-1);
        System.out.println(c1.getRadius());
    }
    catch (RuntimeException ex) {
        System.out.println("RuntimeException in method()");
    }
    catch (Exception ex) {
        System.out.println("Exception in method()");
        throw ex;
    }
}
}

```

12.10 The **File** Class

The **File** class contains the methods for obtaining the properties of a file/directory and for renaming and deleting a file/directory.



Having learned exception handling, you are ready to step into file processing. Data stored in the program are temporary; they are lost when the program terminates. To permanently store the data created in a program, you need to save them in a file on a disk or other permanent storage device. The file can then be transported and read later by other programs. Since data are stored in files, this section introduces how to use the **File** class to obtain file/directory properties, to delete and rename files/directories, and to create directories. The next section introduces how to read/write data from/to text files.

Every file is placed in a directory in the file system. An *absolute file name* (or *full name*) contains a file name with its complete path and drive letter. For example, **c:\book\Welcome.java** is the absolute file name for the file **Welcome.java** on the Windows operating system. Here **c:\book** is referred to as the *directory path* for the file. Absolute file names are machine dependent. On the UNIX platform, the absolute file name may be **/home/liang/book/Welcome.java**, where **/home/liang/book** is the directory path for the file **Welcome.java**.

A *relative file name* is in relation to the current working directory. The complete directory path for a relative file name is omitted. For example, **Welcome.java** is a relative file name. If the current working directory is **c:\book**, the absolute file name would be **c:\book\Welcome.java**.

The **File** class is intended to provide an abstraction that deals with most of the machine-dependent complexities of files and path names in a machine-independent fashion. The **File** class contains the methods for obtaining file and directory properties and for renaming and deleting files and directories, as shown in Figure 12.6. However, the *File* class does not contain the methods for reading and writing file contents.

The file name is a string. The **File** class is a wrapper class for the file name and its directory path. For example, **new File("c:\\book")** creates a **File** object for the directory **c:\book**, and **new File("c:\\book\\test.dat")** creates a **File** object for the file **c:\book\test.dat**, both on Windows. You can use the **File** class's **isDirectory()** method to check whether the object represents a directory, and the **isFile()** method to check whether the object represents a file.

why file?

absolute file name

directory path

relative file name

java.io.File	
+File(pathname: String)	Creates a <code>File</code> object for the specified path name. The path name may be a directory or a file.
+File(parent: String, child: String)	Creates a <code>File</code> object for the child under the directory parent. The child may be a file name or a subdirectory.
+File(parent: File, child: String)	Creates a <code>File</code> object for the child under the directory parent. The parent is a <code>File</code> object. In the preceding constructor, the parent is a string.
+exists(): boolean	Returns true if the file or the directory represented by the <code>File</code> object exists.
+canRead(): boolean	Returns true if the file represented by the <code>File</code> object exists and can be read.
+canWrite(): boolean	Returns true if the file represented by the <code>File</code> object exists and can be written.
+isDirectory(): boolean	Returns true if the <code>File</code> object represents a directory.
+isFile(): boolean	Returns true if the <code>File</code> object represents a file.
+isAbsolute(): boolean	Returns true if the <code>File</code> object is created using an absolute path name.
+isHidden(): boolean	Returns true if the file represented in the <code>File</code> object is hidden. The exact definition of <i>hidden</i> is system-dependent. On Windows, you can mark a file hidden in the File Properties dialog box. On Unix systems, a file is hidden if its name begins with a period(.) character.
+getAbsolutePath(): String	Returns the complete absolute file or directory name represented by the <code>File</code> object.
+getCanonicalPath(): String	Returns the same as <code>getAbsolutePath()</code> except that it removes redundant names, such as "." and "..", from the path name, resolves symbolic links (on Unix), and converts drive letters to standard uppercase (on Windows).
+getName(): String	Returns the last name of the complete directory and file name represented by the <code>File</code> object. For example, new <code>File("c:\\book\\test.dat")</code> . <code>getName()</code> returns <code>test.dat</code> .
+getPath(): String	Returns the complete directory and file name represented by the <code>File</code> object. For example, new <code>File("c:\\book\\test.dat")</code> . <code>getPath()</code> returns <code>c:\\book\\test.dat</code> .
+getParent(): String	Returns the complete parent directory of the current directory or the file represented by the <code>File</code> object. For example, new <code>File("c:\\book\\test.dat")</code> . <code>getParent()</code> returns <code>c:\\book</code> .
+lastModified(): long	Returns the time that the file was last modified.
+length(): long	Returns the size of the file, or 0 if it does not exist or if it is a directory.
+listFile(): File[]	Returns the files under the directory for a directory <code>File</code> object.
+delete(): boolean	Deletes the file or directory represented by this <code>File</code> object. The method returns true if the deletion succeeds.
+renameTo(dest: File): boolean	Renames the file or directory represented by this <code>File</code> object to the specified name represented in dest. The method returns true if the operation succeeds.
+mkdir(): boolean	Creates a directory represented in this <code>File</code> object. Returns true if the directory is created successfully.
+mkdirs(): boolean	Same as <code>mkdir()</code> except that it creates directory along with its parent directories if the parent directories do not exist.

FIGURE 12.6 The `File` class can be used to obtain file and directory properties, to delete and rename files and directories, and to create directories.

\ in file names



Caution

The directory separator for Windows is a backslash (\). The backslash is a special character in Java and should be written as \\ in a string literal (see Table 4.5).

relative file name



Note

Constructing a `File` instance does not create a file on the machine. You can create a `File` instance for any file name regardless whether it exists or not. You can invoke the `exists()` method on a `File` instance to check whether the file exists.

Java directory separator (/)

Do not use absolute file names in your program. If you use a file name such as `c:\\book\\Welcome.java`, it will work on Windows but not on other platforms. You should use a file name relative to the current directory. For example, you may create a `File` object using `new File("Welcome.java")` for the file `Welcome.java` in the current directory. You may create a `File` object using `new File("image/us.gif")` for the file `us.gif` under the `image` directory in the current directory. The forward slash (/) is the Java directory separator, which

is the same as on UNIX. The statement `new File("image/us.gif")` works on Windows, UNIX, and any other platform.

Listing 12.12 demonstrates how to create a `File` object and use the methods in the `File` class to obtain its properties. The program creates a `File` object for the file `us.gif`. This file is stored under the `image` directory in the current directory.

LISTING 12.12 TestFileClass.java

```

1 public class TestFileClass {
2     public static void main(String[] args) {
3         java.io.File file = new java.io.File("image/us.gif");
4         System.out.println("Does it exist? " + file.exists());
5         System.out.println("The file has " + file.length() + " bytes");
6         System.out.println("Can it be read? " + file.canRead());
7         System.out.println("Can it be written? " + file.canWrite());
8         System.out.println("Is it a directory? " + file.isDirectory());
9         System.out.println("Is it a file? " + file.isFile());
10        System.out.println("Is it absolute? " + file.isAbsolute());
11        System.out.println("Is it hidden? " + file.isHidden());
12        System.out.println("Absolute path is " +
13            file.getAbsolutePath());
14        System.out.println("Last modified on " +
15            new java.util.Date(file.lastModified()));
16    }
17 }
```

create a File
exists()
length()
canRead()
canWrite()
isDirectory()
isFile()
isAbsolute()
isHidden()
getAbsolutePath()
lastModified()

The `lastModified()` method returns the date and time when the file was last modified, measured in milliseconds since the beginning of UNIX time (00:00:00 GMT, January 1, 1970). The `Date` class is used to display it in a readable format in lines 14–15.

Figure 12.7a shows a sample run of the program on Windows, and Figure 12.7b, a sample run on UNIX. As shown in the figures, the path-naming conventions on Windows are different from those on UNIX.

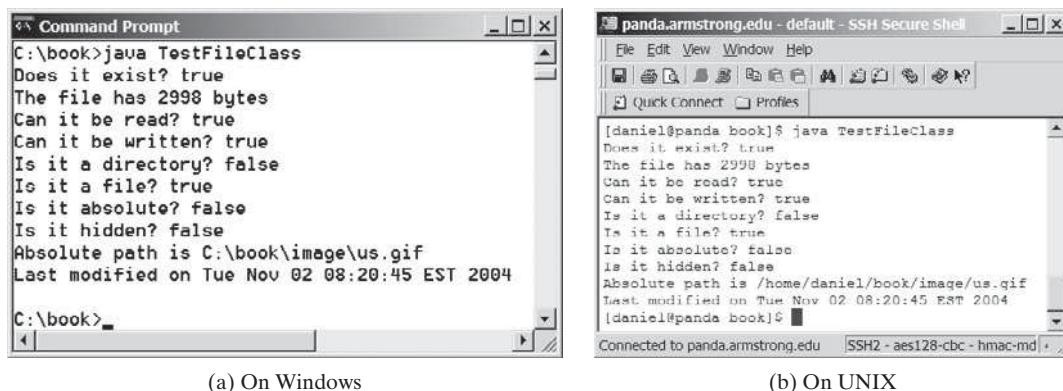


FIGURE 12.7 The program creates a `File` object and displays file properties.

12.27 What is wrong about creating a `File` object using the following statement?

```
new File("c:\book\test.dat");
```



12.28 How do you check whether a file already exists? How do you delete a file? How do you rename a file? Can you find the file size (the number of bytes) using the `File` class? How do you create a directory?

12.29 Can you use the `File` class for I/O? Does creating a `File` object create a file on the disk?

12.11 File Input and Output



Use the **Scanner** class for reading text data from a file and the **PrintWriter** class for writing text data to a file.



VideoNote

Write and read data

A **File** object encapsulates the properties of a file or a path, but it does not contain the methods for creating a file or for writing/reading data to/from a file (referred to as *data input* and *output*, or *I/O* for short). In order to perform I/O, you need to create objects using appropriate Java I/O classes. The objects contain the methods for reading/writing data from/to a file. There are two types of files: text and binary. Text files are essentially characters on disk. This section introduces how to read/write strings and numeric values from/to a text file using the **Scanner** and **PrintWriter** classes. Binary files will be introduced in Chapter 17.

12.11.1 Writing Data Using PrintWriter

The **java.io.PrintWriter** class can be used to create a file and write data to a text file. First, you have to create a **PrintWriter** object for a text file as follows:

```
PrintWriter output = new PrintWriter(filename);
```

Then, you can invoke the **print**, **println**, and **printf** methods on the **PrintWriter** object to write data to a file. Figure 12.8 summarizes frequently used methods in **PrintWriter**.

java.io.PrintWriter	
+ PrintWriter(file: File)	Creates a PrintWriter object for the specified file object.
+ PrintWriter(filename: String)	Creates a PrintWriter object for the specified file-name string.
+ print(s: String): void	Writes a string to the file.
+ print(c: char): void	Writes a character to the file.
+ print(cArray: char[]): void	Writes an array of characters to the file.
+ print(i: int): void	Writes an int value to the file.
+ print(l: long): void	Writes a long value to the file.
+ print(f: float): void	Writes a float value to the file.
+ print(d: double): void	Writes a double value to the file.
+ print(b: boolean): void	Writes a boolean value to the file.
Also contains the overloaded println methods.	A println method acts like a print method; additionally, it prints a line separator. The line-separator string is defined by the system. It is \r\n on Windows and \n on Unix.
Also contains the overloaded printf methods.	The printf method was introduced in §4.6, “Formatting Console Output.”

FIGURE 12.8 The **PrintWriter** class contains the methods for writing data to a text file.

Listing 12.13 gives an example that creates an instance of **PrintWriter** and writes two lines to the file **scores.txt**. Each line consists of a first name (a string), a middle-name initial (a character), a last name (a string), and a score (an integer).

LISTING 12.13 WriteData.java

throws an exception
create File object
file exist?

```
1 public class WriteData {
2     public static void main(String[] args) throws IOException {
3         java.io.File file = new java.io.File("scores.txt");
4         if (file.exists()) {
5             System.out.println("File already exists");
6             System.exit(1);
7         }
8     }
```

```

9 // Create a file
10 java.io.PrintWriter output = new java.io.PrintWriter(file);           create PrintWriter
11
12 // Write formatted output to the file
13 output.print("John T Smith ");
14 output.println(90);
15 output.print("Eric K Jones ");
16 output.println(85);          John T Smith 90 scores.txt
17
18 // Close the file
19 output.close();             Eric K Jones 85
20 }
21 }
```

Lines 4–7 check whether the file scores.txt exists. If so, exit the program (line 6).

Invoking the constructor of `PrintWriter` will create a new file if the file does not exist. If the file already exists, the current content in the file will be discarded without verifying with the user.

Invoking the constructor of `PrintWriter` may throw an I/O exception. Java forces you to write the code to deal with this type of exception. For simplicity, we declare `throws IOException` in the main method header (line 2).

You have used the `System.out.print`, `System.out.println`, and `System.out.printf` methods to write text to the console. `System.out` is a standard Java object for the console output. You can create `PrintWriter` objects for writing text to any file using `print`, `println`, and `printf` (lines 13–16).

The `close()` method must be used to close the file (line 19). If this method is not invoked, the data may not be saved properly in the file.

create a file

throws IOException

print method

close file

12.11.2 Closing Resources Automatically Using try-with-resources

Programmers often forgot to close the file. JDK 7 provides the followings new try-with-resources syntax that automatically closes the files.

```

try (declare and create resources) {
    Use the resource to process the file;
}
```

Using the try-with-resources syntax, we rewrite the code in Listing 12.13 in Listing 12.14.

LISTING 12.14 WriteDataWithAutoClose.java

```

1 public class WriteDataWithAutoClose {
2     public static void main(String[] args) throws Exception {
3         java.io.File file = new java.io.File("scores.txt");
4         if (file.exists()) {
5             System.out.println("File already exists");
6             System.exit(0);
7         }
8
9         try (           declare/create resource
10            // Create a file
11            java.io.PrintWriter output = new java.io.PrintWriter(file);   use the resource
12        ) {
13            // Write formatted output to the file
14            output.print("John T Smith ");
15            output.println(90);
16            output.print("Eric K Jones ");
17            output.println(85);
18        }
19    }
20 }
```

A resource is declared and created followed by the keyword `try`. Note that the resources are enclosed in the parentheses (lines 9–12). The resources must be a subtype of `AutoCloseable` such as a `PrintWriter` that has the `close()` method. A resource must be declared and created in the same statement and multiple resources can be declared and created inside the parentheses. The statements in the block (lines 12–18) immediately following the resource declaration use the resource. After the block is finished, the resource's `close()` method is automatically invoked to close the resource. Using try-with-resources can not only avoid errors but also make the code simpler.

12.11.3 Reading Data Using Scanner

The `java.util.Scanner` class was used to read strings and primitive values from the console in Section 2.3, Reading Input from the Console. A `Scanner` breaks its input into tokens delimited by whitespace characters. To read from the keyboard, you create a `Scanner` for `System.in`, as follows:

```
Scanner input = new Scanner(System.in);
```

To read from a file, create a `Scanner` for a file, as follows:

```
Scanner input = new Scanner(new File(filename));
```

Figure 12.9 summarizes frequently used methods in `Scanner`.

java.util.Scanner	
+Scanner(source: File)	Creates a <code>Scanner</code> that scans tokens from the specified file.
+Scanner(source: String)	Creates a <code>Scanner</code> that scans tokens from the specified string.
+close()	Closes this scanner.
+hasNext(): boolean	Returns true if this scanner has more data to be read.
+next(): String	Returns next token as a string from this scanner.
+nextLine(): String	Returns a line ending with the line separator from this scanner.
+nextByte(): byte	Returns next token as a <code>byte</code> from this scanner.
+nextShort(): short	Returns next token as a <code>short</code> from this scanner.
+nextInt(): int	Returns next token as an <code>int</code> from this scanner.
+nextLong(): long	Returns next token as a <code>long</code> from this scanner.
+nextFloat(): float	Returns next token as a <code>float</code> from this scanner.
+nextDouble(): double	Returns next token as a <code>double</code> from this scanner.
+useDelimiter(pattern: String): Scanner	Sets this scanner's delimiting pattern and returns this scanner.

FIGURE 12.9 The `Scanner` class contains the methods for scanning data.

Listing 12.15 gives an example that creates an instance of `Scanner` and reads data from the file `scores.txt`.

LISTING 12.15 ReadData.java

```
1 import java.util.Scanner;
2
3 public class ReadData {
4     public static void main(String[] args) throws Exception {
5         // Create a File instance
6         java.io.File file = new java.io.File("scores.txt");
7
8         // Create a Scanner for the file
9         Scanner input = new Scanner(file);
```

create a File

create a Scanner

```

10 // Read data from a file
11 while (input.hasNext()) {
12     String firstName = input.next(); ← scores.txt
13     String mi = input.next(); ← John T Smith 90
14     String lastName = input.next(); ← Eric K Jones 85
15     int score = input.nextInt(); ←
16     System.out.println(
17         firstName + " " + mi + " " + lastName + " " + score);
18 }
19
20 // Close the file
21 input.close(); ← has next?
22 } ← read items
23 } ← close file
24 }
```

Note that `new Scanner(String)` creates a `Scanner` for a given string. To create a `Scanner` to read data from a file, you have to use the `java.io.File` class to create an instance of the `File` using the constructor `new File(filename)` (line 6), and use `new Scanner(File)` to create a `Scanner` for the file (line 9).

Invoking the constructor `new Scanner(File)` may throw an I/O exception, so the `main` method declares `throws Exception` in line 4.

Each iteration in the `while` loop reads the first name, middle initial, last name, and score from the text file (lines 12–19). The file is closed in line 22.

It is not necessary to close the input file (line 22), but it is a good practice to do so to release the resources occupied by the file. You can rewrite this program using the try-with-resources syntax. See www.cs.armstrong.edu/liang/intro10e/html/ReadDataWithAutoClose.html.

12.11.4 How Does Scanner Work?

The `nextByte()`, `nextShort()`, `nextInt()`, `nextLong()`, `nextFloat()`, `nextDouble()`, and `next()` methods are known as *token-reading methods*, because they read tokens separated by delimiters. By default, the delimiters are whitespace characters. You can use the `useDelimiter(String regex)` method to set a new pattern for delimiters.

How does an input method work? A token-reading method first skips any delimiters (whitespace characters by default), then reads a token ending at a delimiter. The token is then automatically converted into a value of the `byte`, `short`, `int`, `long`, `float`, or `double` type for `nextByte()`, `nextShort()`, `nextInt()`, `nextLong()`, `nextFloat()`, and `nextDouble()`, respectively. For the `next()` method, no conversion is performed. If the token does not match the expected type, a runtime exception `java.util.InputMismatchException` will be thrown.

Both methods `next()` and `nextLine()` read a string. The `next()` method reads a string delimited by delimiters, and `nextLine()` reads a line ending with a line separator.



Note

The line-separator string is defined by the system. It is `\r\n` on Windows and `\n` on UNIX. To get the line separator on a particular platform, use

```
String lineSeparator = System.getProperty("line.separator");
```

If you enter input from a keyboard, a line ends with the *Enter* key, which corresponds to the `\n` character.

The token-reading method does not read the delimiter after the token. If the `nextLine()` method is invoked after a token-reading method, this method reads characters that start from this delimiter and end with the line separator. The line separator is read, but it is not part of the string returned by `nextLine()`.

has next?
read items

close file

File class

throws Exception

close file

token-reading method
change delimiter

`InputMismatchException`

`next()` vs. `nextLine()`

line separator

behavior of `nextLine()`

input from file

Suppose a text file named **test.txt** contains a line**34 567**

After the following code is executed,

```
Scanner input = new Scanner(new File("test.txt"));
int intValue = input.nextInt();
String line = input.nextLine();
```

intValue contains **34** and **line** contains the characters ' ', **5**, **6**, and **7**.

input from keyboard

What happens if the input is *entered from the keyboard*? Suppose you enter **34**, press the *Enter* key, then enter **567** and press the *Enter* key for the following code:

```
Scanner input = new Scanner(System.in);
int intValue = input.nextInt();
String line = input.nextLine();
```

You will get **34** in **intValue** and an empty string in **line**. Why? Here is the reason. The token-reading method **nextInt()** reads in **34** and stops at the delimiter, which in this case is a line separator (the *Enter* key). The **nextLine()** method ends after reading the line separator and returns the string read before the line separator. Since there are no characters before the line separator, **line** is empty.

scan a string

You can read data from a file or from the keyboard using the **Scanner** class. You can also scan data from a string using the **Scanner** class. For example, the following code

```
Scanner input = new Scanner("13 14");
int sum = input.nextInt() + input.nextInt();
System.out.println("Sum is " + sum);
```

displays

The sum is 27

12.11.5 Case Study: Replacing Text

Suppose you are to write a program named **ReplaceText** that replaces all occurrences of a string in a text file with a new string. The file name and strings are passed as command-line arguments as follows:

```
java ReplaceText sourceFile targetFile oldString newString
```

For example, invoking

```
java ReplaceText FormatString.java t.txt StringBuilder StringBuffer
```

replaces all the occurrences of **StringBuilder** by **StringBuffer** in the file **FormatString.java** and saves the new file in **t.txt**.Listing 12.16 gives the program. The program checks the number of arguments passed to the **main** method (lines 7–11), checks whether the source and target files exist (lines 14–25), creates a **Scanner** for the source file (line 29), creates a **PrintWriter** for the target file (line 30), and repeatedly reads a line from the source file (line 33), replaces the text (line 34), and writes a new line to the target file (line 35).

LISTING 12.16 ReplaceText.java

```
1 import java.io.*;
2 import java.util.*;
```

```

4  public class ReplaceText {
5      public static void main(String[] args) throws Exception {
6          // Check command line parameter usage
7          if (args.length != 4) {                                     check command usage
8              System.out.println(
9                  "Usage: java ReplaceText sourceFile targetFile oldStr newStr");
10             System.exit(1);
11         }
12
13         // Check if source file exists
14         File sourceFile = new File(args[0]);
15         if (!sourceFile.exists()) {                                source file exists?
16             System.out.println("Source file " + args[0] + " does not exist");
17             System.exit(2);
18         }
19
20         // Check if target file exists
21         File targetFile = new File(args[1]);
22         if (targetFile.exists()) {                                target file exists?
23             System.out.println("Target file " + args[1] + " already exists");
24             System.exit(3);
25         }
26
27         try {                                                 try-with-resources
28             // Create input and output files
29             Scanner input = new Scanner(sourceFile);
30             PrintWriter output = new PrintWriter(targetFile);    create a Scanner
31         } {                                                 create a PrintWriter
32             while (input.hasNext()) {                            has next?
33                 String s1 = input.nextLine();                   read a line
34                 String s2 = s1.replaceAll(args[2], args[3]);    output.println(s2);
35                 output.println(s2);
36             }
37         }
38     }
39 }
```

In a normal situation, the program is terminated after a file is copied. The program is terminated abnormally if the command-line arguments are not used properly (lines 7–11), if the source file does not exist (lines 14–18), or if the target file already exists (lines 22–25). The exit status code 1, 2, and 3 are used to indicate these abnormal terminations (lines 10, 17, 24).

- 12.30** How do you create a `PrintWriter` to write data to a file? What is the reason to declare `throws Exception` in the main method in Listing 12.13, WriteData.java? What would happen if the `close()` method were not invoked in Listing 12.13?



- 12.31** Show the contents of the file `temp.txt` after the following program is executed.

```

public class Test {
    public static void main(String[] args) throws Exception {
        java.io.PrintWriter output = new
            java.io.PrintWriter("temp.txt");
        output.printf("amount is %f %e\r\n", 32.32, 32.32);
        output.printf("amount is %5.4f %5.4e\r\n", 32.32, 32.32);
        output.printf("%6b\r\n", (1 > 2));
        output.printf("%6s\r\n", "Java");
        output.close();
    }
}
```

- 12.32** Rewrite the code in the preceding question using a try-with-resources syntax.
- 12.33** How do you create a **Scanner** to read data from a file? What is the reason to define **throws Exception** in the main method in Listing 12.15, `ReadData.java`? What would happen if the **close()** method were not invoked in Listing 12.15?
- 12.34** What will happen if you attempt to create a **Scanner** for a nonexistent file? What will happen if you attempt to create a **PrintWriter** for an existing file?
- 12.35** Is the line separator the same on all platforms? What is the line separator on Windows?
- 12.36** Suppose you enter **45 57.8 789**, then press the *Enter* key. Show the contents of the variables after the following code is executed.

```
Scanner input = new Scanner(System.in);
int intValue = input.nextInt();
double doubleValue = input.nextDouble();
String line = input.nextLine();
```

- 12.37** Suppose you enter **45**, press the *Enter* key, **57.8**, press the *Enter* key, **789**, and press the *Enter* key. Show the contents of the variables after the following code is executed.

```
Scanner input = new Scanner(System.in);
int intValue = input.nextInt();
double doubleValue = input.nextDouble();
String line = input.nextLine();
```

12.12 Reading Data from the Web



Just like you can read data from a file on your computer, you can read data from a file on the Web.

In addition to reading data from a local file on a computer or file server, you can also access data from a file that is on the Web if you know the file's URL (Uniform Resource Locator—the unique address for a file on the Web). For example, www.google.com/index.html is the URL for the file **index.html** located on the Google Web server. When you enter the URL in a Web browser, the Web server sends the data to your browser, which renders the data graphically. Figure 12.10 illustrates how this process works.

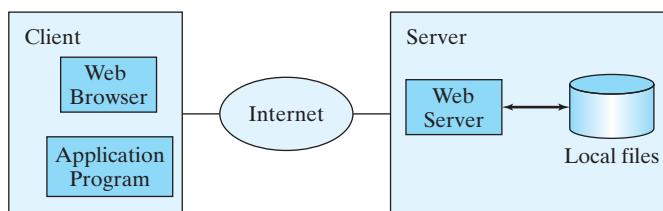


FIGURE 12.10 The client retrieves files from a Web server.

For an application program to read data from a URL, you first need to create a **URL** object using the **java.net.URL** class with this constructor:

```
public URL(String spec) throws MalformedURLException
```

For example, the following statement creates a URL object for <http://www.google.com/index.html>.

```
1 try {
2     URL url = new URL("http://www.google.com/index.html");
3 }
```

```

4 catch (MalformedURLException ex) {
5     ex.printStackTrace();
6 }

```

A **MalformedURLException** is thrown if the URL string has a syntax error. For example, the URL string “`http://www.google.com/index.html`” would cause a **MalformedURLException** runtime error because two slashes (//) are required after the colon (:). Note that the `http://` prefix is required for the **URL** class to recognize a valid URL. It would be wrong if you replace line 2 with the following code:

```
URL url = new URL("www.google.com/index.html");
```

After a **URL** object is created, you can use the **openStream()** method defined in the **URL** class to open an input stream and use this stream to create a **Scanner** object as follows:

```
Scanner input = new Scanner(url.openStream());
```

Now you can read the data from the input stream just like from a local file. The example in Listing 12.17 prompts the user to enter a URL and displays the size of the file.

LISTING 12.17 ReadFileFromURL.java

```

1 import java.util.Scanner;
2
3 public class ReadFileFromURL {
4     public static void main(String[] args) {
5         System.out.print("Enter a URL: ");
6         String urlString = new Scanner(System.in).next();           enter a URL
7
8         try {
9             java.net.URL url = new java.net.URL(urlString);        create a URL object
10            int count = 0;
11            Scanner input = new Scanner(url.openStream());          create a Scanner object
12            while (input.hasNext()) {                                more to read?
13                String line = input.nextLine();                      read a line
14                count += line.length();
15            }
16
17            System.out.println("The file size is " + count + " characters");
18        }
19        catch (java.net.MalformedURLException ex) {               MalformedURLException
20            System.out.println("Invalid URL");
21        }
22        catch (java.io.IOException ex) {                          IOException
23            System.out.println("I/O Errors: no such file");
24        }
25    }
26 }

```

Enter a URL: `http://cs.armstrong.edu/liang/data/Lincoln.txt` 
 The file size is 1469 characters



Enter a URL: `http://www.yahoo.com` 
 The file size is 190006 characters



MalformedURLException

The program prompts the user to enter a URL string (line 6) and creates a `URL` object (line 9). The constructor will throw a `java.net.MalformedURLException` (line 19) if the URL isn't formed correctly.

The program creates a `Scanner` object from the input stream for the URL (line 11). If the URL is formed correctly but does not exist, an `IOException` will be thrown (line 22). For example, `http://google.com/index1.html` uses the appropriate form, but the URL itself does not exist. An `IOException` would be thrown if this URL was used for this program.



12.38 How do you create a `Scanner` object for reading text from a URL?

**Web crawler**

12.13 Case Study: Web Crawler

This case study develops a program that travels the Web by following hyperlinks.

The World Wide Web, abbreviated as WWW, W3, or Web, is a system of interlinked hypertext documents on the Internet. With a Web browser, you can view a document and follow the hyperlinks to view other documents. In this case study, we will develop a program that automatically traverses the documents on the Web by following the hyperlinks. This type of program is commonly known as a *Web crawler*. For simplicity, our program follows for the hyperlink that starts with `http://`. Figure 12.11 shows an example of traversing the Web. We start from a Web page that contains three URLs named `URL1`, `URL2`, and `URL3`. Following `URL1` leads to the page that contains three URLs named `URL11`, `URL12`, and `URL13`. Following `URL2` leads to the page that contains two URLs named `URL21` and `URL22`. Following `URL3` leads to the page that contains four URLs named `URL31`, `URL32`, `URL33`, and `URL34`. Continue to traverse the Web following the new hyperlinks. As you see, this process may continue forever, but we will exit the program once we have traversed 100 pages.



FIGURE 12.11 The client retrieves files from a Web server.

The program follows the URLs to traverse the Web. To ensure that each URL is traversed only once, the program maintains two lists of URLs. One list stores the URLs pending for traversing and the other stores the URLs that have already been traversed. The algorithm for this program can be described as follows:

```

Add the starting URL to a list named listOfPendingURLs;
while listOfPendingURLs is not empty and size of listOfTraversedURLs
<= 100 {
  
```

```
Remove a URL from listOfPendingURLs;  
if this URL is not in listOfTraversedURLs {  
    Add it to listOfTraversedURLs;  
    Display this URL;  
    Read the page from this URL and for each URL contained in the page {  
        Add it to listOfPendingURLs if it is not in listOfTraversedURLs;  
    }  
}  
}
```

Listing 12.18 gives the program that implements this algorithm.

LISTING 12.18 WebCrawler.java

```
1 import java.util.Scanner;
2 import java.util.ArrayList;
3
4 public class WebCrawler {
5     public static void main(String[] args) {
6         java.util.Scanner input = new java.util.Scanner(System.in);
7         System.out.print("Enter a URL: ");
8         String url = input.nextLine();
9         crawler(url); // Traverse the Web from the a starting url
10    }
11
12    public static void crawler(String startingURL) {
13        ArrayList<String> listOfPendingURLs = new ArrayList<>();
14        ArrayList<String> listOfTraversedURLs = new ArrayList<>();
15
16        listOfPendingURLs.add(startingURL);
17        while (!listOfPendingURLs.isEmpty() &&
18            listOfTraversedURLs.size() <= 100) {
19            String urlString = listOfPendingURLs.remove(0);
20            if (!listOfTraversedURLs.contains(urlString)) {
21                listOfTraversedURLs.add(urlString);
22                System.out.println("Craw " + urlString);
23
24                for (String s: getSubURLs(urlString)) {
25                    if (!listOfTraversedURLs.contains(s))
26                        listOfPendingURLs.add(s);
27                }
28            }
29        }
30    }
31
32    public static ArrayList<String> getSubURLs(String urlString) {
33        ArrayList<String> list = new ArrayList<>();
34
35        try {
36            java.net.URL url = new java.net.URL(urlString);
37            Scanner input = new Scanner(url.openStream());
38            int current = 0;
39            while (input.hasNext()) {
40                String line = input.nextLine();
41                current = line.indexOf("http:", current);
42                while (current > 0) {
43                    int endIndex = line.indexOf("\\"", current);
44                    if (endIndex > 0) { // Ensure that a correct URL is found
45                        list.add(line.substring(current, endIndex));
46                        current = line.indexOf("http:", endIndex);
47                    }
48                }
49            }
50        }
51    }
52}
```

```

48         else
49             current = -1;
50         }
51     }
52 }
53 catch (Exception ex) {
54     System.out.println("Error: " + ex.getMessage());
55 }
56
57 return list;
58 }
59 }
```

return URLs



```

Enter a URL: http://cs.armstrong.edu/liang ↵ Enter
Enter a URL: http://www.cs.armstrong.edu/liang
Craw http://www.cs.armstrong.edu/liang
Craw http://www.cs.armstrong.edu
Craw http://www.armstrong.edu
Craw http://www.pearsonhighered.com/liang
...

```

The program prompts the user to enter a starting URL (lines 7–8) and invokes the `crawler(url)` method to traverse the web (line 9).

The `crawler(url)` method adds the starting url to `listOfPendingURLs` (line 16) and repeatedly processes each URL in `listOfPendingURLs` in a while loop (lines 17–29). It removes the first URL in the list (line 19) and processes the URL if it has not been processed (lines 20–28). To process each URL, the program first adds the URL to `listOfTraversedURLs` (line 21). This list stores all the URLs that have been processed. The `getSubURLs(url)` method returns a list of URLs in the Web page for the specified URL (line 24). The program uses a foreach loop to add each URL in the page into `listOfPendingURLs` if it is not in `listOfTraversedURLs` (lines 24–26).

The `getSubURLs(url)` method reads each line from the Web page (line 40) and searches for the URLs in the line (line 41). Note that a correct URL cannot contain line break characters. So it is sufficient to limit the search for a URL in one line of the text in a Web page. For simplicity, we assume that a URL ends with a quotation mark " (line 43). The method obtains a URL and adds it to a list (line 45). A line may contain multiple URLs. The method continues to search for the next URL (line 46). If no URL is found in the line, `current` is set to -1 (line 49). The URLs contained in the page are returned in the form of a list (line 57).

The program terminates when the number of traversed URLs reaches to 100 (line 18).

This is a simple program to traverse the Web. Later you will learn the techniques to make the program more efficient and robust.



12.39 Before a URL is added to `listOfPendingURLs`, line 25 checks whether it has been traversed. Is it possible that `listOfPendingURLs` contains duplicate URLs? If so, give an example.

KEY TERMS

absolute file name 473
chained exception 469
checked exception 457
declare exception 458
directory path 473

exception 450
exception propagation 459
relative file name 473
throw exception 452
unchecked exception 457

CHAPTER SUMMARY

1. Exception handling enables a method to throw an exception to its caller.
2. A Java *exception* is an instance of a class derived from `java.lang.Throwable`. Java provides a number of predefined exception classes, such as `Error`, `Exception`, `RuntimeException`, `ClassNotFoundException`, `NullPointerException`, and `ArithmaticException`. You can also define your own exception class by extending `Exception`.
3. Exceptions occur during the execution of a method. `RuntimeException` and `Error` are *unchecked exceptions*; all other exceptions are *checked*.
4. When *declaring a method*, you have to declare a checked exception if the method might throw it, thus telling the compiler what can go wrong.
5. The keyword for declaring an exception is `throws`, and the keyword for throwing an exception is `throw`.
6. To invoke the method that declares checked exceptions, enclose it in a `try` statement. When an exception occurs during the execution of the method, the `catch` block catches and handles the exception.
7. If an exception is not caught in the current method, it is passed to its caller. The process is repeated until the exception is caught or passed to the `main` method.
8. Various exception classes can be derived from a common superclass. If a `catch` block catches the exception objects of a superclass, it can also catch all the exception objects of the subclasses of that superclass.
9. The order in which exceptions are specified in a `catch` block is important. A compile error will result if you specify an exception object of a class after an exception object of the superclass of that class.
10. When an exception occurs in a method, the method exits immediately if it does not catch the exception. If the method is required to perform some task before exiting, you can catch the exception in the method and then rethrow it to its caller.
11. The code in the `finally` block is executed under all circumstances, regardless of whether an exception occurs in the `try` block or whether an exception is caught if it occurs.
12. Exception handling separates error-handling code from normal programming tasks, thus making programs easier to read and to modify.
13. Exception handling should not be used to replace simple tests. You should perform simple test using `if` statements whenever possible, and reserve exception handling for dealing with situations that cannot be handled with `if` statements.
14. The `File` class is used to obtain file properties and manipulate files. It does not contain the methods for creating a file or for reading/writing data from/to a file.
15. You can use `Scanner` to read string and primitive data values from a text file and use `PrintWriter` to create a file and write data to a text file.
16. You can read from a file on the Web using the `URL` class.

Quiz

Answer the quiz for this chapter online at www.cs.armstrong.edu/liang/intro10e/quiz.html.

MyProgrammingLab™

PROGRAMMING EXERCISES

Sections 12.2–12.9

- *12.1 (*NumberFormatException*) Listing 7.9, Calculator.java, is a simple command-line calculator. Note that the program terminates if any operand is nonnumeric. Write a program with an exception handler that deals with nonnumeric operands; then write another program without using an exception handler to achieve the same objective. Your program should display a message that informs the user of the wrong operand type before exiting (see Figure 12.12).

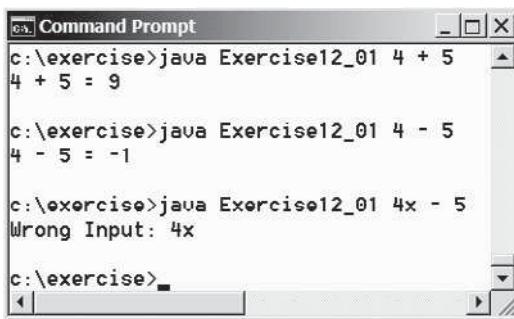


FIGURE 12.12 The program performs arithmetic operations and detects input errors.

- *12.2 (*InputMismatchException*) Write a program that prompts the user to read two integers and displays their sum. Your program should prompt the user to read the number again if the input is incorrect.
- *12.3 (*ArrayIndexOutOfBoundsException*) Write a program that meets the following requirements:
- Creates an array with **100** randomly chosen integers.
 - Prompts the user to enter the index of the array, then displays the corresponding element value. If the specified index is out of bounds, display the message **Out of Bounds**.
- *12.4 (*IllegalArgumentException*) Modify the **Loan** class in Listing 10.2 to throw **IllegalArgumentException** if the loan amount, interest rate, or number of years is less than or equal to zero.
- *12.5 (*IllegalTriangleException*) Programming Exercise 11.1 defined the **Triangle** class with three sides. In a triangle, the sum of any two sides is greater than the other side. The **Triangle** class must adhere to this rule. Create the **IllegalTriangleException** class, and modify the constructor of the **Triangle** class to throw an **IllegalTriangleException** object if a triangle is created with sides that violate the rule, as follows:

```
/** Construct a triangle with the specified sides */
public Triangle(double side1, double side2, double side3)
    throws IllegalTriangleException {
    // Implement it
}
```

***12.6** (*NumberFormatException*) Listing 6.8 implements the `hex2Dec(String hexString)` method, which converts a hex string into a decimal number. Implement the `hex2Dec` method to throw a `NumberFormatException` if the string is not a hex string.

***12.7** (*NumberFormatException*) Write the `bin2Dec(String binaryString)` method to convert a binary string into a decimal number. Implement the `bin2Dec` method to throw a `NumberFormatException` if the string is not a binary string.

***12.8** (*HexFormatException*) Exercise 12.6 implements the `hex2Dec` method to throw a `NumberFormatException` if the string is not a hex string. Define a custom exception called `HexFormatException`. Implement the `hex2Dec` method to throw a `HexFormatException` if the string is not a hex string.



***12.9** (*BinaryFormatException*) Exercise 12.7 implements the `bin2Dec` method to throw a `BinaryFormatException` if the string is not a binary string. Define a custom exception called `BinaryFormatException`. Implement the `bin2Dec` method to throw a `BinaryFormatException` if the string is not a binary string.

***12.10** (*OutOfMemoryError*) Write a program that causes the JVM to throw an `OutOfMemoryError` and catches and handles this error.

Sections 12.10–12.12

****12.11** (*Remove text*) Write a program that removes all the occurrences of a specified string from a text file. For example, invoking

```
java Exercise12_11 John filename
```

removes the string `John` from the specified file. Your program should get the arguments from the command line.

****12.12** (*Reformat Java source code*) Write a program that converts the Java source code from the next-line brace style to the end-of-line brace style. For example, the following Java source in (a) uses the next-line brace style. Your program converts it to the end-of-line brace style in (b).

```
public class Test
{
    public static void main(String[] args)
    {
        // Some statements
    }
}
```

(a) Next-line brace style

```
public class Test {
    public static void main(String[] args) {
        // Some statements
    }
}
```

(b) End-of-line brace style

Your program can be invoked from the command line with the Java source-code file as the argument. It converts the Java source code to a new format. For example, the following command converts the Java source-code file `Test.java` to the end-of-line brace style.

```
java Exercise12_12 Test.java
```

***12.13** (*Count characters, words, and lines in a file*) Write a program that will count the number of characters, words, and lines in a file. Words are separated by whitespace characters. The file name should be passed as a command-line argument, as shown in Figure 12.13.



FIGURE 12.13 The program displays the number of characters, words, and lines in the given file.

***12.14** (*Process scores in a text file*) Suppose that a text file contains an unspecified number of scores separated by blanks. Write a program that prompts the user to enter the file, reads the scores from the file, and displays their total and average.

***12.15** (*Write/read data*) Write a program to create a file named **Exercise12_15.txt** if it does not exist. Write 100 integers created randomly into the file using text I/O. Integers are separated by spaces in the file. Read the data back from the file and display the data in increasing order.

****12.16** (*Replace text*) Listing 12.16, **ReplaceText.java**, gives a program that replaces text in a source file and saves the change into a new file. Revise the program to save the change into the original file. For example, invoking

```
java Exercise12_16 file oldString newString
```

replaces **oldString** in the source file with **newString**.

*****12.17** (*Game: hangman*) Rewrite Programming Exercise 7.35. The program reads the words stored in a text file named **hangman.txt**. Words are delimited by spaces.

****12.18** (*Add package statement*) Suppose you have Java source files under the directories **chapter1**, **chapter2**, ..., **chapter34**. Write a program to insert the statement **package chapteri;** as the first line for each Java source file under the directory **chapteri**. Suppose **chapter1**, **chapter2**, ..., **chapter34** are under the root directory **srcRootDirectory**. The root directory and **chapteri** directory may contain other folders and files. Use the following command to run the program:

```
java Exercise12_18 srcRootDirectory
```

***12.19** (*Count words*) Write a program that counts the number of words in President Abraham Lincoln's Gettysburg address from <http://cs.armstrong.edu/liang/data/Lincoln.txt>.

****12.20** (*Remove package statement*) Suppose you have Java source files under the directories **chapter1**, **chapter2**, ..., **chapter34**. Write a program to remove the statement **package chapteri;** in the first line for each Java source file under the directory **chapteri**. Suppose **chapter1**, **chapter2**, ..., **chapter34** are under the root directory **srcRootDirectory**. The root directory and **chapteri** directory may contain other folders and files. Use the following command to run the program:

```
java Exercise12_20 srcRootDirectory
```

***12.21** (*Data sorted?*) Write a program that reads the strings from file **SortedStrings.txt** and reports whether the strings in the files are stored in increasing order.

If the strings are not sorted in the file, displays the first two strings that are out of the order.

- **12.22** (*Replace text*) Revise Programming Exercise 12.16 to replace a string in a file with a new string for all files in the specified directory using the command:

```
java Exercise12_22 dir oldString newString
```

- **12.23** (*Process scores in a text file on the Web*) Suppose that the text file on the Web <http://cs.armstrong.edu/liang/data/Scores.txt> contains an unspecified number of scores. Write a program that reads the scores from the file and displays their total and average. Scores are separated by blanks.

- *12.24** (*Create large dataset*) Create a data file with 1,000 lines. Each line in the file consists of a faculty member's first name, last name, rank, and salary. The faculty member's first name and last name for the i th line are FirstName i and LastName i . The rank is randomly generated as assistant, associate, and full. The salary is randomly generated as a number with two digits after the decimal point. The salary for an assistant professor should be in the range from 50,000 to 80,000, for associate professor from 60,000 to 110,000, and for full professor from 75,000 to 130,000. Save the file in **Salary.txt**. Here are some sample data:

FirstName1 LastName1 assistant 60055.95

FirstName2 LastName2 associate 81112.45

...

FirstName1000 LastName1000 full 92255.21

- *12.25** (*Process large dataset*) A university posts its employees' salaries at <http://cs.armstrong.edu/liang/data/Salary.txt>. Each line in the file consists of a faculty member's first name, last name, rank, and salary (see Programming Exercise 12.24). Write a program to display the total salary for assistant professors, associate professors, full professors, and all faculty, respectively, and display the average salary for assistant professors, associate professors, full professors, and all faculty, respectively.

- **12.26** (*Create a directory*) Write a program that prompts the user to enter a directory name and creates a directory using the **File**'s **mkdirs** method. The program displays the message "Directory created successfully" if a directory is created or "Directory already exists" if the directory already exists.

- **12.27** (*Replace words*) Suppose you have a lot of files in a directory that contain words **Exercise i _ j** , where i and j are digits. Write a program that pads a 0 before i if i is a single digit and 0 before j if j is a single digit. For example, the word **Exercise2_1** in a file will be replaced by **Exercise02_01**. In Java, when you pass the symbol * from the command line, it refers to all files in the directory (see Supplement III.V). Use the following command to run your program.

```
java Exercise12_27 *
```

- **12.28** (*Rename files*) Suppose you have a lot of files in a directory named **Exercise i _ j** , where i and j are digits. Write a program that pads a 0 before i if i is a single digit. For example, a file named **Exercise2_1** in a directory will be renamed to **Exercise02_1**. In Java, when you pass the symbol * from the command line, it refers to all files in the directory (see Supplement III.V). Use the following command to run your program.

```
java Exercise12_28 *
```

****12.29** (*Rename files*) Suppose you have a lot of files in a directory named **Exercise*i*_j**, where *i* and *j* are digits. Write a program that pads a 0 before *j* if *j* is a single digit. For example, a file named **Exercise2_1** in a directory will be renamed to **Exercise2_01**. In Java, when you pass the symbol * from the command line, it refers to all files in the directory (see Supplement III.V). Use the following command to run your program.

```
java Exercise12_29 *
```

****12.30** (*Occurrences of each letter*) Write a program that prompts the user to enter a file name and displays the occurrences of each letter in the file. Letters are case-insensitive. Here is a sample run:



```
Enter a filename: Lincoln.txt ↵Enter
Number of A's: 56
Number of B's: 134
...
Number of Z's: 9
```

***12.31** (*Baby name popularity ranking*) The popularity ranking of baby names from years 2001 to 2010 is downloaded from www.ssa.gov/oact/babynames and stored in files named **babynameranking2001.txt**, **babynameranking2002.txt**, . . . , **babynameranking2010.txt**. Each file contains one thousand lines. Each line contains a ranking, a boy's name, number for the boy's name, a girl's name, and number for the girl's name. For example, the first two lines in the file **babynameranking2010.txt** are as follows:

1	Jacob	21,875	Isabella	22,731
2	Ethan	17,866	Sophia	20,477

So, the boy's name Jacob and girl's name Isabella are ranked #1 and the boy's name Ethan and girl's name Sophia are ranked #2. 21,875 boys are named Jacob and 22,731 girls are named Isabella. Write a program that prompts the user to enter the year, gender, and followed by a name, and displays the ranking of the name for the year. Here is a sample run:



```
Enter the year: 2010 ↵Enter
Enter the gender: M ↵Enter
Enter the name: Javier ↵Enter
Javier is ranked #190 in year 2010
```



```
Enter the year: 2010 ↵Enter
Enter the gender: F ↵Enter
Enter the name: ABC ↵Enter
The name ABC is not ranked in year 2010
```

- * **12.32** (*Ranking summary*) Write a program that uses the files described in Programming Exercise 12.31 and displays a ranking summary table for the first five girl's and boy's names as follows:

Year	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5
2010	Isabella	Sophia	Emma	Olivia	Ava	Jacob	Ethan	Michael	Jayden	William
2009	Isabella	Emma	Olivia	Sophia	Ava	Jacob	Ethan	Michael	Alexander	William
...										
2001	Emily	Madison	Hannah	Ashley	Alexis	Jacob	Michael	Matthew	Joshua	Christopher

- ** **12.33** (*Search Web*) Modify Listing 12.18 WebCrawler.java to search for the word **Computer Programming** starting from the URL <http://cs.armstrong.edu/liang>. Your program terminates once the word is found. Display the URL for the page that contains the word.

This page intentionally left blank

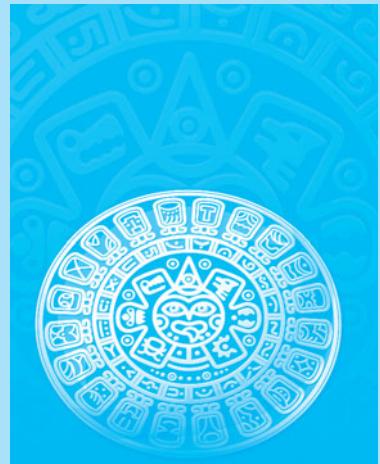
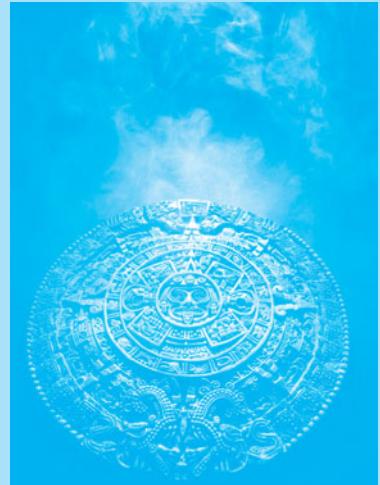
CHAPTER

13

ABSTRACT CLASSES AND INTERFACES

Objectives

- To design and use abstract classes (§13.2).
- To generalize numeric wrapper classes, **BigInteger**, and **BigDecimal** using the abstract **Number** class (§13.3).
- To process a calendar using the **Calendar** and **GregorianCalendar** classes (§13.4).
- To specify common behavior for objects using interfaces (§13.5).
- To define interfaces and define classes that implement interfaces (§13.5).
- To define a natural order using the **Comparable** interface (§13.6).
- To make objects cloneable using the **Cloneable** interface (§13.7).
- To explore the similarities and differences among concrete classes, abstract classes, and interfaces (§13.8).
- To design the **Rational** class for processing rational numbers (§13.9).
- To design classes that follow the class-design guidelines (§13.10).



13.1 Introduction



A superclass defines common behavior for related subclasses. An interface can be used to define common behavior for classes (including unrelated classes).

problem
interface

You can use the `java.util.Arrays.sort` method to sort an array of numbers or strings. Can you apply the same `sort` method to sort an array of geometric objects? In order to write such code, you have to know about interfaces. An *interface* is for defining common behavior for classes (including unrelated classes). Before discussing interfaces, we introduce a closely related subject: abstract classes.

13.2 Abstract Classes



An abstract class cannot be used to create objects. An abstract class can contain abstract methods, which are implemented in concrete subclasses.

VideoNote
Abstract GeometricObject
class
abstract class

abstract method
abstract modifier

In the inheritance hierarchy, classes become more specific and concrete *with each new subclass*. If you move from a subclass back up to a superclass, the classes become more general and less specific. Class design should ensure that a superclass contains common features of its subclasses. Sometimes a superclass is so abstract that it cannot be used to create any specific instances. Such a class is referred to as an *abstract class*.

In Chapter 11, `GeometricObject` was defined as the superclass for `Circle` and `Rectangle`. `GeometricObject` models common features of geometric objects. Both `Circle` and `Rectangle` contain the `getArea()` and `getPerimeter()` methods for computing the area and perimeter of a circle and a rectangle. Since you can compute areas and perimeters for all geometric objects, it is better to define the `getArea()` and `getPerimeter()` methods in the `GeometricObject` class. However, these methods cannot be implemented in the `GeometricObject` class, because their implementation depends on the specific type of geometric object. Such methods are referred to as *abstract methods* and are denoted using the `abstract` modifier in the method header. After you define the methods in `GeometricObject`, it becomes an abstract class. Abstract classes are denoted using the `abstract` modifier in the class header. In UML graphic notation, the names of abstract classes and their abstract methods are italicized, as shown in Figure 13.1. Listing 13.1 gives the source code for the new `GeometricObject` class.

LISTING 13.1 GeometricObject.java

abstract class

```

1  public abstract class GeometricObject {
2      private String color = "white";
3      private boolean filled;
4      private java.util.Date dateCreated;
5
6      /** Construct a default geometric object */
7      protected GeometricObject() {
8          dateCreated = new java.util.Date();
9      }
10
11     /** Construct a geometric object with color and filled value */
12     protected GeometricObject(String color, boolean filled) {
13         dateCreated = new java.util.Date();
14         this.color = color;
15         this.filled = filled;
16     }
17
18     /** Return color */
19     public String getColor() {
20         return color;
21     }
22
23     /** Set color */
24     public void setColor(String color) {
25         this.color = color;
26     }
27
28     /** Return filled status */
29     public boolean getFilled() {
30         return filled;
31     }
32
33     /** Set filled status */
34     public void setFilled(boolean filled) {
35         this.filled = filled;
36     }
37
38     /** Return date created */
39     public java.util.Date getDateCreated() {
40         return dateCreated;
41     }
42
43     /** Set date created */
44     public void setDateCreated(java.util.Date dateCreated) {
45         this.dateCreated = dateCreated;
46     }
47
48     /** Compute area */
49     public abstract double getArea();
50
51     /** Compute perimeter */
52     public abstract double getPerimeter();
53 }
```

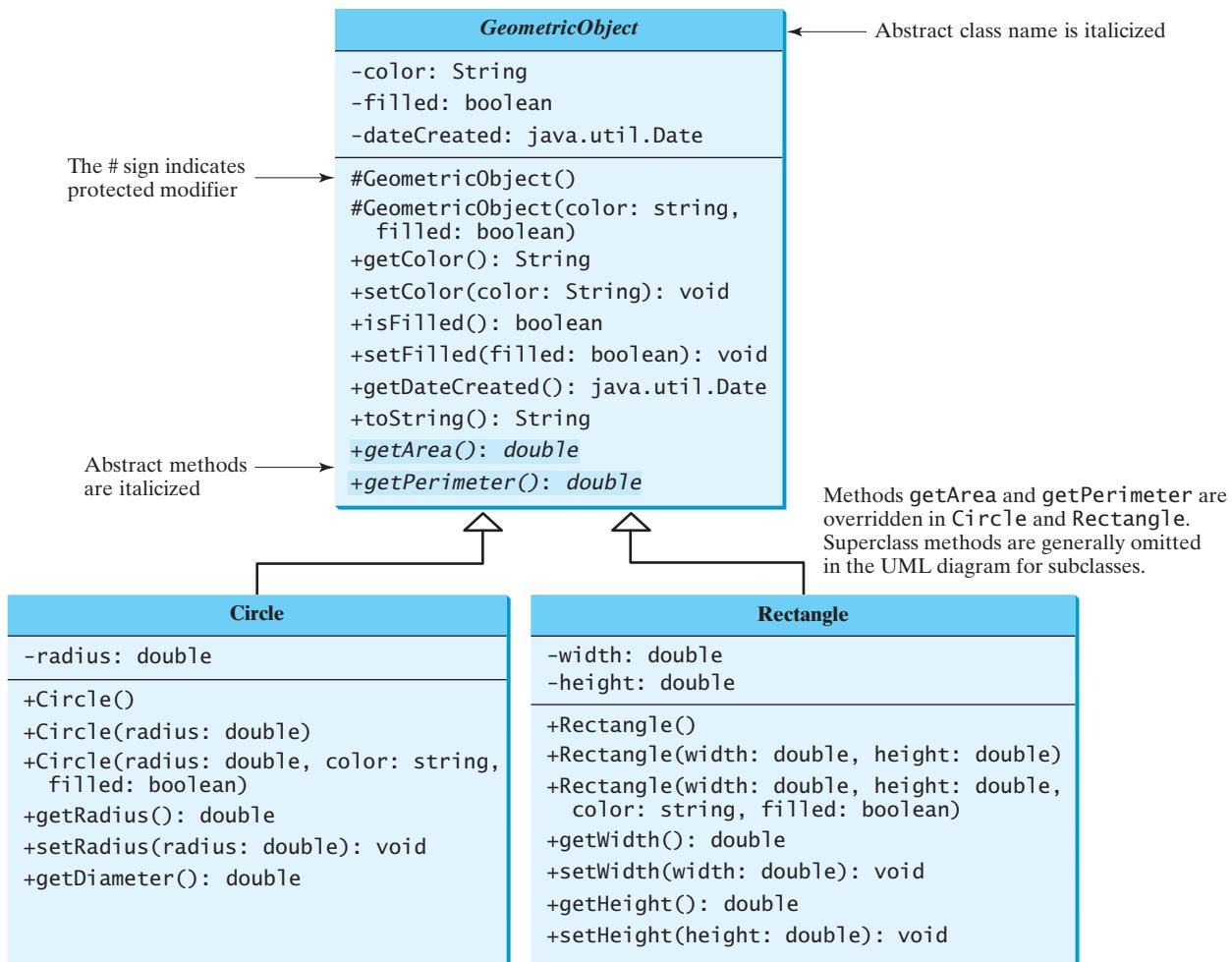


FIGURE 13.1 The new **GeometricObject** class contains abstract methods.

```

21 }
22
23 /**
24  * Set a new color */
25 public void setColor(String color) {
26     this.color = color;
27 }
28
29 /**
30  * Return filled. Since filled is boolean,
31  * the get method is named isFilled */
32 public boolean isFilled() {
33     return filled;
34 }
35
36 /**
37  * Set a new filled */
38 public void setFilled(boolean filled) {
39     this.filled = filled;
40 }
41
42 /**
43  * Get dateCreated */
44 public java.util.Date getDateCreated() {
45     return dateCreated;
46 }
```

```

43
44     @Override
45     public String toString() {
46         return "created on " + dateCreated + "\ncolor: " + color +
47             " and filled: " + filled;
48     }
49
50     /** Abstract method getArea */
51     public abstract double getArea();
52
53     /** Abstract method getPerimeter */
54     public abstract double getPerimeter();
55 }
```

abstract method

abstract method

why protected constructor?

implement Circle
implement Rectangleextends abstract
GeometricObjectextends abstract
GeometricObject

Abstract classes are like regular classes, but you cannot create instances of abstract classes using the `new` operator. An abstract method is defined without implementation. Its implementation is provided by the subclasses. A class that contains abstract methods must be defined as abstract.

The constructor in the abstract class is defined as protected, because it is used only by subclasses. When you create an instance of a concrete subclass, its superclass's constructor is invoked to initialize data fields defined in the superclass.

The `GeometricObject` abstract class defines the common features (data and methods) for geometric objects and provides appropriate constructors. Because you don't know how to compute areas and perimeters of geometric objects, `getArea()` and `getPerimeter()` are defined as abstract methods. These methods are implemented in the subclasses. The implementation of `Circle` and `Rectangle` is the same as in Listings 13.2 and 13.3, except that they extend the `GeometricObject` class defined in this chapter. You can see the complete code for these two programs from www.cs.armstrong.edu/liang/intro10e/html/Circle.html and www.cs.armstrong.edu/liang/intro10e/html/Rectangle.html, respectively.

LISTING 13.2 Circle.java

```

1  public class Circle extends GeometricObject {
2      // Same as lines 3-48 in Listing 11.2, so omitted
3 }
```

LISTING 13.3 Rectangle.java

```

1  public class Rectangle extends GeometricObject {
2      // Same as lines 3-51 in Listing 11.3, so omitted
3 }
```

13.2.1 Why Abstract Methods?

You may be wondering what advantage is gained by defining the methods `getArea()` and `getPerimeter()` as abstract in the `GeometricObject` class. The example in Listing 13.4 shows the benefits of defining them in the `GeometricObject` class. The program creates two geometric objects, a circle and a rectangle, invokes the `equalArea` method to check whether they have equal areas, and invokes the `displayGeometricObject` method to display them.

LISTING 13.4 TestGeometricObject.java

```

1  public class TestGeometricObject {
2      /** Main method */
3      public static void main(String[] args) {
4          // Create two geometric objects
5          GeometricObject geoObject1 = new Circle(5);
6          GeometricObject geoObject2 = new Rectangle(5, 3);
```

create a circle
create a rectangle

```

7     System.out.println("The two objects have the same area? " +
8         equalArea(geoObject1, geoObject2));
9
10    // Display circle
11    displayGeometricObject(geoObject1);
12
13    // Display rectangle
14    displayGeometricObject(geoObject2);
15
16 }
17
18 /** A method for comparing the areas of two geometric objects */
19 public static boolean equalArea(GeometricObject object1,
20     GeometricObject object2) { equalArea
21     return object1.getArea() == object2.getArea();
22 }
23
24 /** A method for displaying a geometric object */
25 public static void displayGeometricObject(GeometricObject object) { displayGeometricObject
26     System.out.println();
27     System.out.println("The area is " + object.getArea());
28     System.out.println("The perimeter is " + object.getPerimeter());
29 }
30 }
```

The two objects have the same area? false

The area is 78.53981633974483

The perimeter is 31.41592653589793

The area is 13.0

The perimeter is 16.0



The methods `getArea()` and `getPerimeter()` defined in the `GeometricObject` class are overridden in the `Circle` class and the `Rectangle` class. The statements (lines 5–6)

```
GeometricObject geoObject1 = new Circle(5);
GeometricObject geoObject2 = new Rectangle(5, 3);
```

create a new circle and rectangle and assign them to the variables `geoObject1` and `geoObject2`. These two variables are of the `GeometricObject` type.

When invoking `equalArea(geoObject1, geoObject2)` (line 9), the `getArea()` method defined in the `Circle` class is used for `object1.getArea()`, since `geoObject1` is a circle, and the `getArea()` method defined in the `Rectangle` class is used for `object2.getArea()`, since `geoObject2` is a rectangle.

Similarly, when invoking `displayGeometricObject(geoObject1)` (line 12), the methods `getArea()` and `getPerimeter()` defined in the `Circle` class are used, and when invoking `displayGeometricObject(geoObject2)` (line 15), the methods `getArea` and `getPerimeter` defined in the `Rectangle` class are used. The JVM dynamically determines which of these methods to invoke at runtime, depending on the actual object that invokes the method.

Note that you could not define the `equalArea` method for comparing whether two geometric objects have the same area if the `getArea` method were not defined in `GeometricObject`. Now you have seen the benefits of defining the abstract methods in `GeometricObject`.

why abstract methods?

13.2.2 Interesting Points about Abstract Classes

The following points about abstract classes are worth noting:

abstract method in abstract class

- An abstract method cannot be contained in a nonabstract class. If a subclass of an abstract superclass does not implement all the abstract methods, the subclass must be defined as abstract. In other words, in a nonabstract subclass extended from an abstract class, all the abstract methods must be implemented. Also note that abstract methods are nonstatic.

object cannot be created from abstract class

- An abstract class cannot be instantiated using the `new` operator, but you can still define its constructors, which are invoked in the constructors of its subclasses. For instance, the constructors of `GeometricObject` are invoked in the `Circle` class and the `Rectangle` class.

abstract class without abstract method

- A class that contains abstract methods must be abstract. However, it is possible to define an abstract class that doesn't contain any abstract methods. In this case, you cannot create instances of the class using the `new` operator. This class is used as a base class for defining subclasses.

concrete method overridden to be abstract

- A subclass can override a method from its superclass to define it as abstract. This is *very unusual*, but it is useful when the implementation of the method in the superclass becomes invalid in the subclass. In this case, the subclass must be defined as abstract.

superclass of abstract class may be concrete

- A subclass can be abstract even if its superclass is concrete. For example, the `Object` class is concrete, but its subclasses, such as `GeometricObject`, may be abstract.

abstract class as type

- You cannot create an instance from an abstract class using the `new` operator, but an abstract class can be used as a data type. Therefore, the following statement, which creates an array whose elements are of the `GeometricObject` type, is correct.

```
GeometricObject[] objects = new GeometricObject[10];
```

You can then create an instance of `GeometricObject` and assign its reference to the array like this:

```
objects[0] = new Circle();
```



13.1 Which of the following classes defines a legal abstract class?

```
class A {
    abstract void unfinished() {
    }
}
```

(a)

```
public class abstract A {
    abstract void unfinished();
}
```

(b)

```
class A {
    abstract void unfinished();
}
```

(c)

```
abstract class A {
    protected void unfinished();
}
```

(d)

```
abstract class A {
    abstract void unfinished();
}
```

(e)

```
abstract class A {
    abstract int unfinished();
}
```

(f)

13.2 The `getArea()` and `getPerimeter()` methods may be removed from the `GeometricObject` class. What are the benefits of defining `getArea()` and `getPerimeter()` as abstract methods in the `GeometricObject` class?

13.3 True or false?

- An abstract class can be used just like a nonabstract class except that you cannot use the `new` operator to create an instance from the abstract class.
- An abstract class can be extended.
- A subclass of a nonabstract superclass cannot be abstract.
- A subclass cannot override a concrete method in a superclass to define it as abstract.
- An abstract method must be nonstatic.

13.3 Case Study: the Abstract **Number** Class

Number is an abstract superclass for numeric wrapper classes, `BigInteger`, and `BigDecimal`.



Section 10.7 introduced numeric wrapper classes and Section 10.9 introduced the `BigInteger` and `BigDecimal` classes. These classes have common methods `byteValue()`, `shortValue()`, `intValue()`, `longValue()`, `floatValue()`, and `doubleValue()` for returning a `byte`, `short`, `int`, `long`, `float`, and `double` value from an object of these classes. These common methods are actually defined in the `Number` class, which is a superclass for the numeric wrapper classes, `BigInteger`, and `BigDecimal`, as shown in Figure 13.2.



FIGURE 13.2 The `Number` class is an abstract superclass for `Double`, `Float`, `Long`, `Integer`, `Short`, `Byte`, `BigInteger` and `BigDecimal`.

Since the `intValue()`, `longValue()`, `floatValue()`, and `doubleValue()` methods cannot be implemented in the `Number` class, they are defined as abstract methods in the `Number` class. The `Number` class is therefore an abstract class. The `byteValue()` and `shortValue()` method are implemented from the `intValue()` method as follows:

```

public byte byteValue() {
    return (byte)intValue();
}

public short shortValue() {
    return (short)intValue();
}
  
```

With `Number` defined as the superclass for the numeric classes, we can define methods to perform common operations for numbers. Listing 13.5 gives a program that finds the largest number in a list of `Number` objects.

LISTING 13.5 LargestNumbers.java

create an array list
add number to list

invoke `getLargestNumber`

`doubleValue`

```

1 import java.util.ArrayList;
2 import java.math.*;
3
4 public class LargestNumbers {
5     public static void main(String[] args) {
6         ArrayList<Number> list = new ArrayList<>();
7         list.add(45); // Add an integer
8         list.add(3445.53); // Add a double
9         // Add a BigInteger
10        list.add(new BigInteger("3432323234344343101"));
11        // Add a BigDecimal
12        list.add(new BigDecimal("2.0909090989091343433344343"));
13
14        System.out.println("The largest number is " +
15            getLargestNumber(list));
16    }
17
18    public static Number getLargestNumber(ArrayList<Number> list) {
19        if (list == null || list.size() == 0)
20            return null;
21
22        Number number = list.get(0);
23        for (int i = 1; i < list.size(); i++)
24            if (number.doubleValue() < list.get(i).doubleValue())
25                number = list.get(i);
26
27        return number;
28    }
29 }
```



The largest number is 3432323234344343101

The program creates an `ArrayList` of `Number` objects (line 6). It adds an `Integer` object, a `Double` object, a `BigInteger` object, and a `BigDecimal` object to the list (lines 7–12). Note that `45` is automatically converted into an `Integer` object and added to the list in line 7 and that `3445.53` is automatically converted into a `Double` object and added to the list in line 8 using autoboxing.

Invoking the `getLargestNumber` method returns the largest number in the list (line 15). The `getLargestNumber` method returns `null` if the list is `null` or the list size is `0` (lines 19–20). To find the largest number in the list, the numbers are compared by invoking their `doubleValue()` method (line 24). The `doubleValue()` method is defined in the `Number` class and implemented in the concrete subclass of `Number`. If a number is an `Integer` object, the `Integer`'s `doubleValue()` is invoked. If a number is a `BigDecimal` object, the `BigDecimal`'s `doubleValue()` is invoked.

If the `doubleValue()` method were not defined in the `Number` class, you will not be able to find the largest number among different types of numbers using the `Number` class.



13.4 Why do the following two lines of code compile but cause a runtime error?

```
Number numberRef = new Integer(0);
Double doubleRef = (Double)numberRef;
```

13.5 Why do the following two lines of code compile but cause a runtime error?

```
Number[] numberArray = new Integer[2];
numberArray[0] = new Double(1.5);
```

13.6 Show the output of the following code.

```
public class Test {
    public static void main(String[] args) {
        Number x = 3;
        System.out.println(x.intValue());
        System.out.println(x.doubleValue());
    }
}
```

13.7 What is wrong in the following code? (Note that the `compareTo` method for the `Integer` and `Double` classes was introduced in Section 10.7.)

```
public class Test {
    public static void main(String[] args) {
        Number x = new Integer(3);
        System.out.println(x.intValue());
        System.out.println(x.compareTo(new Integer(4)));
    }
}
```

13.8 What is wrong in the following code?

```
public class Test {
    public static void main(String[] args) {
        Number x = new Integer(3);
        System.out.println(x.intValue());
        System.out.println((Integer)x.compareTo(new Integer(4)));
    }
}
```

13.4 Case Study: **Calendar** and **GregorianCalendar**

GregorianCalendar is a concrete subclass of the abstract class **Calendar**.

An instance of `java.util.Date` represents a specific instant in time with millisecond precision. `java.util.Calendar` is an abstract base class for extracting detailed calendar information, such as the year, month, date, hour, minute, and second. Subclasses of `Calendar` can implement specific calendar systems, such as the Gregorian calendar, the lunar calendar, and the Jewish calendar. Currently, `java.util.GregorianCalendar` for the Gregorian calendar is supported in Java, as shown in Figure 13.3. The `add` method is abstract in the `Calendar` class, because its implementation is dependent on a concrete calendar system.

You can use `new GregorianCalendar()` to construct a default `GregorianCalendar` with the current time and `new GregorianCalendar(year, month, date)` to construct a `GregorianCalendar` with the specified `year`, `month`, and `date`. The `month` parameter is 0 based—that is, 0 is for January.

The `get(int field)` method defined in the `Calendar` class is useful for extracting the date and time information from a `Calendar` object. The fields are defined as constants, as shown in Table 13.1.

Listing 13.6 gives an example that displays the date and time information for the current time.



Calendar and
GregorianCalendar classes

abstract add method

construct calendar

get(field)

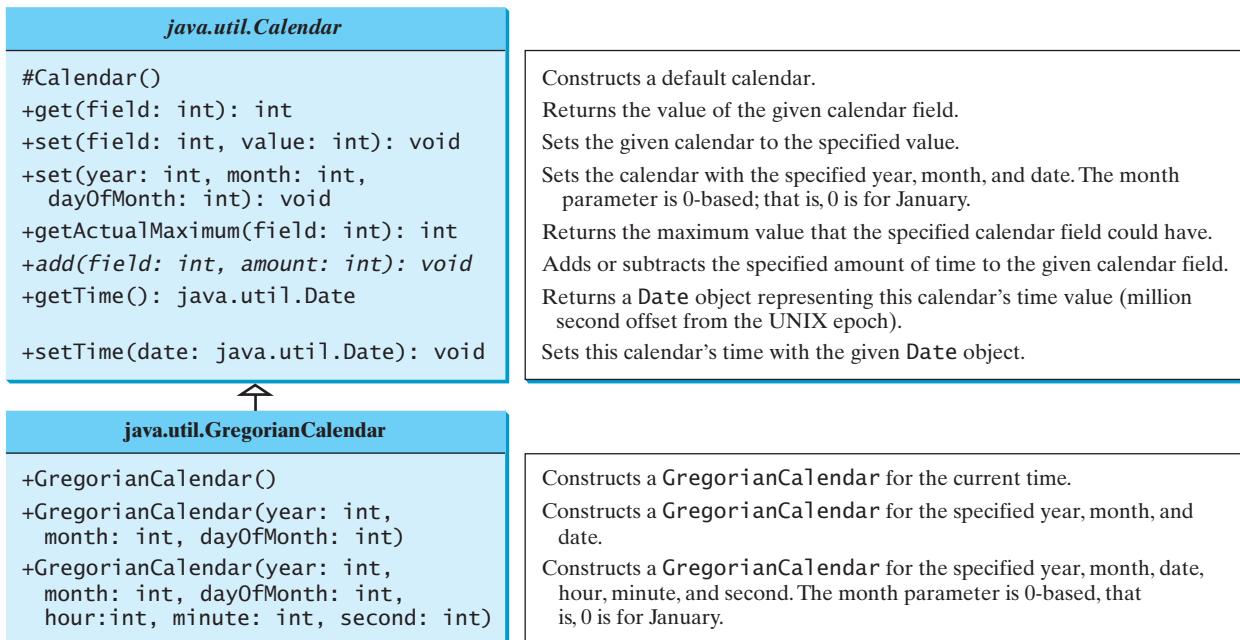


FIGURE 13.3 The abstract `Calendar` class defines common features of various calendars.

TABLE 13.1 Field Constants in the `Calendar` Class

Constant	Description
<code>YEAR</code>	The year of the calendar.
<code>MONTH</code>	The month of the calendar, with 0 for January.
<code>DATE</code>	The day of the calendar.
<code>HOUR</code>	The hour of the calendar (12-hour notation).
<code>HOUR_OF_DAY</code>	The hour of the calendar (24-hour notation).
<code>MINUTE</code>	The minute of the calendar.
<code>SECOND</code>	The second of the calendar.
<code>DAY_OF_WEEK</code>	The day number within the week, with 1 for Sunday.
<code>DAY_OF_MONTH</code>	Same as DATE.
<code>DAY_OF_YEAR</code>	The day number in the year, with 1 for the first day of the year.
<code>WEEK_OF_MONTH</code>	The week number within the month, with 1 for the first week.
<code>WEEK_OF_YEAR</code>	The week number within the year, with 1 for the first week.
<code>AM_PM</code>	Indicator for AM or PM (0 for AM and 1 for PM).

LISTING 13.6 TestCalendar.java

```

1 import java.util.*;
2
3 public class TestCalendar {
4     public static void main(String[] args) {
5         // Construct a Gregorian calendar for the current date and time
6         Calendar calendar = new GregorianCalendar();
7         System.out.println("Current time is " + new Date());
8         System.out.println("YEAR: " + calendar.get(Calendar.YEAR));
  
```

calendar for current time
extract fields in calendar

13.4 Case Study: Calendar and GregorianCalendar 505

```
9     System.out.println("MONTH: " + calendar.get(Calendar.MONTH));
10    System.out.println("DATE: " + calendar.get(Calendar.DATE));
11    System.out.println("HOUR: " + calendar.get(Calendar.HOUR));
12    System.out.println("HOUR_OF_DAY: " +
13        calendar.get(Calendar.HOUR_OF_DAY));
14    System.out.println("MINUTE: " + calendar.get(Calendar.MINUTE));
15    System.out.println("SECOND: " + calendar.get(Calendar.SECOND));
16    System.out.println("DAY_OF_WEEK: " +
17        calendar.get(Calendar.DAY_OF_WEEK));
18    System.out.println("DAY_OF_MONTH: " +
19        calendar.get(Calendar.DAY_OF_MONTH));
20    System.out.println("DAY_OF_YEAR: " +
21        calendar.get(Calendar.DAY_OF_YEAR));
22    System.out.println("WEEK_OF_MONTH: " +
23        calendar.get(Calendar.WEEK_OF_MONTH));
24    System.out.println("WEEK_OF_YEAR: " +
25        calendar.get(Calendar.WEEK_OF_YEAR));
26    System.out.println("AM_PM: " + calendar.get(Calendar.AM_PM));
27
28    // Construct a calendar for September 11, 2001
29    Calendar calendar1 = new GregorianCalendar(2001, 8, 11);           create a calendar
30    String[] dayNameOfWeek = {"Sunday", "Monday", "Tuesday", "Wednesday",
31        "Thursday", "Friday", "Saturday"};
32    System.out.println("September 11, 2001 is a " +
33        dayNameOfWeek[calendar1.get(Calendar.DAY_OF_WEEK) - 1]);
34 }
35 }
```

```
Current time is Sun Nov 27 17:48:15 EST 2011
YEAR: 2011
MONTH: 10
DATE: 27
HOUR: 5
HOUR_OF_DAY: 17
MINUTE: 48
SECOND: 15
DAY_OF_WEEK: 1
DAY_OF_MONTH: 27
DAY_OF_YEAR: 331
WEEK_OF_MONTH: 5
WEEK_OF_YEAR: 49
AM_PM: 1
September 11, 2001 is a Tuesday
```



The `set(int field, value)` method defined in the `Calendar` class can be used to set a field. For example, you can use `calendar.set(Calendar.DAY_OF_MONTH, 1)` to set the `calendar` to the first day of the month.

`set(field, value)`

The `add(field, value)` method adds the specified amount to a given field. For example, `add(Calendar.DAY_OF_MONTH, 5)` adds five days to the current time of the calendar. `add(Calendar.DAY_OF_MONTH, -5)` subtracts five days from the current time of the calendar.

`add(field, amount)`

To obtain the number of days in a month, use `calendar.getActualMaximum(Calendar.DAY_OF_MONTH)`. For example, if the `calendar` were for March, this method would return `31`.

`getActualMaximum(field)`

```
setTime(date)
getTime()
```

You can set a time represented in a `Date` object for the `Calendar` by invoking `calendar.setTime(date)` and retrieve the time by invoking `calendar.getTime()`.



- 13.9** Can you create a `Calendar` object using the `Calendar` class?
13.10 Which method in the `Calendar` class is abstract?
13.11 How do you create a `Calendar` object for the current time?
13.12 For a `Calendar` object `c`, how do you get its year, month, date, hour, minute, and second?

13.5 Interfaces



VideoNote

The concept of interface

An interface is a class-like construct that contains only constants and abstract methods.

In many ways an interface is similar to an abstract class, but its intent is to specify common behavior for objects of related classes or unrelated classes. For example, using appropriate interfaces, you can specify that the objects are comparable, edible, and/or cloneable.

To distinguish an interface from a class, Java uses the following syntax to define an interface:

```
modifier interface InterfaceName {
    /** Constant declarations */
    /** Abstract method signatures */
}
```

Here is an example of an interface:

```
public interface Edible {
    /** Describe how to eat */
    public abstract String howToEat();
}
```

An interface is treated like a special class in Java. Each interface is compiled into a separate bytecode file, just like a regular class. You can use an interface more or less the same way you use an abstract class. For example, you can use an interface as a data type for a reference variable, as the result of casting, and so on. As with an abstract class, you cannot create an instance from an interface using the `new` operator.

You can use the `Edible` interface to specify whether an object is edible. This is accomplished by letting the class for the object implement this interface using the `implements` keyword. For example, the classes `Chicken` and `Fruit` in Listing 13.7 (lines 20, 39) implement the `Edible` interface. The relationship between the class and the interface is known as *interface inheritance*. Since interface inheritance and class inheritance are essentially the same, we will simply refer to both as *inheritance*.

interface inheritance

LISTING 13.7 TestEdible.java

```
1  public class TestEdible {
2      public static void main(String[] args) {
3          Object[] objects = {new Tiger(), new Chicken(), new Apple()};
4          for (int i = 0; i < objects.length; i++) {
5              if (objects[i] instanceof Edible)
6                  System.out.println(((Edible)objects[i]).howToEat());
7
8              if (objects[i] instanceof Animal) {
9                  System.out.println(((Animal)objects[i]).sound());
10             }
11         }
12     }
13 }
```

```

14
15 abstract class Animal {
16     /** Return animal sound */
17     public abstract String sound();
18 }
19
20 class Chicken extends Animal implements Edible {
21     @Override
22     public String howToEat() {
23         return "Chicken: Fry it";
24     }
25
26     @Override
27     public String sound() {
28         return "Chicken: cock-a-doodle-doo";
29     }
30 }
31
32 class Tiger extends Animal {
33     @Override
34     public String sound() {
35         return "Tiger: RROOAARR";
36     }
37 }
38
39 abstract class Fruit implements Edible {
40     // Data fields, constructors, and methods omitted here
41 }
42
43 class Apple extends Fruit {
44     @Override
45     public String howToEat() {
46         return "Apple: Make apple cider";
47     }
48 }
49
50 class Orange extends Fruit {
51     @Override
52     public String howToEat() {
53         return "Orange: Make orange juice";
54     }
55 }

```

Animal class
implements Edible
howToEat()
Tiger class
implements Edible
Apple class
Orange class

```

Tiger: RROOAARR
Chicken: Fry it
Chicken: cock-a-doodle-doo
Apple: Make apple cider

```



This example uses several classes and interfaces. Their inheritance relationship is shown in Figure 13.4.

The **Animal** class defines the **sound** method (line 17). It is an abstract method and will be implemented by a concrete animal class.

The **Chicken** class implements **Edible** to specify that chickens are edible. When a class implements an interface, it implements all the methods defined in the interface with the exact signature and return type. The **Chicken** class implements the **howToEat** method (lines 22–24). **Chicken** also extends **Animal** to implement the **sound** method (lines 27–29).

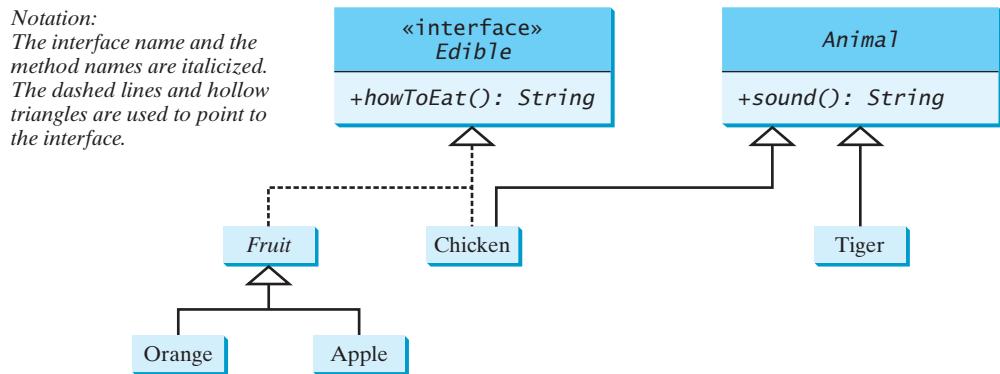


FIGURE 13.4 **Edible** is a supertype for **Chicken** and **Fruit**. **Animal** is a supertype for **Chicken** and **Tiger**. **Fruit** is a supertype for **Orange** and **Apple**.

The **Fruit** class implements **Edible**. Since it does not implement the **howToEat** method, **Fruit** must be denoted as **abstract** (line 39). The concrete subclasses of **Fruit** must implement the **howToEat** method. The **Apple** and **Orange** classes implement the **howToEat** method (lines 45, 52).

The **main** method creates an array with three objects for **Tiger**, **Chicken**, and **Apple** (line 3), and invokes the **howToEat** method if the element is edible (line 6) and the **sound** method if the element is an animal (line 9).

In essence, the **Edible** interface defines common behavior for edible objects. All edible objects have the **howToEat** method.

common behavior

omit modifiers



Note

Since all data fields are **public static final** and all methods are **public abstract** in an interface, Java allows these modifiers to be omitted. Therefore the following interface definitions are equivalent:

```
public interface T {
    public static final int K = 1;

    public abstract void p();
}
```

Equivalent

```
public interface T {
    int K = 1;

    void p();
}
```



13.13 Suppose **A** is an interface. Can you create an instance using **new A()**?

13.14 Suppose **A** is an interface. Can you declare a reference variable **x** with type **A** like this?
A x;

13.15 Which of the following is a correct interface?

```
interface A {
    void print() { };
}
```

(a)

```
abstract interface A extends I1, I2 {
    abstract void print() { };
}
```

(b)

```
abstract interface A {
    print();
}
```

(c)

```
interface A {
    void print();
}
```

(d)

13.16 Show the error in the following code:

```
interface A {
    void m1();
}

class B implements A {
    void m1() {
        System.out.println("m1");
    }
}
```

13.6 The Comparable Interface

The Comparable interface defines the compareTo method for comparing objects.

Suppose you want to design a generic method to find the larger of two objects of the same type, such as two students, two dates, two circles, two rectangles, or two squares. In order to accomplish this, the two objects must be comparable, so the common behavior for the objects must be comparable. Java provides the Comparable interface for this purpose. The interface is defined as follows:

```
// Interface for comparing objects, defined in java.lang
package java.lang;

public interface Comparable<E> {
    public int compareTo(E o);
}
```

java.lang.Comparable

The compareTo method determines the order of this object with the specified object *o* and returns a negative integer, zero, or a positive integer if this object is less than, equal to, or greater than *o*.

The Comparable interface is a generic interface. The generic type *E* is replaced by a concrete type when implementing this interface. Many classes in the Java library implement Comparable to define a natural order for objects. The classes **Byte**, **Short**, **Integer**, **Long**, **Float**, **Double**, **Character**, **BigInteger**, **BigDecimal**, **Calendar**, **String**, and **Date** all implement the Comparable interface. For example, the **Integer**, **BigInteger**, **String**, and **Date** classes are defined as follows in the Java API:

```
public class Integer extends Number
    implements Comparable<Integer> {
    // class body omitted

    @Override
    public int compareTo(Integer o) {
        // Implementation omitted
    }
}
```

```
public class BigInteger extends Number
    implements Comparable<BigInteger> {
    // class body omitted

    @Override
    public int compareTo(BigInteger o) {
        // Implementation omitted
    }
}
```

```
public class String extends Object
    implements Comparable<String> {
    // class body omitted

    @Override
    public int compareTo(String o) {
        // Implementation omitted
    }
}
```

```
public class Date extends Object
    implements Comparable<Date> {
    // class body omitted

    @Override
    public int compareTo(Date o) {
        // Implementation omitted
    }
}
```



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Thus, numbers are comparable, strings are comparable, and so are dates. You can use the `compareTo` method to compare two numbers, two strings, and two dates. For example, the following code

```
1 System.out.println(new Integer(3).compareTo(new Integer(5)));
2 System.out.println("ABC".compareTo("ABE"));
3 java.util.Date date1 = new java.util.Date(2013, 1, 1);
4 java.util.Date date2 = new java.util.Date(2012, 1, 1);
5 System.out.println(date1.compareTo(date2));
```

displays

```
-1
-2
1
```

Line 1 displays a negative value since `3` is less than `5`. Line 2 displays a negative value since `ABC` is less than `ABE`. Line 5 displays a positive value since `date1` is greater than `date2`.

Let `n` be an `Integer` object, `s` be a `String` object, and `d` be a `Date` object. All the following expressions are `true`.

<code>n instanceof Integer</code>
<code>n instanceof Object</code>
<code>n instanceof Comparable</code>

<code>s instanceof String</code>
<code>s instanceof Object</code>
<code>s instanceof Comparable</code>

<code>d instanceof java.util.Date</code>
<code>d instanceof Object</code>
<code>d instanceof Comparable</code>

Since all `Comparable` objects have the `compareTo` method, the `java.util.Arrays.sort(Object[])` method in the Java API uses the `compareTo` method to compare and sorts the objects in an array, provided that the objects are instances of the `Comparable` interface. Listing 13.8 gives an example of sorting an array of strings and an array of `BigInteger` objects.

LISTING 13.8 SortComparableObjects.java

create an array
sort the array

create an array

sort the array

```
1 import java.math.*;
2
3 public class SortComparableObjects {
4     public static void main(String[] args) {
5         String[] cities = {"Savannah", "Boston", "Atlanta", "Tampa"};
6         java.util.Arrays.sort(cities);
7         for (String city: cities)
8             System.out.print(city + " ");
9         System.out.println();
10
11        BigInteger[] hugeNumbers = {new BigInteger("2323231092923992"),
12            new BigInteger("432232323239292"),
13            new BigInteger("54623239292")};
14        java.util.Arrays.sort(hugeNumbers);
15        for (BigInteger number: hugeNumbers)
16            System.out.print(number + " ");
17    }
18 }
```



Atlanta Boston Savannah Tampa
54623239292 432232323239292 2323231092923992

The program creates an array of strings (line 5) and invokes the `sort` method to sort the strings (line 6). The program creates an array of `BigInteger` objects (lines 11–13) and invokes the `sort` method to sort the `BigInteger` objects (line 14).

You cannot use the `sort` method to sort an array of `Rectangle` objects, because `Rectangle` does not implement `Comparable`. However, you can define a new rectangle class that implements `Comparable`. The instances of this new class are comparable. Let this new class be named `ComparableRectangle`, as shown in Listing 13.9.

LISTING 13.9 ComparableRectangle.java

```

1  public class ComparableRectangle extends Rectangle
2      implements Comparable<ComparableRectangle> {
3          /** Construct a ComparableRectangle with specified properties */
4          public ComparableRectangle(double width, double height) {
5              super(width, height);
6          }
7
8          @Override // Implement the compareTo method defined in Comparable
9          public int compareTo(ComparableRectangle o) {
10             if (getArea() > o.getArea())
11                 return 1;
12             else if (getArea() < o.getArea())
13                 return -1;
14             else
15                 return 0;
16         }
17
18         @Override // Implement the toString method in GeometricObject
19         public String toString() {
20             return super.toString() + " Area: " + getArea();
21         }
22     }

```

implements Comparable

implement compareTo

implement toString

`ComparableRectangle` extends `Rectangle` and implements `Comparable`, as shown in Figure 13.5. The keyword `implements` indicates that `ComparableRectangle` inherits all the constants from the `Comparable` interface and implements the methods in the interface. The `compareTo` method compares the areas of two rectangles. An instance of `ComparableRectangle` is also an instance of `Rectangle`, `GeometricObject`, `Object`, and `Comparable`.

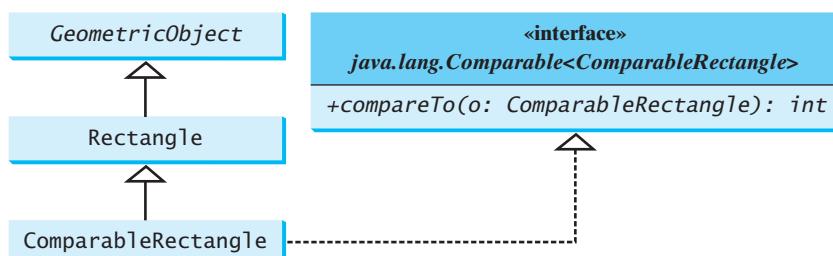


FIGURE 13.5 `ComparableRectangle` extends `Rectangle` and implements `Comparable`.

You can now use the `sort` method to sort an array of `ComparableRectangle` objects, as in Listing 13.10.

LISTING 13.10 SortRectangles.java

```

1  public class SortRectangles {
2      public static void main(String[] args) {
3          ComparableRectangle[] rectangles = {
4              new ComparableRectangle(3.4, 5.4),
5              new ComparableRectangle(13.24, 55.4),
6              new ComparableRectangle(7.4, 35.4),
7              new ComparableRectangle(1.4, 25.4)};
8          java.util.Arrays.sort(rectangles);
9          for (Rectangle rectangle: rectangles) {
10              System.out.print(rectangle + " ");
11              System.out.println();
12          }
13      }
14  }

```

create an array

sort the array

benefits of interface



```

Width: 3.4 Height: 5.4 Area: 18.36
Width: 1.4 Height: 25.4 Area: 35.559999999999995
Width: 7.4 Height: 35.4 Area: 261.96
Width: 13.24 Height: 55.4 Area: 733.496

```

An interface provides another form of generic programming. It would be difficult to use a generic `sort` method to sort the objects without using an interface in this example, because

The `Object` class contains the `equals` method, which is intended for the subclasses of the `Object` class to override in order to compare whether the contents of the objects are the same. Suppose that the `Object` class contains the `compareTo` method, as defined in the `Comparable` interface; the `sort` method can be used to compare a list of *any* objects. Whether a `compareTo` method should be included in the `Object` class is debatable. Since the `compareTo` method is not defined in the `Object` class, the `Comparable` interface is defined in Java to enable objects to be compared if they are instances of the `Comparable` interface. It is strongly recommended (though not required) that `compareTo` should be consistent with `equals`. That is, for two objects `o1` and `o2`, `o1.compareTo(o2) == 0` if and only if `o1.equals(o2)` is `true`.



13.17 True or false? If a class implements `Comparable`, the object of the class can invoke the `compareTo` method.

13.18 Which of the following is the correct method header for the `compareTo` method in the `String` class?

```

public int compareTo(String o)
public int compareTo(Object o)

```

13.19 Can the following code be compiled? Why?

```

Integer n1 = new Integer(3);
Object n2 = new Integer(4);
System.out.println(n1.compareTo(n2));

```

13.20 You can define the `compareTo` method in a class without implementing the `Comparable` interface. What are the benefits of implementing the `Comparable` interface?

13.21 What is wrong in the following code?

```
public class Test {
    public static void main(String[] args) {
        Person[] persons = {new Person(3), new Person(4), new Person(1)};
        java.util.Arrays.sort(persons);
    }
}

class Person {
    private int id;

    Person(int id) {
        this.id = id;
    }
}
```

13.7 The **Cloneable** Interface

The `Cloneable` interface specifies that an object can be cloned.

Often it is desirable to create a copy of an object. To do this, you need to use the `clone` method and understand the `Cloneable` interface.



An interface contains constants and abstract methods, but the `Cloneable` interface is a special case. The `Cloneable` interface in the `java.lang` package is defined as follows:

```
package java.lang;
import java.lang.Cloneable;
```

```
public interface Cloneable { }
```

This interface is empty. An interface with an empty body is referred to as a *marker interface*. A marker interface does not contain constants or methods. It is used to denote that a class possesses certain desirable properties. A class that implements the `Cloneable` interface is marked cloneable, and its objects can be cloned using the `clone()` method defined in the `Object` class.

Many classes in the Java library (e.g., `Date`, `Calendar`, and `ArrayList`) implement `Cloneable`. Thus, the instances of these classes can be cloned. For example, the following code

```
1 Calendar calendar = new GregorianCalendar(2013, 2, 1);
2 Calendar calendar1 = calendar;
3 Calendar calendar2 = (Calendar)calendar.clone();
4 System.out.println("calendar == calendar1 is " +
5   (calendar == calendar1));
6 System.out.println("calendar == calendar2 is " +
7   (calendar == calendar2));
8 System.out.println("calendar.equals(calendar2) is " +
9   calendar.equals(calendar2));
```

displays

```
calendar == calendar1 is true
calendar == calendar2 is false
calendar.equals(calendar2) is true
```

In the preceding code, line 2 copies the reference of `calendar` to `calendar1`, so `calendar` and `calendar1` point to the same `Calendar` object. Line 3 creates a new object that is the clone of `calendar` and assigns the new object's reference to `calendar2`. `calendar2` and `calendar` are different objects with the same contents.

The following code

```

1 ArrayList<Double> list1 = new ArrayList<>();
2 list1.add(1.5);
3 list1.add(2.5);
4 list1.add(3.5);
5 ArrayList<Double> list2 = (ArrayList<Double>)list1.clone();
6 ArrayList<Double> list3 = list1;
7 list2.add(4.5);
8 list3.remove(1.5);
9 System.out.println("list1 is " + list1);
10 System.out.println("list2 is " + list2);
11 System.out.println("list3 is " + list3);

```

displays

```

list1 is [2.5, 3.5]
list2 is [1.5, 2.5, 3.5, 4.5]
list3 is [2.5, 3.5]

```

In the preceding code, line 5 creates a new object that is the clone of `list1` and assigns the new object's reference to `list2`. `list2` and `list1` are different objects with the same contents. Line 6 copies the reference of `list1` to `list3`, so `list1` and `list3` point to the same `ArrayList` object. Line 7 adds `4.5` into `list2`. Line 8 removes `1.5` from `list3`. Since `list1` and `list3` point to the same `ArrayList`, line 9 and 11 display the same content.

clone arrays

You can clone an array using the `clone` method. For example, the following code

```

1 int[] list1 = {1, 2};
2 int[] list2 = list1.clone();
3 list1[0] = 7;
4 list2[1] = 8;
5 System.out.println("list1 is " + list1[0] + ", " + list1[1]);
6 System.out.println("list2 is " + list2[0] + ", " + list2[1]);

```

displays

```

list1 is 7, 2
list2 is 1, 8

```

how to implement `Cloneable`

To define a custom class that implements the `Cloneable` interface, the class must override the `clone()` method in the `Object` class. Listing 13.11 defines a class named `House` that implements `Cloneable` and `Comparable`.

LISTING 13.11 House.java

```

1 public class House implements Cloneable, Comparable<House> {
2     private int id;
3     private double area;
4     private java.util.Date whenBuilt;
5
6     public House(int id, double area) {
7         this.id = id;
8         this.area = area;
9         whenBuilt = new java.util.Date();
10    }

```

```

11  public int getId() {
12      return id;
13  }
14
15
16  public double getArea() {
17      return area;
18  }
19
20  public java.util.Date getWhenBuilt() {
21      return whenBuilt;
22  }
23
24  @Override /** Override the protected clone method defined in
25      the Object class, and strengthen its accessibility */
26  public Object clone() throws CloneNotSupportedException {
27      return super.clone();
28  }
29
30  @Override // Implement the compareTo method defined in Comparable
31  public int compareTo(House o) {
32      if (area > o.area)
33          return 1;
34      else if (area < o.area)
35          return -1;
36      else
37          return 0;
38  }
39 }
```

This exception is thrown if
House does not implement
Cloneable

The **House** class implements the **clone** method (lines 26–28) defined in the **Object** class.
The header is:

```
protected native Object clone() throws CloneNotSupportedException;
```

The keyword **native** indicates that this method is not written in Java but is implemented in the JVM for the native platform. The keyword **protected** restricts the method to be accessed in the same package or in a subclass. For this reason, the **House** class must override the method and change the visibility modifier to **public** so that the method can be used in any package. Since the **clone** method implemented for the native platform in the **Object** class performs the task of cloning objects, the **clone** method in the **House** class simply invokes **super.clone()**. The **clone** method defined in the **Object** class may throw **CloneNotSupportedException**.

CloneNotSupportedException

The **House** class implements the **compareTo** method (lines 31–38) defined in the **Comparable** interface. The method compares the areas of two houses.

You can now create an object of the **House** class and create an identical copy from it, as follows:

```
House house1 = new House(1, 1750.50);
House house2 = (House)house1.clone();
```

house1 and **house2** are two different objects with identical contents. The **clone** method in the **Object** class copies each field from the original object to the target object. If the field is of a primitive type, its value is copied. For example, the value of **area** (**double** type) is copied from **house1** to **house2**. If the field is of an object, the reference of the field is copied. For example, the field **whenBuilt** is of the **Date** class, so its reference is copied into **house2**, as shown in Figure 13.6. Therefore, **house1.whenBuilt == house2.whenBuilt** is true, although **house1 == house2** is false. This is referred to as a *shallow copy* rather than a

shallow copy

deep copy

deep copy, meaning that if the field is of an object type, the object's reference is copied rather than its contents.

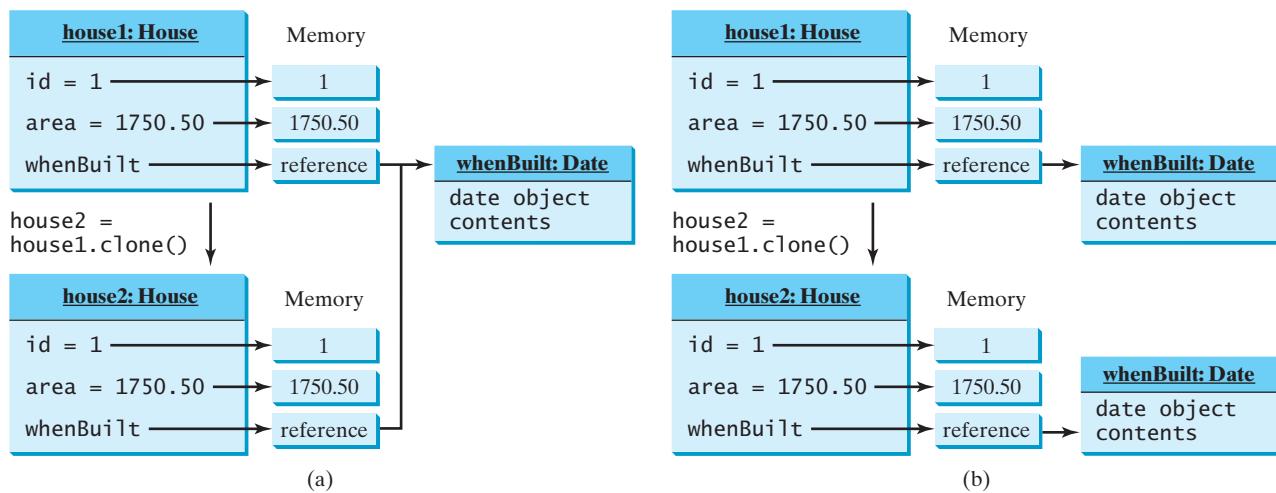


FIGURE 13.6 (a) The default `clone` method performs a shallow copy. (b) The custom `clone` method performs a deep copy.

deep copy

To perform a deep copy for a `House` object, replace the `clone()` method in lines 26–28 with the following code:

```
public Object clone() throws CloneNotSupportedException {
    // Perform a shallow copy
    House houseClone = (House)super.clone();
    // Deep copy on whenBuilt
    houseClone.whenBuilt = (java.util.Date)(whenBuilt.clone());
    return houseClone;
}
```

or

```
public Object clone() {
    try {
        // Perform a shallow copy
        House houseClone = (House)super.clone();
        // Deep copy on whenBuilt
        houseClone.whenBuilt = (java.util.Date)(whenBuilt.clone());
        return houseClone;
    }
    catch (CloneNotSupportedException ex) {
        return null;
    }
}
```

Now if you clone a `House` object in the following code:

```
House house1 = new House(1, 1750.50);
House house2 = (House)house1.clone();
```

`house1.whenBuilt == house2.whenBuilt` will be `false`. `house1` and `house2` contain two different `Date` objects, as shown in Figure 13.6b.



13.22 Can you invoke the `clone()` method to clone an object if the class for the object does not implement the `java.lang.Cloneable`? Does the `Date` class implement `Cloneable`?

13.23 What would happen if the `House` class (defined in Listing 13.11) did not override the `clone()` method or if `House` did not implement `java.lang.Cloneable`?

13.24 Show the output of the following code:

```
java.util.Date date = new java.util.Date();
java.util.Date date1 = date;
java.util.Date date2 = (java.util.Date)(date.clone());
System.out.println(date == date1);
System.out.println(date == date2);
System.out.println(date.equals(date2));
```

13.25 Show the output of the following code:

```
ArrayList<String> list = new ArrayList<>();
list.add("New York");
ArrayList<String> list1 = list;
ArrayList<String> list2 = (ArrayList<String>)(list.clone());
list.add("Atlanta");
System.out.println(list == list1);
System.out.println(list == list2);
System.out.println("list is " + list);
System.out.println("list1 is " + list1);
System.out.println("list2.get(0) is " + list2.get(0));
System.out.println("list2.size() is " + list2.size());
```

13.26 What is wrong in the following code?

```
public class Test {
    public static void main(String[] args) {
        GeometricObject x = new Circle(3);
        GeometricObject y = x.clone();
        System.out.println(x == y);
    }
}
```



13.8 Interfaces vs. Abstract Classes

A class can implement multiple interfaces, but it can only extend one superclass.

An interface can be used more or less the same way as an abstract class, but defining an interface is different from defining an abstract class. Table 13.2 summarizes the differences.

TABLE 13.2 Interfaces vs. Abstract Classes

	Variables	Constructors	Methods
Abstract class	No restrictions.	Constructors are invoked by subclasses through constructor chaining. An abstract class cannot be instantiated using the new operator.	No restrictions.
Interface	All variables must be <code>public static final</code> .	No constructors. An interface cannot be instantiated using the new operator.	All methods must be public abstract instance methods

single inheritance
multiple inheritance

subinterface

Java allows only *single inheritance* for class extension but allows *multiple extensions* for interfaces. For example,

```
public class NewClass extends BaseClass
    implements Interface1, ..., InterfaceN {
    ...
}
```

An interface can inherit other interfaces using the `extends` keyword. Such an interface is called a *subinterface*. For example, `NewInterface` in the following code is a subinterface of `Interface1`, ..., and `InterfaceN`.

```
public interface NewInterface extends Interface1, ..., InterfaceN {
    // constants and abstract methods
}
```

A class implementing `NewInterface` must implement the abstract methods defined in `NewInterface`, `Interface1`, ..., and `InterfaceN`. An interface can extend other interfaces but not classes. A class can extend its superclass and implement multiple interfaces.

All classes share a single root, the `Object` class, but there is no single root for interfaces. Like a class, an interface also defines a type. A variable of an interface type can reference any instance of the class that implements the interface. If a class implements an interface, the interface is like a superclass for the class. You can use an interface as a data type and cast a variable of an interface type to its subclass, and vice versa. For example, suppose that `c` is an instance of `Class2` in Figure 13.7. `c` is also an instance of `Object`, `Class1`, `Interface1`, `Interface1_1`, `Interface1_2`, `Interface2_1`, and `Interface2_2`.

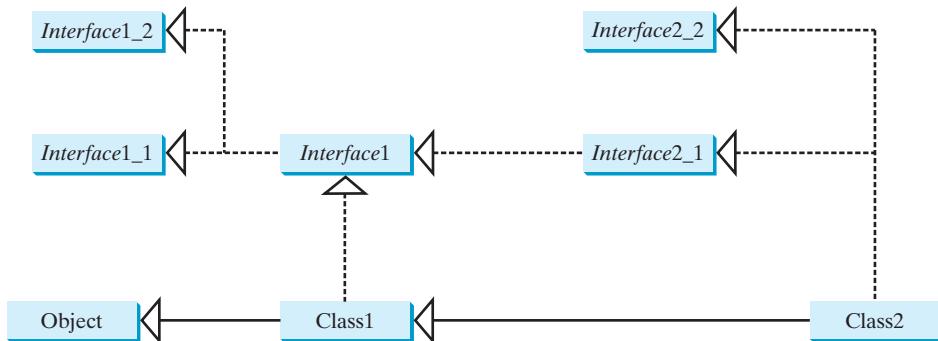


FIGURE 13.7 `Class1` implements `Interface1`; `Interface1` extends `Interface1_1` and `Interface1_2`. `Class2` extends `Class1` and implements `Interface2_1` and `Interface2_2`.

naming convention



Note

Class names are nouns. Interface names may be adjectives or nouns.

is-a relationship
is-kind-of relationship



Design Guide

Abstract classes and interfaces can both be used to specify common behavior of objects. How do you decide whether to use an interface or a class? In general, a *strong is-a relationship* that clearly describes a parent-child relationship should be modeled using classes. For example, Gregorian calendar is a calendar, so the relationship between the class `java.util.GregorianCalendar` and `java.util.Calendar` is modeled using class inheritance. A *weak is-a relationship*, also known as an *is-kind-of relationship*, indicates that an object possesses a certain property. A weak is-a relationship can be modeled using interfaces. For example, all strings are comparable, so the `String` class implements the `Comparable` interface.

In general, interfaces are preferred over abstract classes because an interface can define a common supertype for unrelated classes. Interfaces are more flexible than classes. Consider the **Animal** class. Suppose the **howToEat** method is defined in the **Animal** class, as follows:

```
abstract class Animal {
    public abstract String howToEat();
}
```

interface preferred
Animal class

Two subclasses of **Animal** are defined as follows:

```
class Chicken extends Animal {
    @Override
    public String howToEat() {
        return "Fry it";
    }
}

class Duck extends Animal {
    @Override
    public String howToEat() {
        return "Roast it";
    }
}
```

Chicken class
Duck class

Given this inheritance hierarchy, polymorphism enables you to hold a reference to a **Chicken** object or a **Duck** object in a variable of type **Animal**, as in the following code:

```
public static void main(String[] args) {
    Animal animal = new Chicken();
    eat(animal);

    animal = new Duck();
    eat(animal);
}

public static void eat(Animal animal) {
    animal.howToEat();
}
```

The JVM dynamically decides which **howToEat** method to invoke based on the actual object that invokes the method.

You can define a subclass of **Animal**. However, there is a restriction: The subclass must be for another animal (e.g., **Turkey**).

Interfaces don't have this restriction. Interfaces give you more flexibility than classes, because you don't have to make everything fit into one type of class. You may define the **howToEat()** method in an interface and let it serve as a common supertype for other classes.

For example,

```
public static void main(String[] args) {
    Edible stuff = new Chicken();
    eat(stuff);

    stuff = new Duck();
    eat(stuff);

    stuff = new Broccoli();
    eat(stuff);
}
```

```

public static void eat(Edible stuff) {
    stuff.howToEat();
}

Edible interface

interface Edible {
    public String howToEat();
}

Chicken class

class Chicken implements Edible {
    @Override
    public String howToEat() {
        return "Fry it";
    }
}

Duck class

class Duck implements Edible {
    @Override
    public String howToEat() {
        return "Roast it";
    }
}

Broccoli class

class Broccoli implements Edible {
    @Override
    public String howToEat() {
        return "Stir-fry it";
    }
}

```

To define a class that represents edible objects, simply let the class implement the **Edible** interface. The class is now a subtype of the **Edible** type, and any **Edible** object can be passed to invoke the **howToEat** method.



13.27 Give an example to show why interfaces are preferred over abstract classes.

13.28 Define the terms abstract classes and interfaces. What are the similarities and differences between abstract classes and interfaces?

13.29 True or false?

- An interface is compiled into a separate bytecode file.
- An interface can have static methods.
- An interface can extend one or more interfaces.
- An interface can extend an abstract class.
- An abstract class can extend an interface.

13.9 Case Study: The Rational Class



*This section shows how to design the **Rational** class for representing and processing rational numbers.*

A rational number has a numerator and a denominator in the form **a/b**, where **a** is the numerator and **b** the denominator. For example, **1/3**, **3/4**, and **10/4** are rational numbers.

A rational number cannot have a denominator of **0**, but a numerator of **0** is fine. Every integer **i** is equivalent to a rational number **i/1**. Rational numbers are used in exact computations involving fractions—for example, **1/3 = 0.33333...**. This number cannot be precisely represented in floating-point format using either the data type **double** or **float**. To obtain the exact result, we must use rational numbers.

Java provides data types for integers and floating-point numbers, but not for rational numbers. This section shows how to design a class to represent rational numbers.

Since rational numbers share many common features with integers and floating-point numbers, and **Number** is the root class for numeric wrapper classes, it is appropriate to define **Rational** as a subclass of **Number**. Since rational numbers are comparable, the **Rational** class should also implement the **Comparable** interface. Figure 13.8 illustrates the **Rational** class and its relationship to the **Number** class and the **Comparable** interface.



FIGURE 13.8 The properties, constructors, and methods of the **Rational** class are illustrated in UML.

A rational number consists of a numerator and a denominator. There are many equivalent rational numbers—for example, $1/3 = 2/6 = 3/9 = 4/12$. The numerator and the denominator of $1/3$ have no common divisor except 1, so $1/3$ is said to be in *lowest terms*.

To reduce a rational number to its lowest terms, you need to find the greatest common divisor (GCD) of the absolute values of its numerator and denominator, then divide both the numerator and denominator by this value. You can use the method for computing the GCD of two integers **n** and **d**, as suggested in Listing 5.9, GreatestCommonDivisor.java. The numerator and denominator in a **Rational** object are reduced to their lowest terms.

As usual, let us first write a test program to create two **Rational** objects and test its methods. Listing 13.12 is a test program.

LISTING 13.12 TestRationalClass.java

```

1  public class TestRationalClass {
2      /** Main method */
3      public static void main(String[] args) {
4          // Create and initialize two rational numbers r1 and r2
5          Rational r1 = new Rational(4, 2);
6          Rational r2 = new Rational(2, 3);
7
8          // Display results
  
```

create a Rational
create a Rational

```

add           9     System.out.println(r1 + " + " + r2 + " = " + r1.add(r2));
               10    System.out.println(r1 + " - " + r2 + " = " + r1.subtract(r2));
               11    System.out.println(r1 + " * " + r2 + " = " + r1.multiply(r2));
               12    System.out.println(r1 + " / " + r2 + " = " + r1.divide(r2));
               13    System.out.println(r2 + " is " + r2.doubleValue());
               14  }
               15 }

```



```

2 + 2/3 = 8/3
2 - 2/3 = 4/3
2 * 2/3 = 4/3
2 / 2/3 = 3
2/3 is 0.6666666666666666

```

The `main` method creates two rational numbers, `r1` and `r2` (lines 5–6), and displays the results of `r1 + r2`, `r1 - r2`, `r1 * r2`, and `r1 / r2` (lines 9–12). To perform `r1 + r2`, invoke `r1.add(r2)` to return a new `Rational` object. Similarly, invoke `r1.subtract(r2)` for `r1 - r2`, `r1.multiply(r2)` for `r1 * r2`, and `r1.divide(r2)` for `r1 / r2`.

The `doubleValue()` method displays the double value of `r2` (line 13). The `doubleValue()` method is defined in `java.lang.Number` and overridden in `Rational`.

Note that when a string is concatenated with an object using the plus sign (+), the object's string representation from the `toString()` method is used to concatenate with the string. So `r1 + " + " + r2 + " = " + r1.add(r2)` is equivalent to `r1.toString() + " + " + r2.toString() + " = " + r1.add(r2).toString()`.

The `Rational` class is implemented in Listing 13.13.

LISTING 13.13 Rational.java

```

1  public class Rational extends Number implements Comparable<Rational> {
2      // Data fields for numerator and denominator
3      private long numerator = 0;
4      private long denominator = 1;
5
6      /** Construct a rational with default properties */
7      public Rational() {
8          this(0, 1);
9      }
10
11     /** Construct a rational with specified numerator and denominator */
12     public Rational(long numerator, long denominator) {
13         long gcd = gcd(numerator, denominator);
14         this.numerator = ((denominator > 0) ? 1 : -1) * numerator / gcd;
15         this.denominator = Math.abs(denominator) / gcd;
16     }
17
18     /** Find GCD of two numbers */
19     private static long gcd(long n, long d) {
20         long n1 = Math.abs(n);
21         long n2 = Math.abs(d);
22         int gcd = 1;
23
24         for (int k = 1; k <= n1 && k <= n2; k++) {
25             if (n1 % k == 0 && n2 % k == 0)
26                 gcd = k;
27         }
28
29         return gcd;

```

```

30     }
31
32     /** Return numerator */
33     public long getNumerator() {
34         return numerator;
35     }
36
37     /** Return denominator */
38     public long getDenominator() {
39         return denominator;
40     }
41
42     /** Add a rational number to this rational */
43     public Rational add(Rational secondRational) {
44         long n = numerator * secondRational.getDenominator() +
45             denominator * secondRational.getNumerator();
46         long d = denominator * secondRational.getDenominator();
47         return new Rational(n, d);
48     }
49
50     /** Subtract a rational number from this rational */
51     public Rational subtract(Rational secondRational) {
52         long n = numerator * secondRational.getDenominator()
53             - denominator * secondRational.getNumerator();
54         long d = denominator * secondRational.getDenominator();
55         return new Rational(n, d);
56     }
57
58     /** Multiply a rational number by this rational */
59     public Rational multiply(Rational secondRational) {
60         long n = numerator * secondRational.getNumerator();
61         long d = denominator * secondRational.getDenominator();
62         return new Rational(n, d);
63     }
64
65     /** Divide a rational number by this rational */
66     public Rational divide(Rational secondRational) {
67         long n = numerator * secondRational.getDenominator();
68         long d = denominator * secondRational.numerator;
69         return new Rational(n, d);
70     }
71
72     @Override
73     public String toString() {
74         if (denominator == 1)
75             return numerator + "";
76         else
77             return numerator + "/" + denominator;
78     }
79
80     @Override // Override the equals method in the Object class
81     public boolean equals(Object other) {
82         if ((this.subtract((Rational)(other))).getNumerator() == 0)
83             return true;
84         else
85             return false;
86     }
87
88     @Override // Implement the abstract intValue method in Number
89     public int intValue() {

$$\frac{a}{b} + \frac{c}{d} = \frac{ad + bc}{bd}$$


$$\frac{a}{b} - \frac{c}{d} = \frac{ad - bc}{bd}$$


$$\frac{a}{b} \times \frac{c}{d} = \frac{ac}{bd}$$


$$\frac{a}{b} \div \frac{c}{d} = \frac{ad}{bc}$$


```

```

90     return (int)doubleValue();
91 }
92
93 @Override // Implement the abstract floatValue method in Number
94 public float floatValue() {
95     return (float)doubleValue();
96 }
97
98 @Override // Implement the doubleValue method in Number
99 public double doubleValue() {
100     return numerator * 1.0 / denominator;
101 }
102
103 @Override // Implement the abstract longValue method in Number
104 public long longValue() {
105     return (long)doubleValue();
106 }
107
108 @Override // Implement the compareTo method in Comparable
109 public int compareTo(Rational o) {
110     if (this.subtract(o).getNumerator() > 0)
111         return 1;
112     else if (this.subtract(o).getNumerator() < 0)
113         return -1;
114     else
115         return 0;
116 }
117 }
```

The rational number is encapsulated in a `Rational` object. Internally, a rational number is represented in its lowest terms (line 13), and the numerator determines its sign (line 14). The denominator is always positive (line 15).

The `gcd` method (lines 19–30 in the `Rational` class) is private; it is not intended for use by clients. The `gcd` method is only for internal use by the `Rational` class. The `gcd` method is also static, since it is not dependent on any particular `Rational` object.

The `abs(x)` method (lines 20–21 in the `Rational` class) is defined in the `Math` class and returns the absolute value of `x`.

Two `Rational` objects can interact with each other to perform add, subtract, multiply, and divide operations. These methods return a new `Rational` object (lines 43–70).

The methods `toString` and `equals` in the `Object` class are overridden in the `Rational` class (lines 72–86). The `toString()` method returns a string representation of a `Rational` object in the form `numerator/denominator`, or simply `numerator` if `denominator` is 1. The `equals(Object other)` method returns true if this rational number is equal to the other rational number.

The abstract methods `intValue`, `longValue`, `floatValue`, and `doubleValue` in the `Number` class are implemented in the `Rational` class (lines 88–106). These methods return the `int`, `long`, `float`, and `double` value for this rational number.

The `compareTo(Rational other)` method in the `Comparable` interface is implemented in the `Rational` class (lines 108–116) to compare this rational number to the other rational number.



Tip

The getter methods for the properties `numerator` and `denominator` are provided in the `Rational` class, but the setter methods are not provided, so, once a `Rational` object is created, its contents cannot be changed. The `Rational` class is immutable. The `String` class and the wrapper classes for primitive type values are also immutable.

**Tip**

The numerator and denominator are represented using two variables. It is possible to use an array of two integers to represent the numerator and denominator (see Programming Exercise 13.14). The signatures of the public methods in the `Rational` class are not changed, although the internal representation of a rational number is changed. This is a good example to illustrate the idea that the data fields of a class should be kept private so as to encapsulate the implementation of the class from the use of the class.

encapsulation

overflow

The `Rational` class has serious limitations and can easily overflow. For example, the following code will display an incorrect result, because the denominator is too large.

```
public class Test {
    public static void main(String[] args) {
        Rational r1 = new Rational(1, 123456789);
        Rational r2 = new Rational(1, 123456789);
        Rational r3 = new Rational(1, 123456789);
        System.out.println("r1 * r2 * r3 is " +
            r1.multiply(r2.multiply(r3)));
    }
}
```

```
r1 * r2 * r3 is -1/2204193661661244627
```



To fix it, you can implement the `Rational` class using the `BigInteger` for numerator and denominator (see Programming Exercise 13.15).

**13.30** Show the output of the following code?

```
Rational r1 = new Rational(-2, 6);
System.out.println(r1.getNumerator());
System.out.println(r1.getDenominator());
System.out.println(r1.intValue());
System.out.println(r1.doubleValue());
```

13.31 Why is the following code wrong?

```
Rational r1 = new Rational(-2, 6);
Object r2 = new Rational(1, 45);
System.out.println(r2.compareTo(r1));
```

13.32 Why is the following code wrong?

```
Object r1 = new Rational(-2, 6);
Rational r2 = new Rational(1, 45);
System.out.println(r2.compareTo(r1));
```

13.33 How do you simplify the code in lines 82–85 in Listing 13.13 Rational.java using one line of code without using the if statement?**13.34** Trace the program carefully and show the output of the following code.

```
Rational r1 = new Rational(1, 2);
Rational r2 = new Rational(1, -2);
System.out.println(r1.add(r2));
```

13.10 Class Design Guidelines

Class design guidelines are helpful for designing sound classes.



You have learned how to design classes from the preceding two examples and from many other examples in the preceding chapters. This section summarizes some of the guidelines.

13.10.1 Cohesion

coherent purpose
A class should describe a single entity, and all the class operations should logically fit together to support a coherent purpose. You can use a class for students, for example, but you should not combine students and staff in the same class, because students and staff are different entities.

separate responsibilities
A single entity with many responsibilities can be broken into several classes to separate the responsibilities. The classes `String`, `StringBuilder`, and `StringBuffer` all deal with strings, for example, but have different responsibilities. The `String` class deals with immutable strings, the `StringBuilder` class is for creating mutable strings, and the `StringBuffer` class is similar to `StringBuilder` except that `StringBuffer` contains synchronized methods for updating strings.

13.10.2 Consistency

naming conventions
Follow standard Java programming style and naming conventions. Choose informative names for classes, data fields, and methods. A popular style is to place the data declaration before the constructor and place constructors before methods.

naming consistency
Make the names consistent. It is not a good practice to choose different names for similar operations. For example, the `length()` method returns the size of a `String`, a `StringBuilder`, and a `StringBuffer`. It would be inconsistent if different names were used for this method in these classes.

no-arg constructor
In general, you should consistently provide a public no-arg constructor for constructing a default instance. If a class does not support a no-arg constructor, document the reason. If no constructors are defined explicitly, a public default no-arg constructor with an empty body is assumed.

If you want to prevent users from creating an object for a class, you can declare a private constructor in the class, as is the case for the `Math` class.

13.10.3 Encapsulation

encapsulate data fields
A class should use the `private` modifier to hide its data from direct access by clients. This makes the class easy to maintain.

easy to explain
Provide a getter method only if you want the data field to be readable, and provide a setter method only if you want the data field to be updateable. For example, the `Rational` class provides a getter method for `numerator` and `denominator`, but no setter method, because a `Rational` object is immutable.

13.10.4 Clarity

independent methods
Cohesion, consistency, and encapsulation are good guidelines for achieving design clarity. Additionally, a class should have a clear contract that is easy to explain and easy to understand.

intuitive meaning
Users can incorporate classes in many different combinations, orders, and environments. Therefore, you should design a class that imposes no restrictions on how or when the user can use it, design the properties in a way that lets the user set them in any order and with any combination of values, and design methods that function independently of their order of occurrence. For example, the `Loan` class contains the properties `loanAmount`, `numberOfYears`, and `annualInterestRate`. The values of these properties can be set in any order.

independent properties
Methods should be defined intuitively without causing confusion. For example, the `substring(int beginIndex, int endIndex)` method in the `String` class is somewhat confusing. The method returns a substring from `beginIndex` to `endIndex - 1`, rather than to `endIndex`. It would be more intuitive to return a substring from `beginIndex` to `endIndex`.

You should not declare a data field that can be derived from other data fields. For example, the following `Person` class has two data fields: `birthDate` and `age`. Since `age` can be derived from `birthDate`, `age` should not be declared as a data field.

```
public class Person {
    private java.util.Date birthDate;
```

```
private int age;
...
}
```

13.10.5 Completeness

Classes are designed for use by many different customers. In order to be useful in a wide range of applications, a class should provide a variety of ways for customization through properties and methods. For example, the `String` class contains more than 40 methods that are useful for a variety of applications.

13.10.6 Instance vs. Static

A variable or method that is dependent on a specific instance of the class must be an instance variable or method. A variable that is shared by all the instances of a class should be declared static. For example, the variable `numberOfObjects` in `CircleWithPrivateDataFields` in Listing 9.8 is shared by all the objects of the `CircleWithPrivateDataFields` class and therefore is declared static. A method that is not dependent on a specific instance should be defined as a static method. For instance, the `getNumberOfObjects()` method in `CircleWithPrivateDataFields` is not tied to any specific instance and therefore is defined as a static method.

Always reference static variables and methods from a class name (rather than a reference variable) to improve readability and avoid errors.

Do not pass a parameter from a constructor to initialize a static data field. It is better to use a setter method to change the static data field. Thus, the following class in (a) is better replaced by (b).

```
public class SomeThing {
    private int t1;
    private static int t2;

    public SomeThing(int t1, int t2) {
        ...
    }
}
```

(a)

```
public class SomeThing {
    private int t1;
    private static int t2;

    public SomeThing(int t1) {
        ...
    }

    public static void setT2(int t2) {
        SomeThing.t2 = t2;
    }
}
```

(b)

Instance and static are integral parts of object-oriented programming. A data field or method is either instance or static. Do not mistakenly overlook static data fields or methods. It is a common design error to define an instance method that should have been static. For example, the `factorial(int n)` method for computing the factorial of `n` should be defined static, because it is independent of any specific instance.

A constructor is always instance, because it is used to create a specific instance. A static variable or method can be invoked from an instance method, but an instance variable or method cannot be invoked from a static method.

common design error

13.10.7 Inheritance vs. Aggregation

The difference between inheritance and aggregation is the difference between an is-a and has-a relationship. For example, an apple is a fruit; thus, you would use inheritance to model the relationship between the classes `Apple` and `Fruit`. A person has a name; thus, you would use aggregation to model the relationship between the classes `Person` and `Name`.

13.10.8 Interfaces vs. Abstract Classes

Both interfaces and abstract classes can be used to specify common behavior for objects. How do you decide whether to use an interface or a class? In general, a strong is-a relationship that clearly describes a parent–child relationship should be modeled using classes. For example, since an orange is a fruit, their relationship should be modeled using class inheritance. A weak is-a relationship, also known as an is-kind-of relationship, indicates that an object possesses a certain property. A weak is-a relationship can be modeled using interfaces. For example, all strings are comparable, so the `String` class implements the `Comparable` interface. A circle or a rectangle is a geometric object, so `Circle` can be designed as a subclass of `GeometricObject`. Circles are different and comparable based on their radii, so `Circle` can implement the `Comparable` interface.

Interfaces are more flexible than abstract classes, because a subclass can extend only one superclass but can implement any number of interfaces. However, interfaces cannot contain concrete methods. The virtues of interfaces and abstract classes can be combined by creating an interface with an abstract class that implements it. Then you can use the interface or the abstract class, whichever is convenient. We will give examples of this type of design in Chapter 20, Lists, Stacks, Queues, and Priority Queues.



13.35 Describe class design guidelines.

KEY TERMS

abstract class 496
abstract method 496
deep copy 516
interface 496

marker interface 513
shallow copy 515
subinterface 518

CHAPTER SUMMARY

- 1.** *Abstract classes* are like regular classes with data and methods, but you cannot create instances of abstract classes using the `new` operator.
- 2.** An *abstract method* cannot be contained in a nonabstract class. If a subclass of an abstract superclass does not implement all the inherited abstract methods of the superclass, the subclass must be defined as abstract.
- 3.** A class that contains abstract methods must be abstract. However, it is possible to define an abstract class that doesn't contain any abstract methods.
- 4.** A subclass can be abstract even if its superclass is concrete.
- 5.** An *interface* is a class-like construct that contains only constants and abstract methods. In many ways, an interface is similar to an abstract class, but an abstract class can contain constants and abstract methods as well as variables and concrete methods.
- 6.** An interface is treated like a special class in Java. Each interface is compiled into a separate bytecode file, just like a regular class.
- 7.** The `java.lang.Comparable` interface defines the `compareTo` method. Many classes in the Java library implement `Comparable`.

8. The `java.lang.Cloneable` interface is a *marker interface*. An object of the class that implements the `Cloneable` interface is cloneable.
9. A class can extend only one superclass but can implement one or more interfaces.
10. An interface can extend one or more interfaces.

Quiz

Answer the quiz for this chapter online at www.cs.armstrong.edu/liang/intro10e/quiz.html.

PROGRAMMING EXERCISES

MyProgrammingLab™

Sections 13.2–13.3

****13.1** (*Triangle class*) Design a new `Triangle` class that extends the abstract `GeometricObject` class. Draw the UML diagram for the classes `Triangle` and `GeometricObject` and then implement the `Triangle` class. Write a test program that prompts the user to enter three sides of the triangle, a color, and a Boolean value to indicate whether the triangle is filled. The program should create a `Triangle` object with these sides and set the color and filled properties using the input. The program should display the area, perimeter, color, and true or false to indicate whether it is filled or not.

***13.2** (*Shuffle ArrayList*) Write the following method that shuffles an `ArrayList` of numbers:

```
public static void shuffle(ArrayList<Number> list)
```

***13.3** (*Sort ArrayList*) Write the following method that sorts an `ArrayList` of numbers.

```
public static void sort(ArrayList<Number> list)
```

****13.4** (*Display calendars*) Rewrite the `PrintCalendar` class in Listing 6.12 to display a calendar for a specified month using the `Calendar` and `GregorianCalendar` classes. Your program receives the month and year from the command line. For example:

```
java Exercise13_04 5 2016
```

This displays the calendar shown in Figure 13.9.

Sun	Mon	Tue	Wed	Thu	Fri	Sat
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30	31				

FIGURE 13.9 The program displays a calendar for May 2016.

You also can run the program without the year. In this case, the year is the current year. If you run the program without specifying a month and a year, the month is the current month.

Sections 13.4–13.8

- *13.5 (*Enable GeometricObject comparable*) Modify the **GeometricObject** class to implement the **Comparable** interface, and define a static **max** method in the **GeometricObject** class for finding the larger of two **GeometricObject** objects. Draw the UML diagram and implement the new **GeometricObject** class. Write a test program that uses the **max** method to find the larger of two circles and the larger of two rectangles.
- *13.6 (*The ComparableCircle class*) Define a class named **ComparableCircle** that extends **Circle** and implements **Comparable**. Draw the UML diagram and implement the **compareTo** method to compare the circles on the basis of area. Write a test class to find the larger of two instances of **ComparableCircle** objects.
- *13.7 (*The Colorable interface*) Design an interface named **Colorable** with a **void** method named **howToColor()**. Every class of a colorable object must implement the **Colorable** interface. Design a class named **Square** that extends **GeometricObject** and implements **Colorable**. Implement **howToColor** to display the message **Color all four sides**.
Draw a UML diagram that involves **Colorable**, **Square**, and **GeometricObject**. Write a test program that creates an array of five **GeometricObjects**. For each object in the array, display its area and invoke its **howToColor** method if it is colorable.
- *13.8 (*Revise the MyStack class*) Rewrite the **MyStack** class in Listing 11.10 to perform a deep copy of the **list** field.
- *13.9 (*Enable Circle comparable*) Rewrite the **Circle** class in Listing 13.2 to extend **GeometricObject** and implement the **Comparable** interface. Override the **equals** method in the **Object** class. Two **Circle** objects are equal if their radii are the same. Draw the UML diagram that involves **Circle**, **GeometricObject**, and **Comparable**.
- *13.10 (*Enable Rectangle comparable*) Rewrite the **Rectangle** class in Listing 13.3 to extend **GeometricObject** and implement the **Comparable** interface. Override the **equals** method in the **Object** class. Two **Rectangle** objects are equal if their areas are the same. Draw the UML diagram that involves **Rectangle**, **GeometricObject**, and **Comparable**.
- *13.11 (*The Octagon class*) Write a class named **Octagon** that extends **GeometricObject** and implements the **Comparable** and **Cloneable** interfaces. Assume that all eight sides of the octagon are of equal length. The area can be computed using the following formula:

$$\text{area} = (2 + 4/\sqrt{2}) * \text{side} * \text{side}$$

Draw the UML diagram that involves **Octagon**, **GeometricObject**, **Comparable**, and **Cloneable**. Write a test program that creates an **Octagon** object with side value **5** and displays its area and perimeter. Create a new object using the **clone** method and compare the two objects using the **compareTo** method.

- *13.12 (*Sum the areas of geometric objects*) Write a method that sums the areas of all the geometric objects in an array. The method signature is:

```
public static double sumArea(GeometricObject[] a)
```



VideoNote

Redesign the Rectangle class

Write a test program that creates an array of four objects (two circles and two rectangles) and computes their total area using the `sumArea` method.

- *13.13 (Enable the `Course` class `cloneable`) Rewrite the `Course` class in Listing 10.6 to add a `clone` method to perform a deep copy on the `students` field.

Section 13.9

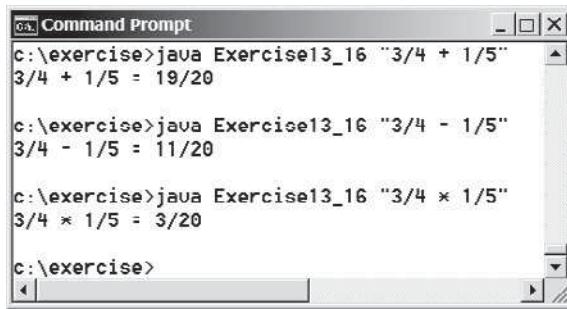
- *13.14 (Demonstrate the benefits of encapsulation) Rewrite the `Rational` class in Listing 13.13 using a new internal representation for the numerator and denominator. Create an array of two integers as follows:

```
private long[] r = new long[2];
```

Use `r[0]` to represent the numerator and `r[1]` to represent the denominator. The signatures of the methods in the `Rational` class are not changed, so a client application that uses the previous `Rational` class can continue to use this new `Rational` class without being recompiled.

- *13.15 (Use `BigInteger` for the `Rational` class) Redesign and implement the `Rational` class in Listing 13.13 using `BigInteger` for the numerator and denominator.

- *13.16 (Create a rational-number calculator) Write a program similar to Listing 7.9, `Calculator.java`. Instead of using integers, use rationals, as shown in Figure 13.10a. You will need to use the `split` method in the `String` class, introduced in Section 10.10.3, Replacing and Splitting Strings, to retrieve the numerator string and denominator string, and convert strings into integers using the `Integer.parseInt` method.



The screenshot shows a Windows Command Prompt window titled "Command Prompt". It contains the following text:

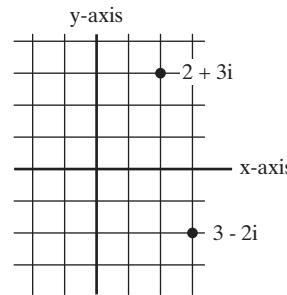
```
c:\exercise>java Exercise13_16 "3/4 + 1/5"
3/4 + 1/5 = 19/20

c:\exercise>java Exercise13_16 "3/4 - 1/5"
3/4 - 1/5 = 11/20

c:\exercise>java Exercise13_16 "3/4 * 1/5"
3/4 * 1/5 = 3/20

c:\exercise>
```

(a)



(b)

FIGURE 13.10 (a) The program takes three arguments (operand1, operator, and operand2) from the command line and displays the expression and the result of the arithmetic operation. (b) A complex number can be interpreted as a point in a plane.

- *13.17 (Math: The `Complex` class) A complex number is a number in the form $a + bi$, where a and b are real numbers and i is $\sqrt{-1}$. The numbers a and b are known as the real part and imaginary part of the complex number, respectively. You can perform addition, subtraction, multiplication, and division for complex numbers using the following formulas:

$$a + bi + c + di = (a + c) + (b + d)i$$

$$a + bi - (c + di) = (a - c) + (b - d)i$$

$$(a + bi)*(c + di) = (ac - bd) + (bc + ad)i$$

$$(a + bi)/(c + di) = (ac + bd)/(c^2 + d^2) + (bc - ad)i/(c^2 + d^2)$$

You can also obtain the absolute value for a complex number using the following formula:

$$|a + bi| = \sqrt{a^2 + b^2}$$

(A complex number can be interpreted as a point on a plane by identifying the (a,b) values as the coordinates of the point. The absolute value of the complex number corresponds to the distance of the point to the origin, as shown in Figure 13.10b.)

Design a class named `Complex` for representing complex numbers and the methods `add`, `subtract`, `multiply`, `divide`, and `abs` for performing complex-number operations, and override `toString` method for returning a string representation for a complex number. The `toString` method returns `(a + bi)` as a string. If `b` is 0, it simply returns `a`. Your `Complex` class should also implement the `Cloneable` interface.

Provide three constructors `Complex(a, b)`, `Complex(a)`, and `Complex()`. `Complex()` creates a `Complex` object for number 0 and `Complex(a)` creates a `Complex` object with 0 for `b`. Also provide the `getRealPart()` and `getImaginaryPart()` methods for returning the real and imaginary part of the complex number, respectively.

Write a test program that prompts the user to enter two complex numbers and displays the result of their addition, subtraction, multiplication, division, and absolute value. Here is a sample run:



```
Enter the first complex number: 3.5 5.5 ↵ Enter
Enter the second complex number: -3.5 1 ↵ Enter
(3.5 + 5.5i) + (-3.5 + 1.0i) = 0.0 + 6.5i
(3.5 + 5.5i) - (-3.5 + 1.0i) = 7.0 + 4.5i
(3.5 + 5.5i) * (-3.5 + 1.0i) = -17.75 + -13.75i
(3.5 + 5.5i) / (-3.5 + 1.0i) = -0.5094 + -1.7i
|(3.5 + 5.5i)| = 6.51920405202649
```

- 13.18** (Use the `Rational` class) Write a program that computes the following summation series using the `Rational` class:

$$\frac{1}{2} + \frac{2}{3} + \frac{3}{4} + \dots + \frac{98}{99} + \frac{99}{100}$$

You will discover that the output is incorrect because of integer overflow (too large). To fix this problem, see Programming Exercise 13.15.

- 13.19** (Convert decimals to fractions) Write a program that prompts the user to enter a decimal number and displays the number in a fraction. Hint: read the decimal number as a string, extract the integer part and fractional part from the string, and use the `BigInteger` implementation of the `Rational` class in Programming Exercise 13.15 to obtain a rational number for the decimal number. Here are some sample runs:



```
Enter a decimal number: 3.25 ↵ Enter
The fraction number is 13/4
```

Enter a decimal number: -0.45452 ↵Enter
 The fraction number is -11363/25000



- 13.20** (*Algebra: solve quadratic equations*) Rewrite Programming Exercise 3.1 to obtain imaginary roots if the determinant is less than 0 using the **Complex** class in Programming Exercise 13.17. Here are some sample runs.

Enter a, b, c: 1 3 1 ↵Enter
 The roots are -0.381966 and -2.61803



Enter a, b, c: 1 2 1 ↵Enter
 The root is -1



Enter a, b, c: 1 2 3 ↵Enter
 The roots are -1.0 + 1.4142i and -1.0 + -1.4142i



- 13.21** (*Algebra: vertex form equations*) The equation of a parabola can be expressed in either standard form ($y = ax^2 + bx + c$) or vertex form ($y = a(x - h)^2 + k$). Write a program that prompts the user to enter a , b , and c as integers in standard form and displays h and k in the vertex form. Here are some sample runs.

Enter a, b, c: 1 3 1 ↵Enter
 h is -3/2 k is -5/4



Enter a, b, c: 2 3 4 ↵Enter
 h is -3/4 k is 23/8

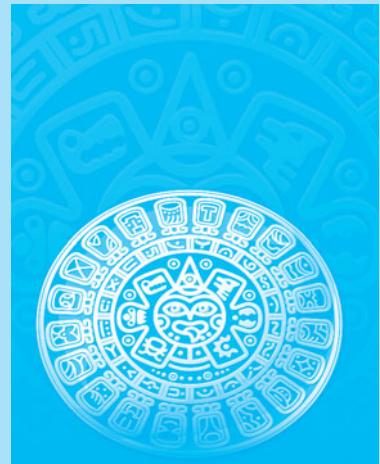
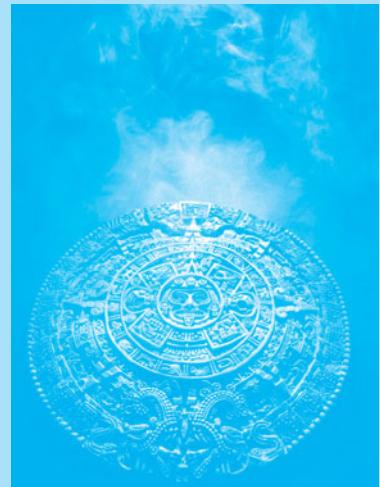


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JAVAFX BASICS

Objectives

- To distinguish between JavaFX, Swing, and AWT (§14.2).
- To write a simple JavaFX program and understand the relationship among stages, scenes, and nodes (§14.3).
- To create user interfaces using panes, UI controls, and shapes (§14.4).
- To update property values automatically through property binding (§14.5).
- To use the common properties **style** and **rotate** for nodes (§14.6).
- To create colors using the **Color** class (§14.7).
- To create fonts using the **Font** class (§14.8).
- To create images using the **Image** class and to create image views using the **ImageView** class (§14.9).
- To layout nodes using **Pane**, **StackPane**, **FlowPane**, **GridPane**, **BorderPane**, **HBox**, and **VBox** (§14.10).
- To display text using the **Text** class and create shapes using **Line**, **Circle**, **Rectangle**, **Ellipse**, **Arc**, **Polygon**, and **Polyline** (§14.11).
- To develop the reusable GUI component **ClockPane** for displaying an analog clock (§14.12).



14.1 Introduction



JavaFX is an excellent pedagogical tool for learning object-oriented programming.

JavaFX is a new framework for developing Java GUI programs. The JavaFX API is an excellent example of how the object-oriented principles are applied. This chapter serves two purposes. First, it presents the basics of JavaFX programming. Second, it uses JavaFX to demonstrate object-oriented design and programming. Specifically, this chapter introduces the framework of JavaFX and discusses JavaFX GUI components and their relationships. You will learn how to develop simple GUI programs using layout panes, buttons, labels, text fields, colors, fonts, images, image views, and shapes.

14.2 JavaFX vs Swing and AWT



Swing and AWT are replaced by the JavaFX platform for developing rich Internet applications.

AWT

Swing

JavaFX

why teaching JavaFX?

When Java was introduced, the GUI classes were bundled in a library known as the *Abstract Windows Toolkit (AWT)*. AWT is fine for developing simple graphical user interfaces, but not for developing comprehensive GUI projects. In addition, AWT is prone to platform-specific bugs. The AWT user-interface components were replaced by a more robust, versatile, and flexible library known as *Swing components*. Swing components are painted directly on canvases using Java code. Swing components depend less on the target platform and use less of the native GUI resources. Swing is designed for developing desktop GUI applications. It is now replaced by a completely new GUI platform known as *JavaFX*. JavaFX incorporates modern GUI technologies to enable you to develop rich Internet applications. A rich Internet application (RIA) is a Web application designed to deliver the same features and functions normally associated with desktop applications. A JavaFX application can run seemlessly on a desktop and from a Web browser. Additionally, JavaFX provides a multi-touch support for touch-enabled devices such as tablets and smart phones. JavaFX has a built-in 2D, 3D, animation support, video and audio playback, and runs as a stand-alone application or from a browser.

This book teaches Java GUI programming using JavaFX for two reasons. First, JavaFX is much simpler to learn and use for new Java programmers. Second, Swing is essentially dead, because it will not receive any further enhancement. JavaFX is the new GUI tool for developing cross-platform-rich Internet applications on desktop computers, on hand-held devices, and on the Web.



14.1 Explain the evolution of Java GUI technologies.

14.2 Explain why this book teaches Java GUI using JavaFX.

14.3 The Basic Structure of a JavaFX Program



The abstract `javafx.application.Application` class defines the essential framework for writing JavaFX programs.

We begin by writing a simple JavaFX program that illustrates the basic structure of a JavaFX program. Every JavaFX program is defined in a class that extends `javafx.application.Application`, as shown in Listing 14.1:

LISTING 14.1 MyJavaFX.java

```

1 import javafx.application.Application;
2 import javafx.scene.Scene;
3 import javafx.scene.control.Button;
4 import javafx.stage.Stage;
```

```

5
6 public class MyJavaFX extends Application {
7     @Override // Override the start method in the Application class
8     public void start(Stage primaryStage) {
9         // Create a scene and place a button in the scene
10        Button btOK = new Button("OK");
11        Scene scene = new Scene(btOK, 200, 250);
12        primaryStage.setTitle("MyJavaFX"); // Set the stage title
13        primaryStage.setScene(scene); // Place the scene in the stage
14        primaryStage.show(); // Display the stage
15    }
16
17    /**
18     * The main method is only needed for the IDE with limited
19     * JavaFX support. Not needed for running from the command line.
20     */
21    public static void main(String[] args) {
22        Application.launch(args);
23    }
24 }
```

You can test and run your program from a command window or from an IDE such as NetBeans or Eclipse. A sample run of the program is shown in Figure 14.1. Supplements II.F–H give the tips for running JavaFX programs from a command window, NetBeans, and Eclipse. A JavaFX program can run stand-alone or from a Web browser. For running a JavaFX program from a Web browser, see Supplement II.I.

JavaFX on NetBenas and
Eclipse



FIGURE 14.1 A simple JavaFX displays a button in the window.

The **Launch** method (line 22) is a static method defined in the **Application** class for launching a stand-alone JavaFX application. The **main** method (lines 21–23) is not needed if you run the program from the command line. It may be needed to launch a JavaFX program from an IDE with a limited JavaFX support. When you run a JavaFX application without a main method, JVM automatically invokes the **Launch** method to run the application.

Launch

The main class overrides the **start** method defined in **javafx.application.Application** (line 8). After a JavaFX application is launched, the JVM constructs an instance of the class using its **no-arg** constructor and invokes its **start** method. The **start** method normally places UI controls in a scene and displays the scene in a stage, as shown in Figure 14.2a.

construct application

Line 10 creates a **Button** object and places it in a **Scene** object (line 11). A **Scene** object can be created using the constructor **Scene(node, width, height)**. This constructor specifies the width and height of the scene and places the node in the scene.

start application

A **Stage** object is a window. A **Stage** object called *primary stage* is automatically created by the JVM when the application is launched. Line 13 sets the scene to the primary stage and line 14 displays the primary stage. JavaFX names the **Stage** and **Scene** classes using the analogy from the theater. You may think stage as the platform to support scenes and nodes as actors to perform in the scenes.

scene

You can create additional stages if needed. The JavaFX program in Listing 14.2 displays two stages, as shown in Figure 14.2b.

primary stage



FIGURE 14.2 (a) Stage is a window for displaying a scene that contains nodes. (b) Multiple stages can be displayed in a JavaFX program.

LISTING 14.2 `MultipleStageDemo.java`

```

primary stage in start
display primary stage
create second stage
display second stage
main method omitted
main method omitted
prevent stage resizing

```

```

1 import javafx.application.Application;
2 import javafx.scene.Scene;
3 import javafx.scene.control.Button;
4 import javafx.stage.Stage;
5
6 public class MultipleStageDemo extends Application {
7     @Override // Override the start method in the Application class
8     public void start(Stage primaryStage) {
9         // Create a scene and place a button in the scene
10        Scene scene = new Scene(new Button("OK"), 200, 250);
11        primaryStage.setTitle("MyJavaFX"); // Set the stage title
12        primaryStage.setScene(scene); // Place the scene in the stage
13        primaryStage.show(); // Display the stage
14
15        Stage stage = new Stage(); // Create a new stage
16        stage.setTitle("Second Stage"); // Set the stage title
17        // Set a scene with a button in the stage
18        stage.setScene(new Scene(new Button("New Stage"), 100, 100));
19        stage.show(); // Display the stage
20    }
21 }

```

Note that the main method is omitted in the listing since it is identical for every JavaFX application. From now on, we will not list the `main` method in our JavaFX source code for brevity.

By default, the user can resize the stage. To prevent the user from resizing the stage, invoke `stage.setResizable(false)`.



- 14.3** How do you define a JavaFX main class? What is the signature of the `start` method? What is a stage? What is a primary stage? Is a primary stage automatically created? How do you display a stage? Can you prevent the user from resizing the stage? Can you replace `Application.launch(args)` by `Launch(args)` in line 22 in Listing 14.1?

- 14.4** Show the output of the following JavaFX program.

```

import javafx.application.Application;
import javafx.stage.Stage;

public class Test extends Application {
    public Test() {
        System.out.println("Test constructor is invoked");
    }
}

```

```

@Override // Override the start method in the Application class
public void start(Stage primaryStage) {
    System.out.println("start method is invoked");
}

public static void main(String[] args) {
    System.out.println("Launch application");
    Application.launch(args);
}
}

```

14.4 Panes, UI Controls, and Shapes

Panes, UI controls, and shapes are subtypes of Node.

When you run MyJavaFX in Listing 14.1, the window is displayed as shown in Figure 14.1. The button is always centered in the scene and occupies the entire window no matter how you resize it. You can fix the problem by setting the position and size properties of a button. However, a better approach is to use container classes, called *panes*, for automatically laying out the nodes in a desired location and size. You place nodes inside a pane and then place the pane into a scene. A *node* is a visual component such as a shape, an image view, a UI control, or a pane. A *shape* refers to a text, line, circle, ellipse, rectangle, arc, polygon, polyline, etc. A *UI control* refers to a label, button, check box, radio button, text field, text area, etc. A scene can be displayed in a stage, as shown in Figure 14.3a. The relationship among **Stage**, **Scene**, **Node**, **Control**, and **Pane** is illustrated in the UML diagram, as shown in Figure 14.3b.

Note that a **Scene** can contain a **Control** or a **Pane**, but not a **Shape** or an **ImageView**. A **Pane** can contain any subtype of **Node**. You can create a **Scene** using the constructor **Scene(Parent, width, height)** or **Scene(Parent)**. The dimension of the scene is automatically decided in the latter constructor. Every subclass of **Node** has a no-arg constructor for creating a default node.

Listing 14.3 gives a program that places a button in a pane, as shown in Figure 14.4



pane

node

shape

UI control

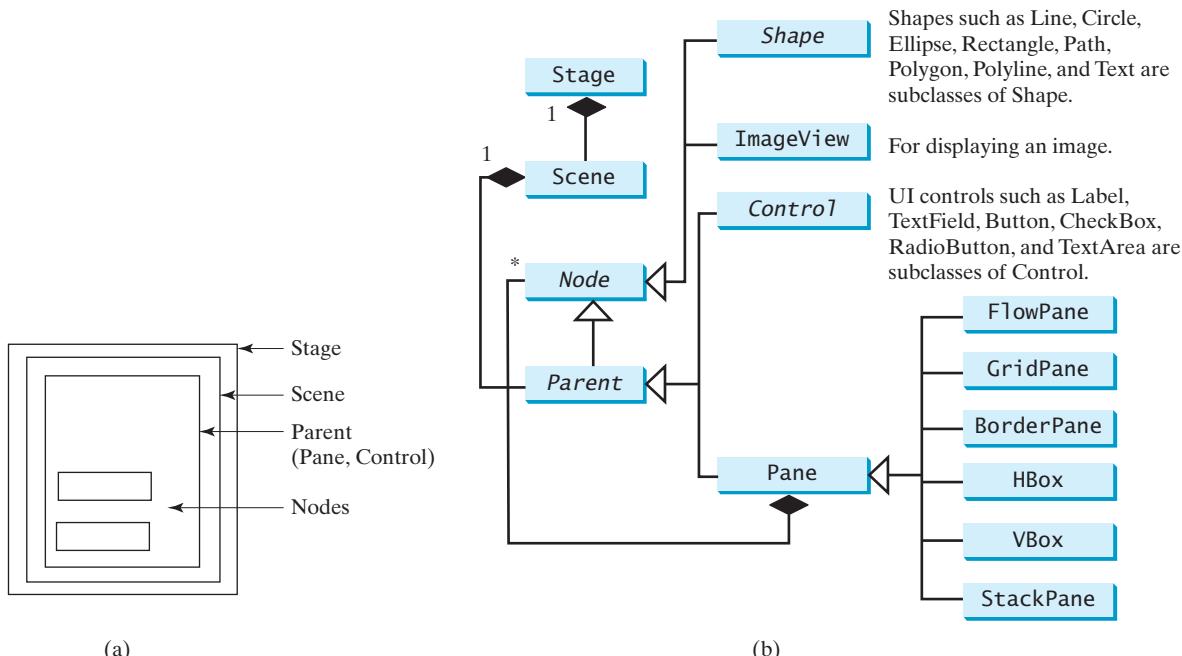


FIGURE 14.3 (a) Panes are used to hold nodes. (b) Nodes can be shapes, image views, UI controls, and panes.

LISTING 14.3 ButtonInPane.java

```

1 import javafx.application.Application;
2 import javafx.scene.Scene;
3 import javafx.scene.control.Button;
4 import javafx.stage.Stage;
5 import javafx.scene.layout.StackPane;
6
7 public class ButtonInPane extends Application {
8     @Override // Override the start method in the Application class
9     public void start(Stage primaryStage) {
10         // Create a scene and place a button in the scene
11         StackPane pane = new StackPane();
12         pane.getChildren().add(new Button("OK"));
13         Scene scene = new Scene(pane, 200, 50);
14         primaryStage.setTitle("Button in a pane"); // Set the stage title
15         primaryStage.setScene(scene); // Place the scene in the stage
16         primaryStage.show(); // Display the stage
17     }
18 }
```

create a pane
add a button
add pane to scene

display stage

main method omitted

**FIGURE 14.4** A button is placed in the center of the pane.

ObservableList

The program creates a **StackPane** (line 11) and adds a button as a child of the pane (line 12). The **getChildren()** method returns an instance of **javafx.collections.ObservableList**. **ObservableList** behaves very much like an **ArrayList** for storing a collection of elements. Invoking **add(e)** adds an element to the list. The **StackPane** places the nodes in the center of the pane on top of each other. Here, there is only one node in the pane. The **StackPane** respects a node's preferred size. So you see the button displayed in its preferred size.

Listing 14.4 gives an example that displays a circle in the center of the pane, as shown in Figure 14.5a.

LISTING 14.4 ShowCircle.javacreate a circle
set circle properties

create a pane

```

1 import javafx.application.Application;
2 import javafx.scene.Scene;
3 import javafx.scene.layout.Pane;
4 import javafx.scene.paint.Color;
5 import javafx.scene.shape.Circle;
6 import javafx.stage.Stage;
7
8 public class ShowCircle extends Application {
9     @Override // Override the start method in the Application class
10    public void start(Stage primaryStage) {
11        // Create a circle and set its properties
12        Circle circle = new Circle();
13        circle.setCenterX(100);
14        circle.setCenterY(100);
15        circle.setRadius(50);
16        circle.setStroke(Color.BLACK);
17        circle.setFill(Color.WHITE);
18
19        // Create a pane to hold the circle
20        Pane pane = new Pane();
```

```

21     pane.getChildren().add(circle);                                add circle to pane
22
23     // Create a scene and place it in the stage
24     Scene scene = new Scene(pane, 200, 200);                      add pane to scene
25     primaryStage.setTitle("ShowCircle"); // Set the stage title
26     primaryStage.setScene(scene); // Place the scene in the stage
27     primaryStage.show(); // Display the stage
28
29 }
  
```

display stage
main method omitted



FIGURE 14.5 (a) A circle is displayed in the center of the scene. (b) The circle is not centered after the window is resized.

The program creates a **Circle** (line 12) and sets its center at (100, 100) (lines 13–14), which is also the center for the scene, since the scene is created with the width and height of 200 (line 24). The radius of the circle is set to 50 (line 15). Note that the measurement units for graphics in Java are all in *pixels*.

The stroke color (i.e., the color to draw the circle) is set to black (line 16). The fill color (i.e., the color to fill the circle) is set to white (line 17). You may set the color to **null** to specify that no color is set.

The program creates a **Pane** (line 20) and places the circle in the pane (line 21). Note that the coordinates of the upper left corner of the pane is (0, 0) in the Java coordinate system, as shown in Figure 14.6a, as opposed to the conventional coordinate system where (0, 0) is at the center of the window, as shown in Figure 14.6b. The *x*-coordinate increases from left to right and the *y*-coordinate increases downward in the Java coordinate system.

The pane is placed in the scene (line 24) and the scene is set in the stage (line 26). The circle is displayed in the center of the stage, as shown in Figure 14.5a. However, if you resize the window, the circle is not centered, as shown in Figure 14.5b. In order to display the circle centered as the window resizes, the *x*- and *y*-coordinates of the circle center need to be reset to the center of the pane. This can be done by using property binding, introduced in the next section.



FIGURE 14.6 The Java coordinate system is measured in pixels, with (0, 0) at its upper-left corner.



- 14.5** How do you create a **Scene** object? How do you set a scene in a stage? How do you place a circle into a scene?
- 14.6** What is a pane? What is a node? How do you place a node in a pane? Can you directly place a **Shape** or an **ImageView** into a **Scene**? Can you directly place a **Control** or a **Pane** into a **Scene**?
- 14.7** How do you create a **Circle**? How do you set its center location and radius? How do you set its stroke color and fill color?



14.5 Property Binding

You can bind a target object to a source object. A change in the source object will be automatically reflected in the target object.

target object
source object
binding object
binding property
bindable object
observable object

JavaFX introduces a new concept called *property binding* that enables a *target object* to be bound to a *source object*. If the value in the source object changes, the target object is also changed automatically. The target object is called a *binding object* or a *binding property* and the source object is called a *bindable object* or *observable object*. As discussed in the preceding listing, the circle is not centered after the window is resized. In order to display the circle centered as the window resizes, the x- and y-coordinates of the circle center need to be reset to the center of the pane. This can be done by binding the **centerX** with pane's **width/2** and **centerY** with pane's **height/2**, as shown in Listing 14.5.



VideoNote

Understand property binding

create a pane

create a circle
bind properties

add circle to pane

add pane to scene

display stage

LISTING 14.5 ShowCircleCentered.java

```

1 import javafx.application.Application;
2 import javafx.scene.Scene;
3 import javafx.scene.layout.Pane;
4 import javafx.scene.paint.Color;
5 import javafx.scene.shape.Circle;
6 import javafx.stage.Stage;
7
8 public class ShowCircleCentered extends Application {
9     @Override // Override the start method in the Application class
10    public void start(Stage primaryStage) {
11        // Create a pane to hold the circle
12        Pane pane = new Pane();
13
14        // Create a circle and set its properties
15        Circle circle = new Circle();
16        circle.centerXProperty().bind(pane.widthProperty().divide(2));
17        circle.centerYProperty().bind(pane.heightProperty().divide(2));
18        circle.setRadius(50);
19        circle.setStroke(Color.BLACK);
20        circle.setFill(Color.WHITE);
21        pane.getChildren().add(circle); // Add circle to the pane
22
23        // Create a scene and place it in the stage
24        Scene scene = new Scene(pane, 200, 200);
25        primaryStage.setTitle("ShowCircleCentered"); // Set the stage title
26        primaryStage.setScene(scene); // Place the scene in the stage
27        primaryStage.show(); // Display the stage
28    }
29 }
```

The **Circle** class has the **centerX** property for representing the x-coordinate of the circle center. This property like many properties in JavaFX classes can be used both as target and source in a property binding. A target listens to the changes in the source and automatically

updates itself once a change is made in the source. A target binds with a source using the **bind** method as follows:

```
target.bind(source);
```

The **bind** method is defined in the **javafx.beans.property.Property** interface. A binding property is an instance of **javafx.beans.property.Property**. A source object is an instance of the **javafx.beans.value.ObservableValue** interface. An **ObservableValue** is an entity that wraps a value and allows to observe the value for changes.

JavaFX defines binding properties for primitive types and strings. For a **double/float/long/int/boolean** value, its binding property type is **DoubleProperty/FloatProperty/LongProperty/IntegerProperty/BooleanProperty**. For a string, its binding property type is **StringProperty**. These properties are also subtypes of **ObservableValue**. So they can also be used as source objects for binding properties.

By convention, each binding property (e.g., **centerX**) in a JavaFX class (e.g., **Circle**) has a getter (e.g., **getCenterX()**) and setter (e.g., **setCenterX(double)**) method for returning and setting the property's value. It also has a getter method for returning the property itself. The naming convention for this method is the property name followed by the word **Property**. For example, the property getter method for **centerX** is **centerXProperty()**. We call the **getCenterX()** method as the *value getter method*, the **setCenterX(double)** method as the *value setter method*, and **centerXProperty()** as the *property getter method*. Note that **getCenterX()** returns a **double** value and **centerXProperty()** returns an object of the **DoubleProperty** type. Figure 14.7a shows the convention for defining a binding property in a class and Figure 14.7b shows a concrete example in which **centerX** is a binding property of the type **DoubleProperty**.

```
public class SomeClassName {
    private PropertyType x;
    /** Value getter method */
    public propertyValueType getX() { ... }
    /** Value setter method */
    public void setX(propertyValueType value) { ... }
    /** Property getter method */
    public PropertyType
        xProperty() { ... }
}
```

(a) x is a binding property

```
public class Circle {
    private DoubleProperty centerX;
    /** Value getter method */
    public double getCenterX() { ... }
    /** Value setter method */
    public void setCenterX(double value) { ... }
    /** Property getter method */
    public DoubleProperty centerXProperty() { ... }
}
```

(b) centerX is binding property

FIGURE 14.7 A binding property has a value getter method, setter method, and property getter method.

The program in Listing 14.5 is the same as in Listing 14.4 except that it binds **circle**'s **centerX** and **centerY** properties to half of **pane**'s width and height (lines 16–17). Note that **circle.centerXProperty()** returns **centerX** and **pane.widthProperty()** returns **width**. Both **centerX** and **width** are binding properties of the **DoubleProperty** type. The numeric binding property classes such as **DoubleProperty** and **IntegerProperty** contain the **add**, **subtract**, **multiply**, and **divide** methods for adding, subtracting, multiplying, and dividing a value in a binding property and returning a new observable property. So, **pane.widthProperty().divide(2)** returns a new observable property that represents half of the **pane**'s width. The statement

```
circle.centerXProperty().bind(pane.widthProperty().divide(2));
```

is same as

```
centerX.bind(width.divide(2));
```

the **Property** interface

the **ObservableValue** interface

common binding properties

common **ObservableValue** objects

value getter method

value setter method

property getter method

Since `centerX` is bound to `width.divide(2)`, when `pane`'s width is changed, `centerX` automatically updates itself to match `pane`'s width / 2.

Listing 14.6 gives another example that demonstrates bindings.

LISTING 14.6 BindingDemo.java

```

1 import javafx.beans.property.DoubleProperty;
2 import javafx.beans.property.SimpleDoubleProperty;
3
4 public class BindingDemo {
5     public static void main(String[] args) {
6         DoubleProperty d1 = new SimpleDoubleProperty(1);
7         DoubleProperty d2 = new SimpleDoubleProperty(2);
8         d1.bind(d2);
9         System.out.println("d1 is " + d1.getValue()
10            + " and d2 is " + d2.getValue());
11         d2.setValue(70.2);
12         System.out.println("d1 is " + d1.getValue()
13            + " and d2 is " + d2.getValue());
14     }
15 }
```

create a DoubleProperty
create a DoubleProperty
bind property

set a new source value



```
d1 is 2.0 and d2 is 2.0
d1 is 70.2 and d2 is 70.2
```

unidirectional binding

bidirectional binding

The program creates an instance of `DoubleProperty` using `SimpleDoubleProperty(1)` (line 6). Note that `DoubleProperty`, `FloatProperty`, `LongProperty`, `IntegerProperty`, and `BooleanProperty` are abstract classes. Their concrete subclasses `SimpleDoubleProperty`, `SimpleFloatProperty`, `SimpleLongProperty`, `SimpleIntegerProperty`, and `SimpleBooleanProperty` are used to create instances of these properties. These classes are very much like wrapper classes `Double`, `Float`, `Long`, `Integer`, and `Boolean` with additional features for binding to a source object.

The program binds `d1` with `d2` (line 8). Now the values in `d1` and `d2` are the same. After setting `d2` to `70.2` (line 11), `d1` also becomes `70.2` (line 13).

The binding demonstrated in this example is known as *unidirectional binding*. Occasionally, it is useful to synchronize two properties so that a change in one property is reflected in another object, and vice versa. This is called a *bidirectional binding*. If the target and source are both binding properties and observable properties, they can be bound bidirectionally using the `bindBidirectional` method.



- 14.8** What is a binding property? What interface defines a binding property? What interface defines a source object? What are the binding object types for `int`, `long`, `float`, `double`, and `boolean`? Are `Integer` and `Double` binding properties? Can `Integer` and `Double` be used as source objects in a binding?
- 14.9** Following the JavaFX binding property naming convention, for a binding property named `age` of the `IntegerProperty` type, what is its value getter method, value setter method, and property getter method?
- 14.10** Can you create an object of `IntegerProperty` using `new IntegerProperty(3)`? If not, what is the correct way to create it? What will the output if line 8 is replaced by `d1.bind(d2.multiply(2))` in Listing 14.6? What will the output if line 8 is replaced by `d1.bind(d2.add(2))` in Listing 14.6?
- 14.11** What is a unidirectional binding and what is bidirectional binding? Are all binding properties capable of bidirectional binding? Write a statement to bind property `d1` with property `d2` bidirectionally.

14.6 Common Properties and Methods for Nodes

The abstract `Node` class defines many properties and methods that are common to all nodes.

Nodes share many common properties. This section introduces two such properties `style` and `rotate`.

JavaFX style properties are similar to cascading style sheets (CSS) used to specify the styles for HTML elements in a Web page. So, the style properties in JavaFX are called *JavaFX CSS*. In JavaFX, a style property is defined with a prefix `-fx-`. Each node has its own style properties. You can find these properties from <http://docs.oracle.com/javafx/2/api/javafx/scene/doc-files/cssref.html>. For information on HTML and CSS, see Supplements V.A and V.B. If you are not familiar with HTML and CSS, you can still use JavaFX CSS.

The syntax for setting a style is `styleName:value`. Multiple style properties for a node can be set together separated by semicolon (`:`). For example, the following statement

```
circle.setStyle("-fx-stroke: black; -fx-fill: red;");
```

setStyle

sets two JavaFX CSS properties for a circle. This statement is equivalent to the following two statements.

```
circle.setStroke(Color.BLACK);
circle.setFill(Color.RED);
```

If an incorrect JavaFX CSS is used, your program will still compile and run, but the style is ignored.

The `rotate` property enables you to specify an angle in degrees for rotating the node from its center. If the degree is positive, the rotation is performed clockwise; otherwise, it is performed counterclockwise. For example, the following code rotates a button 80 degrees.

```
button.setRotate(80);
```

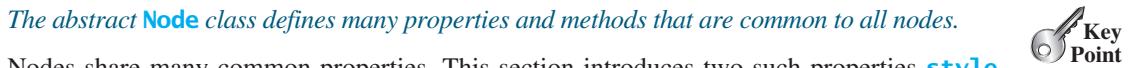
Listing 14.7 gives an example that creates a button, sets its style, and adds it to a pane. It then rotates the pane 45 degrees and set its style with border color red and background color light gray, as shown in Figure 14.8.

LISTING 14.7 NodeStyleRotateDemo.java

```

1 import javafx.application.Application;
2 import javafx.scene.Scene;
3 import javafx.scene.control.Button;
4 import javafx.stage.Stage;
5 import javafx.scene.layout.StackPane;
6
7 public class NodeStyleRotateDemo extends Application {
8     @Override // Override the start method in the Application class
9     public void start(Stage primaryStage) {
10         // Create a scene and place a button in the scene
11         StackPane pane = new StackPane();
12         Button btOK = new Button("OK");
13         btOK.setStyle("-fx-border-color: blue;");
14         pane.getChildren().add(btOK);
15
16         pane.setRotate(45);
17         pane.setStyle(
18             "-fx-border-color: red; -fx-background-color: lightgray;");
19
20         Scene scene = new Scene(pane, 200, 250);
21         primaryStage.setTitle("NodeStyleRotateDemo"); // Set the stage title
22         primaryStage.setScene(scene); // Place the scene in the stage
    
```

rotate the pane
set style for pane



JavaFX CSS

```

23     primaryStage.show(); // Display the stage
24 }
25 }
```

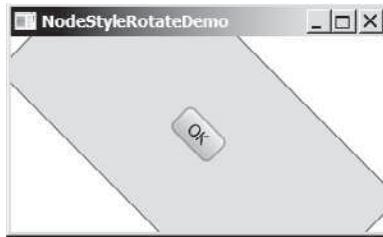


FIGURE 14.8 A pane's style is set and it is rotated 45 degrees.

contains method

As seen in Figure 14.8, the rotate on a pane causes all its containing nodes rotated too.

The **Node** class contains many useful methods that can be applied to all nodes. For example, you can use the **contains(double x, double y)** method to test where a point (x, y) is inside the boundary of a node.



14.12 How do you set a style of a node with border color red? Modify the code to set the text color for the button to red.

14.13 Can you rotate a pane, a text, or a button? Modify the code to rotate the button 15 degrees counterclockwise?



14.7 The Color Class

The Color class can be used to create colors.

JavaFX defines the abstract **Paint** class for painting a node. The **javafx.scene.paint.Color** is a concrete subclass of **Paint**, which is used to encapsulate colors, as shown in Figure 14.9.



FIGURE 14.9 **Color** encapsulates information about colors.

A color instance can be constructed using the following constructor:

```
public Color(double r, double g, double b, double opacity);
```

in which **r**, **g**, and **b** specify a color by its red, green, and blue components with values in the range from **0.0** (darkest shade) to **1.0** (lightest shade). The **opacity** value defines the transparency of a color within the range from **0.0** (completely transparent) to **1.0** (completely opaque). This is known as the **RGBA** model, where **RGBA** stands for red, green, blue, and alpha. The alpha value indicates the opacity. For example,

```
Color color = new Color(0.25, 0.14, 0.333, 0.51);
```

RBGA model

The **Color** class is immutable. Once a **Color** object is created, its properties cannot be changed. The **brighter()** method returns a new **Color** with a larger red, green, and blue values and the **darker()** method returns a new **Color** with a smaller red, green, and blue values. The **opacity** value is the same as in the original **Color** object.

You can also create a **Color** object using the static methods **color(r, g, b)**, **color(r, g, b, opacity)**, **rgb(r, g, b)**, and **rgb(r, g, b, opacity)**.

Alternatively, you can use one of the many standard colors such as **BEIGE**, **BLACK**, **BLUE**, **BROWN**, **CYAN**, **DARKGRAY**, **GOLD**, **GRAY**, **GREEN**, **LIGHTGRAY**, **MAGENTA**, **NAVY**, **ORANGE**, **PINK**, **RED**, **SILVER**, **WHITE**, and **YELLOW** defined as constants in the **Color** class. The following code, for instance, sets the fill color of a circle to red:

```
circle.setFill(Color.RED);
```



14.14 How do you create a color? What is wrong about creating a **Color** using **new Color(1.2, 2.3, 3.5, 4)**? Which of two colors is darker, **new Color(0, 0, 1)** or **new Color(1, 1, 1, 1)**? Does invoking **c.darker()** change the color value in **c**?

14.15 How do you create a **Color** object with a random color?

14.16 How do you set a circle object **c** with blue fill color using the **setFill** method and using the **setStyle** method?



14.8 The **Font** Class

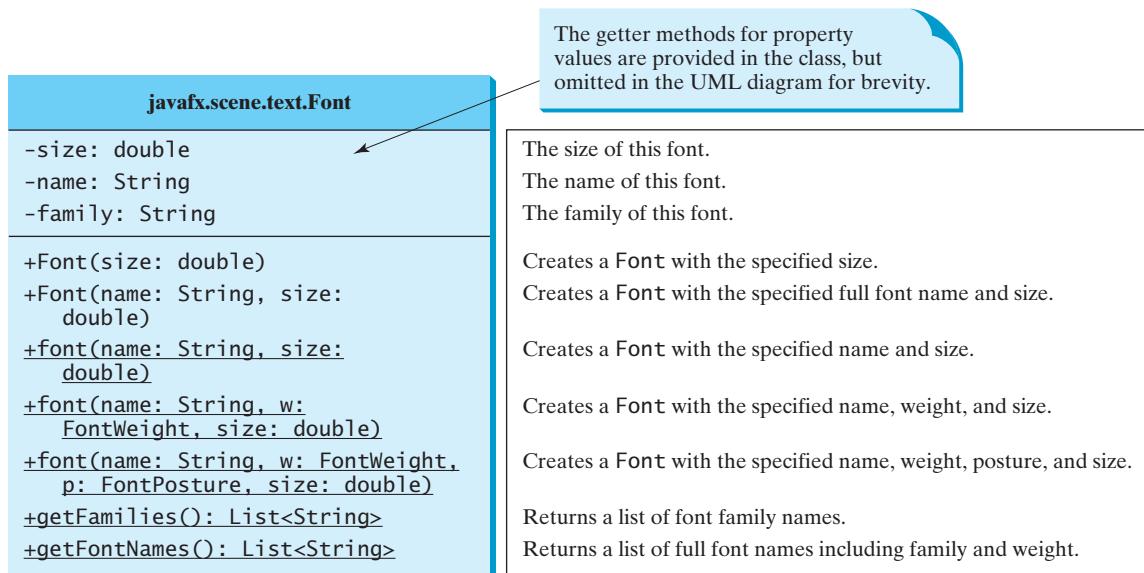
A **Font** describes font name, weight, and size.

You can set fonts for rendering the text. The **javafx.scene.text.Font** class is used to create fonts, as shown in Figure 14.10.

A **Font** instance can be constructed using its constructors or using its static methods. A **Font** is defined by its name, weight, posture, and size. Times, Courier, and Arial are the examples of the font names. You can obtain a list of available font family names by invoking the static **getFamilies()** method. **List** is an interface that defines common methods for a list. **ArrayList** is a concrete implementation of **List**. The font postures are two constants: **FontPosture.ITALIC** and **FontPosture.REGULAR**. For example, the following statements create two fonts.

```
Font font1 = new Font("SansSerif", 16);
Font font2 = Font.font("Times New Roman", FontWeight.BOLD,
    FontPosture.ITALIC, 12);
```

Listing 14.8 gives a program that displays a label using the font (Times New Roman, bold, italic, and size 20), as shown in Figure 14.11.

FIGURE 14.10 `Font` encapsulates information about fonts.**LISTING 14.8** `FontDemo.java`

```

1 import javafx.application.Application;
2 import javafx.scene.Scene;
3 import javafx.scene.layout.*;
4 import javafx.scene.paint.Color;
5 import javafx.scene.shape.Circle;
6 import javafx.scene.text.*;
7 import javafx.scene.control.*;
8 import javafx.stage.Stage;
9
10 public class FontDemo extends Application {
11     @Override // Override the start method in the Application class
12     public void start(Stage primaryStage) {
13         // Create a pane to hold the circle
14         Pane pane = new StackPane();
15
16         // Create a circle and set its properties
17         Circle circle = new Circle();
18         circle.setRadius(50);
19         circle.setStroke(Color.BLACK);
20         circle.setFill(new Color(0.5, 0.5, 0.5, 0.1));
21         pane.getChildren().add(circle); // Add circle to the pane
22
23         // Create a label and set its properties
24         Label label = new Label("JavaFX");
25         label.setFont(Font.font("Times New Roman",
26             FontWeight.BOLD, FontPosture.ITALIC, 20));
27         pane.getChildren().add(label);
28
29         // Create a scene and place it in the stage
30         Scene scene = new Scene(pane);
31         primaryStage.setTitle("FontDemo"); // Set the stage title
32         primaryStage.setScene(scene); // Place the scene in the stage

```

create a StackPane

create a Circle

create a Color

add circle to the pane

create a label

create a font

add label to the pane

```

33     primaryStage.show(); // Display the stage
34 }
35 }
```

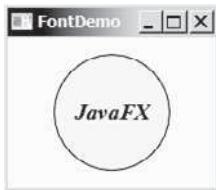


FIGURE 14.11 A label is on top of a circle displayed in the center of the scene.

The program creates a **StackPane** (line 14) and adds a circle and a label to it (lines 21, 27). These two statements can be combined using the following one statement:

```
pane.getChildren().addAll(circle, label);
```

A **StackPane** places the nodes in the center and nodes are placed on top of each other. A custom color is created and set as a fill color for the circle (line 20). The program creates a label and sets a font (line 25) so the text in the label is displayed in Times New Roman, bold, italic, and 20 pixels.

As you resize the window, the circle and label are displayed in the center of the window, because the circle and label are placed in the stack pane. Stack pane automatically places nodes in the center of the pane.

A **Font** object is immutable. Once a **Font** object is created, its properties cannot be changed.

14.17 How do you create a **Font** object with font name **Courier**, size **20**, and weight **bold**?

14.18 How do you find all available fonts on your system?



14.9 The **Image** and **ImageView** Classes

The **Image** class represents a graphical image and the **ImageView** class can be used to display an image.



The **javafx.scene.image.Image** class represents a graphical image and is used for loading an image from a specified filename or a URL. For example, `new Image("image/us.gif")` creates an **Image** object for the image file **us.gif** under the directory **image** in the Java class directory and `new Image("http://www.cs.armstrong.edu/liang/image/us.gif")` creates an **Image** object for the image file in the URL on the Web.

The **javafx.scene.image.ImageView** is a node for displaying an image. An **ImageView** can be created from an **Image** object. For example, the following code creates an **ImageView** from an image file:

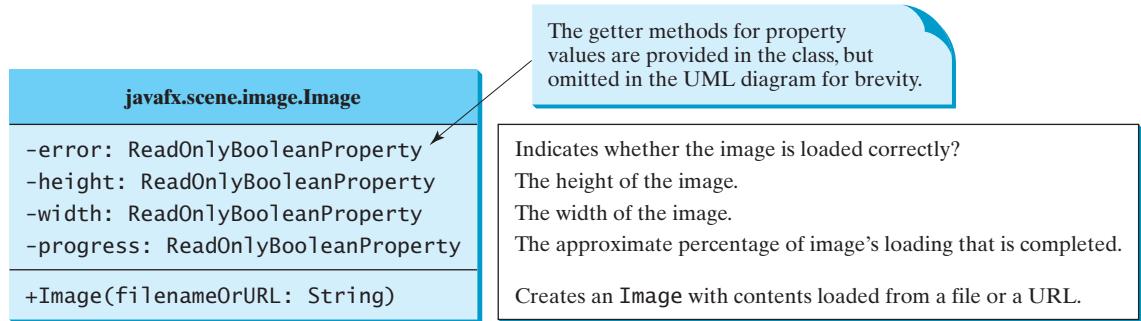
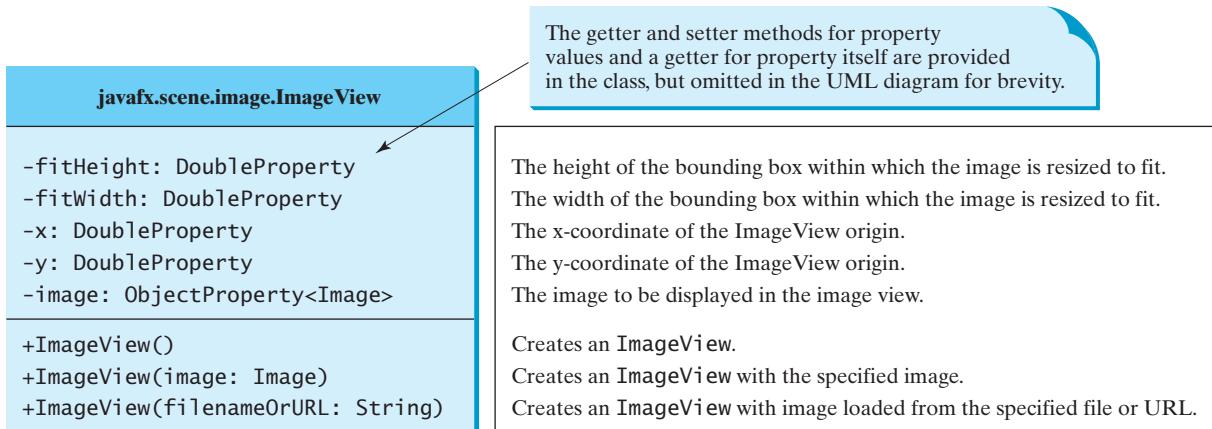
Use Image and ImageView

```
Image image = new Image("image/us.gif");
ImageView imageView = new ImageView(image);
```

Alternatively, you can create an **ImageView** directly from a file or a URL as follows:

```
ImageView imageView = new ImageView("image/us.gif");
```

The UML diagrams for the **Image** and **ImageView** classes are illustrated in Figures 14.12 and 14.13.

**FIGURE 14.12** `Image` encapsulates information about images.**FIGURE 14.13** `ImageView` is a node for displaying an image.

Listing 14.9 displays an image in three image views, as shown in Figure 14.14.

LISTING 14.9 ShowImage.java

```

1 import javafx.application.Application;
2 import javafx.scene.Scene;
3 import javafx.scene.layout.HBox;
4 import javafx.scene.layout.Pane;
5 import javafx.geometry.Insets;
6 import javafx.stage.Stage;
7 import javafx.scene.image.Image;
8 import javafx.scene.image.ImageView;
9
10 public class ShowImage extends Application {
11     @Override // Override the start method in the Application class
12     public void start(Stage primaryStage) {
13         // Create a pane to hold the image views
14         Pane pane = new HBox(10);
15         pane.setPadding(new Insets(5, 5, 5, 5));
16         Image image = new Image("image/us.gif");
17         pane.getChildren().add(new ImageView(image));
18
19         ImageView imageView2 = new ImageView(image);
20         imageView2.setFitHeight(100);
21         imageView2.setFitWidth(100);
    
```

create an HBox

create an image

add an image view to pane

create an image view

set image view properties

```

22     pane.getChildren().add(imageView2);           add an image to pane
23
24     ImageView imageView3 = new ImageView(image);
25     imageView3.setRotate(90);
26     pane.getChildren().add(imageView3);           create an image view
27                                         rotate an image view
28                                         add an image to pane
29
30     // Create a scene and place it in the stage
31     Scene scene = new Scene(pane);
32     primaryStage.setTitle("ShowImage"); // Set the stage title
33     primaryStage.setScene(scene); // Place the scene in the stage
34     primaryStage.show(); // Display the stage
}

```

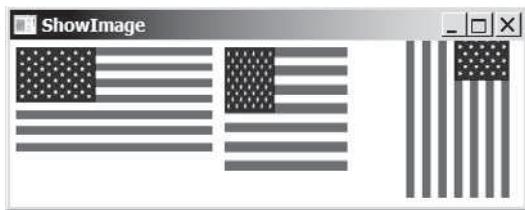


FIGURE 14.14 An image is displayed in three image views placed in a pane.

The program creates an **HBox** (line 14). An **HBox** is a pane that places all nodes horizontally in one row. The program creates an **Image**, and then an **ImageView** for displaying the image, and places the **ImageView** in the **HBox** (line 17).

The program creates the second **ImageView** (line 19), sets its **fitHeight** and **fitWidth** properties (lines 20–21) and places the **ImageView** into the **HBox** (line 22). The program creates the third **ImageView** (line 24), rotates it 90 degrees (line 25), and places it into the **HBox** (line 26). The **setRotate** method is defined in the **Node** class and can be used for any node. Note that an **Image** object can be shared by multiple nodes. In this case, it is shared by three **ImageView**. However, a node such as **ImageView** cannot be shared. You cannot place an **ImageView** multiple times into a pane or scene.

Note that you must place the image file in the same directory as the class file, as shown in the following figure.



If you use the URL to locate the image file, the URL protocol `http://` must be present. So the following code is wrong.

```
new Image("www.cs.armstrong.edu/liang/image/us.gif");
```

It must be replaced by

```
new Image("http://www.cs.armstrong.edu/liang/image/us.gif");
```



- 14.19** How do you create an `Image` from a URL or a filename?
- 14.20** How do you create an `ImageView` from an `Image`, or directly from a file or a URL?
- 14.21** Can you set an `Image` to multiple `ImageView`? Can you display the same `ImageView` multiple times?



14.10 Layout Panes

JavaFX provides many types of panes for automatically laying out nodes in a desired location and size.



Use layout panes

TABLE 14.1 Panes for Containing and Organizing Nodes

Class	Description
<code>Pane</code>	Base class for layout panes. It contains the <code>getChildren()</code> method for returning a list of nodes in the pane.
<code>StackPane</code>	Places the nodes on top of each other in the center of the pane.
<code>FlowPane</code>	Places the nodes row-by-row horizontally or column-by-column vertically.
<code>GridPane</code>	Places the nodes in the cells in a two-dimensional grid.
<code>BorderPane</code>	Places the nodes in the top, right, bottom, left, and center regions.
<code>HBox</code>	Places the nodes in a single row.
<code>VBox</code>	Places the nodes in a single column.

ObservableList
getChildren()

You have used the `Pane` in Listing 14.4, ShowCircle.java. A `Pane` is usually used as a canvas for displaying shapes. `Pane` is the base class for all specialized panes. You have used a specialized pane `StackPane` in Listing 14.3, ButtonInPane.java. Nodes are placed in the center of a `StackPane`. Each pane contains a list for holding nodes in the pane. This list is an instance of `ObservableList`, which can be obtained using pane's `getChildren()` method. You can use the `add(node)` method to add an element to the list, use `addAll(node1, node2, ...)` to add a variable number of nodes to the pane.

14.10.1 FlowPane

`FlowPane` arranges the nodes in the pane horizontally from left to right or vertically from top to bottom in the order in which they were added. When one row or one column is filled, a new row or column is started. You can specify the way the nodes are placed horizontally or vertically using one of two constants: `Orientation.HORIZONTAL` or `Orientation.VERTICAL`. You can also specify the gap between the nodes in pixels. The class diagram for `FlowPane` is shown in Figure 14.15.

Data fields `alignment`, `orientation`, `hgap`, and `vgap` are binding properties. Each binding property in JavaFX has a getter method (e.g., `getHgap()`) that returns its value, a setter method (e.g., `setHgap(double)`) for setting a value, and a getter method that returns the property itself (e.g., `hGapProperty()`). For a data field of `ObjectProperty<T>` type, the value getter method returns a value of type `T` and the property getter method returns a property value of type `ObjectProperty<T>`.



FIGURE 14.15 `FlowPane` lays out nodes row by row horizontally or column by column vertically.

Listing 14.10 gives a program that demonstrates `FlowPane`. The program adds labels and text fields to a `FlowPane`, as shown in Figure 14.16.

LISTING 14.10 ShowFlowPane.java

```

1 import javafx.application.Application;
2 import javafx.geometry.Insets;
3 import javafx.scene.Scene;
4 import javafx.scene.control.Label;
5 import javafx.scene.control.TextField;
6 import javafx.scene.layout.FlowPane;
7 import javafx.stage.Stage;
8
9 public class ShowFlowPane extends Application {                                extend Application
10    @Override // Override the start method in the Application class
11    public void start(Stage primaryStage) {                                     create FlowPane
12        // Create a pane and set its properties
13        FlowPane pane = new FlowPane();                                         add UI controls to pane
14        pane.setPadding(new Insets(11, 12, 13, 14));
15        pane.setHgap(5);
16        pane.setVgap(5);
17
18        // Place nodes in the pane
19        pane.getChildren().addAll(new Label("First Name:"),                   add pane to scene
20            new TextField(), new Label("MI:"));                                 place scene to stage
21        TextField tfMi = new TextField();
22        tfMi.setPrefColumnCount(1);
23        pane.getChildren().addAll(tfMi, new Label("Last Name:"),               display stage
24            new TextField());
25
26        // Create a scene and place it in the stage
27        Scene scene = new Scene(pane, 200, 250);                                }
28        primaryStage.setTitle("ShowFlowPane"); // Set the stage title
29        primaryStage.setScene(scene); // Place the scene in the stage
30        primaryStage.show(); // Display the stage
31    }
32 }
```



FIGURE 14.16 The nodes fill in the rows in the `FlowPane` one after another.

The program creates a `FlowPane` (line 13) and sets its `padding` property with an `Insets` object (line 14). An `Insets` object specifies the size of the border of a pane. The constructor `Insets(11, 12, 13, 14)` creates an `Insets` with the border sizes for top (11), right (12), bottom (13), and left (14) in pixels, as shown in Figure 14.17. You can also use the constructor `Insets(value)` to create an `Insets` with the same value for all four sides. The `hGap` and `vGap` properties are in lines 15–16 to specify the horizontal gap and vertical gap between two nodes in the pane, as shown in Figure 14.17.

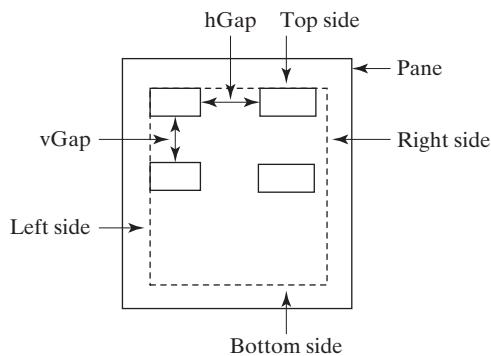


FIGURE 14.17 You can specify `hGap` and `vGap` between the nodes in a `FlowLPane`.

Each `FlowPane` contains an object of `ObservableList` for holding the nodes. This list can be obtained using the `getChildren()` method (line 19). To add a node into a `FlowPane` is to add it to this list using the `add(node)` or `addAll(node1, node2, ...)` method. You can also remove a node from the list using the `remove(node)` method or use the `removeAll()` method to remove all nodes from the pane. The program adds the labels and text fields into the pane (lines 19–24). Invoking `tfMi.setPrefColumnCount(1)` sets the preferred column count to 1 for the MI text field (line 22). The program declares an explicit reference `tfMi` for a `TextField` object for MI. The explicit reference is necessary, because we need to reference the object directly to set its `prefColumnCount` property.

The program adds the pane to the scene (line 27), sets the scene in the stage (line 29), and displays the stage (line 30). Note that if you resize the window, the nodes are automatically rearranged to fit in the pane. In Figure 14.16a, the first row has three nodes, but in Figure 14.16b, the first row has four nodes, because the width has been increased.

Suppose you wish to add the object `tfMi` to a pane ten times; will ten text fields appear in the pane? No, a node such as a text field can be added to only one pane and once. Adding a node to a pane multiple times or to different panes will cause a runtime error.



Note

A node can be placed only in one pane. Therefore, the relationship between a pane and a node is the composition denoted by a filled diamond, as shown in Figure 14.3b.

14.10.2 GridPane

A **GridPane** arranges nodes in a grid (matrix) formation. The nodes are placed in the specified column and row indices. The class diagram for **GridPane** is shown in Figure 14.18.

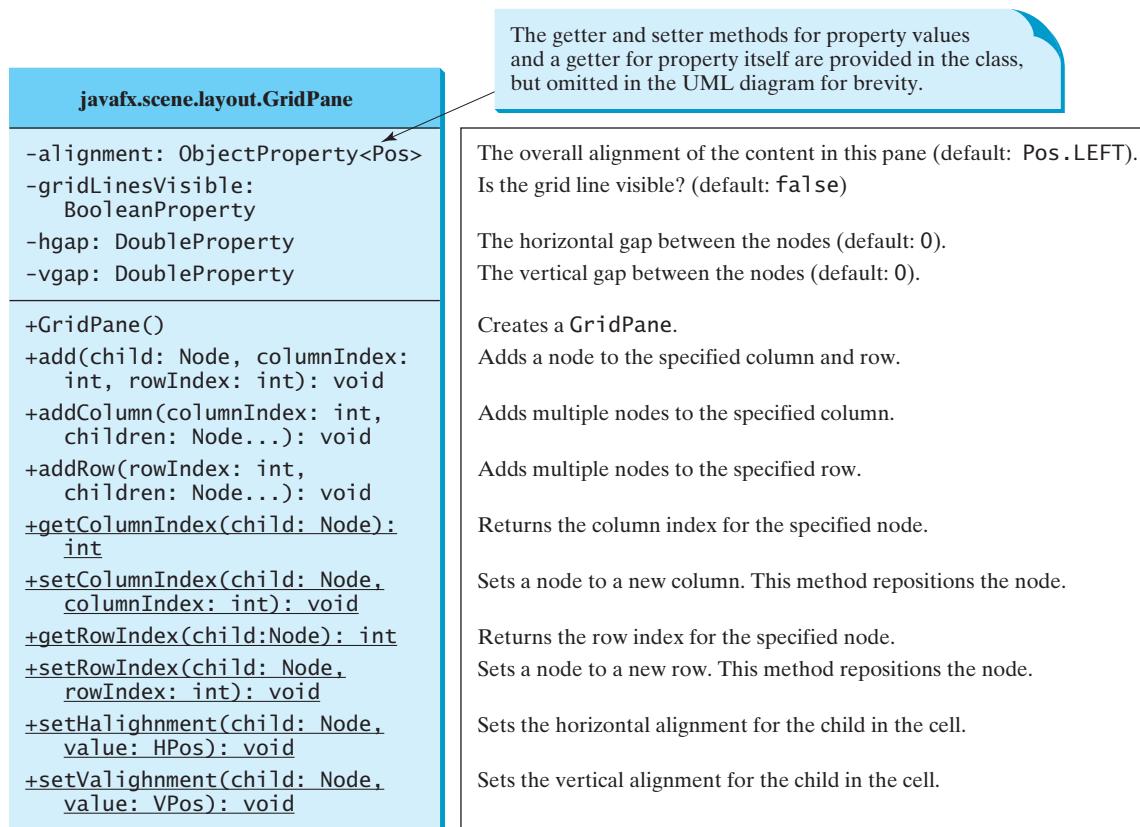


FIGURE 14.18 **GridPane** lays out nodes in the specified cell in a grid.

Listing 14.11 gives a program that demonstrates **GridPane**. The program is similar to the one in Listing 14.10, except that it adds three labels and three text fields, and a button to the specified location in a grid, as shown in Figure 14.19.



FIGURE 14.19 The **GridPane** places the nodes in a grid with a specified column and row indices.

LISTING 14.11 ShowGridPane.java

```

1 import javafx.application.Application;
2 import javafx.geometry.HPos;
3 import javafx.geometry.Insets;

```

```

4 import javafx.geometry.Pos;
5 import javafx.scene.Scene;
6 import javafx.scene.control.Button;
7 import javafx.scene.control.Label;
8 import javafx.scene.control.TextField;
9 import javafx.scene.layout.GridPane;
10 import javafx.stage.Stage;
11
12 public class ShowGridPane extends Application {
13     @Override // Override the start method in the Application class
14     public void start(Stage primaryStage) {
15         // Create a pane and set its properties
16         GridPane pane = new GridPane();
17         pane.setAlignment(Pos.CENTER);
18         pane.setPadding(new Insets(11.5, 12.5, 13.5, 14.5));
19         pane.setHgap(5.5);
20         pane.setVgap(5.5);
21
22         // Place nodes in the pane
23         pane.add(new Label("First Name:"), 0, 0);
24         pane.add(new TextField(), 1, 0);
25         pane.add(new Label("MI:"), 0, 1);
26         pane.add(new TextField(), 1, 1);
27         pane.add(new Label("Last Name:"), 0, 2);
28         pane.add(new TextField(), 1, 2);
29         Button btAdd = new Button("Add Name");
30         pane.add(btAdd, 1, 3);
31         GridPane.setAlignment(btAdd, HPos.RIGHT);
32
33         // Create a scene and place it in the stage
34         Scene scene = new Scene(pane);
35         primaryStage.setTitle("ShowGridPane"); // Set the stage title
36         primaryStage.setScene(scene); // Place the scene in the stage
37         primaryStage.show(); // Display the stage
38     }
39 }

```

create a grid pane
set properties

add label
add text field

add button
align button right

create a scene

display stage

remove nodes

The program creates a **GridPane** (line 16) and sets its properties (line 17–20). The alignment is set to the center position (line 17), which causes the nodes to be placed in the center of the grid pane. If you resize the window, you will see the nodes remains in the center of the grid pane.

The program adds the label in column **0** and row **0** (line 23). The column and row index starts from **0**. The **add** method places a node in the specified column and row. Not every cell in the grid needs to be filled. A button is placed in column 1 and row 3 (line 30), but there are no nodes placed in column 0 and row 3. To remove a node from a **GridPane**, use **pane.getChildren().remove(node)**. To remove all nodes, use **pane.getChildren().removeAll()**.

The program invokes the static **setHAlignment** method to align the button right in the cell (line 31).

Note that the scene size is not set (line 34). In this case, the scene size is automatically computed according to the sizes of the nodes placed inside the scene.

14.10.3 BorderPane

A **BorderPane** can place nodes in five regions: top, bottom, left, right, and center, using the **setTop(node)**, **setBottom(node)**, **setLeft(node)**, **setRight(node)**, and **setCenter(node)** methods. The class diagram for **GridPane** is shown in Figure 14.20.



FIGURE 14.20 `BorderPane` places the nodes in top, bottom, left, right, and center regions.

Listing 14.12 gives a program that demonstrates `BorderPane`. The program places five buttons in the five regions of the pane, as shown in Figure 14.21.

LISTING 14.12 ShowBorderPane.java

```

1 import javafx.application.Application;
2 import javafx.geometry.Insets;
3 import javafx.scene.Scene;
4 import javafx.scene.control.Label;
5 import javafx.scene.layout.BorderPane;
6 import javafx.scene.layout.StackPane;
7 import javafx.stage.Stage;
8
9 public class ShowBorderPane extends Application {
10     @Override // Override the start method in the Application class
11     public void start(Stage primaryStage) {
12         // Create a border pane
13         BorderPane pane = new BorderPane();                                create a border pane
14
15         // Place nodes in the pane
16         pane.setTop(new CustomPane("Top"));                                 add to top
17         pane.setRight(new CustomPane("Right"));                             add to right
18         pane.setBottom(new CustomPane("Bottom"));                            add to bottom
19         pane.setLeft(new CustomPane("Left"));                               add to left
20         pane.setCenter(new CustomPane("Center"));                           add to center
21
22         // Create a scene and place it in the stage
23         Scene scene = new Scene(pane);                                     define a custom pane
24         primaryStage.setTitle("ShowBorderPane"); // Set the stage title
25         primaryStage.setScene(scene); // Place the scene in the stage
26         primaryStage.show(); // Display the stage
27     }
28 }
29
30 // Define a custom pane to hold a label in the center of the pane
31 class CustomPane extends StackPane {
32     public CustomPane(String title) {
33         getChildren().add(new Label(title));
34         setStyle("-fx-border-color: red");
35         setPadding(new Insets(11.5, 12.5, 13.5, 14.5));                add a label to pane
36     }
37 }
```

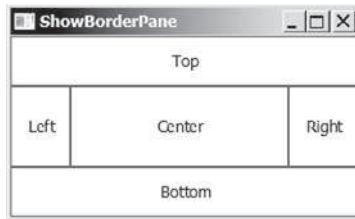


FIGURE 14.21 The **BorderPane** places the nodes in five regions of the pane.

The program defines **CustomPane** that extends **StackPane** (line 31). The constructor of **CustomPane** adds a label with the specified title (line 33), sets a style for the border color, and sets a padding using insets (line 35).

The program creates a **BorderPane** (line 13) and places five instances of **CustomPane** into five regions of the border pane (lines 16–20). Note that a pane is a node. So a pane can be added into another pane. To remove a node from the top region, invoke **setTop(null)**. If a region is not occupied, no space will be allocated for this region.

14.10.4 HBox and VBox

An **HBox** lays out its children in a single horizontal row. A **VBox** lays out its children in a single vertical column. Recall that a **FlowPane** can lay out its children in multiple rows or multiple columns, but an **HBox** or a **VBox** can lay out children only in one row or one column. The class diagrams for **HBox** and **VBox** are shown in Figures 14.22 and 14.23.

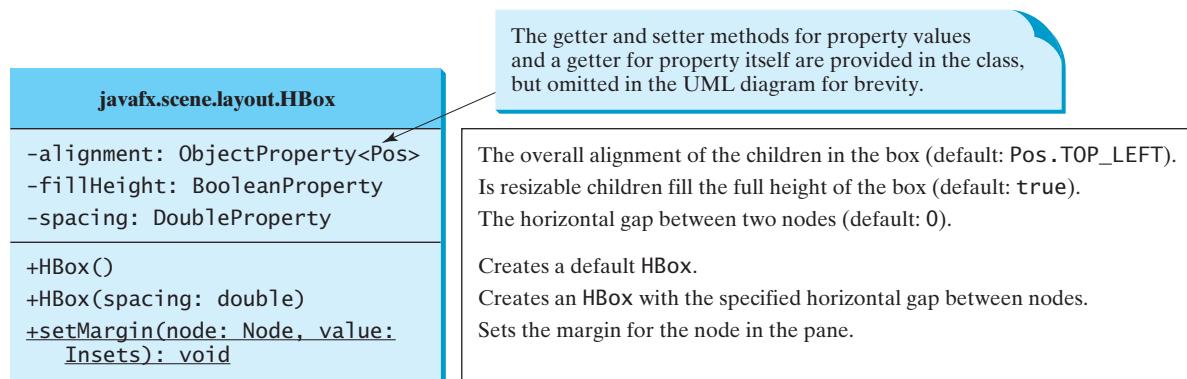


FIGURE 14.22 **HBox** places the nodes in one row.

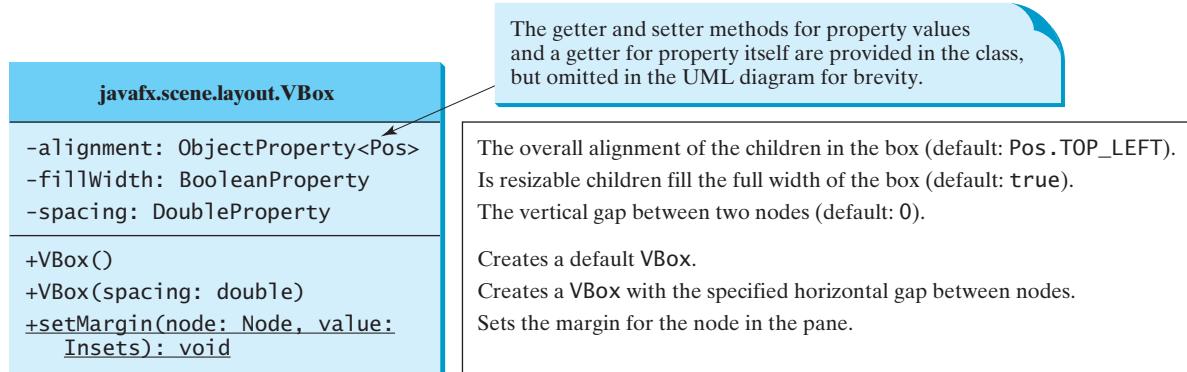


FIGURE 14.23 **VBox** places the nodes in one column.

Listing 14.12 gives a program that demonstrates **HBox** and **VBox**. The program places two buttons in an **HBox** and five labels in a **VBox**, as shown in Figure 14.24.

LISTING 14.13 ShowHBoxVBox.java

```

1 import javafx.application.Application;
2 import javafx.geometry.Insets;
3 import javafx.scene.Scene;
4 import javafx.scene.control.Button;
5 import javafx.scene.control.Label;
6 import javafx.scene.layout.BorderPane;
7 import javafx.scene.layout.HBox;
8 import javafx.scene.layout.VBox;
9 import javafx.stage.Stage;
10 import javafx.scene.image.Image;
11 import javafx.scene.image.ImageView;
12
13 public class ShowHBoxVBox extends Application {
14     @Override // Override the start method in the Application class
15     public void start(Stage primaryStage) {
16         // Create a border pane
17         BorderPane pane = new BorderPane();  
create a border pane
18
19         // Place nodes in the pane
20         pane.setTop(getHBox());  
add an HBox to top
21         pane.setLeft(getVBox());  
add a VBox to left
22
23         // Create a scene and place it in the stage
24         Scene scene = new Scene(pane);
25         primaryStage.setTitle("ShowHBoxVBox"); // Set the stage title
26         primaryStage.setScene(scene); // Place the scene in the stage
27         primaryStage.show(); // Display the stage  
create a scene  
display stage
28     }
29
30     private HBox getHBox() {  
getHBox
31         HBox hBox = new HBox(15);
32         hBox.setPadding(new Insets(15, 15, 15, 15));
33         hBox.setStyle("-fx-background-color: gold");
34         hBox.getChildren().add(new Button("Computer Science"));
35         hBox.getChildren().add(new Button("Chemistry"));
36         ImageView imageView = new ImageView(new Image("image/us.gif"));
37         hBox.getChildren().add(imageView);
38         return hBox;  
add buttons to HBox
39     }
40
41     private VBox getVBox() {  
getVBox
42         VBox vBox = new VBox(15);
43         vBox.setPadding(new Insets(15, 5, 5, 5));
44         vBox.getChildren().add(new Label("Courses"));  
add a label
45
46         Label[] courses = {new Label("CSCI 1301"), new Label("CSCI 1302"),
47             new Label("CSCI 2410"), new Label("CSCI 3720")};  

48
49         for (Label course: courses) {
50             vBox.setMargin(course, new Insets(0, 0, 0, 15));  
set margin
51             vBox.getChildren().add(course);  
add a label
52         }
53
54         return vBox;  
return vBox
55     }
56 }
```



FIGURE 14.24 The `HBox` places the nodes in one row and the `VBox` places the nodes in one column.

The program defines the `getHBox()` method. This method returns an `HBox` that contains two buttons and an image view (lines 30–39). The background color of the `HBox` is set to gold using Java CSS (line 33). The program defines the `getVBox()` method. This method returns a `VBox` that contains five labels (lines 41–55). The first label is added to the `VBox` in line 44 and the other four are added in line 51. The `setMargin` method is used to set a node's margin when placed inside the `VBox` (line 50).



- 14.22** How do you add a node to a `Pane`, `StackPane`, `FlowPane`, `GridPane`, `BorderPane`, `HBox`, and `VBox`? How do you remove a node from these panes?
- 14.23** How do you set the alignment to right for nodes in a `FlowPane`, `GridPane`, `HBox`, and `VBox`?
- 14.24** How do you set the horizontal gap and vertical gap between nodes in 8 pixels in a `FlowPane` and `GridPane` and set spacing in 8 pixels in an `HBox` and `VBox`?
- 14.25** How do you get the column and row index of a node in a `GridPane`? How do you reposition a node in a `GridPane`?
- 14.26** What are the differences between a `FlowPane` and an `HBox` or a `VBox`?

14.11 Shapes



JavaFX provides many shape classes for drawing texts, lines, circles, rectangles, ellipses, arcs, polygons, and polylines.



VideoNote
Use shapes

The `Shape` class is the abstract base class that defines the common properties for all shapes. Among them are the `fill`, `stroke`, and `strokeWidth` properties. The `fill` property specifies a color that fills the interior of a shape. The `stroke` property specifies a color that is used to draw the outline of a shape. The `strokeWidth` property specifies the width of the outline of a shape. This section introduces the classes `Text`, `Line`, `Rectangle`, `Circle`, `Ellipse`, `Arc`, `Polygon`, and `Polyline` for drawing texts and simple shapes. All these are subclasses of `Shape`, as shown in Figure 14.25.

14.11.1 Text

The `Text` class defines a node that displays a string at a starting point (`x`, `y`), as shown in Figure 14.27a. A `Text` object is usually placed in a pane. The pane's upper-left corner point is `(0, 0)` and the bottom-right point is `(pane.getWidth(), pane.getHeight())`. A string may be displayed in multiple lines separated by `\n`. The UML diagram for the `Text` class is shown in Figure 14.26. Listing 14.13 gives an example that demonstrates text, as shown in Figure 14.27b.

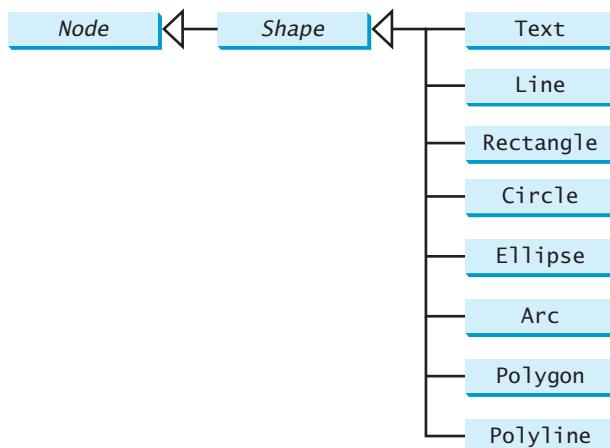


FIGURE 14.25 A shape is a node. The **Shape** class is the root of all shape classes.

javafx.scene.text.Text

-text: StringProperty
 -x: DoubleProperty
 -y: DoubleProperty
 -underline: BooleanProperty
 -strikethrough: BooleanProperty
 -font: ObjectProperty

+Text()
 +Text(text: String)
 +Text(x: double, y: double,
 text: String)

The getter and setter methods for property values
 and a getter for property itself are provided in the class,
 but omitted in the UML diagram for brevity.

Defines the text to be displayed.
 Defines the x-coordinate of text (default 0).
 Defines the y-coordinate of text (default 0).
 Defines if each line has an underline below it (default `false`).
 Defines if each line has a line through it (default `false`).
 Defines the font for the text.

Creates an empty Text.
 Creates a Text with the specified text.
 Creates a Text with the specified x-, y-coordinates and text.

FIGURE 14.26 **Text** defines a node for displaying a text.

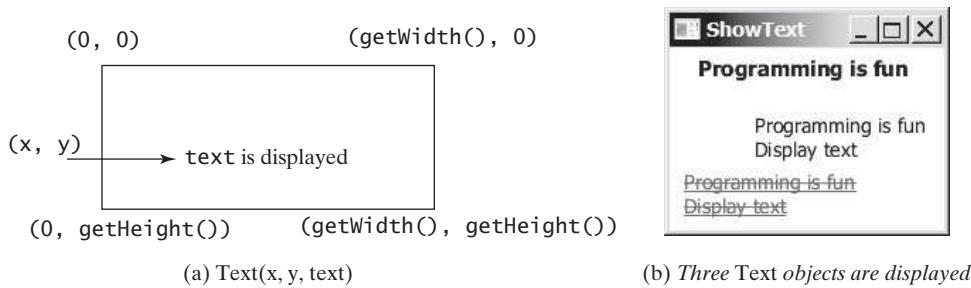


FIGURE 14.27 A **Text** object is created to display a text.

LISTING 14.14 ShowText.java

```

1 import javafx.application.Application;
2 import javafx.scene.Scene;
3 import javafx.scene.layout.Pane;
4 import javafx.scene.paint.Color;
5 import javafx.geometry.Insets;
  
```

```

6 import javafx.stage.Stage;
7 import javafx.scene.text.Text;
8 import javafx.scene.text.Font;
9 import javafx.scene.text.FontWeight;
10 import javafx.scene.text.FontPosture;
11
12 public class ShowText extends Application {
13     @Override // Override the start method in the Application class
14     public void start(Stage primaryStage) {
15         // Create a pane to hold the texts
16         Pane pane = new Pane();
17         pane.setPadding(new Insets(5, 5, 5, 5));
18         Text text1 = new Text(20, 20, "Programming is fun");
19         text1.setFont(Font.font("Courier", FontWeight.BOLD,
20             FontPosture.ITALIC, 15));
21         pane.getChildren().add(text1);
22
23         Text text2 = new Text(60, 60, "Programming is fun\nDisplay text");
24         pane.getChildren().add(text2);
25
26         Text text3 = new Text(10, 100, "Programming is fun\nDisplay text");
27         text3.setFill(Color.RED);
28         text3.setUnderline(true);
29         text3.setStrikethrough(true);
30         pane.getChildren().add(text3);
31
32         // Create a scene and place it in the stage
33         Scene scene = new Scene(pane);
34         primaryStage.setTitle("ShowText"); // Set the stage title
35         primaryStage.setScene(scene); // Place the scene in the stage
36         primaryStage.show(); // Display the stage
37     }
38 }

```

The program creates a `Text` (line 18), sets its font (line 19), and places it to the pane (line 21). The program creates another `Text` with multiple lines (line 23) and places it to the pane (line 24). The program creates the third `Text` (line 26), sets its color (line 27), sets an underline and a strike through line (lines 28–29), and places it to the pane (line 30).

14.11.2 Line

A line connects two points with four parameters `startX`, `startY`, `endX`, and `endY`, as shown in Figure 14.29a. The `Line` class defines a line. The UML diagram for the `Line` class is shown in Figure 14.28. Listing 14.15 gives an example that demonstrates text, as shown in Figure 14.29b.

LISTING 14.15 ShowLine.java

```

1 import javafx.application.Application;
2 import javafx.scene.Scene;
3 import javafx.scene.layout.Pane;
4 import javafx.scene.paint.Color;
5 import javafx.stage.Stage;
6 import javafx.scene.shape.Line;
7
8 public class ShowLine extends Application {
9     @Override // Override the start method in the Application class
10    public void start(Stage primaryStage) {
11        // Create a scene and place it in the stage

```

```

12     Scene scene = new Scene(new LinePane(), 200, 200);
13     primaryStage.setTitle("ShowLine"); // Set the stage title
14     primaryStage.setScene(scene); // Place the scene in the stage
15     primaryStage.show(); // Display the stage
16 }
17 }
18
19 class LinePane extends Pane {
20     public LinePane() {
21         Line line1 = new Line(10, 10, 10, 10);
22         line1.endXProperty().bind(widthProperty().subtract(10));
23         line1.endYProperty().bind(heightProperty().subtract(10));
24         line1.setStrokeWidth(5);
25         line1.setStroke(Color.GREEN);
26         getChildren().add(line1);
27
28         Line line2 = new Line(10, 10, 10, 10);
29         line2.startXProperty().bind(widthProperty().subtract(10));
30         line2.endYProperty().bind(heightProperty().subtract(10));
31         line2.setStrokeWidth(5);
32         line2.setStroke(Color.GREEN);
33         getChildren().add(line2);
34     }
35 }

```

create a pane in scene

define a custom pane

create a line

set stroke width

set stroke

add line to pane

create a line

add line to pane

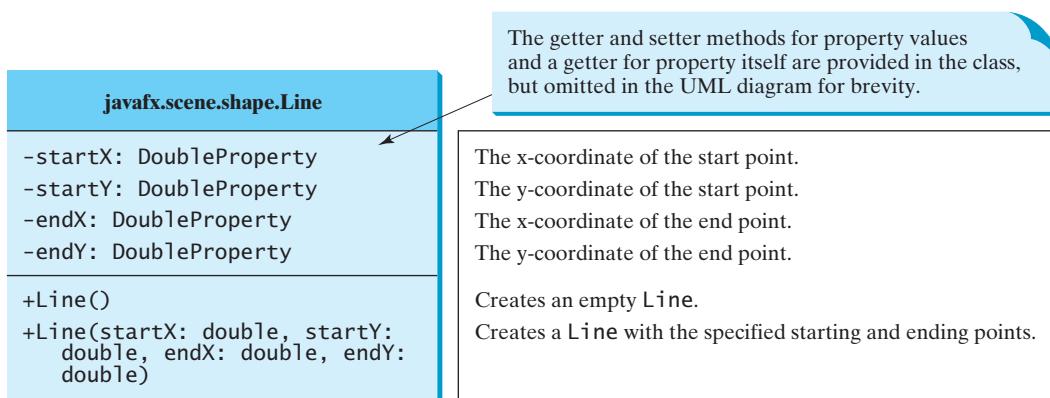


FIGURE 14.28 The **Line** class defines a line.

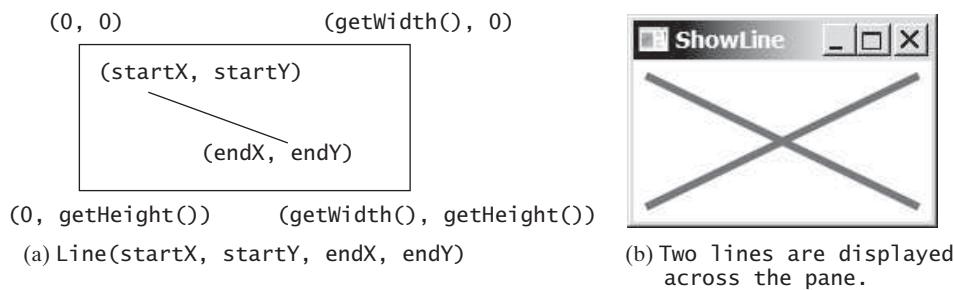


FIGURE 14.29 A **Line** object is created to display a line.

The program defines a custom pane class named **LinePane** (line 19). The custom pane class creates two lines and binds the starting and ending points of the line with the width and height of the pane (lines 22–23, 29–30) so that the two points of the lines are changed as the pane is resized.

14.11.3 Rectangle

A rectangle is defined by the parameters `x`, `y`, `width`, `height`, `arcWidth`, and `arcHeight`, as shown in Figure 14.31a. The rectangle's upper-left corner point is at `(x, y)` and parameter `aw` (`arcWidth`) is the horizontal diameter of the arcs at the corner, and `ah` (`arcHeight`) is the vertical diameter of the arcs at the corner.

The `Rectangle` class defines a rectangle. The UML diagram for the `Rectangle` class is shown in Figure 14.30. Listing 14.15 gives an example that demonstrates rectangles, as shown in Figure 14.31b.



FIGURE 14.30 The `Rectangle` class defines a rectangle.

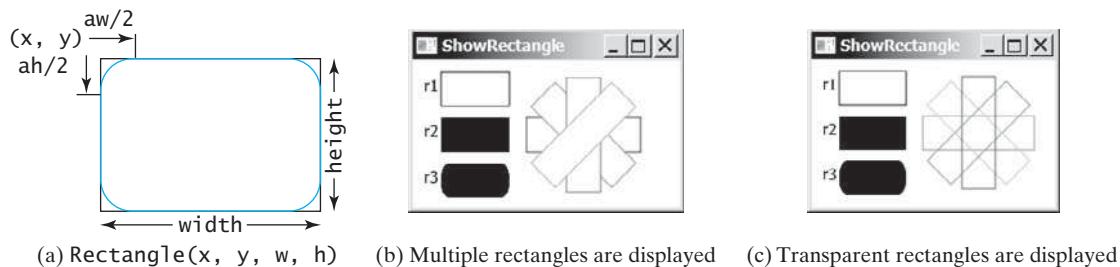


FIGURE 14.31 A `Rectangle` object is created to display a rectangle.

LISTING 14.16 ShowRectangle.java

```

1 import javafx.application.Application;
2 import javafx.scene.Scene;
3 import javafx.scene.layout.Pane;
4 import javafx.scene.paint.Color;
5 import javafx.stage.Stage;
6 import javafx.scene.text.Text;
7 import javafx.scene.shape.Rectangle;
8
9 public class ShowRectangle extends Application {
10     @Override // Override the start method in the Application class
11     public void start(Stage primaryStage) {
12         // Create a pane

```

```

13     Pane pane = new Pane();
14
15     // Create rectangles and add to pane
16     Rectangle r1 = new Rectangle(25, 10, 60, 30);
17     r1.setStroke(Color.BLACK);
18     r1.setFill(Color.WHITE);
19     pane.getChildren().add(new Text(10, 27, "r1"));
20     pane.getChildren().add(r1);
21
22     Rectangle r2 = new Rectangle(25, 50, 60, 30);
23     pane.getChildren().add(new Text(10, 67, "r2"));
24     pane.getChildren().add(r2);
25
26     Rectangle r3 = new Rectangle(25, 90, 60, 30);
27     r3.setArcWidth(15);
28     r3.setArcHeight(25);
29     pane.getChildren().add(new Text(10, 107, "r3"));
30     pane.getChildren().add(r3);
31
32     for (int i = 0; i < 4; i++) {
33         Rectangle r = new Rectangle(100, 50, 100, 30);
34         r.setRotate(i * 360 / 8);
35         r.setStroke(Color.color(Math.random(), Math.random(),
36             Math.random()));
37         r.setFill(Color.WHITE);
38         pane.getChildren().add(r);
39     }
40
41     // Create a scene and place it in the stage
42     Scene scene = new Scene(pane, 250, 150);
43     primaryStage.setTitle("ShowRectangle"); // Set the stage title
44     primaryStage.setScene(scene); // Place the scene in the stage
45     primaryStage.show(); // Display the stage
46 }
47 }
```

The program creates multiple rectangles. By default, the fill color is black. So a rectangle is filled with black color. The stroke color is white by default. Line 17 sets stroke color of rectangle **r1** to black. The program creates rectangle **r3** (line 26) and sets its arc width and arc height (lines 27–28). So **r3** is displayed as a rounded rectangle.

The program repeatedly creates a rectangle (line 33), rotates it (line 34), sets a random stroke color (lines 35–36), its fill color to white (line 37), and adds the rectangle to the pane (line 38).

If line 37 is replaced by the following line

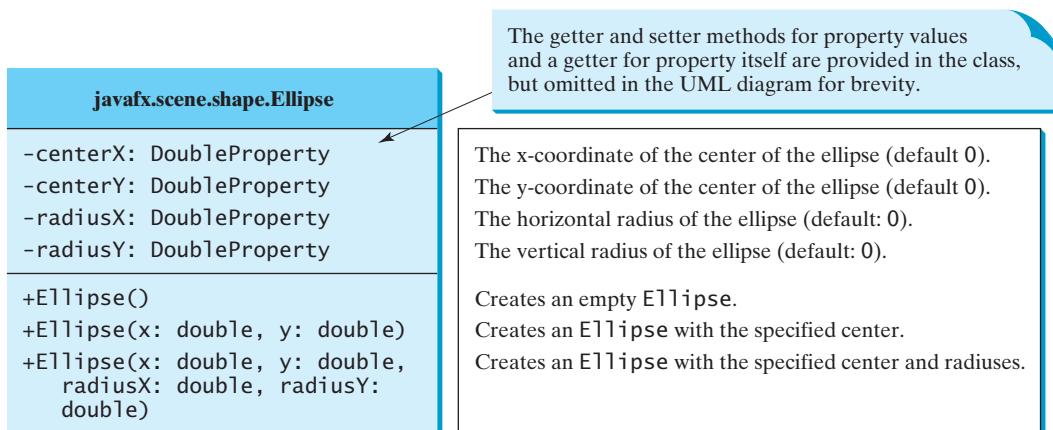
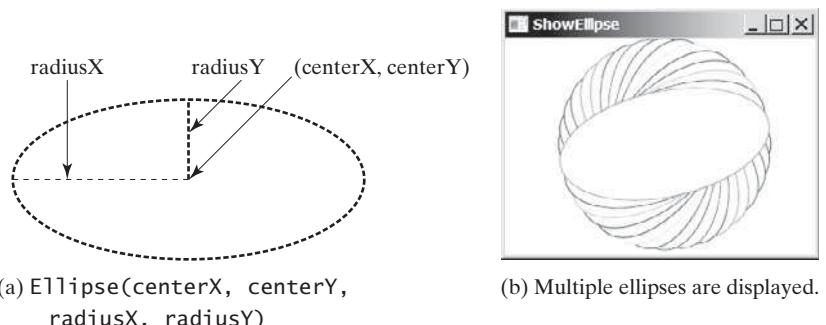
```
r.setFill(null);
```

the rectangle is not filled with a color. So they are displayed as shown in Figure 14.31c.

14.11.4 Circle and Ellipse

You have used circles in several examples early in this chapter. A circle is defined by its parameters **centerX**, **centerY**, and **radius**. The **Circle** class defines a circle. The UML diagram for the **Circle** class is shown in Figure 14.32.

An ellipse is defined by its parameters **centerX**, **centerY**, **radiusX**, and **radiusY**, as shown in Figure 14.34a. The **Ellipse** class defines an ellipse. The UML diagram for the **Ellipse** class is shown in Figure 14.33. Listing 14.17 gives an example that demonstrates ellipses, as shown in Figure 14.34b.

FIGURE 14.32 The **Circle** class defines circles.FIGURE 14.33 The **Ellipse** class defines ellipses.FIGURE 14.34 An **Ellipse** object is created to display an ellipse.**LISTING 14.17 ShowEllipse.java**

```

1 import javafx.application.Application;
2 import javafx.scene.Scene;
3 import javafx.scene.layout.Pane;
4 import javafx.scene.paint.Color;
5 import javafx.stage.Stage;
6 import javafx.scene.shape.Ellipse;
7
8 public class ShowEllipse extends Application {
9   @Override // Override the start method in the Application class
  
```

```

10 public void start(Stage primaryStage) {
11     // Create a pane
12     Pane pane = new Pane();
13
14     for (int i = 0; i < 16; i++) {
15         // Create an ellipse and add it to pane
16         Ellipse e1 = new Ellipse(150, 100, 100, 50);
17         e1.setStroke(Color.color(Math.random(), Math.random(),
18             Math.random()));
19         e1.setFill(Color.WHITE);
20         e1.setRotate(i * 180 / 16);
21         pane.getChildren().add(e1);
22     }
23
24     // Create a scene and place it in the stage
25     Scene scene = new Scene(pane, 300, 200);
26     primaryStage.setTitle("ShowEllipse"); // Set the stage title
27     primaryStage.setScene(scene); // Place the scene in the stage
28     primaryStage.show(); // Display the stage
29 }
30 }
```

The program repeatedly creates an ellipse (line 16), sets a random stroke color (lines 17–18), sets its fill color to white (line 19), rotates it (line 20), and adds the rectangle to the pane (line 21).

14.11.5 Arc

An arc is conceived as part of an ellipse, defined by the parameters `centerX`, `centerY`, `radiusX`, `radiusY`, `startAngle`, `length`, and an arc type (`ArcType.OPEN`, `ArcType.CHORD`, or `ArcType.ROUND`). The parameter `startAngle` is the starting angle; and `length` is the spanning angle (i.e., the angle covered by the arc). Angles are measured in degrees and follow the usual mathematical conventions (i.e., 0 degrees is in the easterly direction, and positive angles indicate counterclockwise rotation from the easterly direction), as shown in Figure 14.36a.

The `Arc` class defines an arc. The UML diagram for the `Arc` class is shown in Figure 14.35. Listing 14.18 gives an example that demonstrates ellipses, as shown in Figure 14.36b.

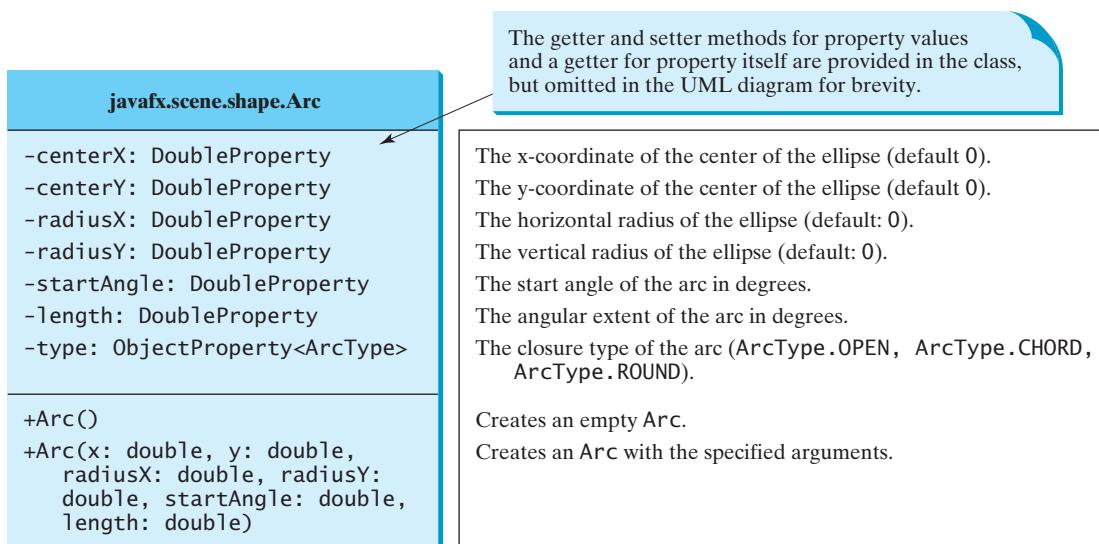
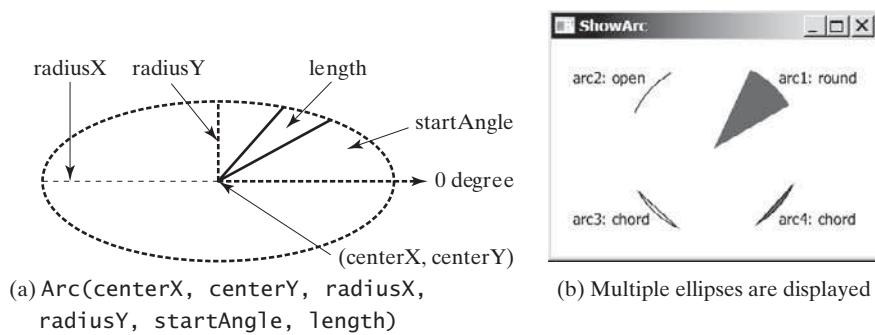


FIGURE 14.35 The `Arc` class defines an arc.

FIGURE 14.36 An `Arc` object is created to display an arc.**LISTING 14.18 ShowArc.java**

```

1 import javafx.application.Application;
2 import javafx.scene.Scene;
3 import javafx.scene.layout.Pane;
4 import javafx.scene.paint.Color;
5 import javafx.stage.Stage;
6 import javafx.scene.shape.Arc;
7 import javafx.scene.shape.ArcType;
8 import javafx.scene.text.Text;
9
10 public class ShowArc extends Application {
11     @Override // Override the start method in the Application class
12     public void start(Stage primaryStage) {
13         // Create a pane
14         Pane pane = new Pane();
15
16         Arc arc1 = new Arc(150, 100, 80, 80, 30, 35); // Create an arc
17         arc1.setFill(Color.RED); // Set fill color
18         arc1.setType(ArcType.ROUND); // Set arc type
19         pane.getChildren().add(new Text(210, 40, "arc1: round"));
20         pane.getChildren().add(arc1); // Add arc to pane
21
22         Arc arc2 = new Arc(150, 100, 80, 80, 30 + 90, 35);
23         arc2.setFill(Color.WHITE);
24         arc2.setType(ArcType.OPEN);
25         arc2.setStroke(Color.BLACK);
26         pane.getChildren().add(new Text(20, 40, "arc2: open"));
27         pane.getChildren().add(arc2);
28
29         Arc arc3 = new Arc(150, 100, 80, 80, 30 + 180, 35);
30         arc3.setFill(Color.WHITE);
31         arc3.setType(ArcType.CHORD);
32         arc3.setStroke(Color.BLACK);
33         pane.getChildren().add(new Text(20, 170, "arc3: chord"));
34         pane.getChildren().add(arc3);
35
36         Arc arc4 = new Arc(150, 100, 80, 80, 30 + 270, 35);
37         arc4.setFill(Color.GREEN);
38         arc4.setType(ArcType.CHORD);

```

create a pane

create arc1
set fill color for arc1
set arc1 as round arc

add arc1 to pane

create arc2
set fill color for arc2
set arc2 as round arc

add arc2 to pane

create arc3
set fill color for arc3
set arc3 as chord arc

add arc3 to pane

create arc4

```

39     arc4.setStroke(Color.BLACK);
40     pane.getChildren().add(new Text(210, 170, "arc4: chord")));
41     pane.getChildren().add(arc4);
42
43     // Create a scene and place it in the stage
44     Scene scene = new Scene(pane, 300, 200);
45     primaryStage.setTitle("ShowArc"); // Set the stage title
46     primaryStage.setScene(scene); // Place the scene in the stage
47     primaryStage.show(); // Display the stage
48 }
49 }
```

add arc4 to pane

The program creates an arc `arc1` centered at (150, 100) with `radiusX 80` and `radiusY 80`. The starting angle is 30 with `length 35` (line 15). `arc1`'s arc type is set to `ArcType.ROUND` (line 18). Since `arc1`'s fill color is red, `arc1` is displayed filled with red round.

The program creates an arc `arc3` centered at (150, 100) with `radiusX 80` and `radiusY 80`. The starting angle is 30+180 with `length 35` (line 29). `arc3`'s arc type is set to `ArcType.CHORD` (line 31). Since `arc3`'s fill color is white and stroke color is black, `arc3` is displayed with black outline as a chord.

Angles may be negative. A negative starting angle sweeps clockwise from the easterly direction, as shown in Figure 14.37. A negative spanning angle sweeps clockwise from the starting angle. The following two statements define the same arc:

```

new Arc(x, y, radiusX, radiusY, -30, -20);
new Arc(x, y, radiusX, radiusY, -50, 20);
```

negative degrees

The first statement uses negative starting angle `-30` and negative spanning angle `-20`, as shown in Figure 14.37a. The second statement uses negative starting angle `-50` and positive spanning angle `20`, as shown in Figure 14.37b.

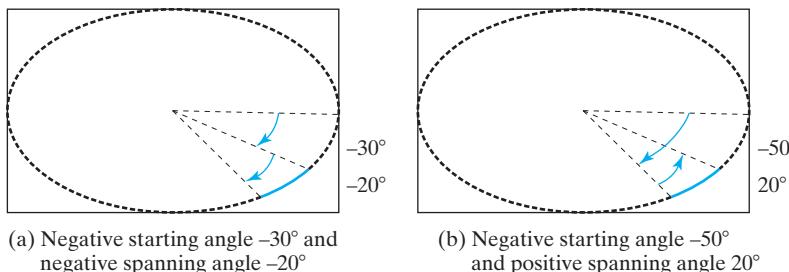


FIGURE 14.37 Angles may be negative.

Note that the trigonometric methods in the `Math` class use the angles in radians, but the angles in the `Arc` class are in degrees.

14.11.6 Polygon and Polyline

The `Polygon` class defines a polygon that connects a sequence of points, as shown in Figure 14.38a. The `Polyline` class is similar to the `Polygon` class except that the `Polyline` class is not automatically closed, as shown in Figure 14.38b.

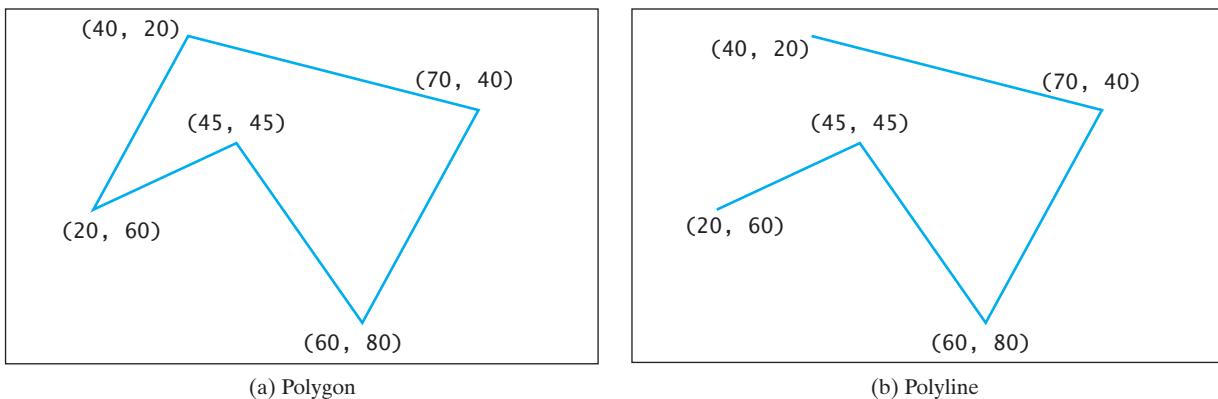


FIGURE 14.38 **Polygon** is closed and **Polyline** is not closed.

The UML diagram for the **Polygon** class is shown in Figure 14.39. Listing 14.19 gives an example that creates a hexagon, as shown in Figure 14.40.

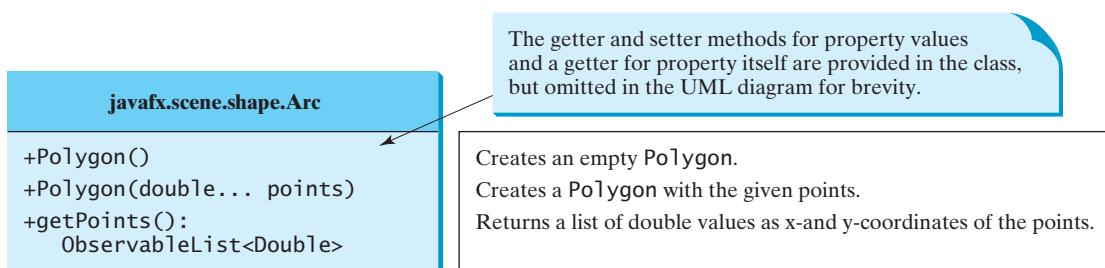


FIGURE 14.39 **Polygon** defines a polygon.

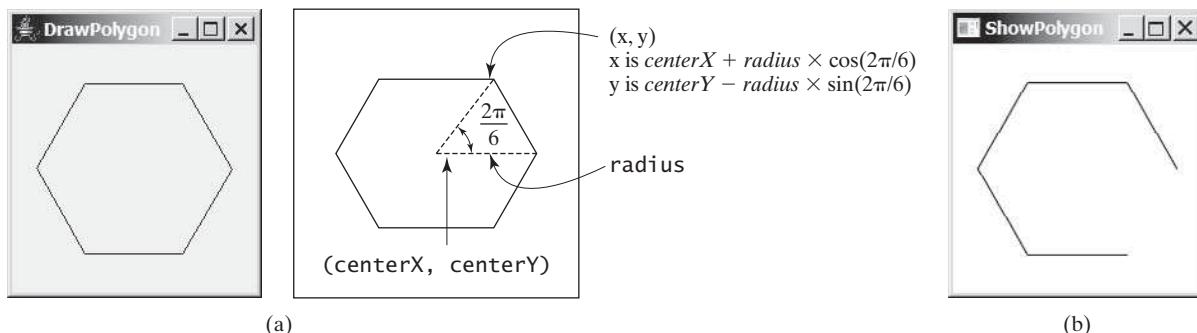


FIGURE 14.40 (a) A **Polygon** is displayed. (b) A **Polyline** is displayed.

LISTING 14.19 ShowPolygon.java

```

1 import javafx.application.Application;
2 import javafx.collections.ObservableList;
3 import javafx.scene.Scene;
4 import javafx.scene.layout.Pane;
5 import javafx.scene.paint.Color;
6 import javafx.stage.Stage;
7 import javafx.scene.shape.Polygon;

```

```

8
9 public class ShowPolygon extends Application {
10    @Override // Override the start method in the Application class
11    public void start(Stage primaryStage) {
12        // Create a pane, a polygon, and place polygon to pane
13        Pane pane = new Pane();
14        Polygon polygon = new Polygon();
15        pane.getChildren().add(polygon);
16        polygon.setFill(Color.WHITE);
17        polygon.setStroke(Color.BLACK);
18        ObservableList<Double> list = polygon.getPoints();
19
20        final double WIDTH = 200, HEIGHT = 200;
21        double centerX = WIDTH / 2, centerY = HEIGHT / 2;
22        double radius = Math.min(WIDTH, HEIGHT) * 0.4;
23
24        // Add points to the polygon list
25        for (int i = 0; i < 6; i++) {
26            list.add(centerX + radius * Math.cos(2 * i * Math.PI / 6));
27            list.add(centerY - radius * Math.sin(2 * i * Math.PI / 6));
28        }
29
30        // Create a scene and place it in the stage
31        Scene scene = new Scene(pane, WIDTH, HEIGHT);
32        primaryStage.setTitle("ShowPolygon"); // Set the stage title
33        primaryStage.setScene(scene); // Place the scene in the stage
34        primaryStage.show(); // Display the stage
35    }
36 }

```

create a pane
create a polygon
add polygon to pane

get a list of points

add x-coordinate of a point
add y-coordinate of a point

add pane to scene

The program creates a polygon (line 14) and adds it to a pane (line 15). The **Polygon**.**getPoints()** method returns an **ObservableList<Double>** (line 18), which contains the **add** method for adding an element to the list (lines 26–27). Note that the value passed to **add(value)** must be a **double** value. If an **int** value is passed, the **int** value would be automatically boxed into an **Integer**. This would cause an error because the **ObservableList<Double>** consists of **Double** elements.

The loop adds six points to the polygon (lines 25–28). Each point is represented by its *x*- and *y*-coordinates. For each point, its *x*-coordinate is added to the polygon's list (line 26) and then its *y*-coordinate is added to the list (line 27). The formula for computing the *x*- and *y*-coordinates for a point in the hexagon is illustrated in Figure 14.40a.

If you replace **Polygon** by **Polyline**, the program displays a polyline as shown in Figure 14.40b. The **Polyline** class is used in the same way as **Polygon** except that the starting and ending point are not connected in **Polyline**.

- 14.27** How do you display a text, line, rectangle, circle, ellipse, arc, polygon, and polyline?
- 14.28** Write code fragments to display a string rotated 45 degrees in the center of the pane.
- 14.29** Write code fragments to display a thick line of **10** pixels from **(10, 10)** to **(70, 30)**.
- 14.30** Write code fragments to fill red color in a rectangle of width **100** and height **50** with the upper-left corner at **(10, 10)**.
- 14.31** Write code fragments to display a round-cornered rectangle with width **100**, height **200** with the upper-left corner at **(10, 10)**, corner horizontal diameter **40**, and corner vertical diameter **20**.
- 14.32** Write code fragments to display an ellipse with horizontal radius **50** and vertical radius **100**.
- 14.33** Write code fragments to display the outline of the upper half of a circle with radius **50**.



- 14.34** Write code fragments to display the lower half of a circle with radius **50** filled with the red color.
- 14.35** Write code fragments to display a polygon connecting the following points: **(20, 40)**, **(30, 50)**, **(40, 90)**, **(90, 10)**, **(10, 30)**, and fill the polygon with green color.
- 14.36** Write code fragments to display a polyline connecting the following points: **(20, 40)**, **(30, 50)**, **(40, 90)**, **(90, 10)**, **(10, 30)**.

14.12 Case Study: The **ClockPane** Class



This case study develops a class that displays a clock on a pane.

The contract of the **ClockPane** class is shown in Figure 14.41.

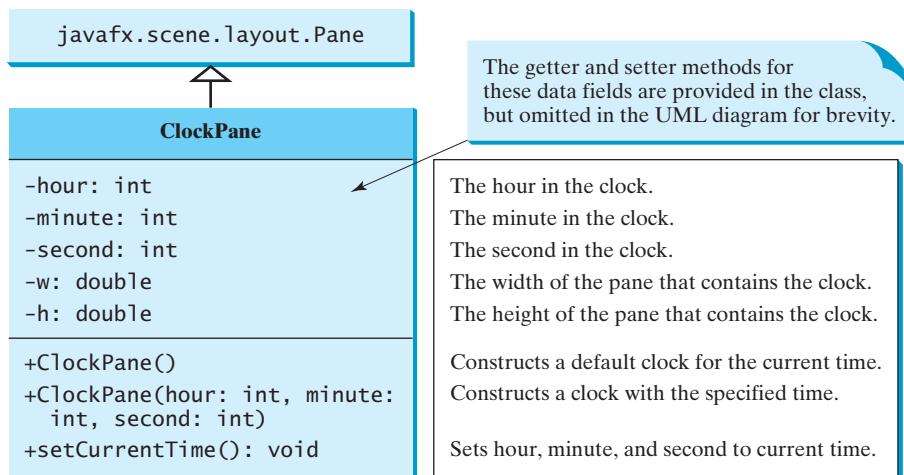


FIGURE 14.41 **ClockPane** displays an analog clock.

Assume **ClockPane** is available; we write a test program in Listing 14.20 to display an analog clock and use a label to display the hour, minute, and second, as shown in Figure 14.42.

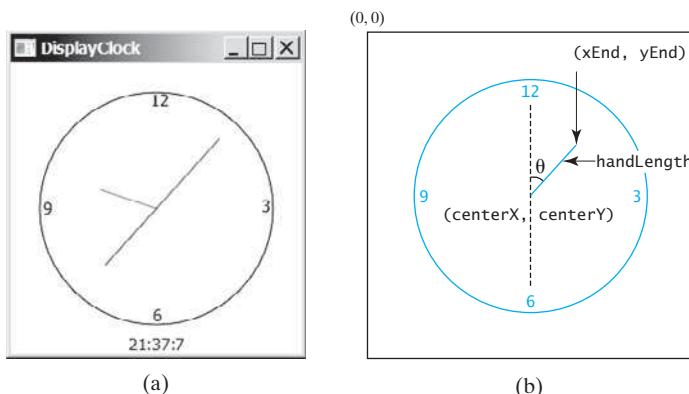


FIGURE 14.42 (a) The **DisplayClock** program displays a clock that shows the current time. (b) The endpoint of a clock hand can be determined, given the spanning angle, the hand length, and the center point.

LISTING 14.20 DisplayClock.java

```

1 import javafx.application.Application;
2 import javafx.geometry.Pos;
3 import javafx.stage.Stage;
4 import javafx.scene.Scene;
5 import javafx.scene.control.Label;
6 import javafx.scene.layout.BorderPane;
7
8 public class DisplayClock extends Application {
9     @Override // Override the start method in the Application class
10    public void start(Stage primaryStage) {
11        // Create a clock and a label
12        ClockPane clock = new ClockPane();
13        String timeString = clock.getHour() + ":" + clock.getMinute()
14            + ":" + clock.getSecond();
15        Label lblCurrentTime = new Label(timeString);
16
17        // Place clock and label in border pane
18        BorderPane pane = new BorderPane();
19        pane.setCenter(clock);
20        pane.setBottom(lblCurrentTime);
21        BorderPane.setAlignment(lblCurrentTime, Pos.TOP_CENTER);
22
23        // Create a scene and place it in the stage
24        Scene scene = new Scene(pane, 250, 250);
25        primaryStage.setTitle("DisplayClock"); // Set the stage title
26        primaryStage.setScene(scene); // Place the scene in the stage
27        primaryStage.show(); // Display the stage
28    }
29 }
```

create a clock
create a label

add a clock
add a label

skip implementation?
implementation

The rest of this section explains how to implement the **ClockPane** class. Since you can use the class without knowing how it is implemented, you may skip the implementation if you wish.

To draw a clock, you need to draw a circle and three hands for the second, minute, and hour. To draw a hand, you need to specify the two ends of the line. As shown in Figure 14.42b, one end is the center of the clock at (**centerX**, **centerY**); the other end, at (**endX**, **endY**), is determined by the following formula:

$$\begin{aligned} \text{endX} &= \text{centerX} + \text{handLength} \times \sin(\theta) \\ \text{endY} &= \text{centerY} - \text{handLength} \times \cos(\theta) \end{aligned}$$

Since there are 60 seconds in one minute, the angle for the second hand is

$$\text{second} \times (2\pi/60)$$

The position of the minute hand is determined by the minute and second. The exact minute value combined with seconds is **minute + second/60**. For example, if the time is 3 minutes and 30 seconds, the total minutes are 3.5. Since there are 60 minutes in one hour, the angle for the minute hand is

$$(\text{minute} + \text{second}/60) \times (2\pi/60)$$

Since one circle is divided into 12 hours, the angle for the hour hand is

$$(\text{hour} + \text{minute}/60 + \text{second}/(60 \times 60)) \times (2\pi/12)$$

For simplicity in computing the angles of the minute hand and hour hand, you can omit the seconds, because they are negligibly small. Therefore, the endpoints for the second hand, minute hand, and hour hand can be computed as:

```
secondX = centerX + secondHandLength * sin(second * (2π/60))
secondY = centerY - secondHandLength * cos(second * (2π/60))
minuteX = centerX + minuteHandLength * sin(minute * (2π/60))
minuteY = centerY - minuteHandLength * cos(minute * (2π/60))
hourX = centerX + hourHandLength * sin((hour + minute/60) * (2π/12))
hourY = centerY - hourHandLength * cos((hour + minute/60) * (2π/12))
```

The `ClockPane` class is implemented in Listing 14.21.

LISTING 14.21 ClockPane.java

```
1  import java.util.Calendar;
2  import java.util.GregorianCalendar;
3  import javafx.scene.layout.Pane;
4  import javafx.scene.paint.Color;
5  import javafx.scene.shape.Circle;
6  import javafx.scene.shape.Line;
7  import javafx.scene.text.Text;
8
9  public class ClockPane extends Pane {
10    private int hour;
11    private int minute;
12    private int second;
13
14    // Clock pane's width and height
15    private double w = 250, h = 250;
16
17    /** Construct a default clock with the current time*/
18    public ClockPane() {
19      setCurrentTime();
20    }
21
22    /** Construct a clock with specified hour, minute, and second */
23    public ClockPane(int hour, int minute, int second) {
24      this.hour = hour;
25      this.minute = minute;
26      this.second = second;
27      paintClock();
28    }
29
30    /** Return hour */
31    public int getHour() {
32      return hour;
33    }
34
35    /** Set a new hour */
36    public void setHour(int hour) {
37      this.hour = hour;
38      paintClock();
39    }
40
41    /** Return minute */
42    public int getMinute() {
43      return minute;
44    }
45
```

clock properties

no-arg constructor

constructor

set a new hour

paint clock

```

46  /** Set a new minute */
47  public void setMinute(int minute) {
48      this.minute = minute;
49      paintClock();
50  }
51
52  /** Return second */
53  public int getSecond() {
54      return second;
55  }
56
57  /** Set a new second */
58  public void setSecond(int second) {
59      this.second = second;
60      paintClock();
61  }
62
63  /** Return clock pane's width */
64  public double getW() {
65      return w;
66  }
67
68  /** Set clock pane's width */
69  public void setW(double w) {
70      this.w = w;
71      paintClock();
72  }
73
74  /** Return clock pane's height */
75  public double getH() {
76      return h;
77  }
78
79  /** Set clock pane's height */
80  public void setH(double h) {
81      this.h = h;
82      paintClock();
83  }
84
85  /* Set the current time for the clock */
86  public void setCurrentTime() {
87      // Construct a calendar for the current date and time
88      Calendar calendar = new GregorianCalendar();
89
90      // Set current hour, minute and second
91      this.hour = calendar.get(Calendar.HOUR_OF_DAY);
92      this.minute = calendar.get(Calendar.MINUTE);
93      this.second = calendar.get(Calendar.SECOND);
94
95      paintClock(); // Repaint the clock
96  }
97
98  /** Paint the clock */
99  protected void paintClock() {
100     // Initialize clock parameters
101     double clockRadius = Math.min(w, h) * 0.8 * 0.5;
102     double centerX = w / 2;
103     double centerY = h / 2;
104
105     // Draw circle

```

set a new minute
paint clock
set a new second
paint clock
set a new width
paint clock
set a new height
paint clock
set current time
paint clock
paint clock
get radius
set center

```

create a circle          106   Circle circle = new Circle(centerX, centerY, clockRadius);
107   circle.setFill(Color.WHITE);
108   circle.setStroke(Color.BLACK);
create texts            109   Text t1 = new Text(centerX - 5, centerY - clockRadius + 12, "12");
110   Text t2 = new Text(centerX - clockRadius + 3, centerY + 5, "9");
111   Text t3 = new Text(centerX + clockRadius - 10, centerY + 3, "3");
112   Text t4 = new Text(centerX - 3, centerY + clockRadius - 3, "6");
113
114   // Draw second hand
115   double sLength = clockRadius * 0.8;
116   double secondX = centerX + sLength *
117     Math.sin(second * (2 * Math.PI / 60));
118   double secondY = centerY - sLength *
119     Math.cos(second * (2 * Math.PI / 60));
120   Line sLine = new Line(centerX, centerY, secondX, secondY);
121   sLine.setStroke(Color.RED);
122
123   // Draw minute hand
124   double mLength = clockRadius * 0.65;
125   double xMinute = centerX + mLength *
126     Math.sin(minute * (2 * Math.PI / 60));
127   double minuteY = centerY - mLength *
128     Math.cos(minute * (2 * Math.PI / 60));
129   Line mLine = new Line(centerX, centerY, xMinute, minuteY);
130   mLine.setStroke(Color.BLUE);
131
132   // Draw hour hand
133   double hLength = clockRadius * 0.5;
134   double hourX = centerX + hLength *
135     Math.sin((hour % 12 + minute / 60.0) * (2 * Math.PI / 12));
136   double hourY = centerY - hLength *
137     Math.cos((hour % 12 + minute / 60.0) * (2 * Math.PI / 12));
138   Line hLine = new Line(centerX, centerY, hourX, hourY);
139   hLine.setStroke(Color.GREEN);
140
141   getChildren().clear();
142   getChildren().addAll(circle, t1, t2, t3, t4, sLine, mLine, hLine);
143 }
144 }
```

create hour hand

clear pane
add to pane

The program displays a clock for the current time using the no-arg constructor (lines 18–20) and displays a clock for the specified hour, minute, and second using the other constructor (lines 23–28). The current hour, minute, and second is obtained by using the **GregorianCalendar** class (lines 86–96). The **GregorianCalendar** class in the Java API enables you to create a **Calendar** instance for the current time using its no-arg constructor. You can then use its methods **get(Calendar.HOUR)**, **get(Calendar.MINUTE)**, and **get(Calendar.SECOND)** to return the hour, minute, and second from a **Calendar** object.

The class defines the properties **hour**, **minute**, and **second** to store the time represented in the clock (lines 10–12) and uses the **w** and **h** properties to represent the width and height of the clock pane (line 15). The initial values of **w** and **h** are set to 250. The **w** and **h** values can be reset using the **setW** and **setH** methods (lines 69, 80). These values are used to draw a clock in the pane in the **paintClock()** method.

The **paintClock()** method paints the clock (lines 99–143). The clock radius is proportional to the width and height of the pane (line 101). A circle for the clock is created at the center of the pane (line 106). The text for showing the hours 12, 3, 6, 9 are created in lines 109–112.

The second hand, minute hand, and hour hand are the lines created in lines 114–139. The `paintClock()` method places all these shapes in the pane using the `addAll` method in a list (line 142). Because the `paintClock()` method is invoked whenever a new property (`hour`, `minute`, `second`, `w`, and `h`) is set (lines 27, 38, 49, 60, 71, 82, 95), before adding new contents into the pane, the old contents are cleared from the pane (line 141).

Key Terms

AWT	536	property getter method	543
bidirectional binding	544	primary stage	537
bindable object	542	shape	539
binding object	542	Swing	536
binding property	542	value getter method	543
JavaFX	536	value setter method	543
node	539	UI control	539
observable object	542	unidirectional binding	544
pane	539		

CHAPTER SUMMARY

1. JavaFX is the new framework for developing rich Internet applications. JavaFX completely replaces Swing and AWT.
2. A main JavaFX class must extend `javafx.application.Application` and implement the `start` method. The primary stage is automatically created by the JVM and passed to the `start` method.
3. A stage is a window for displaying a scene. You can add nodes to a scene. Panes, controls, and shapes are nodes. Panes can be used as the containers for nodes.
4. A binding property can be bound to an observable source object. A change in the source object will be automatically reflected in the binding property. A binding property has a value getter method, value setter method, and property getter method.
5. The `Node` class defines many properties that are common to all nodes. You can apply these properties to panes, controls, and shapes.
6. You can create a `Color` object with the specified red, green, blue components, and opacity value.
7. You can create a `Font` object and set its name, size, weight, and posture.
8. The `javafx.scene.image.Image` class can be used to load an image and this image can be displayed in an `ImageView` object.
9. JavaFX provides many types of panes for automatically laying out nodes in a desired location and size. The `Pane` is the base class for all panes. It contains the `getChildren()` method to return an `ObservableList`. You can use `ObservableList`'s `add(node)` and `addAll(node1, node2, ...)` methods for adding nodes into a pane.

10. A **FlowPane** arranges the nodes in the pane horizontally from left to right or vertically from top to bottom in the order in which they were added. A **GridPane** arranges nodes in a grid (matrix) formation. The nodes are placed in the specified column and row indices. A **BorderPane** can place nodes in five regions: top, bottom, left, right, and center. An **HBox** lays out its children in a single horizontal row. A **VBox** lays out its children in a single vertical column.
11. JavaFX provides many shape classes for drawing texts, lines, circles, rectangles, ellipses, arcs, polygons, and polylines.

Quiz

Answer the quiz for this chapter online at www.cs.armstrong.edu/liang/intro10e/quiz.html.

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PROGRAMMING EXERCISES



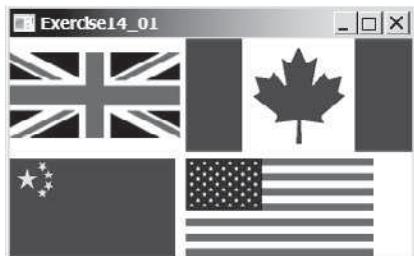
Note

download image files

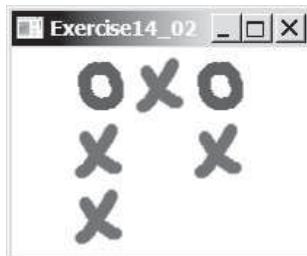
The image files used in the exercises can be obtained from www.cs.armstrong.edu/liang/intro10e/book.zip under the image folder.

Sections 14.2–14.9

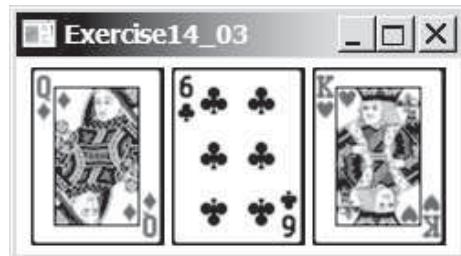
- 14.1** (*Display images*) Write a program that displays four images in a grid pane, as shown in Figure 14.43a.



(a)



(b)



(c)

FIGURE 14.43 (a) Exercise 14.1 displays four images. (b) Exercise 14.2 displays a tic-tac-toe board with images. (c) Three cards are randomly selected.



VideoNote

Display a tictactoe board

- *14.2** (*Tic-tac-toe board*) Write a program that displays a tic-tac-toe board, as shown in Figure 14.43b. A cell may be X, O, or empty. What to display at each cell is randomly decided. The X and O are images in the files **x.gif** and **o.gif**.

- *14.3** (*Display three cards*) Write a program that displays three cards randomly selected from a deck of 52, as shown in Figure 14.43c. The card image files are named **1.png**, **2.png**, ..., **52.png** and stored in the **image/card** directory. All three cards are distinct and selected randomly. Hint: You can select random cards by storing the numbers 1–52 to an array list, perform a random shuffle introduced in Section 11.12, and use the first three numbers in the array list as the file names for the image.

- 14.4** (*Color and font*) Write a program that displays five texts vertically, as shown in Figure 14.44a. Set a random color and opacity for each text and set the font of each text to Times Roman, bold, italic, and 22 pixels.



FIGURE 14.44 (a) Five texts are displayed with a random color and a specified font. (b) A string is displayed around the circle. (c) A checkerboard is displayed using rectangles.

14.5 (*Characters around circle*) Write a program that displays a string Welcome to Java around the circle, as shown in Figure 14.44b. Hint: You need to display each character in the right location with appropriate rotation using a loop.

***14.6** (*Game: display a checkerboard*) Write a program that displays a checkerboard in which each white and black cell is a **Rectangle** with a fill color black or white, as shown in Figure 14.44c.

Sections 14.10–14.11

***14.7** (*Display random 0 or 1*) Write a program that displays a 10-by-10 square matrix, as shown in Figure 14.45a. Each element in the matrix is **0** or **1**, randomly generated. Display each number centered in a text field. Use **TextField**'s **setText** method to set value **0** or **1** as a string. Display a random matrix

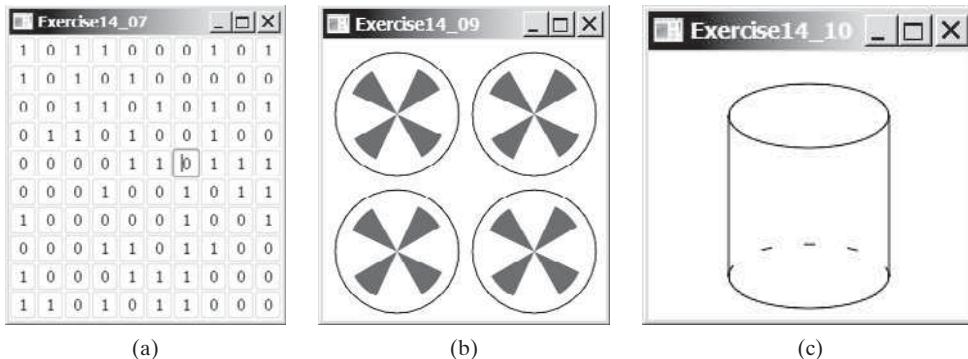


FIGURE 14.45 (a) The program randomly generates 0s and 1s. (b) Exercise 14.9 draws four fans. (c) Exercise 14.10 draws a cylinder.

14.8 (*Display 54 cards*) Expand Exercise 14.3 to display all 54 cards (including two jokers), nine per row. The image files are jokers and are named **53.jpg** and **54.jpg**.

***14.9** (*Create four fans*) Write a program that places four fans in a **GridPane** with two rows and two columns, as shown in Figure 14.45b.

***14.10** (*Display a cylinder*) Write a program that draws a cylinder, as shown in Figure 14.45b. You can use the following method to set the dashed stroke for an arc:

```
arc.getStrokeDashArray().addAll(6.0, 21.0);
```

***14.11** (*Paint a smiley face*) Write a program that paints a smiley face, as shown in Figure 14.46a.



FIGURE 14.46 (a) Exercise 14.11 paints a smiley face. (b) Exercise 14.12 paints a bar chart. (c) Exercise 14.13 paints a pie chart.



****14.12** (*Display a bar chart*) Write a program that uses a bar chart to display the percentages of the overall grade represented by projects, quizzes, midterm exams, and the final exam, as shown in Figure 14.46b. Suppose that projects take 20 percent and are displayed in red, quizzes take 10 percent and are displayed in blue, midterm exams take 30 percent and are displayed in green, and the final exam takes 40 percent and is displayed in orange. Use the `Rectangle` class to display the bars. Interested readers may explore the JavaFX `BarChart` class for further study.

****14.13** (*Display a pie chart*) Write a program that uses a pie chart to display the percentages of the overall grade represented by projects, quizzes, midterm exams, and the final exam, as shown in Figure 14.46c. Suppose that projects take 20 percent and are displayed in red, quizzes take 10 percent and are displayed in blue, midterm exams take 30 percent and are displayed in green, and the final exam takes 40 percent and is displayed in orange. Use the `Arc` class to display the pies. Interested readers may explore the JavaFX `PieChart` class for further study.

14.14 (*Display a rectanguloid*) Write a program that displays a rectanguloid, as shown in Figure 14.47a. The cube should grow and shrink as the window grows or shrinks.

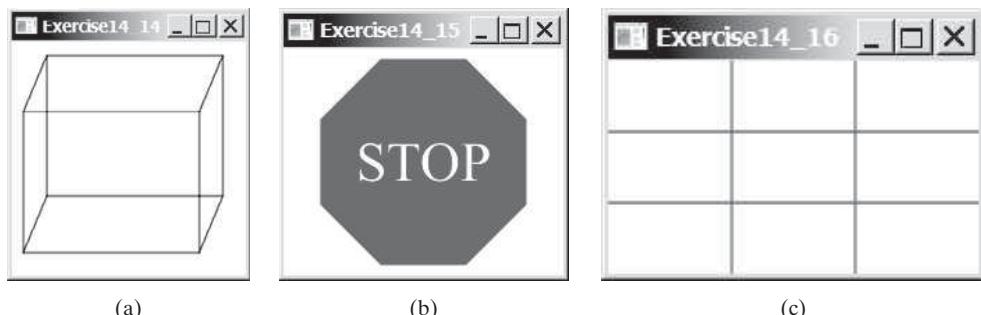


FIGURE 14.47 (a) Exercise 14.14 paints a rectanguloid. (b) Exercise 14.15 paints a STOP sign. (c) Exercise 14.13 paints a grid.

***14.15** (*Display a STOP sign*) Write a program that displays a STOP sign, as shown in Figure 14.47b. The octagon is in red and the sign is in white. (*Hint:* Place an octagon and a text in a stack pane.)

***14.16** (Display a 3×3 grid) Write a program that displays a 3×3 grid, as shown in Figure 14.47c. Use red color for vertical lines and blue for horizontals. The lines are automatically resized when the window is resized.

14.17 (Game: hangman) Write a program that displays a drawing for the popular hangman game, as shown in Figure 14.48a.

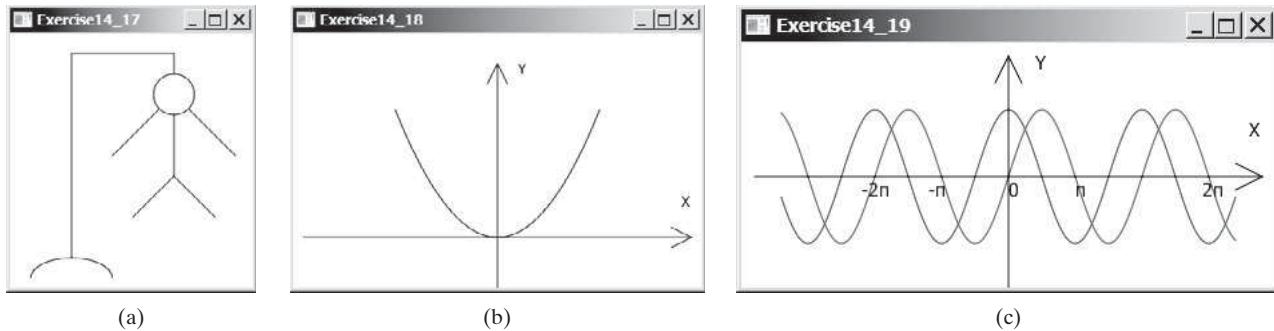


FIGURE 14.48 (a) Exercise 14.17 draws a sketch for the hangman game. (c) Exercise 14.18 plots the quadratic function. (c) Exercise 14.19 plots the sine/cosine functions.

***14.18** (Plot the square function) Write a program that draws a diagram for the function $f(x) = x^2$ (see Figure 14.48b).

Hint: Add points to a polyline using the following code:

```
Polyline polyline = new Polyline();
ObservableList<Double> list = polyline.getPoints();
double scaleFactor = 0.0125;
for (int x = -100; x <= 100; x++) {
    list.add(x + 200.0);
    list.add(scaleFactor * x * x);
}
```

****14.19** (Plot the sine and cosine functions) Write a program that plots the sine function in red and cosine in blue, as shown in Figure 14.48c.

Hint: The Unicode for π is \u03c0. To display -2π , use `Text(x, y, "-2\u03c0")`. For a trigonometric function like `sin(x)`, x is in radians. Use the following loop to add the points to a polyline:

```
Polyline polyline = new Polyline();
ObservableList<Double> list = polyline.getPoints();
double scaleFactor = 50;
for (int x = -170; x <= 170; x++) {
    list.add(x + 200.0);
    list.add(100 - 50 * Math.sin((x / 100.0) * 2 * Math.PI));
```

****14.20** (Draw an arrow line) Write a static method that draws an arrow line from a starting point to an ending point in a pane using the following method header:

```
public static void drawArrowLine(double startX, double startY,
    double endX, double endY, Pane pane)
```

Write a test program that randomly draws an arrow line, as shown in Figure 14.49a.

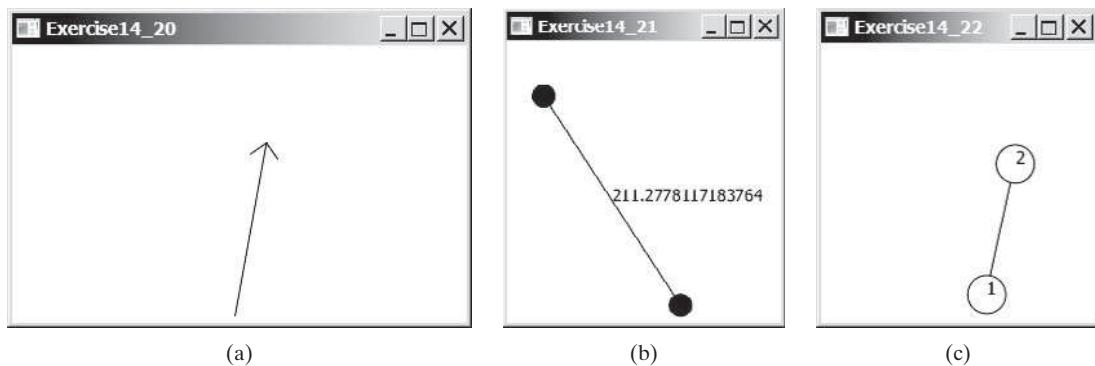


FIGURE 14.49 (a) The program displays an arrow line. (b) Exercise14.21 connects the centers of two filled circles. (c) Exercise14.22 connects two circles from their perimeter.

***14.21** (*Two circles and their distance*) Write a program that draws two filled circles with radius **15** pixels, centered at random locations, with a line connecting the two circles. The distance between the two centers is displayed on the line, as shown in Figure 14.49b.

***14.22** (*Connect two circles*) Write a program that draws two circles with radius **15** pixels, centered at random locations, with a line connecting the two circles. The line should not cross inside the circles, as shown in Figure 14.49c.

***14.23** (*Geometry: two rectangles*) Write a program that prompts the user to enter the center coordinates, width, and height of two rectangles from the command line. The program displays the rectangles and a text indicating whether the two are overlapping, whether one is contained in the other, or whether they don't overlap, as shown in Figure 14.50. See Programming Exercise 10.13 for checking the relationship between two rectangles.

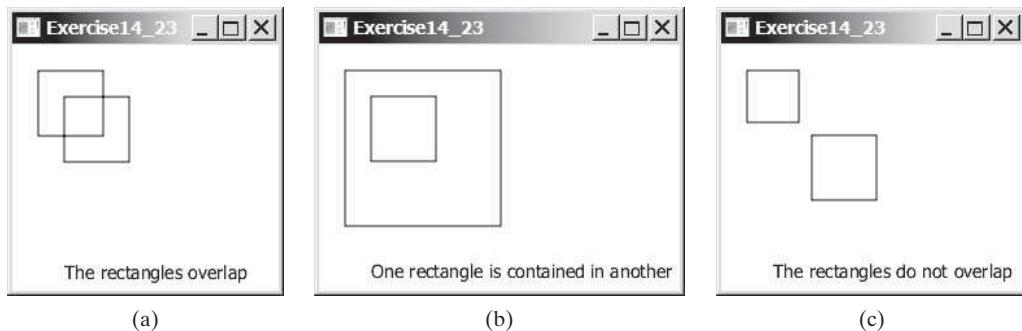


FIGURE 14.50 Two rectangles are displayed.

***14.24** (*Geometry: Inside a polygon?*) Write a program that prompts the user to enter the coordinates of five points from the command line. The first four points form a polygon, and the program displays the polygon and a text that indicates whether the fifth point is inside the polygon, as shown in Figure 14.51a. Hint: Use the **Node's contains** method to test whether a point is inside a node.

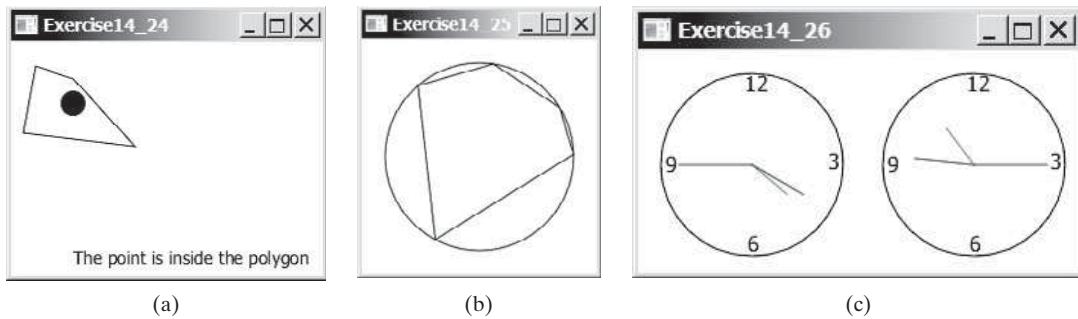


FIGURE 14.51 (a) The polygon and a point are displayed. (b) Exercise14.25 connects five random points on a circle. (c) Exercise 14.26 displays two clocks.

***14.25** (*Random points on a circle*) Modify Programming Exercise 4.6 to create five random points on a circle, form a polygon by connecting the points clockwise, and display the circle and the polygon, as shown in Figure 14.51b.

Section 14.12

14.26 (*Use the ClockPane class*) Write a program that displays two clocks. The hour, minute, and second values are **4, 20, 45** for the first clock and **22, 46, 15** for the second clock, as shown in Figure 14.51c.

***14.27** (*Draw a detailed clock*) Modify the **ClockPane** class in Section 14.12 to draw the clock with more details on the hours and minutes, as shown in Figure 14.52a.

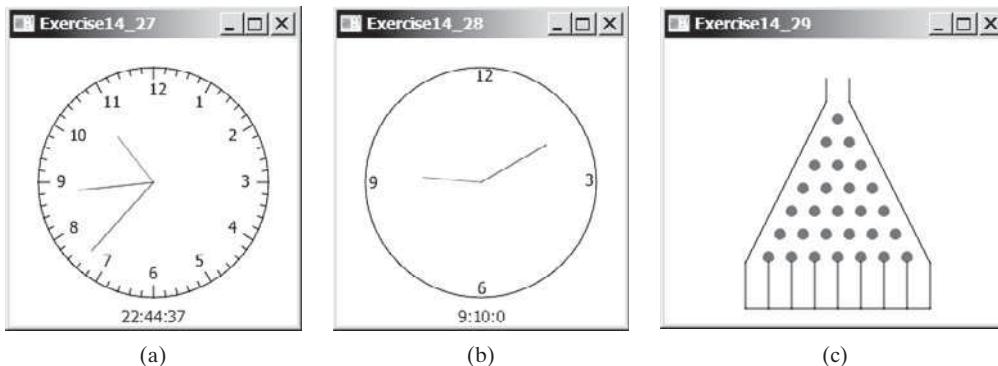


FIGURE 14.52 (a) Exercise 14.27 displays a detailed clock. (b) Exercise 14.28 displays a clock with random hour and minute values. (c) Exercise 14.29 displays a bean machine.

***14.28** (*Random time*) Modify the **ClockPane** class with three new Boolean properties—**hourHandVisible**, **minuteHandVisible**, and **secondHandVisible**—and their associated accessor and mutator methods. You can use the **set** methods to make a hand visible or invisible. Write a test program that displays only the hour and minute hands. The hour and minute values are randomly generated. The hour is between **0** and **11**, and the minute is either **0** or **30**, as shown in Figure 14.52b.

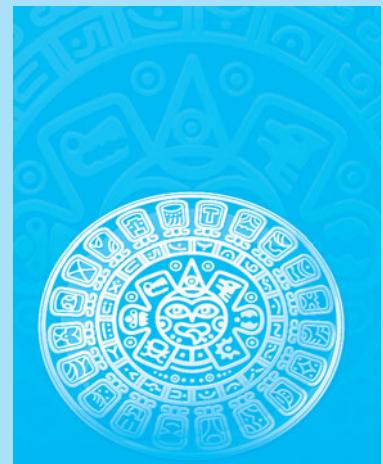
****14.29** (*Game: bean machine*) Write a program that displays a bean machine introduced in Programming Exercise 7.21, as shown in Figure 14.52c.

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EVENT-DRIVEN PROGRAMMING AND ANIMATIONS

Objectives

- To get a taste of event-driven programming (§15.1).
- To describe events, event sources, and event classes (§15.2).
- To define handler classes, register handler objects with the source object, and write the code to handle events (§15.3).
- To define handler classes using inner classes (§15.4).
- To define handler classes using anonymous inner classes (§15.5).
- To simplify event handling using lambda expressions (§15.6).
- To develop a GUI application for a loan calculator (§15.7).
- To write programs to deal with **MouseEvents** (§15.8).
- To write programs to deal with **KeyEvents** (§15.9).
- To create listeners for processing a value change in an observable object (§15.10).
- To use the **Animation**, **PathTransition**, **FadeTransition**, and **Timeline** classes to develop animations (§15.11).
- To develop an animation for simulating a bouncing ball (§15.12).



15.1 Introduction



You can write code to process events such as a button click, mouse movement, and keystrokes.

problem

Suppose you wish to write a GUI program that lets the user enter a loan amount, annual interest rate, and number of years and click the *Calculate* button to obtain the monthly payment and total payment, as shown in Figure 15.1. How do you accomplish the task? You have to use *event-driven programming* to write the code to respond to the button-clicking event.

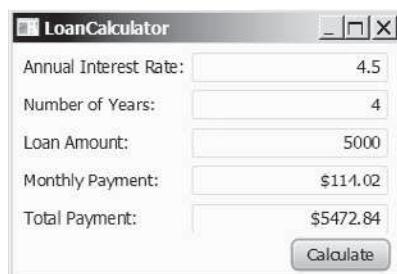


FIGURE 15.1 The program computes loan payments.

problem

Before delving into event-driven programming, it is helpful to get a taste using a simple example. The example displays two buttons in a pane, as shown in Figure 15.2.

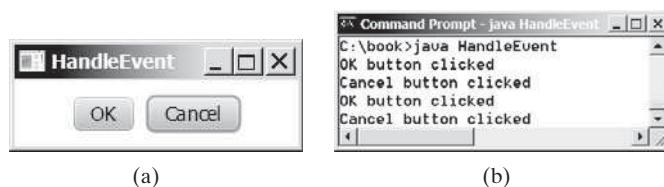


FIGURE 15.2 (a) The program displays two buttons. (b) A message is displayed in the console when a button is clicked.

To respond to a button click, you need to write the code to process the button-clicking action. The button is an *event source object*—where the action originates. You need to create an object capable of handling the action event on a button. This object is called an *event handler*, as shown in Figure 15.3.

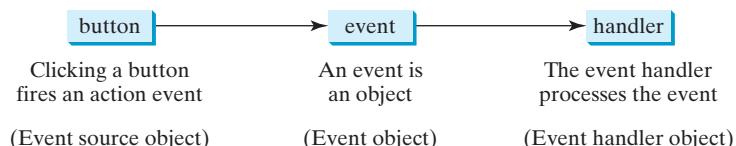


FIGURE 15.3 An event handler processes the event fired from the source object.

Not all objects can be handlers for an action event. To be a handler of an action event, two requirements must be met:

EventHandler interface

setOnAction(handler)

1. The object must be an instance of the `EventHandler<T extends Event>` interface. This interface defines the common behavior for all handlers. `<T extends Event>` denotes that `T` is a generic type that is a subtype of `Event`.
2. The `EventHandler` object `handler` must be registered with the event source object using the method `source.setOnAction(handler)`.

The `EventHandler<ActionEvent>` interface contains the `handle(ActionEvent)` method for processing the action event. Your handler class must override this method to respond to the event. Listing 15.1 gives the code that processes the `ActionEvent` on the two buttons. When you click the *OK* button, the message “OK button clicked” is displayed. When you click the *Cancel* button, the message “Cancel button clicked” is displayed, as shown in Figure 15.2.

LISTING 15.1 HandleEvent.java

```

1  import javafx.application.Application;
2  import javafx.geometry.Pos;
3  import javafx.scene.Scene;
4  import javafx.scene.control.Button;
5  import javafx.scene.layout.HBox;
6  import javafx.stage.Stage;
7  import javafx.event.ActionEvent;
8  import javafx.event.EventHandler;
9
10 public class HandleEvent extends Application {
11     @Override // Override the start method in the Application class
12     public void start(Stage primaryStage) {
13         // Create a pane and set its properties
14         HBox pane = new HBox(10);
15         pane.setAlignment(Pos.CENTER);
16         Button btOK = new Button("OK");
17         Button btCancel = new Button("Cancel");
18         OKHandlerClass handler1 = new OKHandlerClass();
19         btOK.setOnAction(handler1);
20         CancelHandlerClass handler2 = new CancelHandlerClass();
21         btCancel.setOnAction(handler2);
22         pane.getChildren().addAll(btOK, btCancel);
23
24         // Create a scene and place it in the stage
25         Scene scene = new Scene(pane);
26         primaryStage.setTitle("HandleEvent"); // Set the stage title
27         primaryStage.setScene(scene); // Place the scene in the stage
28         primaryStage.show(); // Display the stage
29     }
30 }
31
32 class OKHandlerClass implements EventHandler<ActionEvent> {           handler class
33     @Override
34     public void handle(ActionEvent e) {                                         handle event
35         System.out.println("OK button clicked");
36     }
37 }
38
39 class CancelHandlerClass implements EventHandler<ActionEvent> {          handler class
40     @Override
41     public void handle(ActionEvent e) {                                         handle event
42         System.out.println("Cancel button clicked");
43     }
44 }
```

Two handler classes are defined in lines 32–44. Each handler class implements `EventHandler<ActionEvent>` to process `ActionEvent`. The object `handler1` is an instance of `OKHandlerClass` (line 18), which is registered with the button `btOK` (line 19). When the *OK* button is clicked, the `handle(ActionEvent)` method (line 34) in

`OKHandlerClass` is invoked to process the event. The object `handler2` is an instance of `CancelHandlerClass` (line 20), which is registered with the button `btCancel` in line 21. When the *Cancel* button is clicked, the `handle(ActionEvent)` method (line 41) in `CancelHandlerClass` is invoked to process the event.

You now have seen a glimpse of event-driven programming in JavaFX. You probably have many questions, such as why a handler class is defined to implement the `EventHandler<ActionEvent>`. The following sections will give you all the answers.

15.2 Events and Event Sources



event-driven programming
event

fire event
event source object
source object

When you run a Java GUI program, the program interacts with the user, and the events drive its execution. This is called *event-driven programming*. An *event* can be defined as a signal to the program that something has happened. Events are triggered by external user actions, such as mouse movements, mouse clicks, and keystrokes. The program can choose to respond to or ignore an event. The example in the preceding section gave you a taste of event-driven programming.

The component that creates an event and fires it is called the *event source object*, or simply *source object* or *source component*. For example, a button is the source object for a button-clicking action event. An event is an instance of an event class. The root class of the Java event classes is `java.util.EventObject`. The root class of the JavaFX event classes is `javafx.event.Event`. The hierarchical relationships of some event classes are shown in Figure 15.4.

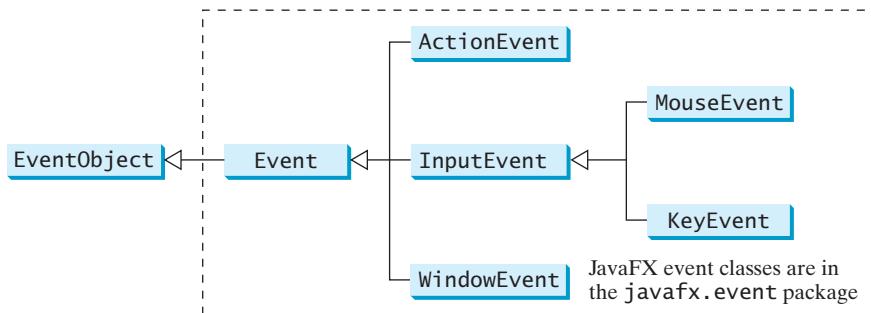


FIGURE 15.4 An event in JavaFX is an object of the `javafx.event.Event` class.

event object
`getSource()`

An *event object* contains whatever properties are pertinent to the event. You can identify the source object of an event using the `getSource()` instance method in the `EventObject` class. The subclasses of `EventObject` deal with specific types of events, such as action events, window events, mouse events, and key events. The first three columns in Table 15.1 list some external user actions, source objects, and event types fired. For example, when clicking a button, the button creates and fires an `ActionEvent`, as indicated in the first line of this table. Here, the button is an event source object, and an `ActionEvent` is the event object fired by the source object, as shown in Figure 15.3.



Note

If a component can fire an event, any subclass of the component can fire the same type of event. For example, every JavaFX shape, layout pane, and control can fire `MouseEvent` and `KeyEvent` since `Node` is the superclass for shapes, layout panes, and controls.

TABLE 15.1 User Action, Source Object, Event Type, Handler Interface, and Handler

User Action	Source Object	Event Type Fired	Event Registration Method
Click a button	<code>Button</code>	<code>ActionEvent</code>	<code>setOnAction(EventHandler<ActionEvent>)</code>
Press Enter in a text field	<code>TextField</code>	<code>ActionEvent</code>	<code>setOnAction(EventHandler<ActionEvent>)</code>
Check or uncheck	<code>RadioButton</code>	<code>ActionEvent</code>	<code>setOnAction(EventHandler<ActionEvent>)</code>
Check or uncheck	<code>CheckBox</code>	<code>ActionEvent</code>	<code>setOnAction(EventHandler<ActionEvent>)</code>
Select a new item	<code>ComboBox</code>	<code>ActionEvent</code>	<code>setOnAction(EventHandler<ActionEvent>)</code>
Mouse pressed	<code>Node, Scene</code>	<code>MouseEvent</code>	<code>setOnMousePressed(EventHandler<MouseEvent>)</code>
Mouse released			<code>setOnMouseReleased(EventHandler<MouseEvent>)</code>
Mouse clicked			<code>setOnMouseClicked(EventHandler<MouseEvent>)</code>
Mouse entered			<code>setOnMouseEntered(EventHandler<MouseEvent>)</code>
Mouse exited			<code>setOnMouseExited(EventHandler<MouseEvent>)</code>
Mouse moved			<code>setOnMouseMoved(EventHandler<MouseEvent>)</code>
Mouse dragged			<code>setOnMouseDragged(EventHandler<MouseEvent>)</code>
Key pressed	<code>Node, Scene</code>	<code>KeyEvent</code>	<code>setOnKeyPressed(EventHandler<KeyEvent>)</code>
Key released			<code>setOnKeyReleased(EventHandler<KeyEvent>)</code>
Key typed			<code>setOnKeyTyped(EventHandler<KeyEvent>)</code>

15.1 What is an event source object? What is an event object? Describe the relationship between an event source object and an event object.



15.2 Can a button fire a `MouseEvent`? Can a button fire a `KeyEvent`? Can a button fire an `ActionEvent`?

15.3 Registering Handlers and Handling Events

A *handler* is an object that must be registered with an event source object, and it must be an instance of an appropriate event-handling interface.



Java uses a delegation-based model for event handling: a source object fires an event, and an object interested in the event handles it. The latter object is called an *event handler* or an *event listener*. For an object to be a handler for an event on a source object, two things are needed, as shown in Figure 15.5.



1. The *handler object must be an instance of the corresponding event-handler interface* to ensure that the handler has the correct method for processing the event. JavaFX defines a unified handler interface `EventHandler<T extends Event>` for an event `T`. The handler interface contains the `handle(T e)` method for processing the event. For example, the handler interface for `ActionEvent` is `EventHandler<ActionEvent>`; each handler for `ActionEvent` should implement the `handle(ActionEvent e)` method for processing an `ActionEvent`.

event-handler interface

`EventHandler<T extends Event>`

event handler

2. The *handler object must be registered by the source object*. Registration methods depend on the event type. For `ActionEvent`, the method is `setOnAction`. For a mouse pressed event, the method is `setOnMousePressed`. For a key pressed event, the method is `setOnKeyPressed`.

register handler

Let's revisit Listing 15.1, HandleEvent.java. Since a `Button` object fires `ActionEvent`, a handler object for `ActionEvent` must be an instance of `EventHandler<ActionEvent>`, so

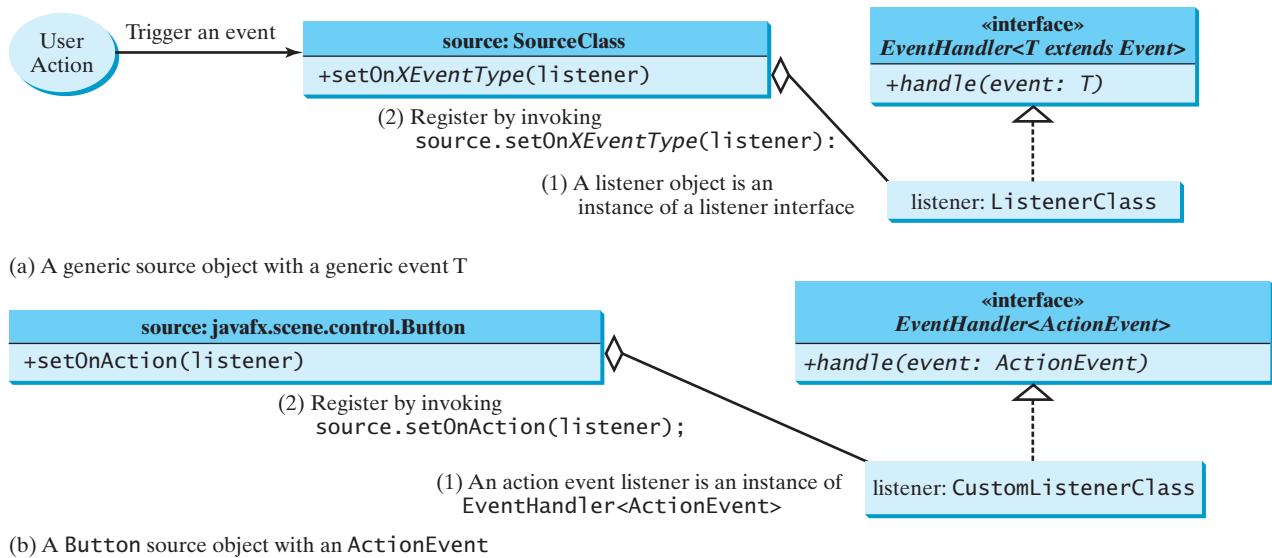


FIGURE 15.5 A listener must be an instance of a listener interface and must be registered with a source object.

the handler class implements `EventHandler<ActionEvent>` in line 34. The source object invokes `setOnAction(handler)` to register a handler, as follows:

create source object
create handler object
register handler

```

Button btOK = new Button("OK"); // Line 16 in Listing 15.1
OKHandlerClass handler1 = new OKHandlerClass(); // Line 18 in Listing 15.1
btOK.setOnAction(handler1); // Line 19 in Listing 15.1
  
```

When you click the button, the `Button` object fires an `ActionEvent` and passes it to invoke the handler's `handle(ActionEvent)` method to handle the event. The event object contains information pertinent to the event, which can be obtained using the methods. For example, you can use `e.getSource()` to obtain the source object that fired the event.

first version

We now write a program that uses two buttons to control the size of a circle, as shown in Figure 15.6. We will develop this program incrementally. First, we write the program in Listing 15.2 that displays the user interface with a circle in the center (lines 15-19) and two buttons on the bottom (lines 21-27).

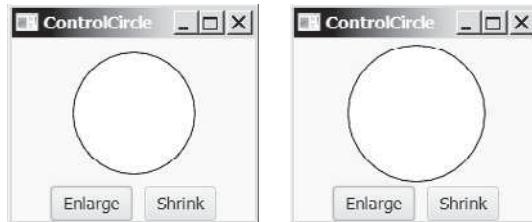


FIGURE 15.6 The user clicks the *Enlarge* and *Shrink* buttons to enlarge and shrink the size of the circle.

LISTING 15.2 ControlCircleWithoutEventHandling.java

```

1 import javafx.application.Application;
2 import javafx.geometry.Pos;
3 import javafx.scene.Scene;
4 import javafx.scene.control.Button;
  
```

```

5 import javafx.scene.layout.StackPane;
6 import javafx.scene.layout.HBox;
7 import javafx.scene.layout.BorderPane;
8 import javafx.scene.paint.Color;
9 import javafx.scene.shape.Circle;
10 import javafx.stage.Stage;
11
12 public class ControlCircleWithoutEventHandling extends Application {
13     @Override // Override the start method in the Application class
14     public void start(Stage primaryStage) {
15         StackPane pane = new StackPane();
16         Circle circle = new Circle(50);                                circle
17         circle.setStroke(Color.BLACK);
18         circle.setFill(Color.WHITE);
19         pane.getChildren().add(circle);
20
21         HBox hBox = new HBox();
22         hBox.setSpacing(10);
23         hBox.setAlignment(Pos.CENTER);
24         Button btEnlarge = new Button("Enlarge");                      buttons
25         Button btShrink = new Button("Shrink");
26         hBox.getChildren().add(btEnlarge);
27         hBox.getChildren().add(btShrink);
28
29         BorderPane borderPane = new BorderPane();
30         borderPane.setCenter(pane);
31         borderPane.setBottom(hBox);
32         BorderPane.setAlignment(hBox, Pos.CENTER);
33
34         // Create a scene and place it in the stage
35         Scene scene = new Scene(borderPane, 200, 150);
36         primaryStage.setTitle("ControlCircle"); // Set the stage title
37         primaryStage.setScene(scene); // Place the scene in the stage
38         primaryStage.show(); // Display the stage
39     }
49 }
```

How do you use the buttons to enlarge or shrink the circle? When the *Enlarge* button is clicked, you want the circle to be repainted with a larger radius. How can you accomplish this? You can expand and modify the program in Listing 15.2 into Listing 15.3 with the following features:

second version

1. Define a new class named **CirclePane** for displaying the circle in a pane (lines 51–68). This new class displays a circle and provides the **enlarge** and **shrink** methods for increasing and decreasing the radius of the circle (lines 60–62, 64–67). It is a good strategy to design a class to model a circle pane with supporting methods so that these related methods along with the circle are coupled in one object.
2. Create a **CirclePane** object and declare **circlePane** as a data field to reference this object (line 15) in the **ControlCircle** class. The methods in the **ControlCircle** class can now access the **CirclePane** object through this data field.
3. Define a handler class named **EnlargeHandler** that implements **EventHandler<ActionEvent>** (lines 43–48). To make the reference variable **circlePane** accessible from the **handle** method, define **EnlargeHandler** as an inner class of the **ControlCircle** class. (*Inner classes* are defined inside another class. We use an inner class here and will introduce it fully in the next section.) inner class
4. Register the handler for the *Enlarge* button (line 29) and implement the **handle** method in **EnlargeHandler** to invoke **circlePane.enlarge()** (line 46).



VideoNote

Handler and its registration

LISTING 15.3 ControlCircle.java

```

1 import javafx.application.Application;
2 import javafx.event.ActionEvent;
3 import javafx.event.EventHandler;
4 import javafx.geometry.Pos;
5 import javafx.scene.Scene;
6 import javafx.scene.control.Button;
7 import javafx.scene.layout.StackPane;
8 import javafx.scene.layout.HBox;
9 import javafx.scene.layout.BorderPane;
10 import javafx.scene.paint.Color;
11 import javafx.scene.shape.Circle;
12 import javafx.stage.Stage;
13
14 public class ControlCircle extends Application {
15     private CirclePane circlePane = new CirclePane();
16
17     @Override // Override the start method in the Application class
18     public void start(Stage primaryStage) {
19         // Hold two buttons in an HBox
20         HBox hBox = new HBox();
21         hBox.setSpacing(10);
22         hBox.setAlignment(Pos.CENTER);
23         Button btEnlarge = new Button("Enlarge");
24         Button btShrink = new Button("Shrink");
25         hBox.getChildren().add(btEnlarge);
26         hBox.getChildren().add(btShrink);
27
28         // Create and register the handler
29         btEnlarge.setOnAction(new EnlargeHandler());
30
31         BorderPane borderPane = new BorderPane();
32         borderPane.setCenter(circlePane);
33         borderPane.setBottom(hBox);
34         BorderPane.setAlignment(hBox, Pos.CENTER);
35
36         // Create a scene and place it in the stage
37         Scene scene = new Scene(borderPane, 200, 150);
38         primaryStage.setTitle("ControlCircle"); // Set the stage title
39         primaryStage.setScene(scene); // Place the scene in the stage
40         primaryStage.show(); // Display the stage
41     }
42
43     class EnlargeHandler implements EventHandler<ActionEvent> {
44         @Override // Override the handle method
45         public void handle(ActionEvent e) {
46             circlePane.enlarge();
47         }
48     }
49 }
50
51 class CirclePane extends StackPane {
52     private Circle circle = new Circle(50);
53
54     CirclePane() {
55         getChildren().add(circle);
56         circle.setStroke(Color.BLACK);
57         circle.setFill(Color.WHITE);
58     }

```

CirclePane class

```

59
60 public void enlarge() {
61     circle.setRadius(circle.getRadius() + 2);
62 }
63
64 public void shrink() {
65     circle.setRadius(circle.getRadius() > 2 ?
66         circle.getRadius() - 2 : circle.getRadius());
67 }
68 }
```

enlarge method

As an exercise, add the code for handling the *Shrink* button to display a smaller circle when the *Shrink* button is clicked.

15.3 Why must a handler be an instance of an appropriate handler interface?

15.4 Explain how to register a handler object and how to implement a handler interface.

15.5 What is the handler method for the `EventHandler<ActionEvent>` interface?

15.6 What is the registration method for a button to register an `ActionEvent` handler?



15.4 Inner Classes

An inner class, or nested class, is a class defined within the scope of another class.

Inner classes are useful for defining handler classes.

Inner classes are used in the preceding section. This section introduces inner classes in detail. First, let us see the code in Figure 15.7. The code in Figure 15.7a defines two separate classes, `Test` and `A`. The code in Figure 15.7b defines `A` as an inner class in `Test`.

```

public class Test {
    ...
}

public class A {
    ...
}
```

(a)

```

public class Test {
    ...
    // Inner class
    public class A {
        ...
    }
}
```

(b)

```

// OuterClass.java: inner class demo
public class OuterClass {
    private int data;

    /** A method in the outer class */
    public void m() {
        // Do something
    }

    // An inner class
    class InnerClass {
        /** A method in the inner class */
        public void mi() {
            // Directly reference data and method
            // defined in its outer class
            data++;
            m();
        }
    }
}
```

(c)

FIGURE 15.7 Inner classes combine dependent classes into the primary class.

The class `InnerClass` defined inside `OuterClass` in Figure 15.7c is another example of an inner class. An inner class may be used just like a regular class. Normally, you define

a class as an inner class if it is used only by its outer class. An inner class has the following features:

- An inner class is compiled into a class named `OuterClassName$InnerClassName.class`. For example, the inner class `A` in `Test` is compiled into `Test$A.class` in Figure 15.7b.
- An inner class can reference the data and the methods defined in the outer class in which it nests, so you need not pass the reference of an object of the outer class to the constructor of the inner class. For this reason, inner classes can make programs simple and concise. For example, `circlePane` is defined in `ControlCircle` in Listing 15.3 (line 15). It can be referenced in the inner class `EnlargeHandler` in line 46.
- An inner class can be defined with a visibility modifier subject to the same visibility rules applied to a member of the class.
- An inner class can be defined as `static`. A `static` inner class can be accessed using the outer class name. A `static` inner class cannot access nonstatic members of the outer class.
- Objects of an inner class are often created in the outer class. But you can also create an object of an inner class from another class. If the inner class is nonstatic, you must first create an instance of the outer class, then use the following syntax to create an object for the inner class:

```
OuterClass.InnerClass innerObject = outerObject.new InnerClass();
```

- If the inner class is static, use the following syntax to create an object for it:

```
OuterClass.InnerClass innerObject = new OuterClass.InnerClass();
```

A simple use of inner classes is to combine dependent classes into a primary class. This reduces the number of source files. It also makes class files easy to organize since they are all named with the primary class as the prefix. For example, rather than creating the two source files `Test.java` and `A.java` as shown in Figure 15.7a, you can merge class `A` into class `Test` and create just one source file, `Test.java` as shown in Figure 15.7b. The resulting class files are `Test.class` and `Test$A.class`.

Another practical use of inner classes is to avoid class-naming conflicts. Two versions of `CirclePane` are defined in Listings 15.2 and 15.3. You can define them as inner classes to avoid a conflict.

A handler class is designed specifically to create a handler object for a GUI component (e.g., a button). The handler class will not be shared by other applications and therefore is appropriate to be defined inside the main class as an inner class.



15.7 Can an inner class be used in a class other than the class in which it nests?

15.8 Can the modifiers `public`, `protected`, `private`, and `static` be used for inner classes?



anonymous inner class

15.5 Anonymous Inner Class Handlers

An anonymous inner class is an inner class without a name. It combines defining an inner class and creating an instance of the class into one step.

Inner-class handlers can be shortened using *anonymous inner classes*. The inner class in Listing 15.3 can be replaced by an anonymous inner class as shown below.

```

public void start(Stage primaryStage) {
    // Omitted

    btEnlarge.setOnAction(
        new EnlargeHandler());
}

class EnlargeHandler
    implements EventHandler<ActionEvent> {
    public void handle(ActionEvent e) {
        circlePane.enlarge();
    }
}

```

(a) Inner class EnlargeListener

```

public void start(Stage primaryStage) {
    // Omitted

    btEnlarge.setOnAction(
        new class EnlargeHandler
            implements EventHandler<ActionEvent>() {
                public void handle(ActionEvent e) {
                    circlePane.enlarge();
                }
            });
}

```

(b) Anonymous inner class

The syntax for an anonymous inner class is shown below

```

new SuperClassName/InterfaceName() {
    // Implement or override methods in superclass or interface

    // Other methods if necessary
}

```

Since an anonymous inner class is a special kind of inner class, it is treated like an inner class with the following features:

- An anonymous inner class must always extend a superclass or implement an interface, but it cannot have an explicit **extends** or **implements** clause.
- An anonymous inner class must implement all the abstract methods in the superclass or in the interface.
- An anonymous inner class always uses the no-arg constructor from its superclass to create an instance. If an anonymous inner class implements an interface, the constructor is **Object()**.
- An anonymous inner class is compiled into a class named **OuterClassName\$n.class**. For example, if the outer class **Test** has two anonymous inner classes, they are compiled into **Test\$1.class** and **Test\$2.class**.

Listing 15.4 gives an example that handles the events from four buttons, as shown in Figure 15.8.



FIGURE 15.8 The program handles the events from four buttons.

LISTING 15.4 AnonymousHandlerDemo.java

```

1 import javafx.application.Application;
2 import javafx.event.ActionEvent;
3 import javafx.event.EventHandler;
4 import javafx.geometry.Pos;
5 import javafx.scene.Scene;

```



VideoNote

Anonymous handler

```

6  import javafx.scene.control.Button;
7  import javafx.scene.layout.HBox;
8  import javafx.stage.Stage;
9
10 public class AnonymousHandlerDemo extends Application {
11     @Override // Override the start method in the Application class
12     public void start(Stage primaryStage) {
13         // Hold two buttons in an HBox
14         HBox hBox = new HBox();
15         hBox.setSpacing(10);
16         hBox.setAlignment(Pos.CENTER);
17         Button btNew = new Button("New");
18         Button btOpen = new Button("Open");
19         Button btSave = new Button("Save");
20         Button btPrint = new Button("Print");
21         hBox.getChildren().addAll(btNew, btOpen, btSave, btPrint);
22
23         // Create and register the handler
24         btNew.setOnAction(new EventHandler<ActionEvent>() {
25             @Override // Override the handle method
26             public void handle(ActionEvent e) {
27                 System.out.println("Process New");
28             }
29         });
30
31         btOpen.setOnAction(new EventHandler<ActionEvent>() {
32             @Override // Override the handle method
33             public void handle(ActionEvent e) {
34                 System.out.println("Process Open");
35             }
36         });
37
38         btSave.setOnAction(new EventHandler<ActionEvent>() {
39             @Override // Override the handle method
40             public void handle(ActionEvent e) {
41                 System.out.println("Process Save");
42             }
43         });
44
45         btPrint.setOnAction(new EventHandler<ActionEvent>() {
46             @Override // Override the handle method
47             public void handle(ActionEvent e) {
48                 System.out.println("Process Print");
49             }
50         });
51
52         // Create a scene and place it in the stage
53         Scene scene = new Scene(hBox, 300, 50);
54         primaryStage.setTitle("AnonymousHandlerDemo"); // Set title
55         primaryStage.setScene(scene); // Place the scene in the stage
56         primaryStage.show(); // Display the stage
57     }
58 }
```

The program creates four handlers using anonymous inner classes (lines 24–50). Without using anonymous inner classes, you would have to create four separate classes. An anonymous handler works the same way as that of an inner class handler. The program is condensed using an anonymous inner class.

The anonymous inner classes in this example are compiled into **AnonymousHandlerDemo\$1.class**, **AnonymousHandlerDemo\$2.class**, **AnonymousHandlerDemo\$3.class**, and **AnonymousHandlerDemo\$4.class**.

- 15.9** If class **A** is an inner class in class **B**, what is the .class file for **A**? If class **B** contains two anonymous inner classes, what are the .class file names for these two classes?



- 15.10** What is wrong in the following code?

```
public class Test extends Application {
    public void start(Stage stage) {
        Button btOK = new Button("OK");
    }

    private class Handler implements
        EventHandler<ActionEvent> {
        public void handle(ActionEvent e) {
            System.out.println(e.getSource());
        }
    }
}
```

(a)

```
public class Test extends Application {
    public void start(Stage stage) {
        Button btOK = new Button("OK");

        btOK.setOnAction(
            new EventHandler<ActionEvent> {
                public void handle
                    (ActionEvent e) {
                        System.out.println
                            (e.getSource());
                }
            } // Something missing here
        );
    }
}
```

(b)



lambda expression

15.6 Simplifying Event Handling Using Lambda Expressions

Lambda expressions can be used to greatly simplify coding for event handling.

Lambda expression is a new feature in Java 8. Lambda expressions can be viewed as an anonymous class with a concise syntax. For example, the following code in (a) can be greatly simplified using a lambda expression in (b) in three lines.

```
btEnlarge.setOnAction(
    new EventHandler<ActionEvent>() {
        @Override
        public void handle(ActionEvent e) {
            // Code for processing event e
        }
    });
}
```

(a) Anonymous inner class event handler

```
btEnlarge.setOnAction(e -> {
    // Code for processing event e
});
```

(b) Lambda expression event handler

The basic syntax for a lambda expression is either

`(type1 param1, type2 param2, ...) -> expression`

or

`(type1 param1, type2 param2, ...) -> { statements; }`

The data type for a parameter may be explicitly declared or implicitly inferred by the compiler. The parentheses can be omitted if there is only one parameter without an explicit data type. In the preceding example, the lambda expression is as follows

```
e -> {
    // Code for processing event e
}
```

functional interface
SAM interface

The compiler treats a lambda expression as if it is an object created from an anonymous inner class. In this case, the compiler understands that the object must be an instance of **EventHandler<ActionEvent>**. Since the **EventHandler** interface defines the **handle** method with a parameter of the **ActionEvent** type, the compiler automatically recognizes that **e** is a parameter of the **ActionEvent** type, and the statements are for the body of the **handle** method. The **EventHandler** interface contains just one method. The statements in the lambda expression are all for that method. If it contains multiple methods, the compiler will not be able to compile the lambda expression. So, for the compiler to understand lambda expressions, the interface must contain exactly one abstract method. Such an interface is known as a *functional interface* or a *Single Abstract Method* (SAM) interface.

Listing 15.4 can be simplified using lambda expressions as shown in Listing 15.5.

LISTING 15.5 LambdaHandlerDemo.java

```
1 import javafx.application.Application;
2 import javafx.event.ActionEvent;
3 import javafx.geometry.Pos;
4 import javafx.scene.Scene;
5 import javafx.scene.control.Button;
6 import javafx.scene.layout.HBox;
7 import javafx.stage.Stage;
8
9 public class LambdaHandlerDemo extends Application {
10     @Override // Override the start method in the Application class
11     public void start(Stage primaryStage) {
12         // Hold two buttons in an HBox
13         HBox hBox = new HBox();
14         hBox.setSpacing(10);
15         hBox.setAlignment(Pos.CENTER);
16         Button btNew = new Button("New");
17         Button btOpen = new Button("Open");
18         Button btSave = new Button("Save");
19         Button btPrint = new Button("Print");
20         hBox.getChildren().addAll(btNew, btOpen, btSave, btPrint);
21
22         // Create and register the handler
23         btNew.setOnAction((ActionEvent e) -> {
24             System.out.println("Process New");
25         });
26
27         btOpen.setOnAction((e) -> {
28             System.out.println("Process Open");
29         });
30
31         btSave.setOnAction(e -> {
32             System.out.println("Process Save");
33         });
34
35         btPrint.setOnAction(e -> System.out.println("Process Print"));
```

lambda handler

lambda handler

lambda handler

lambda handler

```

36
37     // Create a scene and place it in the stage
38     Scene scene = new Scene(hBox, 300, 50);
39     primaryStage.setTitle("LambdaHandlerDemo"); // Set title
40     primaryStage.setScene(scene); // Place the scene in the stage
41     primaryStage.show(); // Display the stage
42 }
43 }
```

The program creates four handlers using lambda expressions (lines 23–35). Using lambda expressions, the code is shorter and cleaner. As seen in this example, lambda expressions may have many variations. Line 23 uses a declared type. Line 27 uses an inferred type since the type can be determined by the compiler. Line 31 omits the parentheses for a single inferred type. Line 35 omits the braces for a single statement in the body.

You can handle events by defining handler classes using inner classes, anonymous inner classes, or lambda expressions. We recommend that you use lambda expressions because it produces a shorter, clearer, and cleaner code.

inner class, anonymous class,
or Lambda?



- 15.11** What is a lambda expression? What is the benefit of using lambda expressions for event handling? What is the syntax of a lambda expression?
- 15.12** What is a functional interface? Why is a functional interface required for a lambda expression?
- 15.13** Show the output of the following code:

```

public class Test {
    public static void main(String[] args) {
        Test test = new Test();
        test.setAction1(() -> System.out.print("Action 1! "));
        test.setAction2(e -> System.out.print(e + " "));
        System.out.println(test.setAction3(e -> e * 2));
    }

    public void setAction1(T1 t) {
        t.m();
    }

    public void setAction2(T2 t) {
        t.m(4.5);
    }

    public double setAction3(T3 t) {
        return t.m(5.5);
    }
}

interface T1 {
    public void m();
}

interface T2 {
    public void m(Double d);
}

interface T3 {
    public double m(Double d);
}
```

15.7 Case Study: Loan Calculator



This case study develops a loan calculator using event-driven programming with GUI controls.

Now, we will write the program for the loan-calculator problem presented at the beginning of this chapter. Here are the major steps in the program:

1. Create the user interface, as shown in Figure 15.9.
 - a. Create a **GridPane**. Add labels, text fields, and button to the pane.
 - b. Set the alignment of the button to the right.
2. Process the event.

Create and register the handler for processing the button-clicking action event. The handler obtains the user input on the loan amount, interest rate, and number of years, computes the monthly and total payments, and displays the values in the text fields.

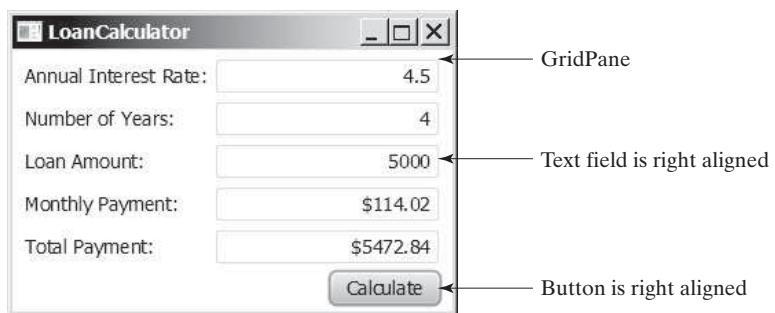


FIGURE 15.9 The program computes loan payments.

The complete program is given in Listing 15.6.

LISTING 15.6 LoanCalculator.java

```

1 import javafx.application.Application;
2 import javafx.geometry.Pos;
3 import javafx.geometry.HPos;
4 import javafx.scene.Scene;
5 import javafx.scene.control.Button;
6 import javafx.scene.control.Label;
7 import javafx.scene.control.TextField;
8 import javafx.scene.layout.GridPane;
9 import javafx.stage.Stage;
10
11 public class LoanCalculator extends Application {
12     private TextField tfAnnualInterestRate = new TextField();
13     private TextField tfNumber0fYears = new TextField();
14     private TextField tfLoanAmount = new TextField();
15     private TextField tfMonthlyPayment = new TextField();
16     private TextField tfTotalPayment = new TextField();
17     private Button btCalculate = new Button("Calculate");
18
19     @Override // Override the start method in the Application class
20     public void start(Stage primaryStage) {
21         // Create UI
22         GridPane gridPane = new GridPane();

```

text fields

button

create a grid pane

```

23     gridPane.setHgap(5);
24     gridPane.setVgap(5);
25     gridPane.add(new Label("Annual Interest Rate:"), 0, 0);           add to grid pane
26     gridPane.add(tfAnnualInterestRate, 1, 0);
27     gridPane.add(new Label("Number of Years:"), 0, 1);
28     gridPane.add(tfNumberOfYears, 1, 1);
29     gridPane.add(new Label("Loan Amount:"), 0, 2);
30     gridPane.add(tfLoanAmount, 1, 2);
31     gridPane.add(new Label("Monthly Payment:"), 0, 3);
32     gridPane.add(tfMonthlyPayment, 1, 3);
33     gridPane.add(new Label("Total Payment:"), 0, 4);
34     gridPane.add(tfTotalPayment, 1, 4);
35     gridPane.add(btCalculate, 1, 5);
36
37     // Set properties for UI
38     gridPane.setAlignment(Pos.CENTER);
39     tfAnnualInterestRate.setAlignment(Pos.BOTTOM_RIGHT);
40     tfNumberOfYears.setAlignment(Pos.BOTTOM_RIGHT);
41     tfLoanAmount.setAlignment(Pos.BOTTOM_RIGHT);
42     tfMonthlyPayment.setAlignment(Pos.BOTTOM_RIGHT);
43     tfTotalPayment.setAlignment(Pos.BOTTOM_RIGHT);
44     tfMonthlyPayment.setEditable(false);
45     tfTotalPayment.setEditable(false);
46     GridPane.setHalignment(btCalculate, HPos.RIGHT);
47
48     // Process events
49     btCalculate.setOnAction(e -> calculateLoanPayment());           register handler
50
51     // Create a scene and place it in the stage
52     Scene scene = new Scene(gridPane, 400, 250);
53     primaryStage.setTitle("LoanCalculator"); // Set title
54     primaryStage.setScene(scene); // Place the scene in the stage
55     primaryStage.show(); // Display the stage
56 }
57
58 private void calculateLoanPayment() {
59     // Get values from text fields
60     double interest =
61         Double.parseDouble(tfAnnualInterestRate.getText());           get input
62     int year = Integer.parseInt(tfNumberOfYears.getText());
63     double loanAmount =
64         Double.parseDouble(tfLoanAmount.getText());
65
66     // Create a loan object. Loan defined in Listing 10.2
67     Loan loan = new Loan(interest, year, loanAmount);           create loan
68
69     // Display monthly payment and total payment
70     tfMonthlyPayment.setText(String.format("%.2f",
71         loan.getMonthlyPayment()));
72     tfTotalPayment.setText(String.format("%.2f",
73         loan.getTotalPayment()));
74 }
75 }
```

The user interface is created in the `start` method (lines 22–46). The button is the source of the event. A handler is created and registered with the button (line 49). The button handler invokes the `calculateLoanPayment()` method to get the interest rate (line 60), number of years (line 62), and loan amount (line 64). Invoking `tfAnnualInterestRate.getText()` returns the string text in the `tfAnnualInterestRate` text field. The `Loan` class is used for

computing the loan payments. This class was introduced in Listing 10.2, `Loan.java`. Invoking `Loan.getMonthlyPayment()` returns the monthly payment for the loan (line 71). The `String.format` method, introduced in Section 10.10.7, is used to format a number into a desirable format and returns it as a string (lines 70, 72). Invoking the `setText` method on a text field sets a string value in the text field.

15.8 Mouse Events



A MouseEvent is fired whenever a mouse button is pressed, released, clicked, moved, or dragged on a node or a scene.

The `MouseEvent` object captures the event, such as the number of clicks associated with it, the location (the *x*- and *y*-coordinates) of the mouse, or which mouse button was pressed, as shown in Figure 15.10.

javafx.scene.input.MouseEvent	
<code>+getButton(): MouseButton</code>	Indicates which mouse button has been clicked.
<code>+getClickCount(): int</code>	Returns the number of mouse clicks associated with this event.
<code>+getX(): double</code>	Returns the <i>x</i> -coordinate of the mouse point in the event source node.
<code>+getY(): double</code>	Returns the <i>y</i> -coordinate of the mouse point in the event source node.
<code>+getSceneX(): double</code>	Returns the <i>x</i> -coordinate of the mouse point in the scene.
<code>+getSceneY(): double</code>	Returns the <i>y</i> -coordinate of the mouse point in the scene.
<code>+getScreenX(): double</code>	Returns the <i>x</i> -coordinate of the mouse point in the screen.
<code>+getScreenY(): double</code>	Returns the <i>y</i> -coordinate of the mouse point in the screen.
<code>+isAltDown(): boolean</code>	Returns true if the Alt key is pressed on this event.
<code>+isControlDown(): boolean</code>	Returns true if the Control key is pressed on this event.
<code>+isMetaDown(): boolean</code>	Returns true if the mouse Meta button is pressed on this event.
<code>+isShiftDown(): boolean</code>	Returns true if the Shift key is pressed on this event.

FIGURE 15.10 The `MouseEvent` class encapsulates information for mouse events.

detect mouse buttons

Four constants—`PRIMARY`, `SECONDARY`, `MIDDLE`, and `NONE`—are defined in `MouseButton` to indicate the left, right, middle, and none mouse buttons. You can use the `getButton()` method to detect which button is pressed. For example, `getButton() == MouseButton.SECONDARY` indicates that the right button was pressed.

The mouse events are listed in Table 15.1. To demonstrate using mouse events, we give an example that displays a message in a pane and enables the message to be moved using a mouse. The message moves as the mouse is dragged, and it is always displayed at the mouse point. Listing 15.7 gives the program. A sample run of the program is shown in Figure 15.11.



FIGURE 15.11 You can move the message by dragging the mouse.



VideoNote

Move message using the mouse

LISTING 15.7 MouseEventDemo.java

```

1 import javafx.application.Application;
2 import javafx.scene.Scene;
3 import javafx.scene.layout.Pane;
```

```

4 import javafx.scene.text.Text;
5 import javafx.stage.Stage;
6
7 public class MouseEventDemo extends Application {
8     @Override // Override the start method in the Application class
9     public void start(Stage primaryStage) {
10         // Create a pane and set its properties
11         Pane pane = new Pane();
12         Text text = new Text(20, 20, "Programming is fun");
13         pane.getChildren().addAll(text);
14         text.setOnMouseDragged(e -> {
15             text.setX(e.getX());
16             text.setY(e.getY());
17         });
18
19         // Create a scene and place it in the stage
20         Scene scene = new Scene(pane, 300, 100);
21         primaryStage.setTitle("MouseEventDemo"); // Set the stage title
22         primaryStage.setScene(scene); // Place the scene in the stage
23         primaryStage.show(); // Display the stage
24     }
25 }
```

create a pane
create a text
add text to a pane
lambda handler
reset text position

Each node or scene can fire mouse events. The program creates a **Text** (line 12) and registers a handler to handle move dragged event (line 14). Whenever a mouse is dragged, the text's x- and y-coordinates are set to the mouse position (lines 15 and 16).

15.14 What method do you use to get the mouse-point position for a mouse event?

15.15 What methods do you use to register a handler for a mouse pressed, released, clicked, entered, exited, moved and dragged event?



15.9 Key Events

A **KeyEvent** is fired whenever a key is pressed, released, or typed on a node or a scene.



Key events enable the use of the keys to control and perform actions or get input from the keyboard. The **KeyEvent** object describes the nature of the event (namely, that a key has been pressed, released, or typed) and the value of the key, as shown in Figure 15.12.

javafx.scene.input.KeyEvent	
+getCharacter(): String	Returns the character associated with the key in this event.
+getCode(): KeyCode	Returns the key code associated with the key in this event.
+getText(): String	Returns a string describing the key code.
+isAltDown(): boolean	Returns true if the Alt key is pressed on this event.
+isControlDown(): boolean	Returns true if the Control key is pressed on this event.
+isMetaDown(): boolean	Returns true if the mouse Meta button is pressed on this event.
+isShiftDown(): boolean	Returns true if the Shift key is pressed on this event.

FIGURE 15.12 The **KeyEvent** class encapsulates information about key events.

Every key event has an associated code that is returned by the **getCode()** method in **KeyEvent**. The *key codes* are constants defined in **KeyCode**. Table 15.2 lists some constants. **KeyCode** is an **enum** type. For use of **enum** types, see Appendix I. For the key-pressed and

key code

key-released events, `getCode()` returns the value as defined in the table, `getText()` returns a string that describes the key code, and `getCharacter()` returns an empty string. For the key-typed event, `getCode()` returns `UNDEFINED` and `getCharacter()` returns the Unicode character or a sequence of characters associated with the key-typed event.

TABLE 15.2 KeyCode Constants

Constant	Description	Constant	Description
<code>HOME</code>	The Home key	<code>CONTROL</code>	The Control key
<code>END</code>	The End key	<code>SHIFT</code>	The Shift key
<code>PAGE_UP</code>	The Page Up key	<code>BACK_SPACE</code>	The Backspace key
<code>PAGE_DOWN</code>	The Page Down key	<code>CAPS</code>	The Caps Lock key
<code>UP</code>	The up-arrow key	<code>NUM_LOCK</code>	The Num Lock key
<code>DOWN</code>	The down-arrow key	<code>ENTER</code>	The Enter key
<code>LEFT</code>	The left-arrow key	<code>UNDEFINED</code>	The <code>keyCode</code> unknown
<code>RIGHT</code>	The right-arrow key	<code>F1 to F12</code>	The function keys from F1 to F12
<code>ESCAPE</code>	The Esc key	<code>0 to 9</code>	The number keys from 0 to 9
<code>TAB</code>	The Tab key	<code>A to Z</code>	The letter keys from A to Z

The program in Listing 15.8 displays a user-input character. The user can move the character up, down, left, and right, using the up, down, left, and right arrow keys. Figure 15.13 contains a sample run of the program.

**FIGURE 15.13** The program responds to key events by displaying a character and moving it up, down, left, or right.**LISTING 15.8** KeyEventDemo.java

create a pane

register handler
get the key pressed
move a character

```

1 import javafx.application.Application;
2 import javafx.scene.Scene;
3 import javafx.scene.layout.Pane;
4 import javafx.scene.text.Text;
5 import javafx.stage.Stage;
6
7 public class KeyEventDemo extends Application {
8     @Override // Override the start method in the Application class
9     public void start(Stage primaryStage) {
10         // Create a pane and set its properties
11         Pane pane = new Pane();
12         Text text = new Text(20, 20, "A");
13
14         pane.getChildren().add(text);
15         text.setOnKeyPressed(e -> {
16             switch (e.getCode()) {
17                 case DOWN: text.setY(text.getY() + 10); break;
18                 case UP: text.setY(text.getY() - 10); break;
19                 case LEFT: text.setX(text.getX() - 10); break;
20                 case RIGHT: text.setX(text.getX() + 10); break;
21             }
22         });
23     }
24 }
```

```

21     default:
22         if (Character.isLetterOrDigit(e.getText().charAt(0)))
23             text.setText(e.getText());                                set a new character
24     }
25 );
26
27 // Create a scene and place it in the stage
28 Scene scene = new Scene(pane);
29 primaryStage.setTitle("KeyEventDemo"); // Set the stage title
30 primaryStage.setScene(scene); // Place the scene in the stage
31 primaryStage.show(); // Display the stage
32
33 text.requestFocus(); // text is focused to receive key input      request focus on text
34 }
35 }
```

The program creates a pane (line 11), creates a text (line 12), and places the text into the pane (line 14). The text registers the handler for the key-pressed event in lines 15–25. When a key is pressed, the handler is invoked. The program uses `e.getCode()` (line 16) to obtain the key code and `e.getText()` (line 23) to get the character for the key. When a nonarrow key is pressed, the character is displayed (lines 22 and 23). When an arrow key is pressed, the character moves in the direction indicated by the arrow key (lines 17–20). Note that in a switch statement for an enum type value, the cases are for the enum constants (lines 16–24). The constants are unqualified. For example, using `KeyCode.DOWN` in the case clause would be wrong (see Appendix I).

Only a focused node can receive `KeyEvent`. Invoking `requestFocus()` on `text` enables `text` to receive key input (line 33). This method must be invoked after the stage is displayed.

`requestFocus()`

We can now add more control for our `ControlCircle` example in Listing 15.3 to increase/decrease the circle radius by clicking the left/right mouse button or by pressing the U and D keys. The new program is given in Listing 15.9.

LISTING 15.9 ControlCircleWithMouseAndKey.java

```

1 import javafx.application.Application;
2 import javafx.geometry.Pos;
3 import javafx.scene.Scene;
4 import javafx.scene.control.Button;
5 import javafx.scene.input.KeyCode;
6 import javafx.scene.input.MouseButton;
7 import javafx.scene.layout.HBox;
8 import javafx.scene.layout.BorderPane;
9 import javafx.stage.Stage;
10
11 public class ControlCircleWithMouseAndKey extends Application {
12     private CirclePane circlePane = new CirclePane();
13
14     @Override // Override the start method in the Application class
15     public void start(Stage primaryStage) {
16         // Hold two buttons in an HBox
17         HBox hBox = new HBox();
18         hBox.setSpacing(10);
19         hBox.setAlignment(Pos.CENTER);
20         Button btEnlarge = new Button("Enlarge");
21         Button btShrink = new Button("Shrink");
22         hBox.getChildren().add(btEnlarge);
23         hBox.getChildren().add(btShrink);
24
25         // Create and register the handler
26         btEnlarge.setOnAction(e -> circlePane.enlarge());           button handler
27         btShrink.setOnAction(e -> circlePane.shrink());
```

```

28
mouse-click handler    29     circlePane.setOnMouseClicked(e -> {
30         if (e.getButton() == MouseButton.PRIMARY) {
31             circlePane.enlarge();
32         }
33         else if (e.getButton() == MouseButton.SECONDARY) {
34             circlePane.shrink();
35         }
36     });
37
key-pressed handler    38     circlePane.setOnKeyPressed(e -> {
39         if (e.getCode() == KeyCode.U) {
40             circlePane.enlarge();
41         }
42         else if (e.getCode() == KeyCode.D) {
43             circlePane.shrink();
44         }
45     });
46
47     BorderPane borderPane = new BorderPane();
48     borderPane.setCenter(circlePane);
49     borderPane.setBottom(hBox);
50     BorderPane.setAlignment(hBox, Pos.CENTER);
51
52     // Create a scene and place it in the stage
53     Scene scene = new Scene(borderPane, 200, 150);
54     primaryStage.setTitle("ControlCircle"); // Set the stage title
55     primaryStage.setScene(scene); // Place the scene in the stage
56     primaryStage.show(); // Display the stage
57
58     circlePane.requestFocus(); // Request focus on circlePane
59 }
60 }
```

mouse clicked event The `CirclePane` class (line 12) is already defined in Listing 15.3 and can be reused in this program.

key pressed event A handler for mouse clicked events is created in lines 29–36. If the left mouse button is clicked, the circle is enlarged (lines 30–32); if the right mouse button is clicked, the circle is shrunk (lines 33–35).

requestFocus() A handler for key pressed events is created in lines 38–45. If the U key is pressed, the circle is enlarged (lines 39–41); if the D key is pressed, the circle is shrunk (lines 42–44).

Invoking `requestFocus()` on `circlePane` (line 58) makes `circlePane` to receive key events. Note that after you click a button, `circlePane` is no longer focused. To fix the problem, invoke `rerequestFocus()` on `circlePane` again after each button is clicked.



15.16 What methods do you use to register handlers for key pressed, key released, and key typed events? In which classes are these methods defined? (See Table 15.1)

15.17 What method do you use to get the key character for a key-typed event? What method do you use to get the key code for a key-pressed or key-released event?

15.18 How do you set focus on a node so it can listen for key events?

15.10 Listeners for Observable Objects



You can add a listener to process a value change in an observable object.

An instance of `Observable` is known as an *observable object*, which contains the `addListener(InvalidationListener Listener)` method for adding a listener. The listener class must implement the `InvalidationListener` interface to override the `invalidated(Observable o)` method for handling the value change. Once

the value is changed in the `Observable` object, the listener is notified by invoking its `invalidated(Observable o)` method. Every binding property is an instance of `Observable`. Listing 15.10 gives an example of observing and handling a change in a observable object `DoubleProperty` object `balance`.

LISTING 15.10 ObservablePropertyDemo.java

```

1 import javafx.beans.InvalidationListener;
2 import javafx.beans.Observable;
3 import javafx.beans.property.DoubleProperty;
4 import javafx.beans.property.SimpleDoubleProperty;
5
6 public class ObservablePropertyDemo {
7     public static void main(String[] args) {
8         DoubleProperty balance = new SimpleDoubleProperty();
9         balance.addListener(new InvalidationListener() {
10             public void invalidated(Observable ov) {
11                 System.out.println("The new value is " +
12                     balance.doubleValue());
13             }
14         });
15         balance.set(4.5);
16     }
17 }
18 }
```

observable property
add listener
handle change

The new value is 4.5



When line 16 is executed, it causes a change in `balance`, which notifies the listener by invoking the listener's `invalidated` method.

Note that the anonymous inner class in lines 9–14 can be simplified using a lambda expression as follows:

```
balance.addListener(ov -> {
    System.out.println("The new value is " +
        balance.doubleValue());
});
```

Recall that in Listing 14.20 `DisplayClock.java`, the clock pane size is not changed when you resize the window. The problem can be fixed by adding a listener to change the clock pane size and register the listener to the window's width and height properties, as shown in Listing 15.11.

LISTING 15.11 DisplayResizableClock.java

```

1 import javafx.application.Application;
2 import javafx.geometry.Pos;
3 import javafx.stage.Stage;
4 import javafx.scene.Scene;
5 import javafx.scene.control.Label;
6 import javafx.scene.layout.BorderPane;
7
8 public class DisplayResizableClock extends Application {
9     @Override // Override the start method in the Application class
10    public void start(Stage primaryStage) {
11        // Create a clock and a label
12        ClockPane clock = new ClockPane();
13        String timeString = clock.getHour() + ":" + clock.getMinute()
14            + ":" + clock.getSecond();
```

```

15     Label lblCurrentTime = new Label(timeString);
16
17     // Place clock and label in border pane
18     BorderPane pane = new BorderPane();
19     pane.setCenter(clock);
20     pane.setBottom(lblCurrentTime);
21     BorderPane.setAlignment(lblCurrentTime, Pos.TOP_CENTER);
22
23     // Create a scene and place it in the stage
24     Scene scene = new Scene(pane, 250, 250);
25     primaryStage.setTitle("DisplayClock"); // Set the stage title
26     primaryStage.setScene(scene); // Place the scene in the stage
27     primaryStage.show(); // Display the stage
28
29     pane.widthProperty().addListener(ov ->
30         clock.setWidth(pane.getWidth())
31     );
32
33     pane.heightProperty().addListener(ov ->
34         clock.setHeight(pane.getHeight())
35     );
36 }
37 }
```

create a listener
set a new width for clock

create a listener
set a new height for clock

The program is identical to Listing 14.19 except that you added the code in lines 29–35 to register listeners for resizing the clock pane upon a change of the width or height of the scene. The code ensures that the clock pane size is synchronized with the scene size.



15.19 What would happen if you replace `pane` with `scene` or `primaryStage` in lines 29 and 33?



15.11 Animation

JavaFX provides the `Animation` class with the core functionality for all animations.

Suppose you want to write a program that animates a rising flag, as shown in Figure 15.14. How do you accomplish the task? There are several ways to program this. An effective one is to use the subclasses of the JavaFX `Animation` class, which is the subject of this section.



Animate a rising flag



FIGURE 15.14 The animation simulates a flag rising.

The abstract `Animation` class provides the core functionalities for animations in JavaFX, as shown in Figure 15.15. Many concrete subclasses of `Animation` are provided in JavaFX. This section introduces `PathTransition`, `FadeTransition` and `Timeline`.

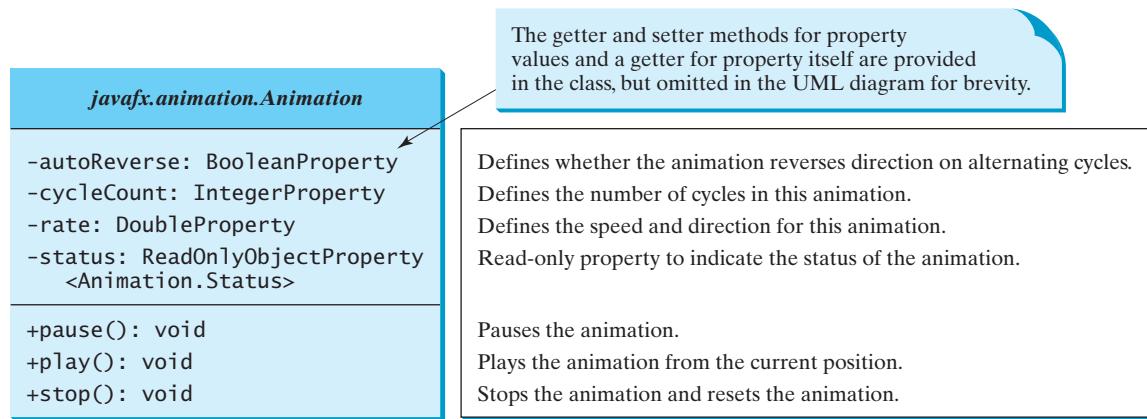


FIGURE 15.15 The abstract `Animation` class is the root class for JavaFX animations.

The `autoReverse` is a Boolean property that indicates whether an animation will reverse its direction on the next cycle. The `cycleCount` indicates the number of the cycles for the animation. You can use the constant `Timeline.INDEFINITE` to indicate an indefinite number of cycles. The `rate` defines the speed of the animation. A negative rate value indicates the opposite direction for the animation. The `status` is a read-only property that indicates the status of the animation (`Animation.Status.PAUSED`, `Animation.Status.RUNNING`, and `Animation.Status.STOPPED`). The methods `pause()`, `play()`, and `stop()` pauses, plays, and stops an animation.

15.11.1 PathTransition

The `PathTransition` class animates the moves of a node along a path from one end to the other over a given time. `PathTransition` is a subtype of `Animation`. The UML class diagram for the class is shown in Figure 15.16.

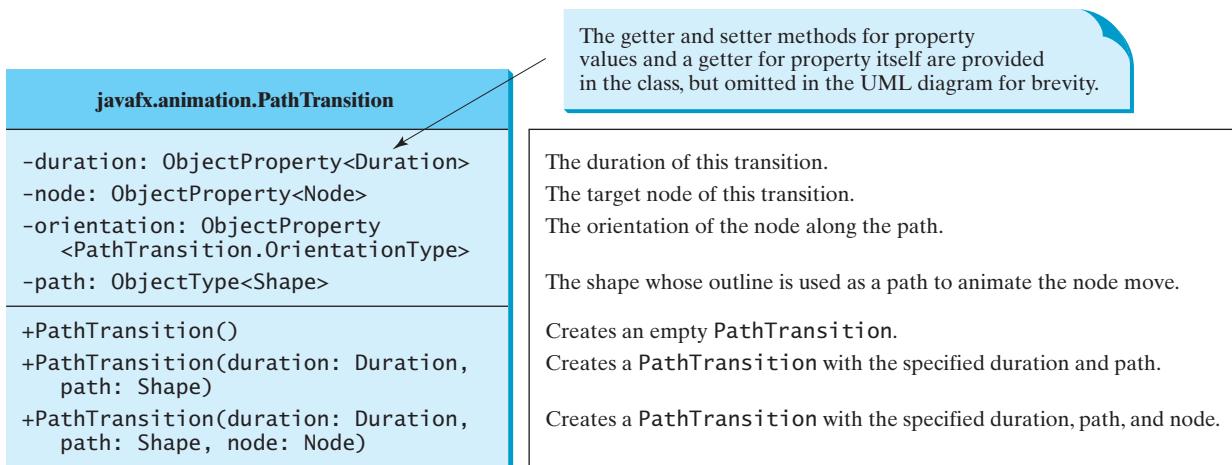


FIGURE 15.16 The `PathTransition` class defines an animation for a node along a path.

The `Duration` class defines a duration of time. It is an immutable class. The class defines constants `INDEFINITE`, `ONE`, `UNKNOWN`, and `ZERO` to represent an indefinite duration, 1 milliseconds, unknown, and 0 duration. You can use `new Duration(double millis)` to create

an instance of `Duration`, the `add`, `subtract`, `multiply`, and `divide` methods to perform arithmetic operations, and the `toHours()`, `toMinutes()`, `toSeconds()`, and `toMillis()` to return the number of hours, minutes, seconds, and milliseconds in this duration. You can also use `compareTo` to compare two durations.

The constants `NONE` and `ORTHOGONAL_TO_TANGENT` are defined in `PathTransition.OrientationType`. The latter specifies that the node is kept perpendicular to the path's tangent along the geometric path.

Listing 15.12 gives an example that moves a rectangle along the outline of a circle, as shown in Figure 15.17a.

LISTING 15.12 PathTransitionDemo.java

```

1  import javafx.animation.PathTransition;
2  import javafx.animation.Timeline;
3  import javafx.application.Application;
4  import javafx.scene.Scene;
5  import javafx.scene.layout.Pane;
6  import javafx.scene.paint.Color;
7  import javafx.scene.shape.Rectangle;
8  import javafx.scene.shape.Circle;
9  import javafx.stage.Stage;
10 import javafx.util.Duration;
11
12 public class PathTransitionDemo extends Application {
13     @Override // Override the start method in the Application class
14     public void start(Stage primaryStage) {
15         // Create a pane
16         Pane pane = new Pane();
17
18         // Create a rectangle
19         Rectangle rectangle = new Rectangle(0, 0, 25, 50);
20         rectangle.setFill(Color.ORANGE);
21
22         // Create a circle
23         Circle circle = new Circle(125, 100, 50);
24         circle.setFill(Color.WHITE);
25         circle.setStroke(Color.BLACK);
26
27         // Add circle and rectangle to the pane
28         pane.getChildren().add(circle);
29         pane.getChildren().add(rectangle);
30
31         // Create a path transition
32         PathTransition pt = new PathTransition();
33         pt.setDuration(Duration.millis(4000));
34         pt.setPath(circle);
35         pt.setNode(rectangle);
36         pt.setOrientation(
37             PathTransition.OrientationType.ORTHOGONAL_TO_TANGENT);
38         pt.setCycleCount(Timeline.INDEFINITE);
39         pt.setAutoReverse(true);
40         pt.play(); // Start animation
41
42         circle.setOnMousePressed(e -> pt.pause());
43         circle.setOnMouseReleased(e -> pt.play());
44
45         // Create a scene and place it in the stage
46         Scene scene = new Scene(pane, 250, 200);
47         primaryStage.setTitle("PathTransitionDemo"); // Set the stage title

```

create a pane

create a rectangle

create a circle

add circle to pane
add rectangle to pane

create a PathTransition
set transition duration
set path in transition
set node in transition
set orientation

set cycle count indefinite
set auto reverse true
play animation

pause animation
resume animation

```

48     primaryStage.setScene(scene); // Place the scene in the stage
49     primaryStage.show(); // Display the stage
50   }
51 }
```

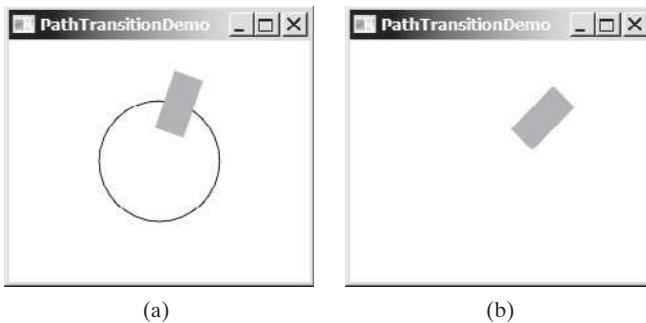


FIGURE 15.17 The **PathTransition** animates a rectangle moving along the circle.

The program creates a pane (line 16), a rectangle (line 19), and a circle (line 23). The circle and rectangle are placed in the pane (lines 28 and 29). If the circle was not placed in the pane, you will see the screen shot as shown in Figure 15.17b.

The program creates a path transition (line 32), sets its duration to 4 seconds for one cycle of animation (line 33), sets circle as the path (line 34), sets rectangle as the node (line 35), and sets the orientation to orthogonal to tangent (line 36).

The cycle count is set to indefinite (line 38) so the animation continues forever. The auto reverse is set to true (line 39) so that the direction of the move is reversed in the alternating cycle. The program starts animation by invoking the **play()** method (line 40).

If the **pause()** method is replaced by the **stop()** method in line 42, the animation will start over from the beginning when it restarts.

Listing 15.13 gives the program that animates a flag rising, as shown in Figure 15.14.

LISTING 15.13 FlagRisingAnimation.java

```

1 import javafx.animation.PathTransition;
2 import javafx.application.Application;
3 import javafx.scene.Scene;
4 import javafx.scene.image.ImageView;
5 import javafx.scene.layout.Pane;
6 import javafx.scene.shape.Line;
7 import javafx.stage.Stage;
8 import javafx.util.Duration;
9
10 public class FlagRisingAnimation extends Application {
11     @Override // Override the start method in the Application class
12     public void start(Stage primaryStage) {
13         // Create a pane
14         Pane pane = new Pane();
15
16         // Add an image view and add it to pane
17         ImageView imageView = new ImageView("image/us.gif");
18         pane.getChildren().add(imageView);
19
20         // Create a path transition
21         PathTransition pt = new PathTransition(Duration.millis(10000),
```

create a pane

create an image view

add image view to pane

create a path transition

```

set cycle count          22      new Line(100, 200, 100, 0), imageView);
play animation          23      pt.setCycleCount(5);
                                24      pt.play(); // Start animation
                                25
                                26      // Create a scene and place it in the stage
                                27      Scene scene = new Scene(pane, 250, 200);
                                28      primaryStage.setTitle("FlagRisingAnimation"); // Set the stage title
                                29      primaryStage.setScene(scene); // Place the scene in the stage
                                30      primaryStage.show(); // Display the stage
                                31  }
                                32 }

```

The program creates a pane (line 14), an image view from an image file (line 17), and places the image view to the page (line 18). A path transition is created with duration of 10 seconds using a line as a path and the image view as the node (lines 21 and 22). The image view will move along the line. Since the line is not placed in the scene, you will not see the line in the window.

The cycle count is set to 5 (line 23) so that the animation is repeated five times.

15.11.2 FadeTransition

The **FadeTransition** class animates the change of the opacity in a node over a given time. **FadeTransition** is a subtype of **Animation**. The UML class diagram for the class is shown in Figure 15.18.

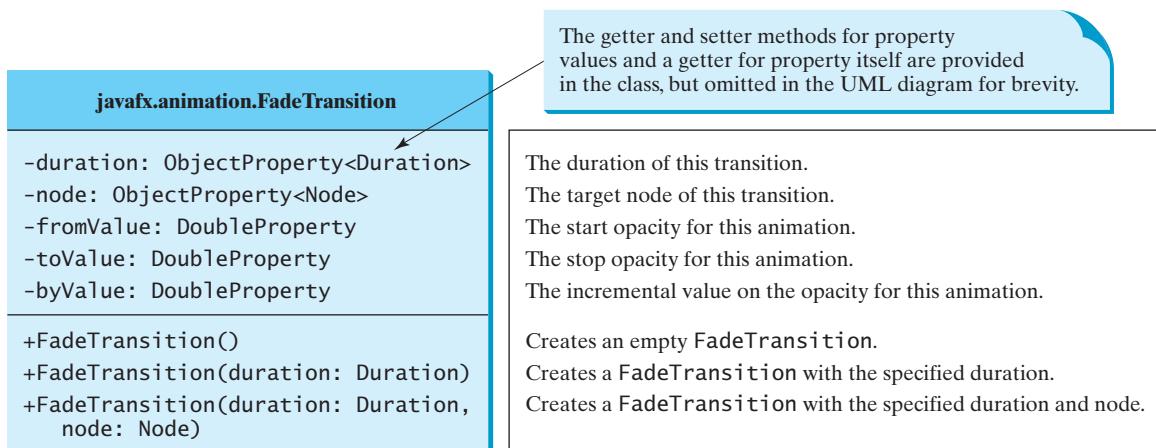


FIGURE 15.18 The **FadeTransition** class defines an animation for the change of opacity in a node.

Listing 15.14 gives an example that applies a fade transition to the filled color in an ellipse, as shown in Figure 15.19.

LISTING 15.14 FadeTransitionDemo.java

```

1 import javafx.animation.FadeTransition;
2 import javafx.animation.Timeline;
3 import javafx.application.Application;
4 import javafx.scene.Scene;
5 import javafx.scene.layout.Pane;
6 import javafx.scene.paint.Color;
7 import javafx.scene.shape.Ellipse;
8 import javafx.stage.Stage;

```

```

9 import javafx.util.Duration;
10
11 public class FadeTransitionDemo extends Application {
12     @Override // Override the start method in the Application class
13     public void start(Stage primaryStage) {
14         // Place an ellipse to the pane
15         Pane pane = new Pane();
16         Ellipse ellipse = new Ellipse(10, 10, 100, 50);
17         ellipse.setFill(Color.RED);
18         ellipse.setStroke(Color.BLACK);
19         ellipse.centerXProperty().bind(pane.widthProperty().divide(2));
20         ellipse.centerYProperty().bind(pane.heightProperty().divide(2));
21         ellipse.radiusXProperty().bind(
22             pane.widthProperty().multiply(0.4));
23         ellipse.radiusYProperty().bind(
24             pane.heightProperty().multiply(0.4));
25         pane.getChildren().add(ellipse);
26
27         // Apply a fade transition to ellipse
28         FadeTransition ft =
29             new FadeTransition(Duration.millis(3000), ellipse);
30         ft.setFromValue(1.0);
31         ft.setToValue(0.1);
32         ft.setCycleCount(Timeline.INDEFINITE);
33         ft.setAutoReverse(true);
34         ft.play(); // Start animation
35
36         // Control animation
37         ellipse.setOnMousePressed(e -> ft.pause());
38         ellipse.setOnMouseReleased(e -> ft.play());
39
40         // Create a scene and place it in the stage
41         Scene scene = new Scene(pane, 200, 150);
42         primaryStage.setTitle("FadeTransitionDemo"); // Set the stage title
43         primaryStage.setScene(scene); // Place the scene in the stage
44         primaryStage.show(); // Display the stage
45     }
46 }
```

create a pane
create an ellipse
set ellipse fill color
set ellipse stroke color
bind ellipse properties

add ellipse to pane

create a FadeTransition

set start opaque value
set end opaque value
set cycle count
set auto reverse true
play animation

pause animation
resume animation

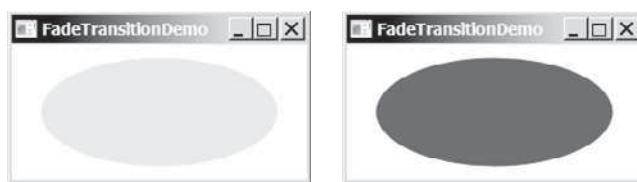


FIGURE 15.19 The **FadeTransition** animates the change of opacity in the ellipse.

The program creates a pane (line 15) and an ellipse (line 16) and places the ellipse into the pane (line 25). The ellipse's **centerX**, **centerY**, **radiusX**, and **radiusY** properties are bound to the pane's size (lines 19–24).

A fade transition is created with a duration of 3 seconds for the ellipse (line 29). It sets the start opaque to 1.0 (line 30) and the stop opaque 0.1 (line 31). The cycle count is set to infinite so the animation is repeated indefinitely (line 32). When the mouse is pressed, the animation is paused (line 37). When the mouse is released, the animation resumes from where it was paused (line 38).

15.11.3 Timeline

`PathTransition` and `FadeTransition` define specialized animations. The `Timeline` class can be used to program any animation using one or more `KeyFrames`. Each `KeyFrame` is executed sequentially at a specified time interval. `Timeline` inherits from `Animation`. You can construct a `Timeline` using the constructor `new Timeline(KeyFrame... keyframes)`. A `KeyFrame` can be constructed using

```
new KeyFrame(Duration duration, EventHandler<ActionEvent> onFinish)
```

The handler `onFinish` is called when the duration for the key frame is elapsed.

Listing 15.15 gives an example that displays a flashing text, as shown in Figure 15.20. The text is on and off alternating to animate flashing.



VideoNote
Flashing text

create a stack pane
create a text

add text to pane

handler for changing text

set text empty

set text

create a Timeline
create a KeyFrame for handler
set cycle count indefinite
play animation

resume animation

pause animation

LISTING 15.15 TimelineDemo.java

```

1 import javafx.animation.Animation;
2 import javafx.application.Application;
3 import javafx.stage.Stage;
4 import javafx.animation.KeyFrame;
5 import javafx.animation.Timeline;
6 import javafx.event.ActionEvent;
7 import javafx.event.EventHandler;
8 import javafx.scene.Scene;
9 import javafx.scene.layout.StackPane;
10 import javafx.scene.paint.Color;
11 import javafx.scene.text.Text;
12 import javafx.util.Duration;
13
14 public class TimelineDemo extends Application {
15     @Override // Override the start method in the Application class
16     public void start(Stage primaryStage) {
17         StackPane pane = new StackPane();
18         Text text = new Text(20, 50, "Programming is fun");
19         text.setFill(Color.RED);
20         pane.getChildren().add(text); // Place text into the stack pane
21
22         // Create a handler for changing text
23         EventHandler<ActionEvent> eventHandler = e -> {
24             if (text.getText().length() != 0) {
25                 text.setText("");
26             }
27             else {
28                 text.setText("Programming is fun");
29             }
30         };
31
32         // Create an animation for alternating text
33         Timeline animation = new Timeline(
34             new KeyFrame(Duration.millis(500), eventHandler));
35         animation.setCycleCount(Timeline.INDEFINITE);
36         animation.play(); // Start animation
37
38         // Pause and resume animation
39         text.setOnMouseClicked(e -> {
40             if (animation.getStatus() == Animation.Status.PAUSED) {
41                 animation.play();
42             }
43             else {
44                 animation.pause();
45             }
46         });
47     }
48 }
```

```

45     }
46   });
47
48   // Create a scene and place it in the stage
49   Scene scene = new Scene(pane, 250, 250);
50   primaryStage.setTitle("TimelineDemo"); // Set the stage title
51   primaryStage.setScene(scene); // Place the scene in the stage
52   primaryStage.show(); // Display the stage
53 }
54 }
```



FIGURE 15.20 The handler is called to set the text to Programming is fun or empty in turn.

The program creates a stack pane (line 17) and a text (line 18) and places the text into the pane (line 20). A handler is created to change the text to empty (lines 24–26) if it is not empty or to **Programming is fun** if it is empty (lines 27–29). A **KeyFrame** is created to run an action event in every half second (line 34). A **Timeline** animation is created to contain a key frame (lines 33 and 34). The animation is set to run indefinitely (line 35).

The mouse clicked event is set for the text (lines 39–46). A mouse click on the text resumes the animation if the animation is paused (lines 40–42), and a mouse click on the text pauses the animation if the animation is running (lines 43–45).

In Section 14.12, Case Study: The **ClockPane** Class, you drew a clock to show the current time. The clock does not tick after it is displayed. What can you do to make the clock display a new current time every second? The key to making the clock tick is to repaint it every second with a new current time. You can use a **Timeline** to control the repainting of the clock with the code in Listing 15.16. The sample run of the program is shown in Figure 15.21.

LISTING 15.16 ClockAnimation.java

```

1 import javafx.application.Application;
2 import javafx.stage.Stage;
3 import javafx.animation.KeyFrame;
4 import javafx.animation.Timeline;
5 import javafx.event.ActionEvent;
6 import javafx.event.EventHandler;
7 import javafx.scene.Scene;
8 import javafx.util.Duration;
9
10 public class ClockAnimation extends Application {
11   @Override // Override the start method in the Application class
12   public void start(Stage primaryStage) {
13     ClockPane clock = new ClockPane(); // Create a clock           create a clock
14
15     // Create a handler for animation
16     EventHandler<ActionEvent> eventHandler = e -> {          create a handler
17       clock.setCurrentTime(); // Set a new clock time
18     };
19
20     // Create an animation for a running clock
21     Timeline animation = new Timeline(
```

```

create a key frame          22      new KeyFrame(Duration.millis(1000), eventHandler));
set cycle count indefinite 23      animation.setCycleCount(Timeline.INDEFINITE);
play animation              24      animation.play(); // Start animation
                                25
                                26      // Create a scene and place it in the stage
                                27      Scene scene = new Scene(clock, 250, 50);
                                28      primaryStage.setTitle("ClockAnimation"); // Set the stage title
                                29      primaryStage.setScene(scene); // Place the scene in the stage
                                30      primaryStage.show(); // Display the stage
                                31  }
                                32 }

```



FIGURE 15.21 A live clock is displayed in the window.

The program creates an instance `clock` of `ClockPane` for displaying a clock (line 13). The `ClockPane` class is defined in Listing 14.21. The clock is placed in the scene in line 27. An event handler is created for setting the current time in the clock (lines 16–18). This handler is called every second in the key frame in the time line animation (lines 21–24). So the clock time is updated every second in the animation.



- 15.20** How do you set the cycle count of an animation to infinite? How do you auto reverse an animation? How do you start, pause, and stop an animation?
- 15.21** Are `PathTransition`, `FadeTransition`, and `Timeline` a subtype of `Animation`?
- 15.22** How do you create a `PathTransition`? How do you create a `FadeTransition`? How do you create a `Timeline`?
- 15.23** How do you create a `KeyFrame`?



15.12 Case Study: Bouncing Ball

This section presents an animation that displays a ball bouncing in a pane.

The program uses `Timeline` to animation ball bouncing, as shown in Figure 15.22.



FIGURE 15.22 A ball is bouncing in a pane.

Here are the major steps to write this program:

1. Define a subclass of **Pane** named **BallPane** to display a ball bouncing, as shown in Listing 15.17.
2. Define a subclass of **Application** named **BounceBallControl** to control the bouncing ball with mouse actions, as shown in Listing 15.18. The animation pauses when the mouse is pressed and resumes when the mouse is released. Pressing the UP and DOWN arrow keys increases/decreases animation speed.

The relationship among these classes is shown in Figure 15.23.



FIGURE 15.23 **BounceBallControl** contains **BallPane**.

LISTING 15.17 BallPane.java

```

1 import javafx.animation.KeyFrame;
2 import javafx.animation.Timeline;
3 import javafx.beans.property.DoubleProperty;
4 import javafx.scene.layout.Pane;
5 import javafx.scene.paint.Color;
6 import javafx.scene.shape.Circle;
7 import javafx.util.Duration;
8
9 public class BallPane extends Pane {
10     public final double radius = 20;
11     private double x = radius, y = radius;
12     private double dx = 1, dy = 1;
13     private Circle circle = new Circle(x, y, radius);
14     private Timeline animation;
15
16     public BallPane() {
17         circle.setFill(Color.GREEN); // Set ball color
18         getChildren().add(circle); // Place a ball into this pane
  
```

```

19
20    // Create an animation for moving the ball
21    animation = new Timeline(
22        new KeyFrame(Duration.millis(50), e -> moveBall()));
23    animation.setCycleCount(Timeline.INDEFINITE);
24    animation.play(); // Start animation
25 }
26
27 public void play() {
28     animation.play();
29 }
30
31 public void pause() {
32     animation.pause();
33 }
34
35 public void increaseSpeed() {
36     animation.setRate(animation.getRate() + 0.1);
37 }
38
39 public void decreaseSpeed() {
40     animation.setRate(
41         animation.getRate() > 0 ? animation.getRate() - 0.1 : 0);
42 }
43
44 public DoubleProperty rateProperty() {
45     return animation.rateProperty();
46 }
47
48 protected void moveBall() {
49     // Check boundaries
50     if (x < radius || x > getWidth() - radius) {
51         dx *= -1; // Change ball move direction
52     }
53     if (y < radius || y > getHeight() - radius) {
54         dy *= -1; // Change ball move direction
55     }
56
57     // Adjust ball position
58     x += dx;
59     y += dy;
60     circle.setCenterX(x);
61     circle.setCenterY(y);
62 }
63 }

```

BallPane extends **Pane** to display a moving ball (line 9). An instance of **Timeline** is created to control animation (lines 21 and 22). This instance contains a **KeyFrame** object that invokes the **moveBall()** method at a fixed rate. The **moveBall()** method moves the ball to simulate animation. The center of the ball is at **(x, y)**, which changes to **(x + dx, y + dy)** on the next move (lines 58–61). When the ball is out of the horizontal boundary, the sign of **dx** is changed (from positive to negative or vice versa) (lines 50–52). This causes the ball to change its horizontal movement direction. When the ball is out of the vertical boundary, the sign of **dy** is changed (from positive to negative or vice versa) (lines 53–55). This causes the ball to change its vertical movement direction. The **pause** and **play** methods (lines 27–33) can be used to pause and resume the animation. The **increaseSpeed()** and **decreaseSpeed()** methods (lines 35–42) can be used to increase and decrease animation speed. The **rateProperty()**

method (lines 44–46) returns a binding property value for rate. This binding property is useful for binding the rate in future applications in the next chapter.

LISTING 15.18 BounceBallControl.java

```

1 import javafx.application.Application;
2 import javafx.stage.Stage;
3 import javafx.scene.Scene;
4 import javafx.scene.input.KeyCode;
5
6 public class BounceBallControl extends Application {
7     @Override // Override the start method in the Application class
8     public void start(Stage primaryStage) {
9         BallPane ballPane = new BallPane(); // Create a ball pane
10        create a ball pane
11        // Pause and resume animation
12        ballPane.setOnMousePressed(e -> ballPane.pause());
13        ballPane.setOnMouseReleased(e -> ballPane.play()); pause animation
14        // Increase and decrease animation
15        ballPane.setOnKeyPressed(e -> {
16            if (e.getCode() == KeyCode.UP) {
17                ballPane.increaseSpeed(); increase speed
18            }
19            else if (e.getCode() == KeyCode.DOWN) {
20                ballPane.decreaseSpeed(); decrease speed
21            }
22        });
23    }
24
25    // Create a scene and place it in the stage
26    Scene scene = new Scene(ballPane, 250, 150);
27    primaryStage.setTitle("BounceBallControl"); // Set the stage title
28    primaryStage.setScene(scene); // Place the scene in the stage
29    primaryStage.show(); // Display the stage
30
31    // Must request focus after the primary stage is displayed
32    ballPane.requestFocus(); request focus on pane
33}
34

```

The **BounceBallControl** class is the main JavaFX class that extends **Application** to display the ball pane with control functions. The mouse-pressed and mouse-released handlers are implemented for the ball pane to pause the animation and resume the animation (lines 12 and 13). When the UP arrow key is pressed, the ball pane's **increaseSpeed()** method is invoked to increase the ball's movement (line 18). When the DOWN arrow key is pressed, the ball pane's **decreaseSpeed()** method is invoked to reduce the ball's movement (line 21).

Invoking **ballPane.requestFocus()** in line 32 sets the input focus to **ballPane**.

15.24 How does the program make the ball moving?

15.25 How does the code in Listing 15.17 BallPane.java change the direction of the ball movement?

15.26 What does the program do when the mouse is pressed on the ball pane? What does the program do when the mouse is released on the ball pane?

15.27 If line 32 in Listing 15.18 BounceBallControl.java is not in the program, what would happen when you press the UP or the DOWN arrow key?

15.28 If line 23 is not in Listing 15.17, what would happen?



KEY TERMS

anonymous inner class	594	functional interface	598
event	588	lambda expression	597
event-driven programming	588	inner class	591
event handler	589	key code	604
event-handler interface	589	observable object	607
event object	588	single abstract method interface	598
event source object	588		

CHAPTER SUMMARY

1. The root class of the JavaFX event classes is `javafx.event.Event`, which is a subclass of `java.util.EventObject`. The subclasses of `Event` deal with special types of events, such as action events, window events, mouse events, and key events. If a node can fire an event, any subclass of the node can fire the same type of event.
2. The handler object's class must implement the corresponding *event-handler interface*. JavaFX provides a handler interface `EventHandler<T extends Event>` for every event class `T`. The handler interface contains the `handle(T e)` method for handling event `e`.
3. The handler object must be registered by the *source object*. Registration methods depend on the event type. For an action event, the method is `setOnAction`. For a mouse-pressed event, the method is `setOnMousePressed`. For a key-pressed event, the method is `setOnKeyPressed`.
4. An *inner class*, or *nested class*, is defined within the scope of another class. An inner class can reference the data and methods defined in the outer class in which it nests, so you need not pass the reference of the outer class to the constructor of the inner class.
5. An anonymous inner class can be used to shorten the code for event handling. Furthermore, a lambda expression can be used to greatly simplify the event-handling code for functional interface handlers.
6. A *functional interface* is an interface with exactly one abstract method. This is also known as a single abstract method (SAM) interface.
7. A `MouseEvent` is fired whenever a mouse button is pressed, released, clicked, moved, or dragged on a node or a scene. The `getButton()` method can be used to detect which mouse button is pressed for the event.
8. A `KeyEvent` is fired whenever a key is pressed, released, or typed on a node or a scene. The `getCode()` method can be used to return the code value for the key.
9. An instance of `Observable` is known as an observable object, which contains the `addListener(InvalidationListener listener)` method for adding a listener. Once the value is changed in the property, a listener is notified. The listener class should implement the `InvalidationListener` interface, which uses the `invalidated` method to handle the property value change.
10. The abstract `Animation` class provides the core functionalities for animations in JavaFX. `PathTransition`, `FadeTransition`, and `Timeline` are specialized classes for implementing animations.

Quiz

Answer the quiz for this chapter online at www.cs.armstrong.edu/liang/intro10e/quiz.html.

PROGRAMMING EXERCISES

[MyProgrammingLab™](#)

Sections 15.2–15.7

- *15.1 (Pick four cards) Write a program that lets the user click the *Refresh* button to display four cards from a deck of 52 cards, as shown in Figure 15.24a. (See the hint in Programming Exercise 14.3 on how to obtain four random cards.)



FIGURE 15.24 (a) Exercise 15.1 displays four cards randomly. (b) Exercise 15.2 rotates the rectangle. (c) Exercise 15.3 uses the buttons to move the ball.

- 15.2 (Rotate a rectangle) Write a program that rotates a rectangle 15 degrees right when the *Rotate* button is clicked, as shown in Figure 15.24b.

- *15.3 (Move the ball) Write a program that moves the ball in a pane. You should define a pane class for displaying the ball and provide the methods for moving the ball left, right, up, and down, as shown in Figure 15.24c. Check the boundary to prevent the ball from moving out of sight completely.

- *15.4 (Create a simple calculator) Write a program to perform addition, subtraction, multiplication, and division, as shown in Figure 15.25a.

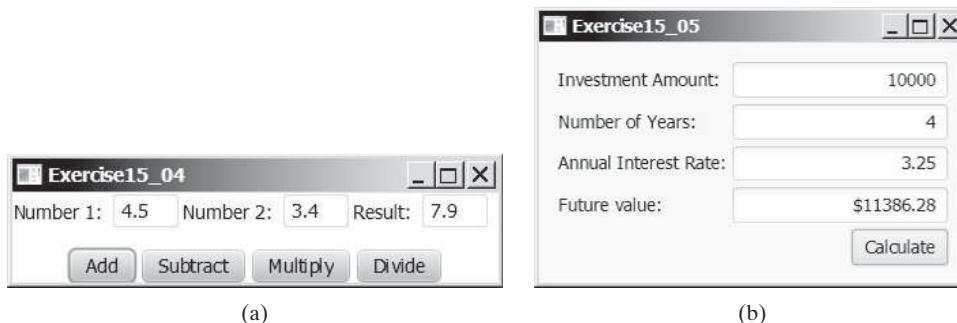


FIGURE 15.25 (a) Exercise 15.4 performs addition, subtraction, multiplication, and division on double numbers. (b) The user enters the investment amount, years, and interest rate to compute future value.

- *15.5 (Create an investment-value calculator) Write a program that calculates the future value of an investment at a given interest rate for a specified number of years. The formula for the calculation is:

```
futureValue = investmentAmount * (1 + monthlyInterestRate)years*12
```

Use text fields for the investment amount, number of years, and annual interest rate. Display the future amount in a text field when the user clicks the *Calculate* button, as shown in Figure 15.25b.

Sections 15.8 and 15.9

- **15.6** (*Alternate two messages*) Write a program to display the text **Java is fun** and **Java is powerful** alternately with a mouse click.
- *15.7** (*Change color using a mouse*) Write a program that displays the color of a circle as black when the mouse button is pressed and as white when the mouse button is released.
- *15.8** (*Display the mouse position*) Write two programs, such that one displays the mouse position when the mouse button is clicked (see Figure 15.26a) and the other displays the mouse position when the mouse button is pressed and ceases to display it when the mouse button is released.

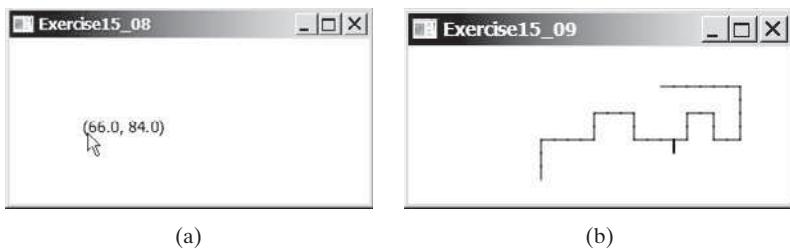


FIGURE 15.26 (a) Exercise 15.8 displays the mouse position. (b) Exercise 15.9 uses the arrow keys to draw the lines.

- *15.9** (*Draw lines using the arrow keys*) Write a program that draws line segments using the arrow keys. The line starts from the center of the pane and draws toward east, north, west, or south when the right-arrow key, up-arrow key, left-arrow key, or down-arrow key is pressed, as shown in Figure 15.26b.
- **15.10** (*Enter and display a string*) Write a program that receives a string from the keyboard and displays it on a pane. The *Enter* key signals the end of a string. Whenever a new string is entered, it is displayed on the pane.
- *15.11** (*Move a circle using keys*) Write a program that moves a circle up, down, left, or right using the arrow keys.
- **15.12** (*Geometry: inside a circle?*) Write a program that draws a fixed circle centered at **(100, 60)** with radius **50**. Whenever the mouse is moved, display a message indicating whether the mouse point is inside the circle at the mouse point or outside of it, as shown in Figure 15.27a.



VideoNote

Check mouse point location

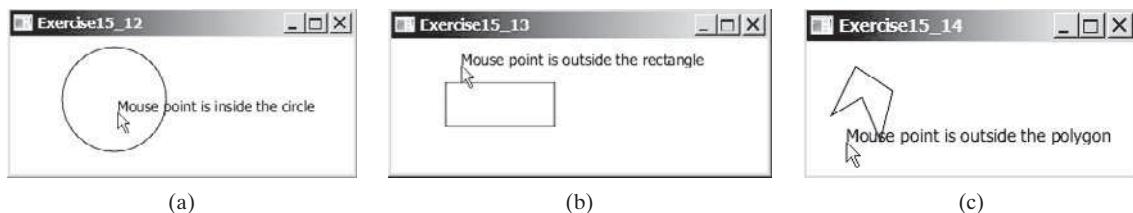


FIGURE 15.27 Detect whether a point is inside a circle, a rectangle, or a polygon.

****15.13** (*Geometry: inside a rectangle?*) Write a program that draws a fixed rectangle centered at (100, 60) with width 100 and height 40. Whenever the mouse is moved, display a message indicating whether the mouse point is inside the rectangle at the mouse point or outside of it, as shown in Figure 15.27b. To detect whether a point is inside a polygon, use the **contains** method defined in the **Node** class.

****15.14** (*Geometry: inside a polygon?*) Write a program that draws a fixed polygon with points at (40, 20), (70, 40), (60, 80), (45, 45), and (20, 60). Whenever the mouse is moved, display a message indicating whether the mouse point is inside the polygon at the mouse point or outside of it, as shown in Figure 15.27c. To detect whether a point is inside a polygon, use the **contains** method defined in the **Node** class.

****15.15** (*Geometry: add and remove points*) Write a program that lets the user click on a pane to dynamically create and remove points (see Figure 15.28a). When the user left-clicks the mouse (primary button), a point is created and displayed at the mouse point. The user can remove a point by pointing to it and right-clicking the mouse (secondary button).

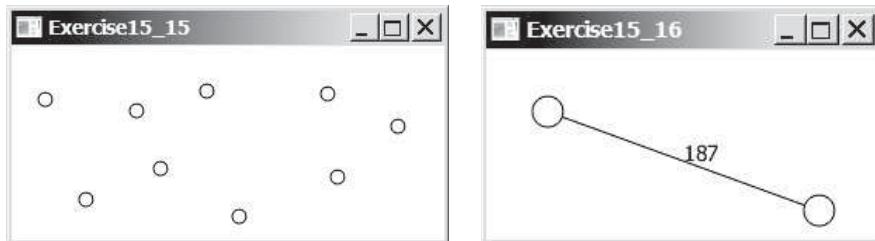


FIGURE 15.28 (a) Exercise 15.15 allows the user to create/remove points dynamically.
(b) Exercise 15.16 displays two vertices and a connecting edge.

***15.16** (*Two movable vertices and their distances*) Write a program that displays two circles with radius 10 at location (40, 40) and (120, 150) with a line connecting the two circles, as shown in Figure 15.28b. The distance between the circles is displayed along the line. The user can drag a circle. When that happens, the circle and its line are moved and the distance between the circles is updated.

****15.17** (*Geometry: find the bounding rectangle*) Write a program that enables the user to add and remove points in a two-dimensional plane dynamically, as shown in Figure 15.29a. A minimum bounding rectangle is updated as the points are added and removed. Assume that the radius of each point is 10 pixels.



FIGURE 15.29 (a) Exercise 15.17 enables the user to add/remove points dynamically and displays the bounding rectangle. (b) When you click a circle, a new circle is displayed at a random location. (c) After 20 circles are clicked, the time spent is displayed in the pane.

- **15.18** (*Move a rectangle using mouse*) Write a program that displays a rectangle. You can point the mouse inside the rectangle and drag (i.e., move with mouse pressed) the rectangle wherever the mouse goes. The mouse point becomes the center of the rectangle.
- **15.19** (*Game: eye-hand coordination*) Write a program that displays a circle of radius 10 pixels filled with a random color at a random location on a pane, as shown in Figure 15.29b. When you click the circle, it disappears and a new random-color circle is displayed at another random location. After twenty circles are clicked, display the time spent in the pane, as shown in Figure 15.29c.
- **15.20** (*Geometry: display angles*) Write a program that enables the user to drag the vertices of a triangle and displays the angles dynamically as the triangle shape changes, as shown in Figure 15.30a. The formula to compute angles is given in Listing 4.1.

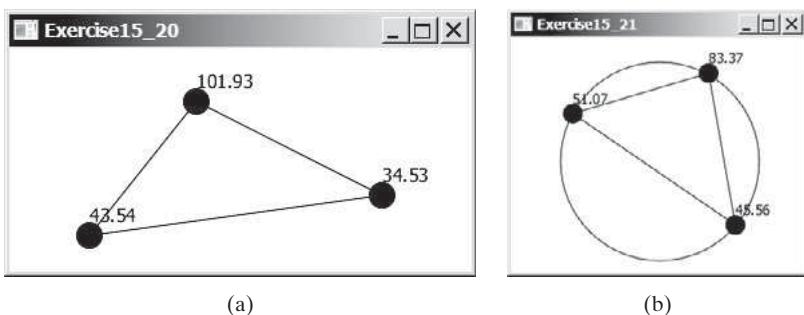


FIGURE 15.30 (a) Exercise 15.20 enables the user to drag vertices and display the angles dynamically. (b) Exercise 15.21 enables the user to drag vertices along the circle and display the angles in the triangle dynamically.

- *15.21** (*Drag points*) Draw a circle with three random points on the circle. Connect the points to form a triangle. Display the angles in the triangle. Use the mouse to drag a point along the perimeter of the circle. As you drag it, the triangle and angles are redisplayed dynamically, as shown in Figure 15.30b. For computing angles in a triangle, see Listing 4.1.

Section 15.10

- *15.22** (*Auto resize cylinder*) Rewrite Programming Exercise 14.10 so that the cylinder's width and height are automatically resized when the window is resized.
- *15.23** (*Auto resize stop sign*) Rewrite Programming Exercise 14.15 so that the stop sign's width and height are automatically resized when the window is resized.

Section 15.11

- **15.24** (*Animation: palindrome*) Write a program that animates a palindrome swing as shown in Figure 15.31. Press/release the mouse to pause/resume the animation.



FIGURE 15.31 The program animates a palindrome swing.

- ** 15.25** (*Animation: ball on curve*) Write a program that animates a ball moving along a sine curve, as shown in Figure 15.32. When the ball gets to the right border, it starts over from the left. Enable the user to resume/pause the animation with a click on the left/right mouse button.

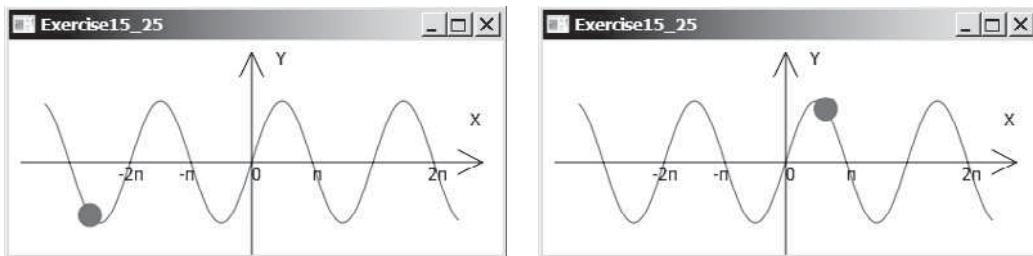


FIGURE 15.32 The program animates a ball traveling along a sine curve.

- * 15.26** (*Change opacity*) Rewrite Programming Exercise 15.24 so that the ball's opacity is changed as it swings.

- * 15.27** (*Control a moving text*) Write a program that displays a moving text, as shown in Figure 15.33a and b. The text moves from left to right circularly. When it disappears in the right, it reappears from the left. The text freezes when the mouse is pressed and moves again when the button is released.

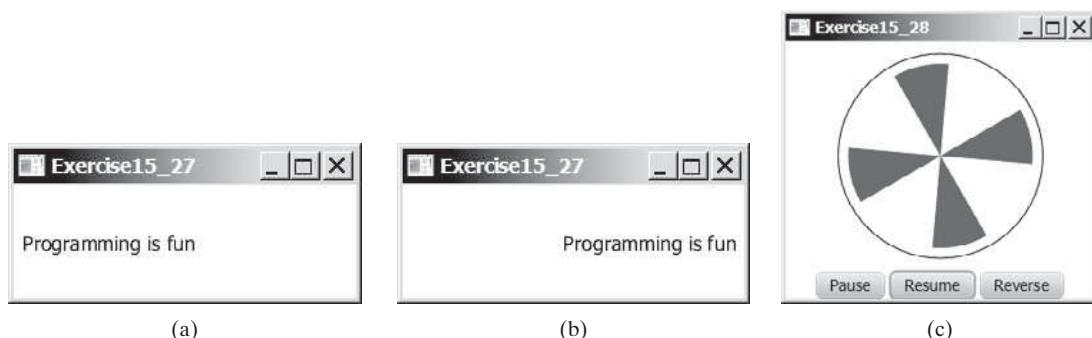


FIGURE 15.33 (a and b) A text is moving from left to right circularly. (c) The program simulates a fan running.

- ** 15.28** (*Display a running fan*) Write a program that displays a running fan, as shown in Figure 15.33c. Use the *Pause*, *Resume*, *Reverse* buttons to pause, resume, and reverse fan running.

- ** 15.29** (*Racing car*) Write a program that simulates car racing, as shown in Figure 15.34a. The car moves from left to right. When it hits the right end, it restarts from the left and continues the same process. You can use a timer to control animation. Redraw the car with a new base coordinates (x, y), as shown in Figure 15.34b. Also let the user pause/resume the animation with a button press/release and increase/decrease the car speed by pressing the UP and DOWN arrow keys.

- ** 15.30** (*Slide show*) Twenty-five slides are stored as image files (`slide0.jpg`, `slide1.jpg`, . . . , `slide24.jpg`) in the `image` directory downloadable along with the source code in the book. The size of each image is 800×600 . Write a program that automatically displays the slides repeatedly. Each slide is shown for

 **VideoNote**
Display a running fan



FIGURE 15.34 (a) The program displays a moving car. (b) You can redraw a car with a new base point.

two seconds. The slides are displayed in order. When the last slide finishes, the first slide is redisplayed, and so on. Click to pause if the animation is currently playing. Click to resume if the animation is currently paused.

****15.31** (*Geometry: pendulum*) Write a program that animates a pendulum swinging, as shown in Figure 15.35. Press the UP arrow key to increase the speed and the DOWN key to decrease it. Press the S key to stop animation and the R key to resume it.



FIGURE 15.35 Exercise 15.31 animates a pendulum swinging.

* 15.32 (Control a clock) Modify Listing 14.21, ClockPane.java, to add the animation into this class and add two methods `start()` and `stop()` to start and stop the clock. Write a program that lets the user control the clock with the *Start* and *Stop* buttons, as shown in Figure 15.36a.

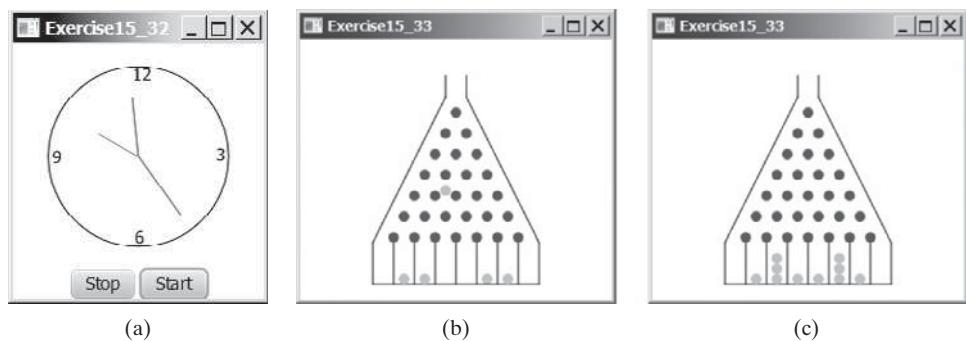


FIGURE 15.36 (a) Exercise 15.32 allows the user to start and stop a clock. (b and c) The balls are dropped into the bean machine.

*****15.33** (*Game: bean-machine animation*) Write a program that animates the bean machine introduced in Programming Exercise 7.21. The animation terminates after ten balls are dropped, as shown in Figure 15.36b and c.

*****15.34** (*Simulation: self-avoiding random walk*) A self-avoiding walk in a lattice is a path from one point to another that does not visit the same point twice. Self-avoiding walks have applications in physics, chemistry, and mathematics. They can be used to model chain-like entities such as solvents and polymers. Write a program that displays a random path that starts from the center and ends at a point on the boundary, as shown in Figure 15.37a or ends at a dead-end point (i.e., surrounded by four points that have already been visited), as shown in Figure 15.37b. Assume the size of the lattice is 16 by 16.



FIGURE 15.37 (a) A path ends at a boundary point. (b) A path ends at dead-end point. (c and d) Animation shows the progress of a path step by step.

*****15.35** (*Animation: self-avoiding random walk*) Revise the preceding exercise to display the walk step by step in an animation, as shown in Figure 15.37c and d.

****15.36** (*Simulation: self-avoiding random walk*) Write a simulation program to show that the chance of getting dead-end paths increases as the grid size increases. Your program simulates lattices with size from 10 to 80. For each lattice size, simulate a self-avoiding random walk 10,000 times and display the probability of the dead-end paths, as shown in the following sample output:

```
For a lattice of size 10, the probability of dead-end paths is 10.6%
For a lattice of size 11, the probability of dead-end paths is 14.0%
...
For a lattice of size 80, the probability of dead-end paths is 99.5%
```



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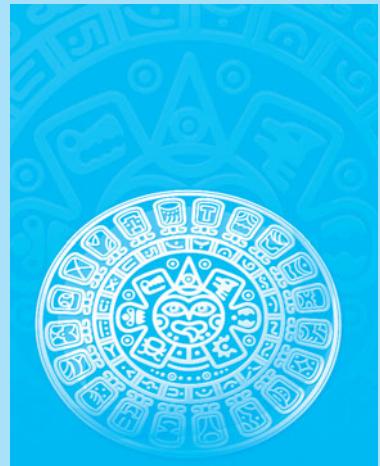
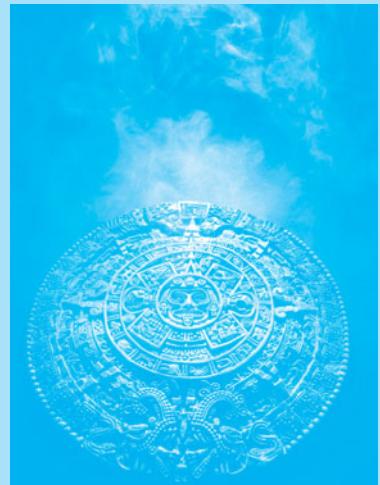
CHAPTER

16

JAVAFX UI CONTROLS AND MULTIMEDIA

Objectives

- To create graphical user interfaces with various user-interface controls (§§16.2–16.11).
- To create a label with text and graphic using the **Label** class and explore properties in the abstract **Labeled** class (§16.2).
- To create a button with text and graphic using the **Button** class and set a handler using the **setOnAction** method in the abstract **ButtonBase** class (§16.3).
- To create a check box using the **CheckBox** class (§16.4).
- To create a radio button using the **RadioButton** class and group radio buttons using a **ToggleGroup** (§16.5).
- To enter data using the **TextField** class and password using the **PasswordField** class (§16.6).
- To enter data in multiple lines using the **TextArea** class (§16.7).
- To select a single item using **ComboBox** (§16.8).
- To select a single or multiple items using **ListView** (§16.9).
- To select a range of values using **ScrollBar** (§16.10).
- To select a range of values using **Slider** and explore differences between **ScrollBar** and **Slider** (§16.11).
- To develop a tic-tac-toe game (§16.12).
- To view and play video and audio using the **Media**, **MediaPlayer**, and **MediaView** (§16.13).
- To develop a case study for showing the national flag and playing anthem (§16.14).





16.1 Introduction

JavaFX provides many UI controls for developing a comprehensive user interface.

A graphical user interface (GUI) makes a system user-friendly and easy to use. Creating a GUI requires creativity and knowledge of how UI controls work. Since the UI controls in JavaFX are very flexible and versatile, you can create a wide assortment of useful user interfaces for rich Internet applications.

Oracle provides tools for visually designing and developing GUIs. This enables the programmer to rapidly assemble the elements of a GUI with minimum coding. Tools, however, cannot do everything. You have to modify the programs they produce. Consequently, before you begin to use the visual tools, you must understand the basic concepts of JavaFX GUI programming.

Previous chapters used UI controls such as **Button**, **Label**, and **TextField**. This chapter introduces the frequently used UI controls in detail (see Figure 16.1).

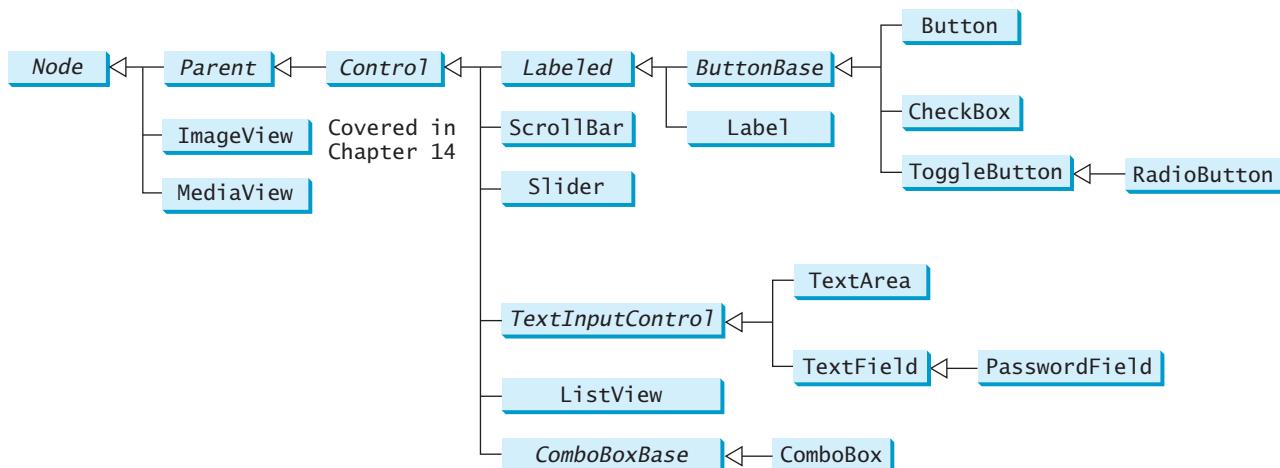


FIGURE 16.1 These UI controls are frequently used to create user interfaces.

naming convention
for controls



Note

Throughout this book, the prefixes **lbl**, **bt**, **chk**, **rb**, **tf**, **pf**, **ta**, **cbo**, **lv**, **scb**, **sld**, and **mp** are used to name reference variables for **Label**, **Button**, **CheckBox**, **RadioButton**, **TextField**, **PasswordField**, **TextArea**, **ComboBox**, **ListView**, **ScrollBar**, **Slider**, and **MediaPlayer**.

16.2 Labeled and Label

A *label* is a display area for a short text, a node, or both. It is often used to label other controls (usually text fields). Labels and buttons share many common properties. These common properties are defined in the **Labeled** class, as shown in Figure 16.2.

A **Label** can be constructed using one of the three constructors as shown in Figure 16.3.

The **graphic** property can be any node such as a shape, an image, or a control. Listing 16.1 gives an example that displays several labels with text and images in the label, as shown in Figure 16.4.

LISTING 16.1 LabelWithGraphic.java

```

1 import javafx.application.Application;
2 import javafx.stage.Stage;
3 import javafx.scene.Scene;
4 import javafx.scene.control.ContentDisplay;
5 import javafx.scene.control.Label;
  
```

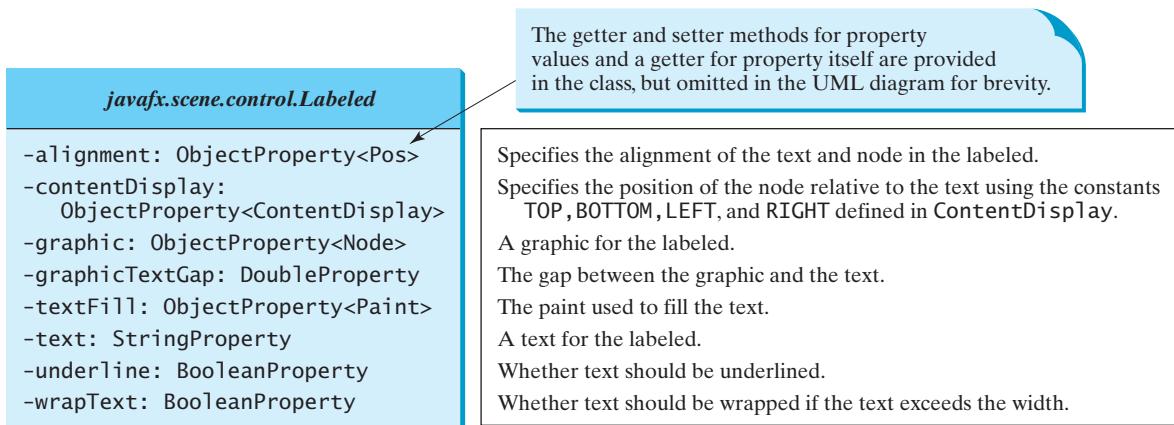


FIGURE 16.2 `Labeled` defines common properties for `Label`, `Button`, `CheckBox`, and `RadioButton`.

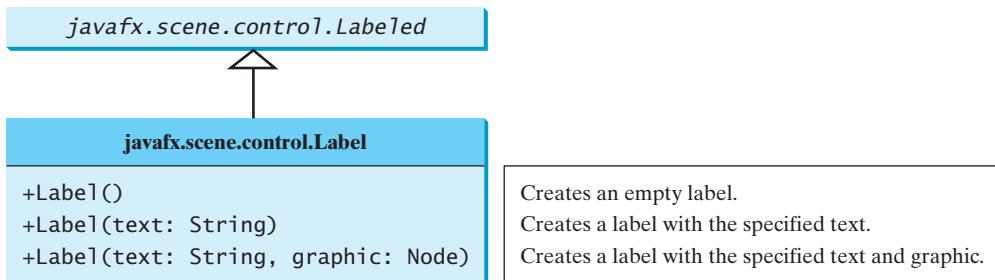


FIGURE 16.3 `Label` is created to display a text or a node, or both.

```

6 import javafx.scene.image.Image;
7 import javafx.scene.image.ImageView;
8 import javafx.scene.layout.HBox;
9 import javafx.scene.layout.StackPane;
10 import javafx.scene.paint.Color;
11 import javafx.scene.shape.Circle;
12 import javafx.scene.shape.Rectangle;
13 import javafx.scene.shape.Ellipse;
14
15 public class LabelWithGraphic extends Application {
16     @Override // Override the start method in the Application class
17     public void start(Stage primaryStage) {
18         ImageView us = new ImageView(new Image("image/us.gif"));
19         Label lb1 = new Label("US\n50 States", us);           create a label
20         lb1.setStyle("-fx-border-color: green; -fx-border-width: 2");    set node position
21         lb1.setContentDisplay(ContentDisplay.BOTTOM);
22         lb1.setTextFill(Color.RED);
23
24         Label lb2 = new Label("Circle", new Circle(50, 50, 25));      create a label
25         lb2.setContentDisplay(ContentDisplay.TOP);                      set node position
26         lb2.setTextFill(Color.ORANGE);
27
28         Label lb3 = new Label("Retangle", new Rectangle(10, 10, 50, 25));   create a label
29         lb3.setContentDisplay(ContentDisplay.RIGHT);
30
31         Label lb4 = new Label("Ellipse", new Ellipse(50, 50, 50, 25));    create a label
32         lb4.setContentDisplay(ContentDisplay.LEFT);
33

```

```

34     Ellipse ellipse = new Ellipse(50, 50, 50, 25);
35     ellipse.setStroke(Color.GREEN);
36     ellipse.setFill(Color.WHITE);
37     StackPane stackPane = new StackPane();
38     stackPane.getChildren().addAll(ellipse, new Label("JavaFX"));
39     Label lb5 = new Label("A pane inside a label", stackPane);
40     lb5.setContentDisplay(ContentDisplay.BOTTOM);
41
42     HBox pane = new HBox(20);
43     pane.getChildren().addAll(lb1, lb2, lb3, lb4, lb5);
44
45     // Create a scene and place it in the stage
46     Scene scene = new Scene(pane, 450, 150);
47     primaryStage.setTitle("LabelWithGraphic"); // Set the stage title
48     primaryStage.setScene(scene); // Place the scene in the stage
49     primaryStage.show(); // Display the stage
50 }
51 }
```

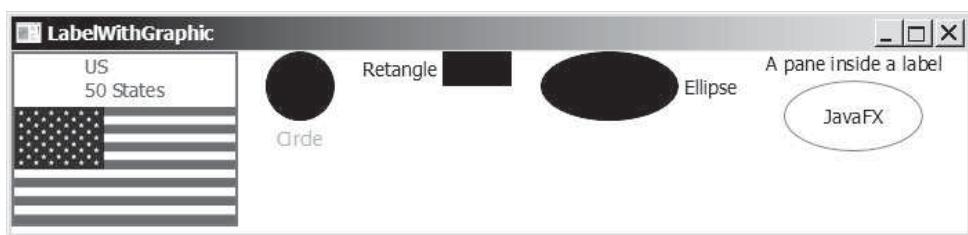


FIGURE 16.4 The program displays labels with texts and nodes.

The program creates a label with a text and an image (line 19). The text is **US\n50 States** so it is displayed in two lines. Line 21 specifies that the image is placed at the bottom of the text.

The program creates a label with a text and a circle (line 24). The circle is placed on top of the text (line 25). The program creates a label with a text and a rectangle (line 28). The rectangle is placed on the right of the text (line 29). The program creates a label with a text and an ellipse (line 31). The ellipse is placed on the left of the text (line 32).

The program creates an ellipse (line 34), places it along with a label to a stack pane (line 38), and creates a label with a text and the stack pane as the node (line 39). As seen from this example, you can place any node in a label.

The program creates an **HBox** (line 42) and places all five labels into the **HBox** (line 43).

Check Point

- 16.1** How do you create a label with a node without a text?
- 16.2** How do you place a text on the right of the node in a label?
- 16.3** Can you display multiple lines of text in a label?
- 16.4** Can the text in a label be underlined?

16.3 Button

A **button** is a control that triggers an action event when clicked. JavaFX provides regular buttons, toggle buttons, check box buttons, and radio buttons. The common features of these buttons are defined in **ButtonBase** and **Labeled** classes as shown in Figure 16.5.

The **Labeled** class defines the common properties for labels and buttons. A button is just like a label except that the button has the **onAction** property defined in the **ButtonBase** class, which sets a handler for handling a button's action.

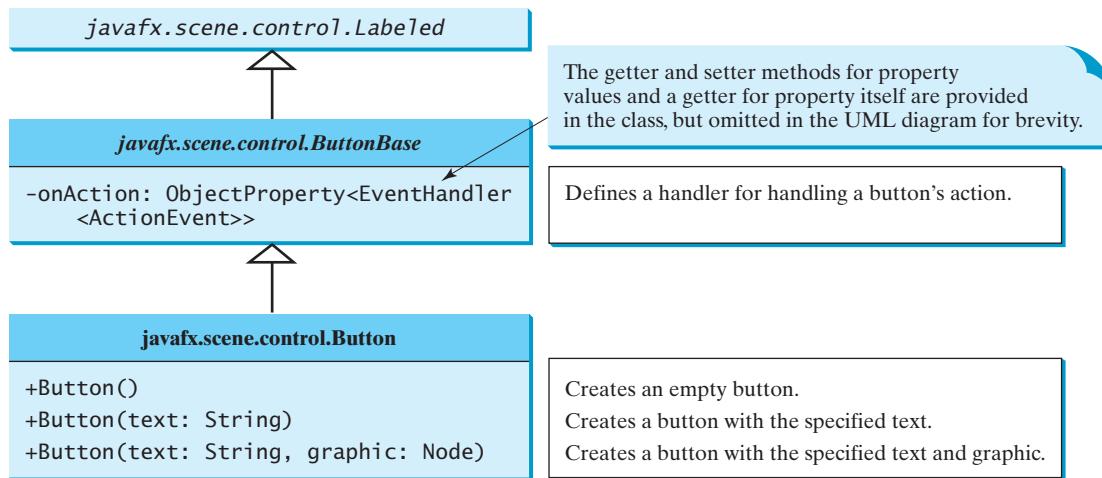


FIGURE 16.5 `ButtonBase` extends `Labeled` and defines common features for all buttons.

Listing 16.2 gives a program that uses the buttons to control the movement of a text, as shown in Figure 16.6.

LISTING 16.2 ButtonDemo.java

```

1 import javafx.application.Application;
2 import javafx.stage.Stage;
3 import javafx.geometry.Pos;
4 import javafx.scene.Scene;
5 import javafx.scene.control.Button;
6 import javafx.scene.image.ImageView;
7 import javafx.scene.layout.BorderPane;
8 import javafx.scene.layout.HBox;
9 import javafx.scene.layout.Pane;
10 import javafx.scene.text.Text;
11
12 public class ButtonDemo extends Application {
13     protected Text text = new Text(50, 50, "JavaFX Programming");
14
15     protected BorderPane getPane() {
16         HBox paneForButtons = new HBox(20);
17         Button btLeft = new Button("Left",
18             new ImageView("image/left.gif"));
19         Button btRight = new Button("Right",
20             new ImageView("image/right.gif"));
21         paneForButtons.getChildren().addAll(btLeft, btRight);           create a button
22         paneForButtons.setAlignment(Pos.CENTER);                         add buttons to pane
23         paneForButtons.setStyle("-fx-border-color: green");
24
25         BorderPane pane = new BorderPane();
26         pane.setBottom(paneForButtons);                                create a border pane
27
28         Pane paneForText = new Pane();
29         paneForText.getChildren().add(text);
30         pane.setCenter(paneForText);                                  add buttons to the bottom
31
32         btLeft.setOnAction(e -> text.setX(text.getX() - 10));      add an action handler
33         btRight.setOnAction(e -> text.setX(text.getX() + 10));
34
35     return pane;
36 }

```

```

36     }
37
38     @Override // Override the start method in the Application class
39     public void start(Stage primaryStage) {
40         // Create a scene and place it in the stage
41         Scene scene = new Scene(getPane(), 450, 200);
42         primaryStage.setTitle("ButtonDemo"); // Set the stage title
43         primaryStage.setScene(scene); // Place the scene in the stage
44         primaryStage.show(); // Display the stage
45     }
46 }
```

set pane to scene

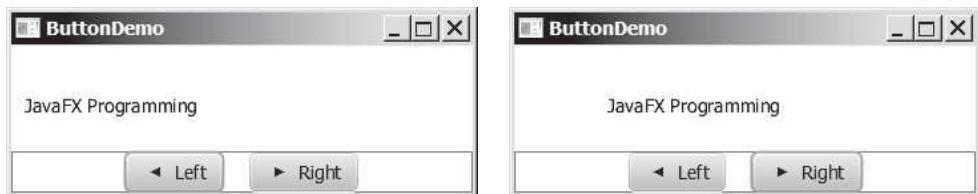


FIGURE 16.6 The program demonstrates using buttons.

The program creates two buttons `btLeft` and `btRight` with each button containing a text and an image (lines 17–20). The buttons are placed in an `HBox` (line 21) and the `HBox` is placed in the bottom of a border pane (line 26). A text is created in line 13 and is placed in the center of the border pane (line 30). The action handler for `btLeft` moves the text to the left (line 32). The action handler for `btRight` moves the text to the right (line 33).

getPane() protected

The program purposely defines a protected `getPane()` method to return a pane (line 15). This method will be overridden by subclasses in the upcoming examples to add more nodes in the pane. The text is declared protected so that it can be accessed by subclasses (line 13).



- 16.5** How do you create a button with a text and a node? Can you apply all the methods for `Labeled` to `Button`?
- 16.6** Why is the `getPane()` method protected in Listing 16.2? Why is the data field `text` protected?
- 16.7** How do you set a handler for processing a button-clicked action?

16.4 CheckBox

A `CheckBox` is used for the user to make a selection. Like `Button`, `CheckBox` inherits all the properties such as `onAction`, `text`, `graphic`, `alignment`, `graphicTextGap`, `textFill`, `contentDisplay` from `ButtonBase` and `Labeled`, as shown in Figure 16.7. Additionally, it provides the `selection` property to indicate whether a check box is selected.

Here is an example of a check box with text `US`, a graphic image, green text color, and black border, and initially selected.

```

CheckBox chkUS = new CheckBox("US");
chkUS.setGraphic(new ImageView("image/usIcon.gif"));
chkUS.setTextFill(Color.GREEN);
chkUS.setContentDisplay(ContentDisplay.LEFT);
chkUS.setStyle("-fx-border-color: black");
chkUS.setSelected(true);
chkUS.setPadding(new Insets(5, 5, 5, 5));
```



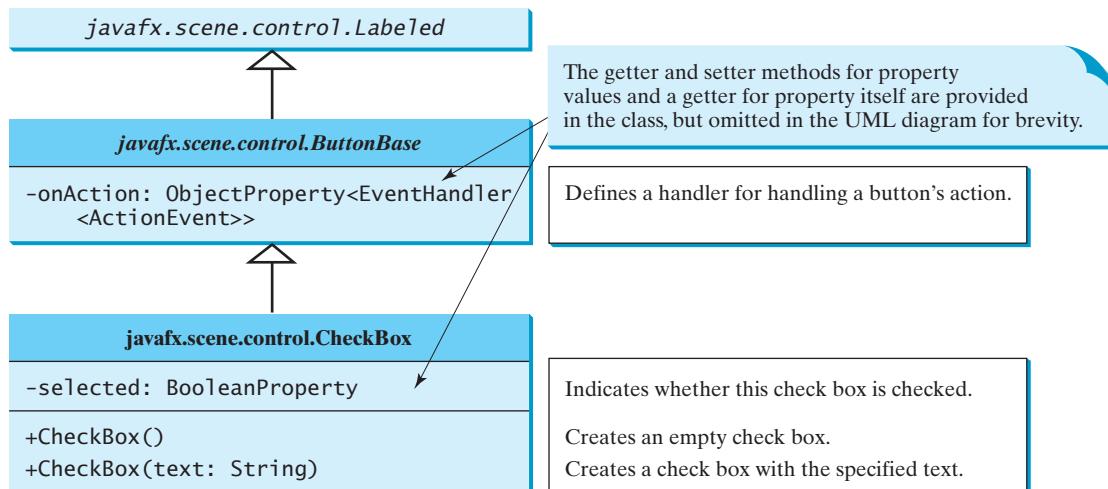


FIGURE 16.7 `CheckBox` contains the properties inherited from `ButtonBase` and `Labeled`.

When a check box is clicked (checked or unchecked), it fires an `ActionEvent`. To see if a check box is selected, use the `isSelected()` method.

We now write a program that adds two check boxes named `Bold` and `Italic` to the preceding example to let the user specify whether the message is in bold or italic, as shown in Figure 16.8.

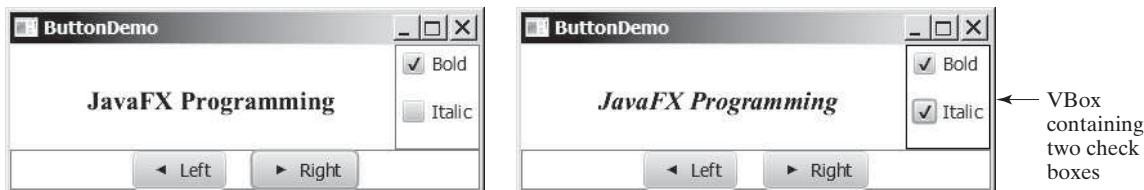


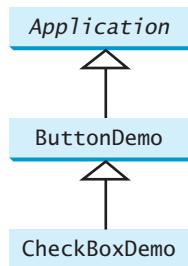
FIGURE 16.8 The program demonstrates check boxes.

There are at least two approaches to writing this program. The first is to revise the preceding `ButtonDemo` class to insert the code for adding the check boxes and processing their events. The second is to define a subclass that extends `ButtonDemo`. Please implement the first approach as an exercise. Listing 16.3 gives the code to implement the second approach.

LISTING 16.3 CheckBoxDemo.java

```

1 import javafx.event.ActionEvent;
2 import javafx.event.EventHandler;
3 import javafx.geometry.Insets;
4 import javafx.scene.control.CheckBox;
5 import javafx.scene.layout.BorderPane;
6 import javafx.scene.layout.VBox;
7 import javafx.scene.text.Font;
8 import javafx.scene.text.FontPosture;
9 import javafx.scene.text.FontWeight;
10
11 public class CheckBoxDemo extends ButtonDemo {
12     @Override // Override the getPane() method in the super class
13     protected BorderPane getPane() {
14         BorderPane pane = super.getPane();
  
```



override getPane()
invoke super.getPane()

```

15
create fonts    16     Font fontBoldItalic = Font.font("Times New Roman",
17                     FontWeight.BOLD, FontPosture.ITALIC, 20);
18     Font fontBold = Font.font("Times New Roman",
19                     FontWeight.BOLD, FontPosture.REGULAR, 20);
20     Font fontItalic = Font.font("Times New Roman",
21                     FontWeight.NORMAL, FontPosture.ITALIC, 20);
22     Font fontNormal = Font.font("Times New Roman",
23                     FontWeight.NORMAL, FontPosture.REGULAR, 20);
24
25     text.setFont(fontNormal);
26
pane for check boxes 27     VBox paneForCheckBoxes = new VBox(20);
28     paneForCheckBoxes.setPadding(new Insets(5, 5, 5, 5));
29     paneForCheckBoxes.setStyle("-fx-border-color: green");
30     CheckBox chkBold = new CheckBox("Bold");
31     CheckBox chkItalic = new CheckBox("Italic");
32     paneForCheckBoxes.getChildren().addAll(chkBold, chkItalic);
33     pane.setRight(paneForCheckBoxes);
34
create a handler 35     EventHandler<ActionEvent> handler = e -> {
36         if (chkBold.isSelected() && chkItalic.isSelected()) {
37             text.setFont(fontBoldItalic); // Both check boxes checked
38         }
39         else if (chkBold.isSelected()) {
40             text.setFont(fontBold); // The Bold check box checked
41         }
42         else if (chkItalic.isSelected()) {
43             text.setFont(fontItalic); // The Italic check box checked
44         }
45         else {
46             text.setFont(fontNormal); // Both check boxes unchecked
47         }
48     };
49
set handler for action 50     chkBold.setOnAction(handler);
51     chkItalic.setOnAction(handler);
52
return a pane 53     return pane; // Return a new pane
54 }
55 }

```

CheckBoxDemo extends **ButtonDemo** and overrides the **getPane()** method (line 13). The new **getPane()** method invokes the **super.getPane()** method from the **ButtonDemo** class to obtain a border pane that contains the buttons and a text (line 14). The check boxes are created and added to **paneForCheckBoxes** (lines 30–32). **paneForCheckBoxes** is added to the border pane (lines 33).

The handler for processing the action event on check boxes is created in lines 35–48. It sets the appropriate font based on the status of the check boxes.

The **start** method for this JavaFX program is defined in **ButtonDemo** and inherited in **CheckBoxDemo**. So when you run **CheckBoxDemo**, the **start** method in **ButtonDemo** is invoked. Since the **getPane()** method is overridden in **CheckBoxDemo**, the method in **CheckBoxDemo** is invoked from line 41 in Listing 16.2, **ButtonDemo.java**.



16.8 How do you test if a check box is selected?

16.9 Can you apply all the methods for **Labeled** to **CheckBox**?

16.10 Can you set a node for the **graphic** property in a check box?

16.5 RadioButton

Radio buttons, also known as *option buttons*, enable the user to choose a single item from a group of choices. In appearance radio buttons resemble check boxes, but check boxes display a square that is either checked or blank, whereas radio buttons display a circle that is either filled (if selected) or blank (if not selected).

RadioButton is a subclass of **ToggleButton**. The difference between a radio button and a toggle button is that a radio button displays a circle, but a toggle button is rendered similar to a button. The UML diagrams for **ToggleButton** and **RadioButton** are shown in Figure 16.9.



FIGURE 16.9 **ToggleButton** and **RadioButton** are specialized buttons for making selections.

Here is an example of a radio button with text **US**, a graphic image, green text color, and black border, and initially selected.

```
RadioButton rbUS = new RadioButton("US");
rbUS.setGraphic(new ImageView("image/usIcon.gif"));
rbUS.setTextFill(Color.GREEN);
rbUS.setContentDisplay(ContentDisplay.LEFT);
rbUS.setStyle("-fx-border-color: black");
rbUS.setSelected(true);
rbUS.setPadding(new Insets(5, 5, 5, 5));
```



To group radio buttons, you need to create an instance of **ToggleGroup** and set a radio button's **toggleGroup** property to join the group, as follows:

```
ToggleGroup group = new ToggleGroup();
rbRed.setToggleGroup(group);
rbGreen.setToggleGroup(group);
rbBlue.setToggleGroup(group);
```

This code creates a button group for radio buttons **rbRed**, **rbGreen**, and **rbBlue** so that buttons **rbRed**, **rbGreen**, and **rbBlue** are selected mutually exclusively. Without grouping, these buttons would be independent.

When a radio button is changed (selected or deselected), it fires an **ActionEvent**. To see if a radio button is selected, use the **isSelected()** method.

We now give a program that adds three radio buttons named Red, Green, and Blue to the preceding example to let the user choose the color of the message, as shown in Figure 16.10.

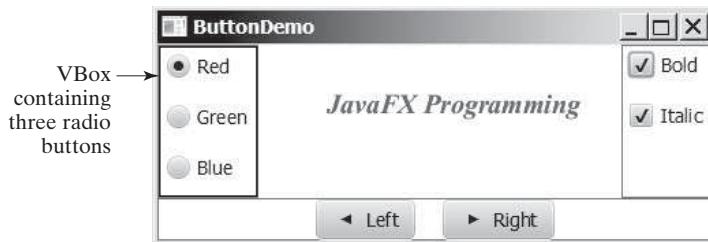


FIGURE 16.10 The program demonstrates using radio buttons.

Again there are at least two approaches to writing this program. The first is to revise the preceding `CheckBoxDemo` class to insert the code for adding the radio buttons and processing their events. The second is to define a subclass that extends `CheckBoxDemo`. Listing 16.4 gives the code to implement the second approach.

LISTING 16.4 RadioButtonDemo.java

```

Application
  |
  +--> ButtonDemo
  |
  +--> CheckBoxDemo
  |
  +--> RadioButtonDemo
    |
    +--> override getPane()
    +--> invoke super.getPane()
    |
    +--> pane for radio buttons
    |
    +--> create radio buttons
    |
    +--> add to border pane
    |
    +--> group radio buttons
    |
    +--> handle radio button

import javafx.geometry.Insets;
import javafx.scene.control.RadioButton;
import javafx.scene.control.ToggleGroup;
import javafx.scene.layout.BorderPane;
import javafx.scene.layout.VBox;
import javafx.scene.paint.Color;
public class RadioButtonDemo extends CheckBoxDemo {
    @Override // Override the getPane() method in the super class
    protected BorderPane getPane() {
        BorderPane pane = super.getPane();
        VBox paneForRadioButtons = new VBox(20);
        paneForRadioButtons.setPadding(new Insets(5, 5, 5, 5));
        paneForRadioButtons.setStyle("-fx-border-color: green");
        paneForRadioButtons.setStyle(
            "-fx-border-width: 2px; -fx-border-color: green");
        RadioButton rbRed = new RadioButton("Red");
        RadioButton rbGreen = new RadioButton("Green");
        RadioButton rbBlue = new RadioButton("Blue");
        paneForRadioButtons.getChildren().addAll(rbRed, rbGreen, rbBlue);
        pane.setLeft(paneForRadioButtons);
        ToggleGroup group = new ToggleGroup();
        rbRed.setToggleGroup(group);
        rbGreen.setToggleGroup(group);
        rbBlue.setToggleGroup(group);
        rbRed.setOnAction(e -> {
            if (rbRed.isSelected()) {
                text.setFill(Color.RED);
            }
        });
        rbGreen.setOnAction(e -> {
            if (rbGreen.isSelected()) {
                text.setFill(Color.GREEN);
            }
        });
    }
}

```

```

38         }
39     });
40
41     rbBlue.setOnAction(e -> {
42         if (rbBlue.isSelected()) {
43             text.setFill(Color.BLUE);
44         }
45     });
46
47     return pane;
48 }
49 }  

    return border pane  

    main method omitted

```

RadioButtonDemo extends **CheckBoxDemo** and overrides the **getPane()** method (line 10). The new **getPane()** method invokes the **getPane()** method from the **CheckBoxDemo** class to create a border pane that contains the check boxes, buttons, and a text (line 11). This border pane is returned from invoking **super.getPane()**. The radio buttons are created and added to **paneForRadioButtons** (lines 18–21). **paneForRadioButtons** is added to the border pane (lines 22).

The radio buttons are grouped together in lines 24–27. The handlers for processing the action event on radio buttons are created in lines 29–45. It sets the appropriate color based on the status of the radio buttons.

The **start** method for this JavaFX program is defined in **ButtonDemo** and inherited in **CheckBoxDemo** and then in **RadioButtonDemo**. So when you run **RadioButtonDemo**, the **start** method in **ButtonDemo** is invoked. Since the **getPane()** method is overridden in **RadioButtonDemo**, the method in **RadioButtonDemo** is invoked from line 41 in Listing 16.2, **ButtonDemo.java**.

16.11 How do you test if a radio button is selected?



16.12 Can you apply all the methods for **Labeled** to **RadioButton**?

16.13 Can you set any node in the **graphic** property in a radio button?

16.14 How do you group radio buttons?

16.6 TextField

A text field can be used to enter or display a string. **TextField** is a subclass of **TextInputControl**. Figure 16.11 lists the properties and constructors in **TextField**.

Here is an example of creating a noneditable text field with red text color, a specified font, and right horizontal alignment:

```

TextField tfMessage = new TextField("T-Strom");
tfMessage.setEditable(false);
tfMessage.setStyle("-fx-text-fill: red");
tfMessage.setFont(Font.font("Times", 20));
tfMessage.setAlignment(Pos.BASELINE_RIGHT);
```



When you move the cursor in the text field and press the Enter key, it fires an **ActionEvent**.

Listing 16.5 gives a program that adds a text field to the preceding example to let the user set a new message, as shown in Figure 16.12.

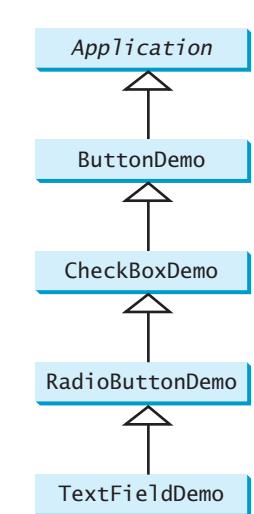
LISTING 16.5 TextFieldDemo.java

```

1 import javafx.geometry.Insets;
2 import javafx.geometry.Pos;
```



FIGURE 16.11 `TextField` enables the user to enter or display a string.



override getPane()
invoke super.getPane()

pane for label and text field

create text field

add to border pane

handle text field action

return border pane

main method omitted



FIGURE 16.12 The program demonstrates using text fields.

```

3 import javafx.scene.control.Label;
4 import javafx.scene.control.TextField;
5 import javafx.scene.layout.BorderPane;
6
7 public class TextFieldDemo extends RadioButtonDemo {
8     @Override // Override the getPane() method in the super class
9     protected BorderPane getPane() {
10         BorderPane pane = super.getPane();
11
12         BorderPane paneForTextField = new BorderPane();
13         paneForTextField.setPadding(new Insets(5, 5, 5, 5));
14         paneForTextField.setStyle("-fx-border-color: green");
15         paneForTextField.setLeft(new Label("Enter a new message: "));
16
17         TextField tf = new TextField();
18         tf.setAlignment(Pos.BOTTOM_RIGHT);
19         paneForTextField.setCenter(tf);
20         pane.setTop(paneForTextField);
21
22         tf.setOnAction(e -> text.setText(tf.getText()));
23
24     return pane;
25 }
26 }
```

TextFieldDemo extends **RadioButtonDemo** (line 7) and adds a label and a text field to let the user enter a new text (lines 12–19). After you set a new text in the text field and press the Enter key, a new message is displayed (line 22). Pressing the Enter key on the text field triggers an action event.



Note

If a text field is used for entering a password, use **PasswordField** to replace **TextField**. **PasswordField** extends **TextField** and hides the input text with echo characters *****.

PasswordField



Check Point

- 16.15 Can you disable editing of a text field?
- 16.16 Can you apply all the methods for **TextInputControl** to **TextField**?
- 16.17 Can you set a node as the **graphic** property in a text field?
- 16.18 How do you align the text in a text field to the right?



Key Point

16.7 TextArea

A **TextArea** enables the user to enter multiple lines of text.

If you want to let the user enter multiple lines of text, you may create several instances of **TextField**. A better alternative, however, is to use **TextArea**, which enables the user to enter multiple lines of text. Figure 16.13 lists the properties and constructors in **TextArea**.



FIGURE 16.13 **TextArea** enables the user to enter or display multiple lines of characters.

Here is an example of creating a text area with 5 rows and 20 columns, wrapped to the next line, red text color, and Courier font 20 pixels.

```

TextArea taNote = new TextArea("This is a text area");
taNote.setPrefColumnCount(20);
taNote.setPrefRowCount(5);
taNote.setWrapText(true);
taNote.setStyle("-fx-text-fill: red");
taNote.setFont(Font.font("Times", 20));

```

TextArea provides scrolling, but often it is useful to create a **ScrollPane** object to hold an instance of **TextArea** and let **ScrollPane** handle scrolling for **TextArea**, as follows:

```
// Create a scroll pane to hold text area
ScrollPane scrollPane = new ScrollPane(taNote);
```

ScrollPane

**Tip**

You can place any node in a **ScrollPane**. **ScrollPane** provides vertical and horizontal scrolling automatically if the control is too large to fit in the viewing area.

We now give a program that displays an image and a short text in a label, and a long text in a text area, as shown in Figure 16.14.



FIGURE 16.14 The program displays an image in a label, a title in a label, and text in the text area.

Here are the major steps in the program:

1. Define a class named **DescriptionPane** that extends **BorderPane**, as shown in Listing 16.6. This class contains a text area inside a scroll pane, and a label for displaying an image icon and a title. The class **DescriptionPane** will be reused in later examples.
2. Define a class named **TextAreaDemo** that extends **Application**, as shown in Listing 16.7. Create an instance of **DescriptionPane** and add it to the scene. The relationship between **DescriptionPane** and **TextAreaDemo** is shown in Figure 16.15.



FIGURE 16.15 **TextAreaDemo** uses **DescriptionPane** to display an image, title, and text description of a national flag.

LISTING 16.6 DescriptionPane.java

```

1 import javafx.geometry.Insets;
2 import javafx.scene.control.Label;
3 import javafx.scene.control.ContentDisplay;
```

```

4 import javafx.scene.control.ScrollPane;
5 import javafx.scene.control.TextArea;
6 import javafx.scene.image.ImageView;
7 import javafx.scene.layout.BorderPane;
8 import javafx.scene.text.Font;
9
10 public class DescriptionPane extends BorderPane {
11     /** Label for displaying an image and a title */
12     private Label lblImageTitle = new Label();                                label
13
14     /** Text area for displaying text */
15     private TextArea taDescription = new TextArea();                           text area
16
17     public DescriptionPane() {
18         // Center the icon and text and place the text under the icon
19         lblImageTitle.setContentDisplay(ContentDisplay.TOP);                  label properties
20         lblImageTitle.setPrefSize(200, 100);
21
22         // Set the font in the label and the text field
23         lblImageTitle.setFont(new Font("SansSerif", 16));
24         taDescription.setFont(new Font("Serif", 14));
25
26         taDescription.setWrapText(true);                                         wrap text
27         taDescription.setEditable(false);                                       read only
28
29         // Create a scroll pane to hold the text area
30         ScrollPane scrollPane = new ScrollPane(taDescription);                scroll pane
31
32         // Place label and scroll pane in the border pane
33         setLeft(lblImageTitle);
34         setCenter(scrollPane);
35         setPadding(new Insets(5, 5, 5, 5));
36     }
37
38     /** Set the title */
39     public void setTitle(String title) {
40         lblImageTitle.setText(title);
41     }
42
43     /** Set the image view */
44     public void setImageView(ImageView icon) {
45         lblImageTitle.setGraphic(icon);
46     }
47
48     /** Set the text description */
49     public void setDescription(String text) {
50         taDescription.setText(text);
51     }
52 }

```

The text area is inside a **ScrollPane** (line 30), which provides scrolling functions for the text area.

The **wrapText** property is set to **true** (line 26) so that the line is automatically wrapped when the text cannot fit in one line. The text area is set as noneditable (line 27), so you cannot edit the description in the text area.

It is not necessary to define a separate class for **DescriptionPane** in this example. However, this class was defined for reuse in the next section, where you will use it to display a description pane for various images.

LISTING 16.7 TextAreaDemo.java

```

1 import javafx.application.Application;
2 import javafx.stage.Stage;
3 import javafx.scene.Scene;
4 import javafx.scene.image.ImageView;
5
6 public class TextAreaDemo extends Application {
7     @Override // Override the start method in the Application class
8     public void start(Stage primaryStage) {
9         // Declare and create a description pane
10        DescriptionPane descriptionPane = new DescriptionPane();
11
12        // Set title, text, and image in the description pane
13        descriptionPane.setTitle("Canada");
14        String description = "The Canadian national flag ...";
15        descriptionPane.setImageView(new ImageView("image/ca.gif"));
16        descriptionPane.setDescription(description);
17
18        // Create a scene and place it in the stage
19        Scene scene = new Scene(descriptionPane, 450, 200);
20        primaryStage.setTitle("TextAreaDemo"); // Set the stage title
21        primaryStage.setScene(scene); // Place the scene in the stage
22        primaryStage.show(); // Display the stage
23    }
24 }
```

The program creates an instance of **DescriptionPane** (line 10), and sets the title (line 13), image (line 15), and text in the description pane (line 16). **DescriptionPane** is a subclass of **Pane**. **DescriptionPane** contains a label for displaying an image and a title, and a text area for displaying a description of the image.



16.19 How do you create a text area with **10** rows and **20** columns?

16.20 How do you obtain the text from a text area?

16.21 Can you disable editing of a text area?

16.22 What method do you use to wrap text to the next line in a text area?

**16.8 ComboBox**

A *combo box*, also known as a *choice list* or *drop-down list*, contains a list of items from which the user can choose.

A combo box is useful for limiting a user's range of choices and avoids the cumbersome validation of data input. Figure 16.16 lists several frequently used properties and constructors in **ComboBox**. **ComboBox** is defined as a generic class. The generic type **T** specifies the element type for the elements stored in a combo box.

The following statements create a combo box with four items, red color, and value set to the first item.

```

ComboBox<String> cbo = new ComboBox<>();
cbo.getItems().addAll("Item 1", "Item 2",
    "Item 3", "Item 4");
cbo.setStyle("-fx-color: red");
cbo.setValue("Item 1");
```



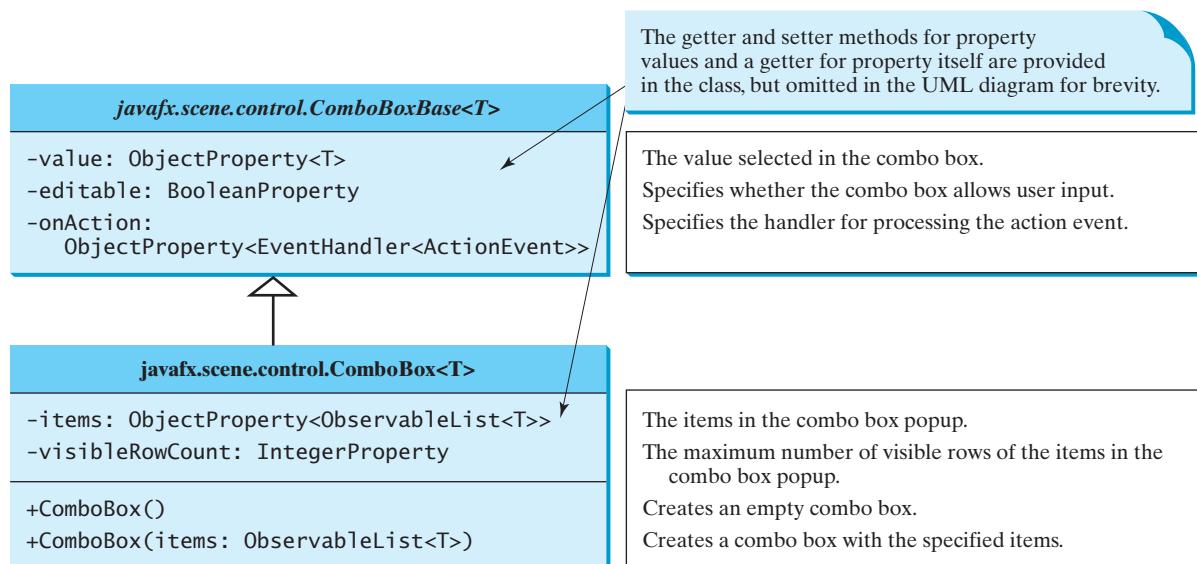


FIGURE 16.16 `ComboBox` enables the user to select an item from a list of items.

`ComboBox` inherits from `ComboBoxBase`. `ComboBox` can fire an `ActionEvent`. Whenever an item is selected, an `ActionEvent` is fired. `ObservableList` is a subinterface of `java.util.List`. So you can apply all the methods defined in `List` for an `ObservableList`. For convenience, JavaFX provides the static method `FXCollections.observableArrayList(arrayOfElements)` for creating an `ObservableList` from an array of elements.

Listing 16.8 gives a program that lets the user view an image and a description of a country's flag by selecting the country from a combo box, as shown in Figure 16.17.

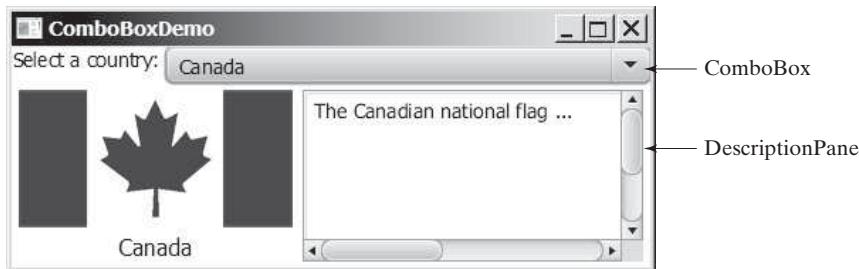


FIGURE 16.17 Information about a country, including an image and a description of its flag, is displayed when the country is selected in the combo box.

Here are the major steps in the program:

1. Create the user interface.

Create a combo box with country names as its selection values. Create a `DescriptionPane` object (the `DescriptionPane` class was introduced in the preceding section). Place the combo box at the top of the border pane and the description pane in the center of the border pane.

2. Process the event.

Create a handler for handling action event from the combo box to set the flag title, image, and text in the description pane for the selected country name.

LISTING 16.8 ComboBoxDemo.java

```

1 import javafx.application.Application;
2 import javafx.stage.Stage;
3 import javafx.collections.FXCollections;
4 import javafx.collections.ObservableList;
5 import javafx.scene.Scene;
6 import javafx.scene.control.ComboBox;
7 import javafx.scene.control.Label;
8 import javafx.scene.image.ImageView;
9 import javafx.scene.layout.BorderPane;
10
11 public class ComboBoxDemo extends Application {
12     // Declare an array of Strings for flag titles
13     private String[] flagTitles = {"Canada", "China", "Denmark",
14         "France", "Germany", "India", "Norway", "United Kingdom",
15         "United States of America"};
16
17     // Declare an ImageView array for the national flags of 9 countries
18     private ImageView[] flagImage = {new ImageView("image/ca.gif"),
19         new ImageView("image/china.gif"),
20         new ImageView("image/denmark.gif"),
21         new ImageView("image/fr.gif"),
22         new ImageView("image/germany.gif"),
23         new ImageView("image/india.gif"),
24         new ImageView("image/norway.gif"),
25         new ImageView("image/uk.gif"), new ImageView("image/us.gif")};
26
27     // Declare an array of strings for flag descriptions
28     private String[] flagDescription = new String[9];
29
30     // Declare and create a description pane
31     private DescriptionPane descriptionPane = new DescriptionPane();
32
33     // Create a combo box for selecting countries
34     private ComboBox<String> cbo = new ComboBox<>(); // flagTitles;
35
36     @Override // Override the start method in the Application class
37     public void start(Stage primaryStage) {
38         // Set text description
39         flagDescription[0] = "The Canadian national flag ...";
40         flagDescription[1] = "Description for China ... ";
41         flagDescription[2] = "Description for Denmark ... ";
42         flagDescription[3] = "Description for France ... ";
43         flagDescription[4] = "Description for Germany ... ";
44         flagDescription[5] = "Description for India ... ";
45         flagDescription[6] = "Description for Norway ... ";
46         flagDescription[7] = "Description for UK ... ";
47         flagDescription[8] = "Description for US ... ";
48
49         // Set the first country (Canada) for display
50         setDisplay(0);
51
52         // Add combo box and description pane to the border pane
53         BorderPane pane = new BorderPane();
54
55         BorderPane paneForComboBox = new BorderPane();
56         paneForComboBox.setLeft(new Label("Select a country: "));
57         paneForComboBox.setCenter(cbo);
58         pane.setTop(paneForComboBox);

```

countries

image views

description

combo box

```

59     cbo.setPrefWidth(400);
60     cbo.setValue("Canada");
61
62     ObservableList<String> items =
63         FXCollections.observableArrayList(flagTitles);
64     cbo.getItems().addAll(items);
65     pane.setCenter(descriptionPane);
66
67     // Display the selected country
68     cbo.setOnAction(e -> setDisplay(items.indexOf(cbo.getValue())));
69
70     // Create a scene and place it in the stage
71     Scene scene = new Scene(pane, 450, 170);
72     primaryStage.setTitle("ComboBoxDemo"); // Set the stage title
73     primaryStage.setScene(scene); // Place the scene in the stage
74     primaryStage.show(); // Display the stage
75 }
76
77 /** Set display information on the description pane */
78 public void setDisplay(int index) {
79     descriptionPane.setTitle(flagTitles[index]);
80     descriptionPane.setImageView(flagImage[index]);
81     descriptionPane.setDescription(flagDescription[index]);
82 }
83 }
```

The program stores the flag information in three arrays: `flagTitles`, `flagImage`, and `flagDescription` (lines 13–28). The array `flagTitles` contains the names of nine countries, the array `flagImage` contains image views of the nine countries' flags, and the array `flagDescription` contains descriptions of the flags.

The program creates an instance of `DescriptionPane` (line 31), which was presented in Listing 16.6, `DescriptionPane.java`. The program creates a combo box with values from `flagTitles` (lines 62–63). The `getItems()` method returns a list from the combo box (line 64) and the `addAll` method adds multiple items into the list.

When the user selects an item in the combo box, the action event triggers the execution of the handler. The handler finds the selected index (line 68) and invokes the `setDisplay(int index)` method to set its corresponding flag title, flag image, and flag description on the pane (lines 78–82).

- 16.23** How do you create a combo box and add three items to it?
- 16.24** How do you retrieve an item from a combo box? How do you retrieve a selected item from a combo box?
- 16.25** How do you get the number of items in a combo box? How do you retrieve an item at a specified index in a combo box?
- 16.26** What events would a `ComboBox` fire upon selecting a new item?



16.9 ListView

A list view is a control that basically performs the same function as a combo box, but it enables the user to choose a single value or multiple values.



Figure 16.18 lists several frequently used properties and constructors in `ListView`. `ListView` is defined as a generic class. The generic type `T` specifies the element type for the elements stored in a list view.

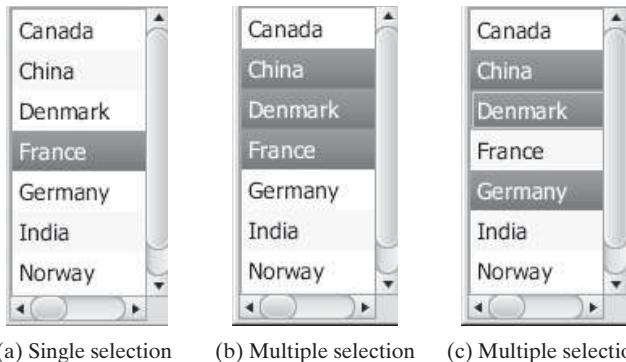


Use ListView

javafx.scene.control.ListView<T> <ul style="list-style-type: none"> -items: ObjectProperty<ObservableList<T>> -orientation: BooleanProperty -selectionModel: ObjectProperty<MultipleSelectionModel<T>> <ul style="list-style-type: none"> +ListView() +ListView(items: ObservableList<T>) 	<p>The getter and setter methods for property values and a getter for property itself are provided in the class, but omitted in the UML diagram for brevity.</p>
	<p>The items in the list view.</p> <p>Indicates whether the items are displayed horizontally or vertically in the list view.</p> <p>Specifies how items are selected. The SelectionMode is also used to obtain the selected items.</p>
	<p>Creates an empty list view.</p> <p>Creates a list view with the specified items.</p>

FIGURE 16.18 **ListView** enables the user to select one or multiple items from a list of items.

The **getSelectionModel()** method returns an instance of **SelectionMode**, which contains the methods for setting a selection mode and obtaining selected indices and items. The selection mode is defined in one of the two constants **SelectionMode.MULTIPLE** and **SelectionMode.SINGLE**, which indicates whether a single item or multiple items can be selected. The default value is **SelectionMode.SINGLE**. Figure 16.19a shows a single selection and Figure 16.19b–c show multiple selections.



(a) Single selection (b) Multiple selection (c) Multiple selection

FIGURE 16.19 **SelectionMode** has two selection modes: single selection and multiple-interval selection.

The following statements create a list view of six items with multiple selections allowed.

```
ObservableList<String> items =
    FXCollections.observableArrayList("Item 1", "Item 2",
                                    "Item 3", "Item 4", "Item 5", "Item 6");
ListView<String> lv = new ListView<>(items);
lv.getSelectionModel().setSelectionMode(SelectionMode.MULTIPLE);
```

The selection model in a list view has the **selectedItemProperty** property, which is an instance of **Observable**. As discussed in Section 15.10, you can add a listener to this property for handling the property change as follows:

```
lv.getSelectionModel().selectedItemProperty().addListener(
    new InvalidationListener() {
        public void invalidated(Observable ov) {
            System.out.println("Selected indices: "
                + lv.getSelectionModel().getSelectedIndices());
```

```

        System.out.println("Selected items: "
            + lv.getSelectionModel().getSelectedItems());
    }
});

```

This anonymous inner class can be simplified using a lambda expression as follows:

```

lv.getSelectionModel().selectedItemProperty().addListener(ov -> {
    System.out.println("Selected indices: "
        + lv.getSelectionModel().getSelectedIndices());
    System.out.println("Selected items: "
        + lv.getSelectionModel().getSelectedItems());
});

```

Listing 16.9 gives a program that lets users select the countries in a list view and displays the flags of the selected countries in the image views. Figure 16.20 shows a sample run of the program.

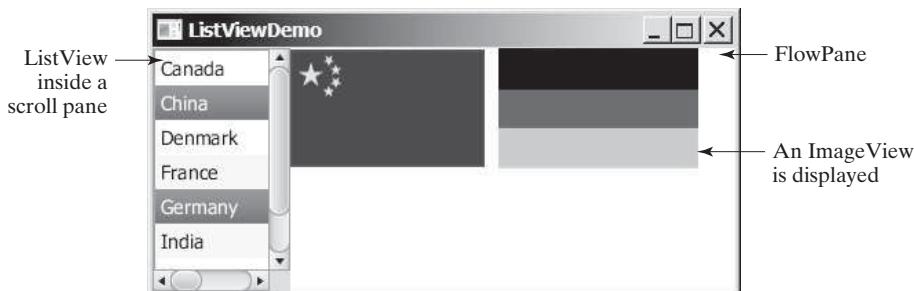


FIGURE 16.20 When the countries in the list view are selected, corresponding images of their flags are displayed in the image views.

Here are the major steps in the program:

1. Create the user interface.

Create a list view with nine country names as selection values, and place the list view inside a scroll pane. Place the scroll pane on the left of a border pane. Create nine image views to be used to display the countries' flag images. Create a flow pane to hold the image views and place the pane in the center of the border pane.

2. Process the event.

Create a listener to implement the `invalidated` method in the `InvalidationListener` interface to place the selected countries' flag image views in the pane.

LISTING 16.9 ListViewDemo.java

```

1 import javafx.application.Application;
2 import javafx.stage.Stage;
3 import javafx.collections.FXCollections;
4 import javafx.scene.Scene;
5 import javafx.scene.control.ListView;
6 import javafx.scene.control.ScrollPane;
7 import javafx.scene.control.SelectionMode;
8 import javafx.scene.image.ImageView;
9 import javafx.scene.layout.BorderPane;
10 import javafx.scene.layout.FlowPane;
11
12 public class ListViewDemo extends Application {

```

```

13     // Declare an array of Strings for flag titles
14     private String[] flagTitles = {"Canada", "China", "Denmark",
15         "France", "Germany", "India", "Norway", "United Kingdom",
16         "United States of America"};
17
18     // Declare an ImageView array for the national flags of 9 countries
19     private ImageView[] ImageViews = {
20         new ImageView("image/ca.gif"),
21         new ImageView("image/china.gif"),
22         new ImageView("image/denmark.gif"),
23         new ImageView("image/fr.gif"),
24         new ImageView("image/germany.gif"),
25         new ImageView("image/india.gif"),
26         new ImageView("image/norway.gif"),
27         new ImageView("image/uk.gif"),
28         new ImageView("image/us.gif")
29     };
30
31     @Override // Override the start method in the Application class
32     public void start(Stage primaryStage) {
33         ListView<String> lv = new ListView<>
34             (FXCollections.observableArrayList(flagTitles));
35         lv.setPrefSize(400, 400);
36         lv.getSelectionModel().setSelectionMode(SelectionMode.MULTIPLE);
37
38         // Create a pane to hold image views
39         FlowPane imagePane = new FlowPane(10, 10);
40         BorderPane pane = new BorderPane();
41         pane.setLeft(new ScrollPane(lv));
42         pane.setCenter(imagePane);
43
44         lv.getSelectionModel().selectedItemProperty().addListener(
45             ov -> {
46                 imagePane.getChildren().clear();
47                 for (Integer i: lv.getSelectionModel().getSelectedIndices()) {
48                     imagePane.getChildren().add(ImageViews[i]);
49                 }
50             });
51
52         // Create a scene and place it in the stage
53         Scene scene = new Scene(pane, 450, 170);
54         primaryStage.setTitle("ListViewDemo"); // Set the stage title
55         primaryStage.setScene(scene); // Place the scene in the stage
56         primaryStage.show(); // Display the stage
57     }
58 }

```

create a list view

set list view properties

place list view in pane

listen to item selected

add image views of selected items

The program creates an array of strings for countries (lines 14–16) and an array of nine image views for displaying flag images for nine countries (lines 19–29) in the same order as in the array of countries (line 34). Thus, the index 0 of the image view array corresponds to the first country in the list view.

The list view is placed in a scroll pane (line 41) so that it can be scrolled when the number of items in the list extends beyond the viewing area.

By default, the selection mode of the list view is single. The selection mode for the list view is set to multiple (line 36), which allows the user to select multiple items in the list view. When the user selects countries in the list view, the listener's handler (lines 44–50) is executed, which gets the indices of the selected items and adds their corresponding image views to the flow pane.

16.27 How do you create an observable list with an array of strings?

16.28 How do you set the orientation in a list view?

16.29 What selection modes are available for a list view? What is the default selection mode? How do you set a selection mode?

16.30 How do you obtain the selected items and selected indices?



16.10 ScrollBar

ScrollBar is a control that enables the user to select from a range of values.

Figure 16.21 shows a scroll bar. Normally, the user changes the value of a scroll bar by making a gesture with the mouse. For example, the user can drag the scroll bar's thumb, click on the scroll bar track, or the scroll bar's left or right buttons.

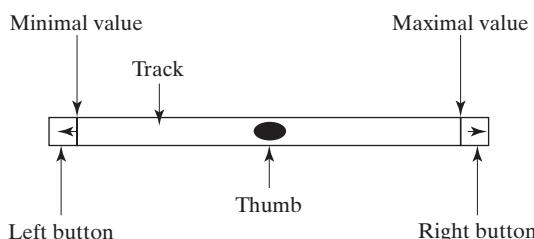


FIGURE 16.21 A scroll bar represents a range of values graphically.

ScrollBar has the following properties, as shown in Figure 16.22.

javafx.scene.control.ScrollBar	<p>The getter and setter methods for property values and a getter for property itself are provided in the class, but omitted in the UML diagram for brevity.</p>
<pre>-blockIncrement: DoubleProperty -max: DoubleProperty -min: DoubleProperty -unitIncrement: DoubleProperty -value: DoubleProperty -visibleAmount: DoubleProperty -orientation: ObjectProperty<Orientation> +ScrollBar() +increment() +decrement()</pre>	<p>The amount to adjust the scroll bar if the track of the bar is clicked (default: 10). The maximum value represented by this scroll bar (default: 100). The minimum value represented by this scroll bar (default: 0). The amount to adjust the scroll bar when the <code>increment()</code> and <code>decrement()</code> methods are called (default: 1). Current value of the scroll bar (default: 0). The width of the scroll bar (default: 15). Specifies the orientation of the scroll bar (default: HORIZONTAL). Creates a default horizontal scroll bar. Increments the value of the scroll bar by <code>unitIncrement</code>. Decrements the value of the scroll bar by <code>unitIncrement</code>.</p>

FIGURE 16.22 **ScrollBar** enables the user to select from a range of values.



Note

The width of the scroll bar's track corresponds to `max + visibleAmount`. When a scroll bar is set to its maximum value, the left side of the bubble is at `max`, and the right side is at `max + visibleAmount`.

When the user changes the value of the scroll bar, it notifies the listener of the change. You can register a listener on the scroll bar's `valueProperty` for responding to this change as follows:

```
ScrollBar sb = new ScrollBar();
sb.valueProperty().addListener(ov -> {
    System.out.println("old value: " + oldVal);
    System.out.println("new value: " + newVal);
});
```

Listing 16.10 gives a program that uses horizontal and vertical scroll bars to move a text displayed on a pane. The horizontal scroll bar is used to move the text to the left and the right, and the vertical scroll bar to move it up and down. A sample run of the program is shown in Figure 16.23.



FIGURE 16.23 The scroll bars move the message on a pane horizontally and vertically.

Here are the major steps in the program:

1. Create the user interface.

Create a `Text` object and place it in the center of the border pane. Create a vertical scroll bar and place it on the right of the border pane. Create a horizontal scroll bar and place it at the bottom of the border pane.

2. Process the event.

Create listeners to move the text according to the bar movement in the scroll bars upon the change of the `value` property.

LISTING 16.10 ScrollBarDemo.java

```
1 import javafx.application.Application;
2 import javafx.stage.Stage;
3 import javafx.geometry.Orientation;
4 import javafx.scene.Scene;
5 import javafx.scene.control.ScrollBar;
6 import javafx.scene.layout.BorderPane;
7 import javafx.scene.layout.Pane;
8 import javafx.scene.text.Text;
9
10 public class ScrollBarDemo extends Application {
11     @Override // Override the start method in the Application class
12     public void start(Stage primaryStage) {
13         Text text = new Text(20, 20, "JavaFX Programming");
14
15         ScrollBar sbHorizontal = new ScrollBar();
16         ScrollBar sbVertical = new ScrollBar();
17         sbVertical.setOrientation(Orientation.VERTICAL);
18
19         // Create a text in a pane
```

horizontal scroll bar
vertical scroll bar

```

20     Pane paneForText = new Pane();
21     paneForText.getChildren().add(text);                                add text to a pane
22
23     // Create a border pane to hold text and scroll bars
24     BorderPane pane = new BorderPane();
25     pane.setCenter(paneForText);
26     pane.setBottom(sbHorizontal);
27     pane.setRight(sbVertical);
28
29     // Listener for horizontal scroll bar value change
30     sbHorizontal.valueProperty().addListener(ov ->
31         text.setX(sbHorizontal.getValue() * paneForText.getWidth() /      set new location for text
32             sbHorizontal.getMax()));
33
34     // Listener for vertical scroll bar value change
35     sbVertical.valueProperty().addListener(ov ->
36         text.setY(sbVertical.getValue() * paneForText.getHeight() /      set new location for text
37             sbVertical.getMax()));
38
39     // Create a scene and place it in the stage
40     Scene scene = new Scene(pane, 450, 170);
41     primaryStage.setTitle("ScrollBarDemo"); // Set the stage title
42     primaryStage.setScene(scene); // Place the scene in the stage
43     primaryStage.show(); // Display the stage
44 }
45 }
```

The program creates a text (line 13) and two scroll bars (**sbHorizontal** and **sbVertical**) (lines 15–16). The text is placed in a pane (line 21) that is then placed in the center of the border pane (line 25). If the text were directly placed in the center of the border pane, the position of the text cannot be changed by resetting its *x* and *y* properties. The **sbHorizontal** and **sbVertical** are placed on the right and at the bottom of the border pane (lines 26–27), respectively.

You can specify the properties of the scroll bar. By default, the property value is **100** for **max**, **0** for **min**, **10** for **blockIncrement**, and **15** for **visibleAmount**.

A listener is registered to listen for the **sbHorizontal value** property change (lines 30–32). When the value of the scroll bar changes, the listener is notified by invoking the handler to set a new *x* value for the text that corresponds to the current value of **sbHorizontal** (lines 31–32).

A listener is registered to listen for the **sbVertical value** property change (lines 35–37). When the value of the scroll bar changes, the listener is notified by invoking the handler to set a new *y* value for the text that corresponds to the current value of **sbVertical** (lines 36–37).

Alternatively, the code in lines 30–37 can be replaced by using binding properties as follows:

```

text.xProperty().bind(sbHorizontal.valueProperty() .
    multiply(paneForText.widthProperty()) .
    divide(sbHorizontal.maxProperty()));

text.yProperty().bind(sbVertical.valueProperty().multiply(
    paneForText.heightProperty().divide(
        sbVertical.maxProperty())));
```

16.31 How do you create a horizontal scroll bar? How do you create a vertical scroll bar?

16.32 How do you write the code to respond to the **value** property change of a scroll bar?

16.33 How do you get the value from a scroll bar? How do you get the maximum value from a scroll bar?



16.11 Slider



Slider is similar to **ScrollBar**, but **Slider** has more properties and can appear in many forms.



VideoNote
Use Slider

Figure 16.24 shows two sliders. **Slider** lets the user graphically select a value by sliding a knob within a bounded interval. The slider can show both major tick marks and minor tick marks between them. The number of pixels between the tick marks is specified by the **majorTickUnit** and **minorTickCount** properties. Sliders can be displayed horizontally or vertically, with or without ticks, and with or without labels.

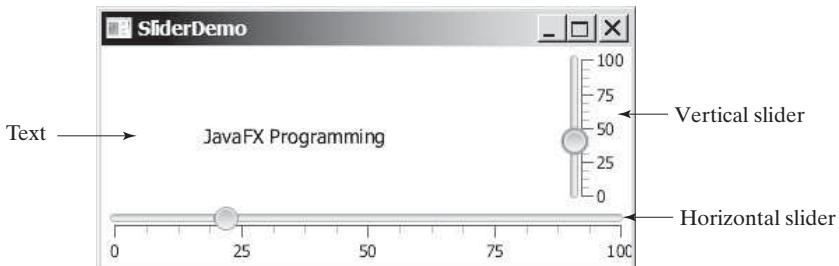


FIGURE 16.24 The sliders move the message on a pane horizontally and vertically.

The frequently used constructors and properties in **Slider** are shown in Figure 16.25.

javafx.scene.control.Slider	blockIncrement : DoubleProperty -max : DoubleProperty -min : DoubleProperty -value : DoubleProperty -orientation : ObjectProperty<Orientation> -majorTickUnit : DoubleProperty -minorTickCount : IntegerProperty -showTickLabels : BooleanProperty -showTickMarks : BooleanProperty	The getter and setter methods for property values and a getter for property itself are provided in the class, but omitted in the UML diagram for brevity.
	+Slider() +Slider(min: double, max: double, value: double)	The amount to adjust the slider if the track of the bar is clicked (default: 10). The maximum value represented by this slider (default: 100). The minimum value represented by this slider (default: 0). Current value of the slider (default: 0). Specifies the orientation of the slider (default: HORIZONTAL). The unit distance between major tick marks. The number of minor ticks to place between two major ticks. Specifies whether the labels for tick marks are shown. Specifies whether the tick marks are shown.
		Creates a default horizontal slider. Creates a slider with the specified min, max, and value.

FIGURE 16.25 **Slider** enables the user to select from a range of values.



Note

The values of a vertical scroll bar increase from top to bottom, but the values of a vertical slider decrease from top to bottom.

You can add a listener to listen for the **value** property change in a slider in the same way as in a scroll bar. We now rewrite the program in the preceding section using the sliders to move a text displayed on a pane in Listing 16.11. A sample run of the program is shown in Figure 16.24.

LISTING 16.11 SliderDemo.java

```

1 import javafx.application.Application;
2 import javafx.stage.Stage;
3 import javafx.geometry.Orientation;
4 import javafx.scene.Scene;
5 import javafx.scene.control.Slider;
6 import javafx.scene.layout.BorderPane;
7 import javafx.scene.layout.Pane;
8 import javafx.scene.text.Text;
9
10 public class SliderDemo extends Application {
11     @Override // Override the start method in the Application class
12     public void start(Stage primaryStage) {
13         Text text = new Text(20, 20, "JavaFX Programming");
14
15         Slider slHorizontal = new Slider();
16         slHorizontal.setShowTickLabels(true);
17         slHorizontal.setShowTickMarks(true);                                horizontal slider
18
19         Slider slVertical = new Slider();
20         slVertical.setOrientation(Orientation.VERTICAL);
21         slVertical.setShowTickLabels(true);
22         slVertical.setShowTickMarks(true);
23         slVertical.setValue(100);                                         set slider properties
24
25         // Create a text in a pane
26         Pane paneForText = new Pane();
27         paneForText.getChildren().add(text);                               add text to a pane
28
29         // Create a border pane to hold text and scroll bars
30         BorderPane pane = new BorderPane();
31         pane.setCenter(paneForText);                                     border pane
32         pane.setBottom(slHorizontal);
33         pane.setRight(slVertical);
34
35         slHorizontal.valueProperty().addListener(ov ->                set new location for text
36             text.setX(slHorizontal.getValue() * paneForText.getWidth() / 37
37             slHorizontal.getMax()));
38
39         slVertical.valueProperty().addListener(ov ->                  set new location for text
40             text.setY((slVertical.getMax() - slVertical.getValue()) * 41
41             paneForText.getHeight() / slVertical.getMax()));
42
43         // Create a scene and place it in the stage
44         Scene scene = new Scene(pane, 450, 170);
45         primaryStage.setTitle("SliderDemo"); // Set the stage title
46         primaryStage.setScene(scene); // Place the scene in the stage
47         primaryStage.show(); // Display the stage
48     }
49 }
```

Slider is similar to **ScrollBar** but has more features. As shown in this example, you can specify labels, major ticks, and minor ticks on a **Slider** (lines 16–17).

A listener is registered to listen for the **slHorizontal value** property change (lines 35–37) and another one is for the **sbVertical value** property change (lines 39–41). When the value of the slider changes, the listener is notified by invoking the handler to set a new position for the text (lines 36–37, 40–41). Note that since the value of a vertical slider decreases from top to bottom, the corresponding y value for the text is adjusted accordingly.

The code in lines 35–41 can be replaced by using binding properties as follows:

```
text.xProperty().bind(s1Horizontal.valueProperty() .
    multiply(paneForText.widthProperty()).
    divide(s1Horizontal.maxProperty()));

text.yProperty().bind((s1Vertical.maxProperty().subtract(
    s1Vertical.valueProperty()).multiply(
    paneForText.heightProperty().divide(
    s1Vertical.maxProperty()))));
```

Listing 15.17 gives a program that displays a bouncing ball. You can add a slider to control the speed of the ball movement as shown in Figure 16.26. The new program is given in Listing 16.12.

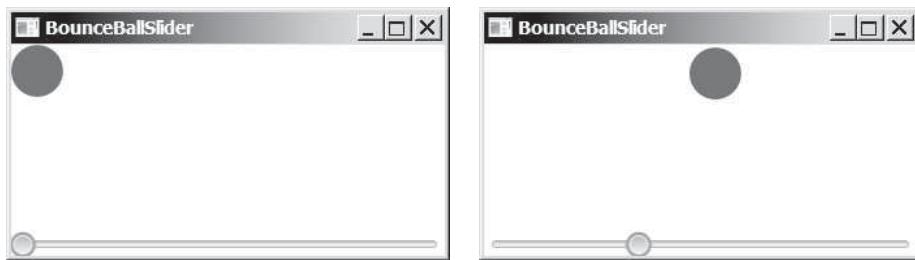


FIGURE 16.26 You can increase or decrease the speed of the ball using a slider.

LISTING 16.12 BounceBallSlider.java

```
1 import javafx.application.Application;
2 import javafx.stage.Stage;
3 import javafx.scene.Scene;
4 import javafx.scene.control.Slider;
5 import javafx.scene.layout.BorderPane;
6
7 public class BounceBallSlider extends Application {
8     @Override // Override the start method in the Application class
9     public void start(Stage primaryStage) {
10         BallPane ballPane = new BallPane();
11         Slider s1Speed = new Slider();
12         s1Speed.setMax(20);
13         ballPane.rateProperty().bind(s1Speed.valueProperty());
14
15         BorderPane pane = new BorderPane();
16         pane.setCenter(ballPane);
17         pane.setBottom(s1Speed);
18
19         // Create a scene and place it in the stage
20         Scene scene = new Scene(pane, 250, 250);
21         primaryStage.setTitle("BounceBallSlider"); // Set the stage title
22         primaryStage.setScene(scene); // Place the scene in the stage
23         primaryStage.show(); // Display the stage
24     }
25 }
```

create a ball pane
create a slider
set max value for slider
bind rate with slider value

create a border pane
add ball pane to center
add slider to the bottom

The **BallPane** class defined in Listing 15.17 animates a ball bouncing in a pane. The **rateProperty()** method in **BallPane** returns a property value for animation rate.

The animation stops if the rate is 0. If the rate is greater than 20, the animation will be too fast. So, we purposely set the rate to a value between 0 and 20. This value is bound to the slider value (line 13). So the slider max value is set to 20 (line 12).

16.34 How do you create a horizontal slider? How do you create a vertical slider?

16.35 How do you add a listener to handle the property value change of a slider?

16.36 How do you get the value from a slider? How do you get the maximum value from a slider?



16.12 Case Study: Developing a Tic-Tac-Toe Game

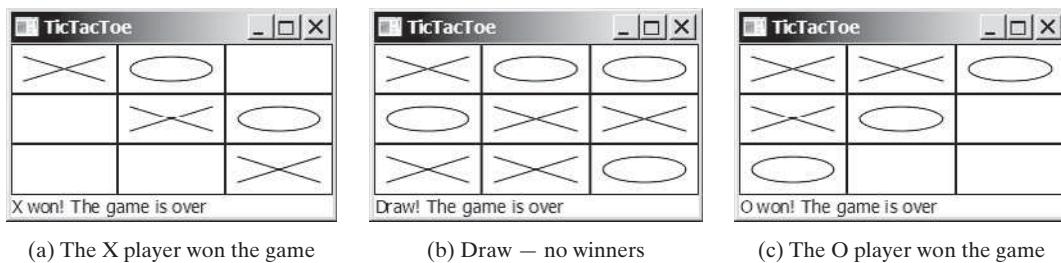
This section develops a program for playing tic-tac-toe.

From the many examples in this and earlier chapters you have learned about objects, classes, arrays, class inheritance, GUI, and event-driven programming. Now it is time to put what you have learned to work in developing comprehensive projects. In this section, we will develop a JavaFX program with which to play the popular game of tic-tac-toe.

Two players take turns marking an available cell in a 3×3 grid with their respective tokens (either X or O). When one player has placed three tokens in a horizontal, vertical, or diagonal row on the grid, the game is over and that player has won. A draw (no winner) occurs when all the cells on the grid have been filled with tokens and neither player has achieved a win. Figure 16.27 shows the representative sample runs of the game.



TicTacToe



(a) The X player won the game

(b) Draw – no winners

(c) The O player won the game

FIGURE 16.27 Two players play a tic-tac-toe game.

All the examples you have seen so far show simple behaviors that are easy to model with classes. The behavior of the tic-tac-toe game is somewhat more complex. To define classes that model the behavior, you need to study and understand the game.

Assume that all the cells are initially empty, and that the first player takes the X token and the second player the O token. To mark a cell, the player points the mouse to the cell and clicks it. If the cell is empty, the token (X or O) is displayed. If the cell is already filled, the player's action is ignored.

From the preceding description, it is obvious that a cell is a GUI object that handles the mouse-click event and displays tokens. There are many choices for this object. We will use a pane to model a cell and to display a token (X or O). How do you know the state of the cell (empty, X, or O)? You use a property named `token` of the `char` type in the `Cell` class. The `Cell` class is responsible for drawing the token when an empty cell is clicked, so you need to write the code for listening to the mouse-clicked action and for painting the shapes for tokens X and O. The `Cell` class can be defined as shown in Figure 16.28.

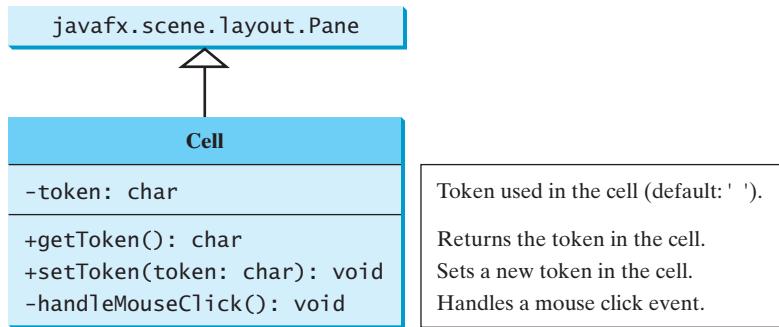


FIGURE 16.28 The **Cell** class displays the token in a cell.

The tic-tac-toe board consists of nine cells, created using `new Cell[3][3]`. To determine which player's turn it is, you can introduce a variable named `whoseTurn` of the `char` type. `whoseTurn` is initially '`'X'`', then changes to '`'O'`', and subsequently changes between '`'X'`' and '`'O'`' whenever a new cell is occupied. When the game is over, set `whoseTurn` to '`' '`'.

How do you know whether the game is over, whether there is a winner, and who the winner, if any? You can define a method named `isWon(char token)` to check whether a specified token has won and a method named `isFull()` to check whether all the cells are occupied.

Clearly, two classes emerge from the foregoing analysis. One is the **Cell** class, which handles operations for a single cell; the other is the **TicTacToe** class, which plays the whole game and deals with all the cells. The relationship between these two classes is shown in Figure 16.29.

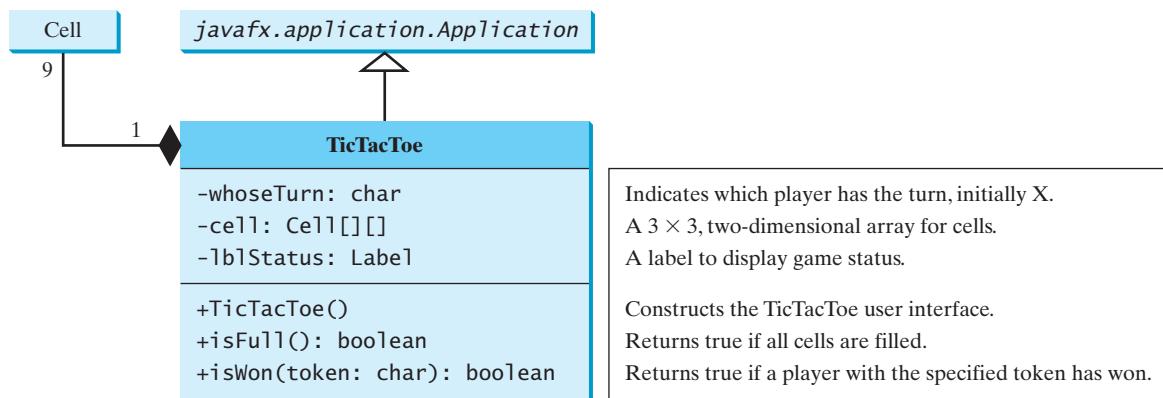


FIGURE 16.29 The **TicTacToe** class contains nine cells.

Since the **Cell** class is only to support the **TicTacToe** class, it can be defined as an inner class in **TicTacToe**. The complete program is given in Listing 16.13.

LISTING 16.13 TicTacToe.java

```

1 import javafx.application.Application;
2 import javafx.stage.Stage;
3 import javafx.scene.Scene;
4 import javafx.scene.control.Label;
5 import javafx.scene.layout.BorderPane;

```

```

6 import javafx.scene.layout.GridPane;
7 import javafx.scene.layout.Pane;
8 import javafx.scene.paint.Color;
9 import javafx.scene.shape.Line;
10 import javafx.scene.shape.Ellipse;
11
12 public class TicTacToe extends Application { main class TicTacToe
13     // Indicate which player has a turn, initially it is the X player
14     private char whoseTurn = 'X';
15
16     // Create and initialize cell
17     private Cell[][] cell = new Cell[3][3];
18
19     // Create and initialize a status label
20     private Label lblStatus = new Label("X's turn to play");
21
22     @Override // Override the start method in the Application class
23     public void start(Stage primaryStage) {
24         // Pane to hold cell
25         GridPane pane = new GridPane();
26         for (int i = 0; i < 3; i++) hold nine cells
27             for (int j = 0; j < 3; j++)
28                 pane.add(cell[i][j] = new Cell(), j, i);
29
30         BorderPane borderPane = new BorderPane();
31         borderPane.setCenter(pane);
32         borderPane.setBottom(lblStatus); create a cell
33
34         // Create a scene and place it in the stage
35         Scene scene = new Scene(borderPane, 450, 170);
36         primaryStage.setTitle("TicTacToe"); // Set the stage title
37         primaryStage.setScene(scene); // Place the scene in the stage
38         primaryStage.show(); // Display the stage
39     }
40
41     /** Determine if the cell are all occupied */
42     public boolean isFull() { check isFull
43         for (int i = 0; i < 3; i++)
44             for (int j = 0; j < 3; j++)
45                 if (cell[i][j].getToken() == ' ')
46                     return false;
47
48         return true;
49     }
50
51     /** Determine if the player with the specified token wins */
52     public boolean isWon(char token) { check rows
53         for (int i = 0; i < 3; i++)
54             if (cell[i][0].getToken() == token
55                 && cell[i][1].getToken() == token
56                 && cell[i][2].getToken() == token) {
57                 return true;
58             }
59
60         for (int j = 0; j < 3; j++) check columns
61             if (cell[0][j].getToken() == token
62                 && cell[1][j].getToken() == token
63                 && cell[2][j].getToken() == token) {
64                 return true;
65             }

```

```

66
check major diagonal      67     if (cell[0][0].getToken() == token
68         && cell[1][1].getToken() == token
69         && cell[2][2].getToken() == token) {
70     return true;
71 }
72
check subdiagonal        73     if (cell[0][2].getToken() == token
74         && cell[1][1].getToken() == token
75         && cell[2][0].getToken() == token) {
76     return true;
77 }
78
79     return false;
80 }
81
82 // An inner class for a cell
83 public class Cell extends Pane {
84     // Token used for this cell
85     private char token = ' ';
86
87     public Cell() {
88         setStyle("-fx-border-color: black");
89         this.setPrefSize(2000, 2000);
90         this.setOnMouseClicked(e -> handleMouseClick());
91     }
92
93     /** Return token */
94     public char getToken() {
95         return token;
96     }
97
98     /** Set a new token */
99     public void setToken(char c) {
100        token = c;
101
102        if (token == 'X') {
103            Line line1 = new Line(10, 10,
104                this.getWidth() - 10, this.getHeight() - 10);
105            line1.endXProperty().bind(this.widthProperty().subtract(10));
106            line1.endYProperty().bind(this.heightProperty().subtract(10));
107            Line line2 = new Line(10, this.getHeight() - 10,
108                this.getWidth() - 10, 10);
109            line2.startYProperty().bind(
110                this.heightProperty().subtract(10));
111            line2.endXProperty().bind(this.widthProperty().subtract(10));
112
113            // Add the lines to the pane
114            this.getChildren().addAll(line1, line2);
115        }
116        else if (token == 'O') {
117            Ellipse ellipse = new Ellipse(this.getWidth() / 2,
118                this.getHeight() / 2, this.getWidth() / 2 - 10,
119                this.getHeight() / 2 - 10);
120            ellipse.centerXProperty().bind(
121                this.widthProperty().divide(2));
122            ellipse.centerYProperty().bind(
123                this.heightProperty().divide(2));
124            ellipse.radiusXProperty().bind(
125                this.widthProperty().divide(2).subtract(10));

```

```

126     ellipse.radiusYProperty().bind(
127         this.heightProperty().divide(2).subtract(10));
128     ellipse.setStroke(Color.BLACK);
129     ellipse.setFill(Color.WHITE);
130
131     getChildren().add(ellipse); // Add the ellipse to the pane
132 }
133 }
134
135 /* Handle a mouse click event */
136 private void handleMouseClicked() {                                handle mouse click
137     // If cell is empty and game is not over
138     if (token == ' ' && whoseTurn != ' ') {
139         setToken(whoseTurn); // Set token in the cell
140
141         // Check game status
142         if (isWon(whoseTurn)) {
143             lblStatus.setText(whoseTurn + " won! The game is over");
144             whoseTurn = ' '; // Game is over
145         }
146         else if (isFull()) {
147             lblStatus.setText("Draw! The game is over");
148             whoseTurn = ' '; // Game is over
149         }
150         else {
151             // Change the turn
152             whoseTurn = (whoseTurn == 'X') ? 'O' : 'X';
153             // Display whose turn
154             lblStatus.setText(whoseTurn + "'s turn");
155         }
156     }
157 }
158 }
159 }
```

The **TicTacToe** class initializes the user interface with nine cells placed in a grid pane (lines 25–28). A label named **lblStatus** is used to show the status of the game (line 20). The variable **whoseTurn** (line 14) is used to track the next type of token to be placed in a cell. The methods **isFull** (lines 42–49) and **isWon** (lines 52–80) are for checking the status of the game.

Since **Cell** is an inner class in **TicTacToe**, the variable (**whoseTurn**) and methods (**isFull** and **isWon**) defined in **TicTacToe** can be referenced from the **Cell** class. The inner class makes programs simple and concise. If **Cell** were not defined as an inner class of **TicTacToe**, you would have to pass an object of **TicTacToe** to **Cell** in order for the variables and methods in **TicTacToe** to be used in **Cell**.

The listener for the mouse-click action is registered for the cell (line 90). If an empty cell is clicked and the game is not over, a token is set in the cell (line 138). If the game is over, **whoseTurn** is set to ' ' (lines 144, 148). Otherwise, **whoseTurn** is alternated to a new turn (line 152).



Tip

Use an incremental approach in developing and testing a Java project of this kind. For example, this program can be divided into five steps:

incremental development and testing

1. Lay out the user interface and display a fixed token X on a cell.
2. Enable the cell to display a fixed token X upon a mouse click.
3. Coordinate between the two players so as to display tokens X and O alternately.
4. Check whether a player wins, or whether all the cells are occupied without a winner.
5. Implement displaying a message on the label upon each move by a player.



- 16.37** When the game starts, what value is in `whoseTurn`? When the game is over, what value is in `whoseTurn`?
- 16.38** What happens when the user clicks on an empty cell if the game is not over? What happens when the user clicks on an empty cell if the game is over?
- 16.39** How does the program check whether a player wins? How does the program check whether all cells are filled?



16.13 Video and Audio

You can use the `Media` class to obtain the source of the media, the `MediaPlayer` class to play and control the media, and the `MediaView` class to display the video.



VideoNote

Use `Media`, `MediaPlayer`, and `MediaView`

Media (video and audio) is essential in developing rich Internet applications. JavaFX provides the `Media`, `MediaPlayer`, and `MediaView` classes for working with media. Currently, JavaFX supports MP3, AIFF, WAV, and MPEG-4 audio formats and FLV and MPEG-4 video formats.

The `Media` class represents a media source with properties `duration`, `width`, and `height`, as shown in Figure 16.30. You can construct a `Media` object from an Internet URL string.

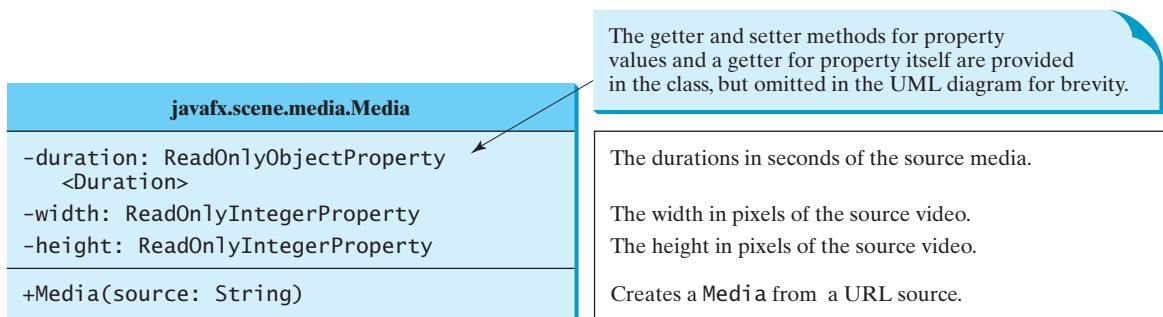


FIGURE 16.30 `Media` represents a media source such as a video or an audio.

The `MediaPlayer` class plays and controls the media with properties such as `autoPlay`, `currentCount`, `cycleCount`, `mute`, `volume`, and `totalDuration`, as shown in Figure 16.31. You can construct a `MediaPlayer` object from a media and use the `pause()` and `play()` method to pause and resume playing.



FIGURE 16.31 `MediaPlayer` plays and controls a media.

The **MediaView** class is a subclass of **Node** that provides a view of the **Media** being played by a **MediaPlayer**. The **MediaView** class provides the properties for viewing the media, as shown in Figure 16.32.

javafx.scene.media.MediaView	
-x: DoubleProperty	Specifies the current x-coordinate of the media view.
-y: DoubleProperty	Specifies the current y-coordinate of the media view.
-mediaPlayer: ObjectProperty<MediaPlayer>	Specifies a media player for the media view.
-fitWidth: DoubleProperty	Specifies the width of the view for the media to fit.
-fitHeight: DoubleProperty	Specifies the height of the view for the media to fit.
+MediaView()	Creates an empty media view.
+MediaView(mediaPlayer: MediaPlayer)	Creates a media view with the specified media player.

FIGURE 16.32 **MediaView** provides the properties for viewing the media.

Listing 16.14 gives an example that displays a video in a view, as shown in Figure 16.33. You can use the play/pause button to play or pause the video and use the rewind button to restart the video, and use the slider to control the volume of the audio.

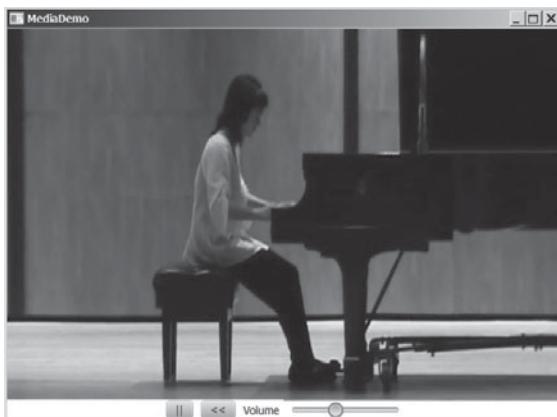


FIGURE 16.33 The program controls and plays a video.

LISTING 16.14 MediaDemo.java

```

1 import javafx.application.Application;
2 import javafx.stage.Stage;
3 import javafx.geometry.Pos;
4 import javafx.scene.Scene;
5 import javafx.scene.control.Button;
6 import javafx.scene.control.Label;
7 import javafx.scene.control.Slider;
8 import javafx.scene.layout.BorderPane;
9 import javafx.scene.layout.HBox;
10 import javafx.scene.layout.Region;
11 import javafx.scene.media.Media;

```

```

12 import javafx.scene.media.MediaPlayer;
13 import javafx.scene.media.MediaView;
14 import javafx.util.Duration;
15
16 public class MediaDemo extends Application {
17     private static final String MEDIA_URL =
18         "http://cs.armstrong.edu/~liang/common/sample.mp4";
19
20     @Override // Override the start method in the Application class
21     public void start(Stage primaryStage) {
22         Media media = new Media(MEDIA_URL);
23         MediaPlayer mediaPlayer = new MediaPlayer(media);
24         MediaView mediaView = new MediaView(mediaPlayer);
25
26         Button playButton = new Button(">");
27         playButton.setOnAction(e -> {
28             if (playButton.getText().equals(">")) {
29                 mediaPlayer.play();
30                 playButton.setText("||");
31             } else {
32                 mediaPlayer.pause();
33                 playButton.setText(">");
34             }
35         });
36
37         Button rewindButton = new Button("<<");
38         rewindButton.setOnAction(e -> mediaPlayer.seek(Duration.ZERO));
39
40         Slider slVolume = new Slider();
41         slVolume.setPrefWidth(150);
42         slVolume.setMaxWidth(Region.USE_PREF_SIZE);
43         slVolume.setMinWidth(30);
44         slVolume.setValue(50);
45         mediaPlayer.volumeProperty().bind(
46             slVolume.valueProperty().divide(100));
47
48         HBox hBox = new HBox(10);
49         hBox.setAlignment(Pos.CENTER);
50         hBox.getChildren().addAll(playButton, rewindButton,
51             new Label("Volume"), slVolume);
52
53         BorderPane pane = new BorderPane();
54         pane.setCenter(mediaView);
55         pane.setBottom(hBox);
56
57         // Create a scene and place it in the stage
58         Scene scene = new Scene(pane, 650, 500);
59         primaryStage.setTitle("MediaDemo"); // Set the stage title
60         primaryStage.setScene(scene); // Place the scene in the stage
61         primaryStage.show(); // Display the stage
62     }
63 }

```

The source of the media is a URL string defined in lines 17 and 18. The program creates a **Media** object from this URL (line 22), a **MediaPlayer** from the **Media** object (line 23), and a **MediaView** from the **MediaPlayer** object (line 24). The relationship among these three objects is shown in Figure 16.34.

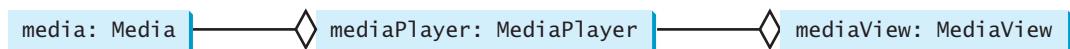


FIGURE 16.34 The media represents the source, the media player controls the playing, and the media view displays the video.

A **Media** object supports live streaming. You can now download a large media file and play it in the same time. A **Media** object can be shared by multiple media players and different views can use the same **MediaPlayer** object.

A play button is created (line 26) to play/pause the media (line 29). The button's text is changed to **||** (line 30) if the button's current text is **>** (line 28). If the button's current text is **||**, it is changed to **>** (line 33) and the player is paused (line 32).

A rewind button is created (line 37) to reset the playback time to the beginning of the media stream by invoking **seek(Duration.ZERO)** (line 38).

A slider is created (line 40) to set the volume. The media player's volume property is bound to the slider (lines 45 and 46).

The buttons and slider are placed in an **HBox** (lines 48–51) and the media view is placed in the center of the border pane (line 54) and the **HBox** is placed at the bottom of the border pane (line 55).

- 16.40** How do you create a **Media** from a URL? How do you create a **MediaPlayer**? How do you create a **MediaView**?



- 16.41** If the URL is typed as `cs.armstrong.edu/liang/common/sample.mp4` without `http://` in front of it, will it work?

- 16.42** Can you place a **Media** in multiple **MediaPlayer**s? Can you place a **MediaPlayer** in multiple **MediaView**s? Can you place a **MediaView** in multiple **Panes**?



16.14 Case Study: National Flags and Anthems

This case study presents a program that displays a nation's flag and plays its anthem.



The images for seven national flags, named **flag0.gif**, **flag1.gif**, . . . , **flag6.gif** for Denmark, Germany, China, India, Norway, United Kingdom, and United States are stored under www.cs.armstrong.edu/liang/common/image. The audio consists of national anthems for these seven nations, named **anthem0.mp3**, **anthem1.mp3**, . . . , and **anthem6.mp3**. They are stored under www.cs.armstrong.edu/liang/common/audio.

The program enables the user to select a nation from a combo box and then displays its flag and plays its anthem. The user can suspend the audio by clicking the **||** button and resume it by clicking the **<** button, as shown in Figure 16.35.



FIGURE 16.35 The program displays a national flag and plays its anthem.

The program is given in Listing 16.15.



VideoNote

Audio and image

URLBase for image and audio
track current image/audio

image array
media player array

load image
load audio

create play button
handle button action

pause audio

play audio

create image view
create combo box
create observable list

process combo selection

choose a new nation

play audio

LISTING 16.15 FlagAnthem.java

```

1 import javafx.application.Application;
2 import javafx.collections.FXCollections;
3 import javafx.collections.ObservableList;
4 import javafx.stage.Stage;
5 import javafx.geometry.Pos;
6 import javafx.scene.Scene;
7 import javafx.scene.control.Button;
8 import javafx.scene.control.ComboBox;
9 import javafx.scene.control.Label;
10 import javafx.scene.image.Image;
11 import javafx.scene.image.ImageView;
12 import javafx.scene.layout.BorderPane;
13 import javafx.scene.layout.HBox;
14 import javafx.scene.media.Media;
15 import javafx.scene.media.MediaPlayer;
16
17 public class FlagAnthem extends Application {
18     private final static int NUMBER_OF_NATIONS = 7;
19     private final static String URLBase =
20         "http://cs.armstrong.edu/liang/common";
21     private int currentIndex = 0;
22
23     @Override // Override the start method in the Application class
24     public void start(Stage primaryStage) {
25         Image[] images = new Image[NUMBER_OF_NATIONS];
26         MediaPlayer[] mp = new MediaPlayer[NUMBER_OF_NATIONS];
27
28         // Load images and audio
29         for (int i = 0; i < NUMBER_OF_NATIONS; i++) {
30             images[i] = new Image(URLBase + "/image/flag" + i + ".gif");
31             mp[i] = new MediaPlayer(new Media(
32                 URLBase + "/audio/anthem/anthem" + i + ".mp3"));
33         }
34
35         Button btPlayPause = new Button(">");
36         btPlayPause.setOnAction(e -> {
37             if (btPlayPause.getText().equals(">")) {
38                 btPlayPause.setText("||");
39                 mp[currentIndex].pause();
40             } else {
41                 btPlayPause.setText(">");
42                 mp[currentIndex].play();
43             }
44         });
45
46         ImageView imageView = new ImageView(images[currentIndex]);
47         ComboBox<String> cboNation = new ComboBox<>();
48         ObservableList<String> items = FXCollections.observableArrayList
49             ("Denmark", "Germany", "China", "India", "Norway", "UK", "US");
50         cboNation.getItems().addAll(items);
51         cboNation.setValue(items.get(0));
52         cboNation.setOnAction(e -> {
53             mp[currentIndex].stop();
54             currentIndex = items.indexOf(cboNation.getValue());
55             imageView.setImage(images[currentIndex]);
56             mp[currentIndex].play();
57         });

```

```

58     HBox hBox = new HBox(10);
59     hBox.getChildren().addAll(btPlayPause,
60         new Label("Select a nation: "), cboNation);
61     hBox.setAlignment(Pos.CENTER);
62
63     // Create a pane to hold nodes
64     BorderPane pane = new BorderPane();
65     pane.setCenter(imageView);
66     pane.setBottom(hBox);
67
68     // Create a scene and place it in the stage
69     Scene scene = new Scene(pane, 350, 270);
70     primaryStage.setTitle("FlagAnthem"); // Set the stage title
71     primaryStage.setScene(scene); // Place the scene in the stage
72     primaryStage.show(); // Display the stage
73 }
74 }
75 }
```

The program loads the image and audio from the Internet (lines 29–33). A play/pause button is created to control the playing of the audio (line 35). When the button is clicked, if the button's current text is > (line 37), its text is changed to || (line 38) and the player is paused (line 39); If the button's current text is ||, it is changed to > (line 41) and the player is paused (line 42).

An image view is created to display a flag image (line 46). A combo box is created for selecting a nation (line 47–49). When a new country name in the combo box is selected, the current audio is stopped (line 53) and the newly selected nation's image is displayed (line 55) and the new anthem is played (line 56).

JavaFX also provides the `AudioClip` class for creating auto clips. An `AudioClip` object can be created using `new AudioClip(URL)`. An audio clip stores the audio in memory. `AudioClip` is more efficient for playing a small audio clip in the program than using `MediaPlayer`. `AudioClip` has the similar methods as in the `MediaPlayer` class.

- 16.43** In Listing 16.15, which code sets the initial image icon and which code plays the audio?
- 16.44** In Listing 16.15, what does the program do when a new nation is selected in the combo box?



CHAPTER SUMMARY

1. The abstract `Labeled` class is the base class for `Label`, `Button`, `CheckBox`, and `RadioButton`. It defines properties `alignment`, `contentDisplay`, `text`, `graphic`, `graphicTextGap`, `textFill`, `underline`, and `wrapText`.
2. The abstract `ButtonBase` class is the base class for `Button`, `CheckBox`, and `RadioButton`. It defines the `onAction` property for specifying a handler for action events.
3. The abstract `TextInputControl` class is the base class for `TextField` and `TextArea`. It defines the properties `text` and `editable`.
4. A `TextField` fires an action event when clicking the Enter key with the text field focused. A `TextArea` is often used for editing a multiline text.
5. `ComboBox<T>` and `ListView<T>` are generic classes for storing elements of type `T`. The elements in a combo box or a list view are stored in an observable list.

6. A **ComboBox** fires an action event when a new item is selected.
7. You can set a single item or multiple item selection for a **ListView** and add a listener for processing selected items.
8. You can use a **ScrollBar** or **Slider** to select a range of values and add a listener to the **value** property to respond to the change of the value.
9. JavaFX provides the **Media** class for loading a media, the **MediaPlayer** class for controlling a media, and the **MediaView** for displaying a media.

Quiz

Answer the quiz for this chapter online at www.cs.armstrong.edu/liang/intro10e/quiz.html.

MyProgrammingLab™

PROGRAMMING EXERCISES

Sections 16.2–16.5

- *16.1** (*Use radio buttons*) Write a GUI program as shown in Figure 16.36a. You can use buttons to move the message to the left and right and use the radio buttons to change the color for the message displayed.

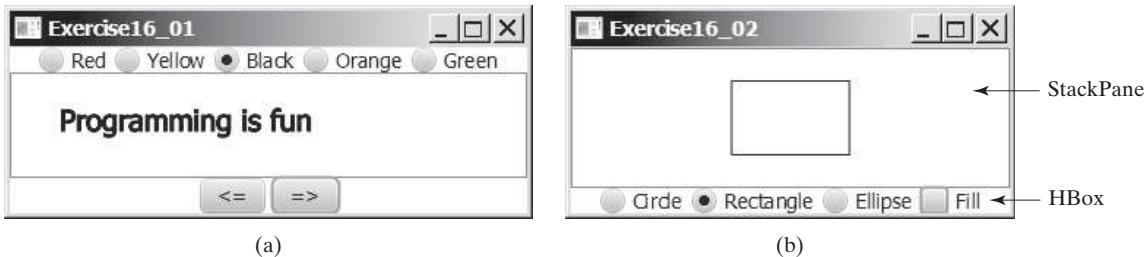


FIGURE 16.36 (a) The <= and => buttons move the message, and the radio buttons change the color for the message.
 (b) The program displays a circle, rectangle, and ellipse when you select a shape type.

- *16.2** (*Select geometric figures*) Write a program that draws various figures, as shown in Figure 16.36b. The user selects a figure from a radio button and uses a check box to specify whether it is filled.

- **16.3** (*Traffic lights*) Write a program that simulates a traffic light. The program lets the user select one of three lights: red, yellow, or green. When a radio button is selected, the light is turned on. Only one light can be on at a time (see Figure 16.37a). No light is on when the program starts.



FIGURE 16.37 (a) The radio buttons are grouped to let you turn only one light on at a time. (b) The program converts miles to kilometers, and vice versa. (c) The program converts between decimal, hex, and binary numbers.

***16.4** (*Create a miles/kilometers converter*) Write a program that converts miles and kilometers, as shown in Figure 16.37b. If you enter a value in the Mile text field and press the *Enter* key, the corresponding kilometer measurement is displayed in the Kilometer text field. Likewise, if you enter a value in the Kilometer text field and press the *Enter* key, the corresponding miles is displayed in the Mile text field.

***16.5** (*Convert numbers*) Write a program that converts between decimal, hex, and binary numbers, as shown in Figure 16.37c. When you enter a decimal value in the decimal-value text field and press the *Enter* key, its corresponding hex and binary numbers are displayed in the other two text fields. Likewise, you can enter values in the other fields and convert them accordingly. (Hint: Use the `Integer.parseInt(s, radix)` method to parse a string to a decimal and use `Integer.toHexString(decimal)` and `Integer.toBinaryString(decimal)` to obtain a hex number or a binary number from a decimal.)

***16.6** (*Demonstrate `TextField` properties*) Write a program that sets the horizontal-alignment and column-size properties of a text field dynamically, as shown in Figure 16.38a.

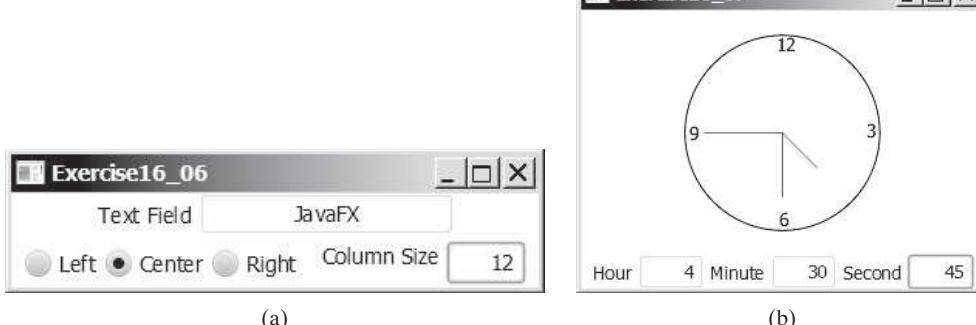
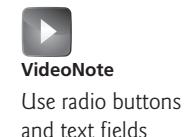


FIGURE 16.38 (a) You can set a text field's properties for the horizontal alignment and column size dynamically. (b) The program displays the time specified in the text fields.

***16.7** (*Set clock time*) Write a program that displays a clock and sets the time with the input from three text fields, as shown in Figure 16.38b. Use the **ClockPane** in Listing 14.21. Resize the clock to the center of the pane.

****16.8** (*Geometry: two circles intersect?*) Write a program that enables the user to specify the location and size of the circles and displays whether the two circles intersect, as shown in Figure 16.39a. Enable the user to point the mouse inside a circle and drag it. As the circle is being dragged, the circle's center coordinates in the text fields are updated.

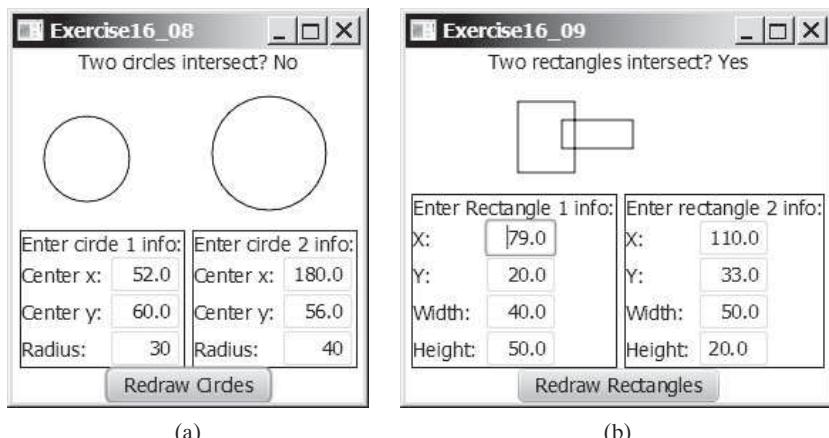


FIGURE 16.39 Check whether two circles and two rectangles are overlapping.

****16.9** (*Geometry: two rectangles intersect?*) Write a program that enables the user to specify the location and size of the rectangles and displays whether the two rectangles intersect, as shown in Figure 16.39b. Enable the user to point the mouse inside a rectangle and drag it. As the rectangle is being dragged, the rectangle's center coordinates in the text fields are updated.

Sections 16.6–16.8

****16.10** (*Text viewer*) Write a program that displays a text file in a text area, as shown in Figure 16.40a. The user enters a file name in a text field and clicks the *View* button; the file is then displayed in a text area.

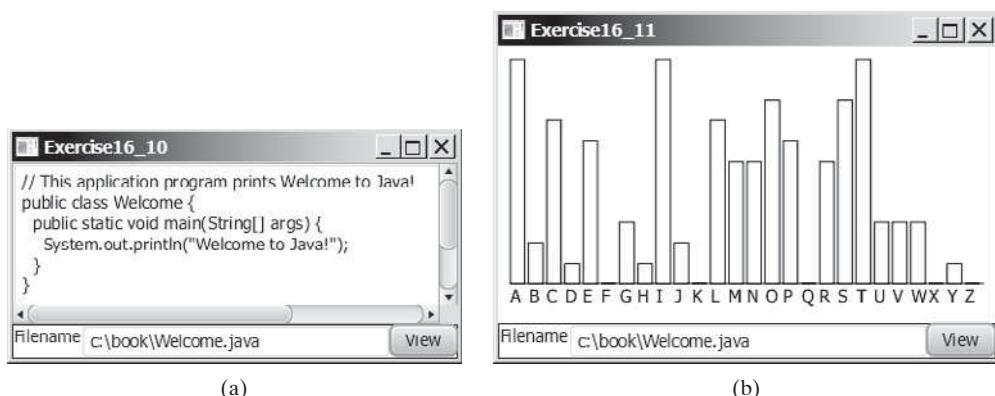


FIGURE 16.40 (a) The program displays the text from a file in a text area. (b) The program displays a histogram that shows the occurrences of each letter in the file.

****16.11** (*Create a histogram for occurrences of letters*) Write a program that reads a file and displays a histogram to show the occurrences of each letter in the file, as shown in Figure 16.40b. The file name is entered from a text field. Pressing the *Enter* key on the text field causes the program to start to read and process the file and displays the histogram. The histogram is displayed in the center of the window. Define a class named **Histogram** that extends **Pane**. The class contains the property **counts** that is an array of 26 elements. **counts[0]** stores the number of **A**, **counts[1]** the number of **B**, and so on. The class also contains a setter method for setting a new **counts** and displaying the histogram for the new **counts**.

***16.12** (*Demonstrate TextArea properties*) Write a program that demonstrates the properties of a text area. The program uses a check box to indicate whether the text is wrapped onto next line, as shown in Figure 16.41a.

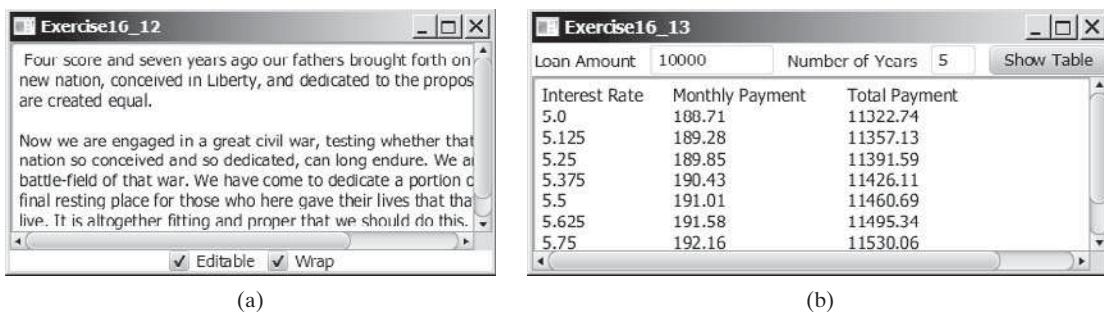


FIGURE 16.41 (a) You can set the options to enable text editing and text wrapping. (b) The program displays a table for monthly payments and total payments on a given loan based on various interest rates.

***16.13** (*Compare loans with various interest rates*) Rewrite Programming Exercise 5.21 to create a GUI, as shown in Figure 16.41b. Your program should let the user enter the loan amount and loan period in the number of years from text fields, and it should display the monthly and total payments for each interest rate starting from **5** percent to **8** percent, with increments of one-eighth, in a text area.

****16.14** (*Select a font*) Write a program that can dynamically change the font of a text in a label displayed on a stack pane. The text can be displayed in bold and italic at the same time. You can select the font name or font size from combo boxes, as shown in Figure 16.42a. The available font names can be obtained using **Font.getFamilies()**. The combo box for the font size is initialized with numbers from **1** to **100**.

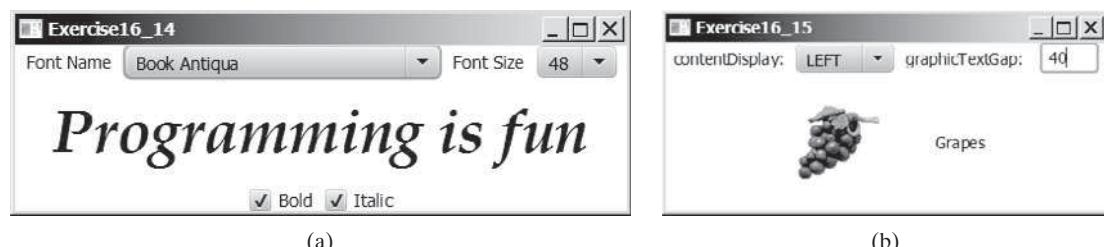


FIGURE 16.42 You can dynamically set the font for the message. (b) You can set the alignment and text-position properties of a label dynamically.

****16.15** (Demonstrate `Label` properties) Write a program to let the user dynamically set the properties `contentDisplay` and `graphicTextGap`, as shown in Figure 16.42b.

***16.16** (Use `ComboBox` and `ListView`) Write a program that demonstrates selecting items in a list. The program uses a combo box to specify a selection mode, as shown in Figure 16.43a. When you select items, they are displayed in a label below the list.



FIGURE 16.43 (a) You can choose single or multiple selection mode in a list. (b) The color changes in the text as you adjust the scroll bars. (c) The program simulates a running fan.

Sections 16.6–16.8

****16.17** (Use `ScrollBar` and `Slider`) Write a program that uses scroll bars or sliders to select the color for a text, as shown in Figure 16.43b. Four horizontal scroll bars are used for selecting the colors: red, green, blue, and opacity percentages.

****16.18** (Simulation: a running fan) Rewrite Programming Exercise 15.28 to add a slider to control the speed of the fan, as shown in Figure 16.43c.

****16.19** (Control a group of fans) Write a program that displays three fans in a group, with control buttons to start and stop all of them, as shown in Figure 16.44.

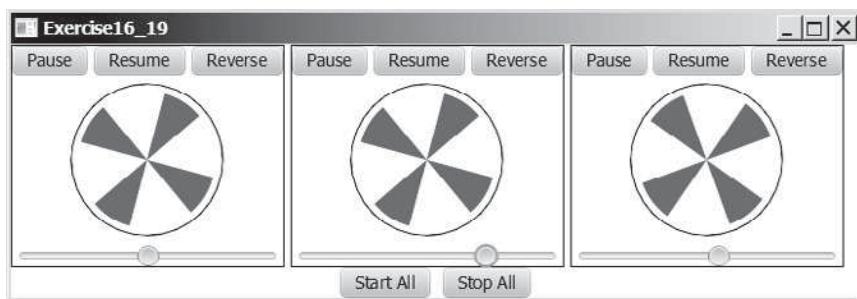


FIGURE 16.44 The program runs and controls a group of fans.

***16.20** (Count-up stopwatch) Write a program that simulates a stopwatch, as shown in Figure 16.45a. When the user clicks the *Start* button, the button's label is changed to *Pause*, as shown in Figure 16.45b. When the user clicks the *Pause*

button, the button's label is changed to *Resume*, as shown in Figure 16.45c. The *Clear* button resets the count to 0 and resets the button's label to *Start*.



FIGURE 16.45 (a–c) The program counts up the time. (d) The program counts down the time.

***16.21** (*Count-down stopwatch*) Write a program that allows the user to enter time in seconds in the text field and press the *Enter* key to count down the seconds, as shown in Figure 16.45d. The remaining seconds are redisplayed every one second. When the seconds are expired, the program starts to play music continuously.

16.22 (*Play, loop, and stop a sound clip*) Write a program that meets the following requirements:

- Get an audio file from the class directory using **AudioClip**.
- Place three buttons labeled *Play*, *Loop*, and *Stop*, as shown in Figure 16.46a.
- If you click the *Play* button, the audio file is played once. If you click the *Loop* button, the audio file keeps playing repeatedly. If you click the *Stop* button, the playing stops.

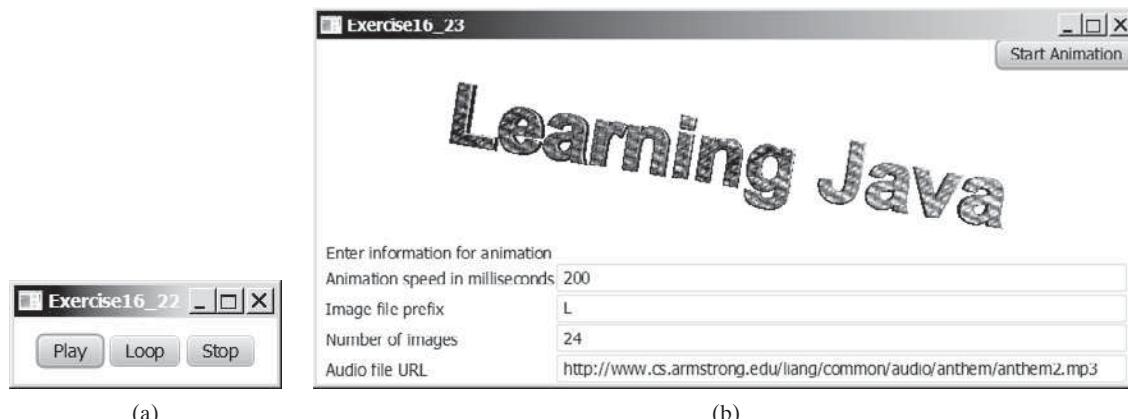


FIGURE 16.46 (a) Click *Play* to play an audio clip once, click *Loop* to play an audio repeatedly, and click *Stop* to terminate playing. (b) The program lets the user specify image files, an audio file, and the animation speed.

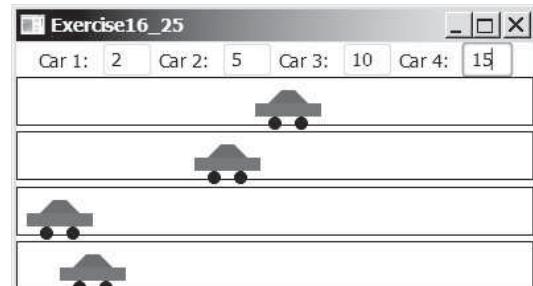
****16.23** (*Create an image animator with audio*) Create animation in Figure 16.46b to meet the following requirements:

- Allow the user to specify the animation speed in a text field.
- Get the number of images and image's file-name prefix from the user. For example, if the user enters **n** for the number of images and **L** for the image prefix, then the files are **L1.gif**, **L2.gif**, and so on, to **Ln.gif**. Assume that the images are stored in the **image** directory, a subdirectory of the program's class directory. The animation displays the images one after the other.
- Allow the user to specify an audio file URL. The audio is played while the animation runs.

****16.24** (*Revise Listing 16.14 MediaDemo.java*) Add a slider to enable the user to set the current time for the video and a label to display the current time and the total time for the video. As shown in Figure 16.47a, the total time is 5 minutes and 3 seconds and the current time is 3 minutes and 58 seconds. As the video plays, the slider value and current time are continuously updated.



(a)



(b)

FIGURE 16.47 (a) A slider for current video time and a label to show the current time and total time are added. (b) You can set the speed for each car.

****16.25** (*Racing cars*) Write a program that simulates four cars racing, as shown in Figure 16.47b. You can set the speed for each car, with maximum 100.

****16.26** (*Simulation: raise flag and play anthem*) Write a program that displays a flag rising up, as shown in Figure 15.14. As the national flag rises, play the national anthem. (You may use a flag image and anthem audio file from Listing 16.15.)

Comprehensive

****16.27** (*Display country flag and flag description*) Listing 16.4, `ComboBoxDemo.java`, gives a program that lets the user view a country's flag image and description by selecting the country from a combo box. The description is a string coded in the program. Rewrite the program to read the text description from a file. Suppose that the descriptions are stored in the files **description0.txt**, . . . , and

description8.txt under the **text** directory for the nine countries Canada, China, Denmark, France, Germany, India, Norway, United Kingdom, and United States, in this order.

****16.28** (*Slide show*) Programming Exercise 15.30 developed a slide show using images. Rewrite that program to develop a slide show using text files. Suppose ten text files named **slide0.txt**, **slide1.txt**, . . . , and **slide9.txt** are stored in the **text** directory. Each slide displays the text from one file. Each slide is shown for one second, and the slides are displayed in order. When the last slide finishes, the first slide is redisplayed, and so on. Use a text area to display the slide.

*****16.29** (*Display a calendar*) Write a program that displays the calendar for the current month. You can use the *Prior* and *Next* buttons to show the calendar of the previous or next month. Display the dates in the current month in black and display the dates in the previous month and next month in gray, as shown in Figure 16.48.



FIGURE 16.48 The program displays the calendar for the current month.

****16.30** (*Pattern recognition: consecutive four equal numbers*) Write a GUI program for Programming Exercise 8.19, as shown in Figure 16.49a–b. Let the user enter the numbers in the text fields in a grid of 6 rows and 7 columns. The user can click the *Solve* button to highlight a sequence of four equal numbers, if it exists. Initially, the values in the text fields are filled with numbers from 0 to 9 randomly.

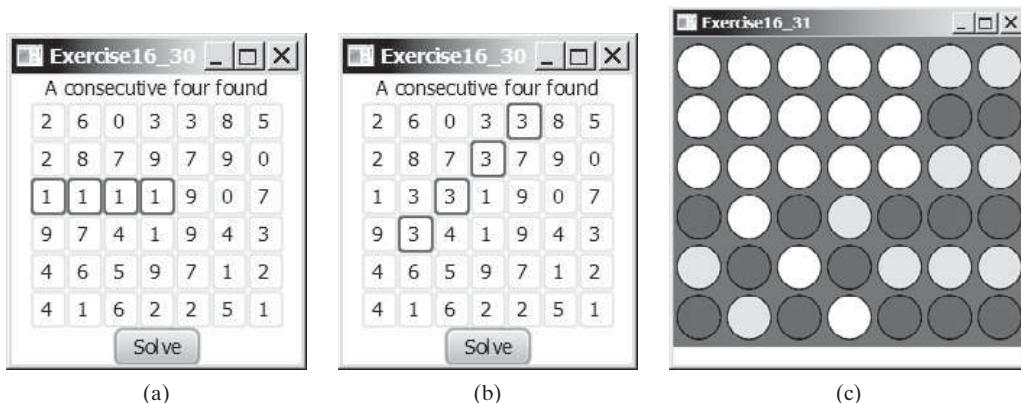


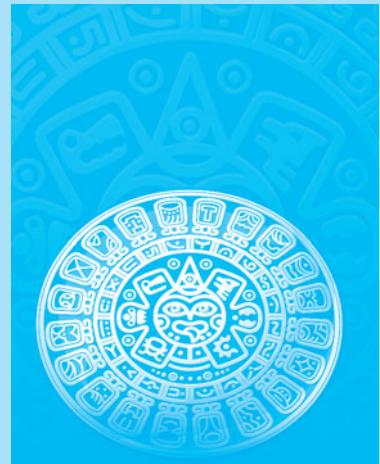
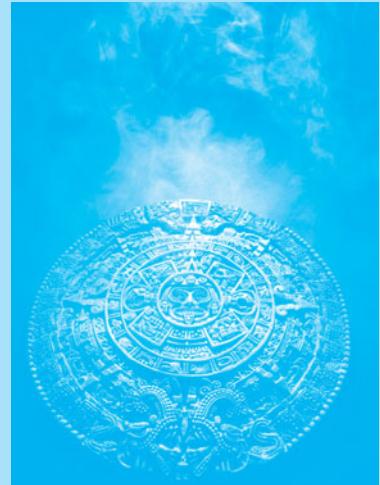
FIGURE 16.49 (a–b) Clicking the *Solve* button highlights the four consecutive numbers in a row, a column, or a diagonal. (c) The program enables two players to play the connect-four game.

*****16.31** (*Game: connect four*) Programming Exercise 8.20 enables two players to play the connect-four game on the console. Rewrite a GUI version for the program, as shown in Figure 16.49c. The program enables two players to place red and yellow discs in turn. To place a disk, the player needs to click an available cell. An *available cell* is unoccupied and its downward neighbor is occupied. The program flashes the four winning cells if a player wins and reports no winners if all cells are occupied with no winners.

BINARY I/O

Objectives

- To discover how I/O is processed in Java (§17.2).
- To distinguish between text I/O and binary I/O (§17.3).
- To read and write bytes using `FileInputStream` and `FileOutputStream` (§17.4.1).
- To filter data using the base classes `FilterInputStream` and `FilterOutputStream` (§17.4.2).
- To read and write primitive values and strings using `DataInputStream` and `DataOutputStream` (§17.4.3).
- To improve I/O performance by using `BufferedInputStream` and `BufferedOutputStream` (§17.4.4).
- To write a program that copies a file (§17.5).
- To store and restore objects using `ObjectOutputStream` and `ObjectInputStream` (§17.6).
- To implement the `Serializable` interface to make objects serializable (§17.6.1).
- To serialize arrays (§17.6.2).
- To read and write files using the `RandomAccessFile` class (§17.7).



17.1 Introduction



text file
binary file

why binary I/O?

text I/O
binary I/O

Java provides many classes for performing text I/O and binary I/O.

Files can be classified as either text or binary. A file that can be processed (read, created, or modified) using a text editor such as Notepad on Windows or vi on UNIX is called a *text file*. All the other files are called *binary files*. You cannot read binary files using a text editor—they are designed to be read by programs. For example, Java source programs are text files and can be read by a text editor, but Java class files are binary files and are read by the JVM.

Although it is not technically precise and correct, you can envision a text file as consisting of a sequence of characters and a binary file as consisting of a sequence of bits. Characters in a text file are encoded using a character encoding scheme such as ASCII or Unicode. For example, the decimal integer 199 is stored as a sequence of three characters 1, 9, 9 in a text file, and the same integer is stored as a byte-type value C7 in a binary file, because decimal 199 equals hex C7 ($199 = 12 \times 16^1 + 7$). The advantage of binary files is that they are more efficient to process than text files.

Java offers many classes for performing file input and output. These can be categorized as *text I/O classes* and *binary I/O classes*. In Section 12.11, File Input and Output, you learned how to read and write strings and numeric values from/to a text file using **Scanner** and **PrintWriter**. This chapter introduces the classes for performing binary I/O.

17.2 How Is Text I/O Handled in Java?



*Text data are read using the **Scanner** class and written using the **PrintWriter** class.*

Recall that a **File** object encapsulates the properties of a file or a path but does not contain the methods for reading/writing data from/to a file. In order to perform I/O, you need to create objects using appropriate Java I/O classes. The objects contain the methods for reading/writing data from/to a file. For example, to write text to a file named **temp.txt**, you can create an object using the **PrintWriter** class as follows:

```
PrintWriter output = new PrintWriter("temp.txt");
```

You can now invoke the **print** method on the object to write a string to the file. For example, the following statement writes **Java 101** to the file.

```
output.print("Java 101");
```

The next statement closes the file.

```
output.close();
```

There are many I/O classes for various purposes. In general, these can be classified as input classes and output classes. An *input class* contains the methods to read data, and an *output class* contains the methods to write data. **PrintWriter** is an example of an output class, and **Scanner** is an example of an input class. The following code creates an input object for the file **temp.txt** and reads data from the file.

```
Scanner input = new Scanner(new File("temp.txt"));
System.out.println(input.nextLine());
```

If **temp.txt** contains the text **Java 101**, **input.nextLine()** returns the string **"Java 101"**.

Figure 17.1 illustrates Java I/O programming. An input object reads a *stream* of data from a file, and an output object writes a stream of data to a file. An input object is also called an *input stream* and an output object an *output stream*.

stream
input stream
output stream

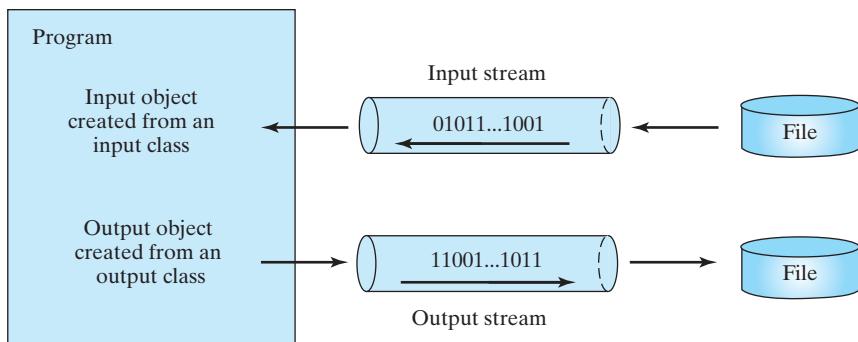


FIGURE 17.1 The program receives data through an input object and sends data through an output object.

17.1 What is a text file and what is a binary file? Can you view a text file or a binary file using a text editor?



17.2 How do you read or write text data in Java? What is a stream?

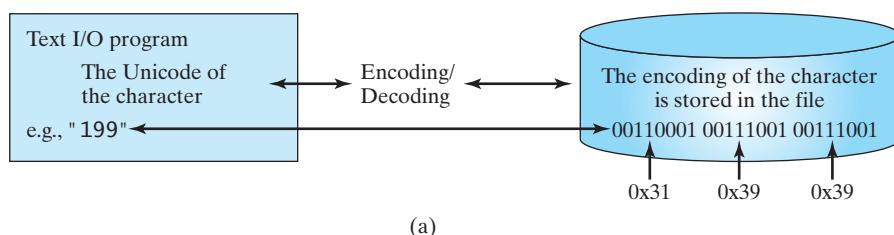


17.3 Text I/O vs. Binary I/O

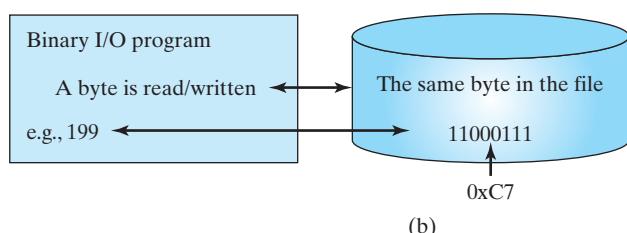
Binary I/O does not involve encoding or decoding and thus is more efficient than text I/O.



Computers do not differentiate between binary files and text files. All files are stored in binary format, and thus all files are essentially binary files. Text I/O is built upon binary I/O to provide a level of abstraction for character encoding and decoding, as shown in Figure 17.2a. Encoding and decoding are automatically performed for text I/O. The JVM converts Unicode to a file-specific encoding when writing a character, and it converts a file-specific encoding to Unicode when reading a character. For example, suppose you write the string "199" using text I/O to a file, each character is written to the file. Since the Unicode for character **1** is **0x0031**, the Unicode **0x0031** is converted to a code that depends on the encoding scheme for the file. (Note that the prefix **0x** denotes a hex number.) In the United States, the default encoding for text files on Windows is ASCII. The ASCII code for character **1** is **49 (0x31)** in



(a)



(b)

FIGURE 17.2 Text I/O requires encoding and decoding, whereas binary I/O does not.

hex) and for character 9 is 57 (0x39 in hex). Thus, to write the characters 199, three bytes—0x31, 0x39, and 0x39—are sent to the output, as shown in Figure 17.2a.

Binary I/O does not require conversions. If you write a numeric value to a file using binary I/O, the exact value in the memory is copied into the file. For example, a byte-type value 199 is represented as 0xC7 (199 = $12 \times 16^1 + 7$) in the memory and appears exactly as 0xC7 in the file, as shown in Figure 17.2b. When you read a byte using binary I/O, one byte value is read from the input.

In general, you should use text input to read a file created by a text editor or a text output program, and use binary input to read a file created by a Java binary output program.

Binary I/O is more efficient than text I/O, because binary I/O does not require encoding and decoding. Binary files are independent of the encoding scheme on the host machine and thus are portable. Java programs on any machine can read a binary file created by a Java program. This is why Java class files are binary files. Java class files can run on a JVM on any machine.

.txt and .dat



Note

For consistency, this book uses the extension **.txt** to name text files and **.dat** to name binary files.



17.3 What are the differences between text I/O and binary I/O?

17.4 How is a Java character represented in the memory, and how is a character represented in a text file?

17.5 If you write the string "ABC" to an ASCII text file, what values are stored in the file?

17.6 If you write the string "100" to an ASCII text file, what values are stored in the file? If you write a numeric byte-type value 100 using binary I/O, what values are stored in the file?

17.7 What is the encoding scheme for representing a character in a Java program? By default, what is the encoding scheme for a text file on Windows?



17.4 Binary I/O Classes

The abstract **InputStream** is the root class for reading binary data, and the abstract **OutputStream** is the root class for writing binary data.

The design of the Java I/O classes is a good example of applying inheritance, where common operations are generalized in superclasses, and subclasses provide specialized operations. Figure 17.3 lists some of the classes for performing binary I/O. **InputStream** is the root for

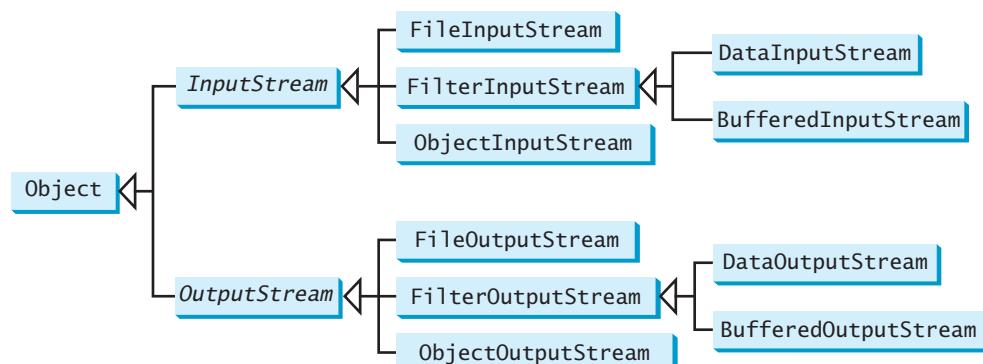


FIGURE 17.3 **InputStream**, **OutputStream**, and their subclasses are for performing binary I/O.

java.io.InputStream	
+read(): int	Reads the next byte of data from the input stream. The value byte is returned as an <code>int</code> value in the range 0 to 255. If no byte is available because the end of the stream has been reached, the value -1 is returned.
+read(b: byte[]): int	Reads up to <code>b.length</code> bytes into array <code>b</code> from the input stream and returns the actual number of bytes read. Returns -1 at the end of the stream.
+read(b: byte[], off: int, len: int): int	Reads bytes from the input stream and stores them in <code>b[off]</code> , <code>b[off+1]</code> , . . . , <code>b[off+len-1]</code> . The actual number of bytes read is returned. Returns -1 at the end of the stream.
+available(): int	Returns an estimate of the number of bytes that can be read from the input stream.
+close(): void	Closes this input stream and releases any system resources occupied by it.
+skip(n: long): long	Skips over and discards <code>n</code> bytes of data from this input stream. The actual number of bytes skipped is returned.
+markSupported(): boolean	Tests whether this input stream supports the <code>mark</code> and <code>reset</code> methods.
+mark(readlimit: int): void	Marks the current position in this input stream.
+reset(): void	Repositions this stream to the position at the time the <code>mark</code> method was last called on this input stream.

FIGURE 17.4 The abstract `InputStream` class defines the methods for the input stream of bytes.

binary input classes, and `OutputStream` is the root for binary output classes. Figures 17.4 and 17.5 list all the methods in the classes `InputStream` and `OutputStream`.



Note

All the methods in the binary I/O classes are declared to throw `java.io.IOException` or a subclass of `java.io.IOException`.

`throws IOException`

java.io.OutputStream	
+write(int b): void	Writes the specified byte to this output stream. The parameter <code>b</code> is an <code>int</code> value. (<code>byte</code>) <code>b</code> is written to the output stream.
+write(b: byte[]): void	Writes all the bytes in array <code>b</code> to the output stream.
+write(b: byte[], off: int, len: int): void	Writes <code>b[off]</code> , <code>b[off+1]</code> , . . . , <code>b[off+len-1]</code> into the output stream.
+close(): void	Closes this output stream and releases any system resources occupied by it.
+flush(): void	Flushes this output stream and forces any buffered output bytes to be written out.

FIGURE 17.5 The abstract `OutputStream` class defines the methods for the output stream of bytes.

17.4.1 FileInputStream/FileOutputStream

`FileInputStream/FileOutputStream` is for reading/writing bytes from/to files.

All the methods in these classes are inherited from `InputStream` and `OutputStream`.

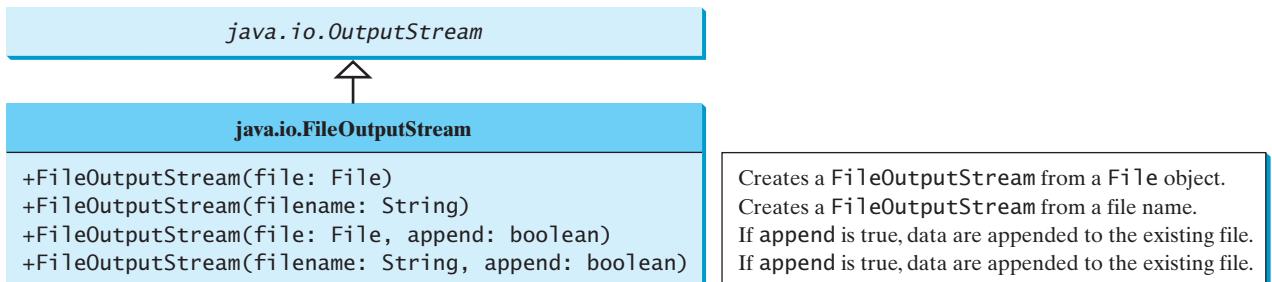
`FileInputStream/FileOutputStream` does not introduce new methods. To construct a `FileInputStream`, use the constructors shown in Figure 17.6.

A `java.io.FileNotFoundException` will occur if you attempt to create a `FileInputStream` with a nonexistent file.

`FileNotFoundException`

To construct a `FileOutputStream`, use the constructors shown in Figure 17.7.

If the file does not exist, a new file will be created. If the file already exists, the first two constructors will delete the current content of the file. To retain the current content and append new data into the file, use the last two constructors and pass `true` to the `append` parameter.

FIGURE 17.6 **FileInputStream** inputs a stream of bytes from a file.FIGURE 17.7 **FileOutputStream** outputs a stream of bytes to a file.

IOException

Almost all the methods in the I/O classes throw **java.io.IOException**. Therefore, you have to declare to throw **java.io.IOException** in the method or place the code in a try-catch block, as shown below:

Declaring exception in the method

```
public static void main(String[] args)
    throws IOException {
    // Perform I/O operations
}
```

Using try-catch block

```
public static void main(String[] args) {
    try {
        // Perform I/O operations
    } catch (IOException ex) {
        ex.printStackTrace();
    }
}
```

Listing 17.1 uses binary I/O to write ten byte values from **1** to **10** to a file named **temp.dat** and reads them back from the file.

LISTING 17.1 TestFileStream.java

```

import java.io.*;
1 import java.io.*;
2
3 public class TestFileStream {
4     public static void main(String[] args) throws IOException {
5         try {
6             // Create an output stream to the file
7             FileOutputStream output = new FileOutputStream("temp.dat");
8         } {
9             // Output values to the file
10            for (int i = 1; i <= 10; i++)
11                output.write(i);
12        }
13
14        try (

```

output stream

output

```

15     // Create an input stream for the file
16     FileInputStream input = new FileInputStream("temp.dat");           input stream
17 }
18     // Read values from the file
19     int value;
20     while ((value = input.read()) != -1)                                input
21         System.out.print(value + " ");
22     }
23 }
24 }
```

1 2 3 4 5 6 7 8 9 10



The program uses the try-with-resources to declare and create input and output streams so that they will be automatically closed after they are used. The `java.io.InputStream` and `java.io.OutputStream` classes implement the `AutoClosable` interface. The `AutoClosable` interface defines the `close()` method that closes a resource. Any object of the `AutoClosable` type can be used with the try-with-resources syntax for automatic closing.

AutoClosable

A `FileOutputStream` is created for the file `temp.dat` in line 7. The `for` loop writes ten byte values into the file (lines 10–11). Invoking `write(i)` is the same as invoking `write((byte)i)`. Line 16 creates a `FileInputStream` for the file `temp.dat`. Values are read from the file and displayed on the console in lines 19–21. The expression `((value = input.read()) != -1)` (line 20) reads a byte from `input.read()`, assigns it to `value`, and checks whether it is `-1`. The input value of `-1` signifies the end of a file.

end of a file

The file `temp.dat` created in this example is a binary file. It can be read from a Java program but not from a text editor, as shown in Figure 17.8.



FIGURE 17.8 A binary file cannot be displayed in text mode.



Tip

When a stream is no longer needed, always close it using the `close()` method or automatically close it using a try-with-resource statement. Not closing streams may cause data corruption in the output file, or other programming errors.

close stream



Note

The root directory for the file is the classpath directory. For the example in this book, the root directory is `c:\book`, so the file `temp.dat` is located at `c:\book`. If you wish to place `temp.dat` in a specific directory, replace line 6 with

where is the file?

```
FileOutputStream output =
    new FileOutputStream ("directory/temp.dat");
```



Note

An instance of `FileInputStream` can be used as an argument to construct a `Scanner`, and an instance of `FileOutputStream` can be used as an argument to construct a `PrintWriter`. You can create a `PrintWriter` to append text into a file using

appending to text file

```
new PrintWriter(new FileOutputStream("temp.txt", true));
```

If **temp.txt** does not exist, it is created. If **temp.txt** already exists, new data are appended to the file.

17.4.2 FilterInputStream/FilterOutputStream

Filter streams are streams that filter bytes for some purpose. The basic byte input stream provides a **read** method that can be used only for reading bytes. If you want to read integers, doubles, or strings, you need a filter class to wrap the byte input stream. Using a filter class enables you to read integers, doubles, and strings instead of bytes and characters. **FilterInputStream** and **FilterOutputStream** are the base classes for filtering data. When you need to process primitive numeric types, use **DataInputStream** and **DataOutputStream** to filter bytes.

17.4.3 DataInputStream/DataOutputStream

DataInputStream reads bytes from the stream and converts them into appropriate primitive-type values or strings. **DataOutputStream** converts primitive-type values or strings into bytes and outputs the bytes to the stream.

DataInputStream extends **FilterInputStream** and implements the **DataInput** interface, as shown in Figure 17.9. **DataOutputStream** extends **FilterOutputStream** and implements the **DataOutput** interface, as shown in Figure 17.10.

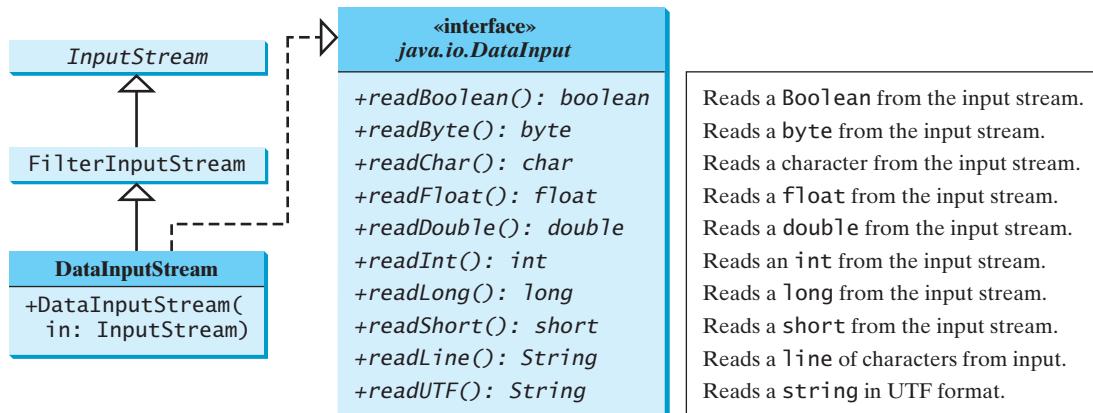


FIGURE 17.9 **DataInputStream** filters an input stream of bytes into primitive data-type values and strings.

DataInputStream implements the methods defined in the **DataInput** interface to read primitive data-type values and strings. **DataOutputStream** implements the methods defined in the **DataOutput** interface to write primitive data-type values and strings. Primitive values are copied from memory to the output without any conversions. Characters in a string may be written in several ways, as discussed in the next section.

Characters and Strings in Binary I/O

A Unicode character consists of two bytes. The **writeChar(char c)** method writes the Unicode of character **c** to the output. The **writeChars(String s)** method writes the Unicode for each character in the string **s** to the output. The **writeBytes(String s)** method writes the lower byte of the Unicode for each character in the string **s** to the output. The high byte of the Unicode is discarded. The **writeBytes** method is suitable for strings that consist

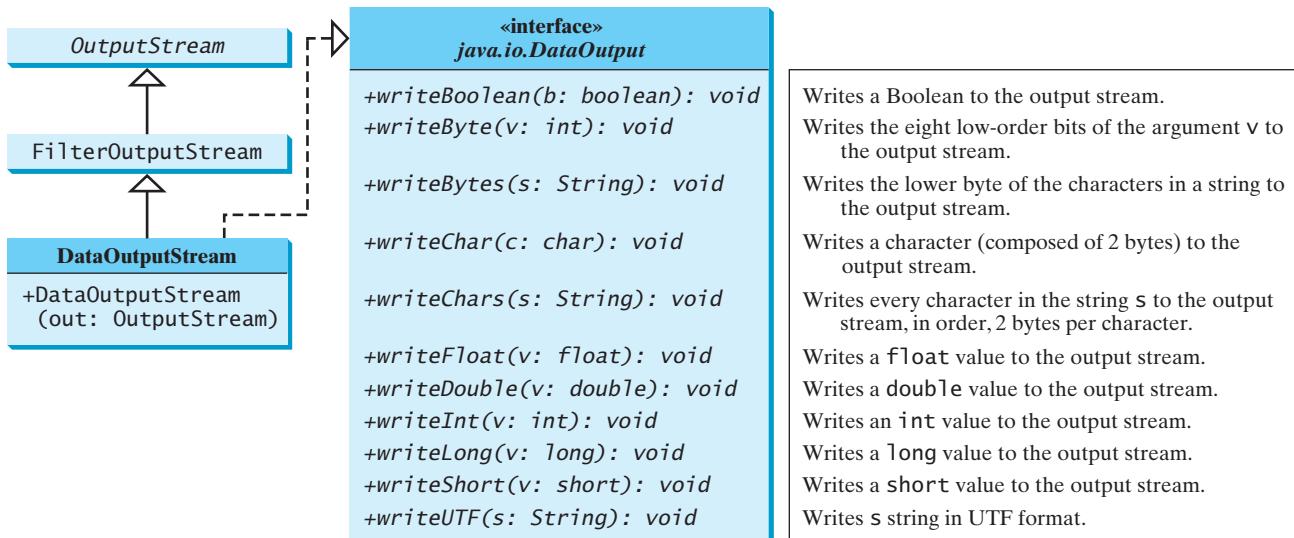


FIGURE 17.10 `DataOutputStream` enables you to write primitive data-type values and strings into an output stream.

of ASCII characters, since an ASCII code is stored only in the lower byte of a Unicode. If a string consists of non-ASCII characters, you have to use the `writeChars` method to write the string.

The `writeUTF(String s)` method writes two bytes of length information to the output stream, followed by the modified UTF-8 representation of every character in the string `s`. UTF-8 is a coding scheme that allows systems to operate with both ASCII and Unicode. Most operating systems use ASCII. Java uses Unicode. The ASCII character set is a subset of the Unicode character set. Since most applications need only the ASCII character set, it is a waste to represent an 8-bit ASCII character as a 16-bit Unicode character. The modified UTF-8 scheme stores a character using one, two, or three bytes. Characters are coded in one byte if their code is less than or equal to `0x7F`, in two bytes if their code is greater than `0x7F` and less than or equal to `0x7FF`, or in three bytes if their code is greater than `0x7FF`.

The initial bits of a UTF-8 character indicate whether a character is stored in one byte, two bytes, or three bytes. If the first bit is `0`, it is a one-byte character. If the first bits are `110`, it is the first byte of a two-byte sequence. If the first bits are `1110`, it is the first byte of a three-byte sequence. The information that indicates the number of characters in a string is stored in the first two bytes preceding the UTF-8 characters. For example, `writeUTF("ABCDEF")` actually writes eight bytes (i.e., `00 06 41 42 43 44 45 46`) to the file, because the first two bytes store the number of characters in the string.

The `writeUTF(String s)` method converts a string into a series of bytes in the UTF-8 format and writes them into an output stream. The `readUTF()` method reads a string that has been written using the `writeUTF` method.

The UTF-8 format has the advantage of saving a byte for each ASCII character, because a Unicode character takes up two bytes and an ASCII character in UTF-8 only one byte. If most of the characters in a long string are regular ASCII characters, using UTF-8 is more efficient.

Creating `DataInputStream/DataOutputStream`

`DataInputStream/DataOutputStream` are created using the following constructors (see Figures 17.9 and 17.10):

```

public DataInputStream(InputStream instream)
public DataOutputStream(OutputStream outstream)

```

The following statements create data streams. The first statement creates an input stream for the file **in.dat**; the second statement creates an output stream for the file **out.dat**.

```
1 DataInputStream input =
2     new DataInputStream(new FileInputStream("in.dat"));
3 DataOutputStream output =
4     new DataOutputStream(new FileOutputStream("out.dat"));
```

Listing 17.2 writes student names and scores to a file named **temp.dat** and reads the data back from the file.

LISTING 17.2 TestDataStream.java

```
1 import java.io.*;
2
3 public class TestDataStream {
4     public static void main(String[] args) throws IOException {
5         try { // Create an output stream for file temp.dat
6             DataOutputStream output =
7                 new DataOutputStream(new FileOutputStream("temp.dat"));
8         } {
9             // Write student test scores to the file
10            output.writeUTF("John");
11            output.writeDouble(85.5);
12            output.writeUTF("Jim");
13            output.writeDouble(185.5);
14            output.writeUTF("George");
15            output.writeDouble(105.25);
16        }
17
18        try { // Create an input stream for file temp.dat
19            DataInputStream input =
20                new DataInputStream(new FileInputStream("temp.dat"));
21        } {
22            // Read student test scores from the file
23            System.out.println(input.readUTF() + " " + input.readDouble());
24            System.out.println(input.readUTF() + " " + input.readDouble());
25            System.out.println(input.readUTF() + " " + input.readDouble());
26        }
27    }
28 }
```



John 85.5
Susan 185.5
Kim 105.25

A **DataOutputStream** is created for file **temp.dat** in lines 6 and 7. Student names and scores are written to the file in lines 10–15. A **DataInputStream** is created for the same file in lines 19–20. Student names and scores are read back from the file and displayed on the console in lines 23–25.

DataInputStream and **DataOutputStream** read and write Java primitive-type values and strings in a machine-independent fashion, thereby enabling you to write a data file on one machine and read it on another machine that has a different operating system or file structure. An application uses a data output stream to write data that can later be read by a program using a data input stream.

DataInputStream filters data from an input stream into appropriate primitive-type values or strings. **DataOutputStream** converts primitive-type values or strings into bytes and

outputs the bytes to an output stream. You can view **DataInputStream/FileInputStream** and **DataOutputStream/FileOutputStream** working in a pipe line as shown in Figure 17.11.

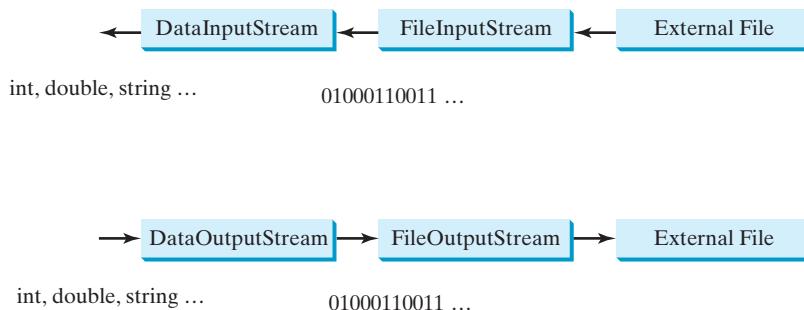


FIGURE 17.11 **DataInputStream** filters an input stream of byte to data and **DataOutputStream** converts data into a stream of bytes.



Caution

You have to read data in the same order and format in which they are stored. For example, since names are written in UTF-8 using **writeUTF**, you must read names using **readUTF**.

Detecting the End of a File

If you keep reading data at the end of an **InputStream**, an **EOFException** will occur. This exception can be used to detect the end of a file, as shown in Listing 17.3.

LISTING 17.3 DetectEndOfFile.java

```

1 import java.io.*;
2
3 public class DetectEndOfFile {
4     public static void main(String[] args) {
5         try {
6             try (DataOutputStream output =
7                 new DataOutputStream(new FileOutputStream("test.dat"))) {
8                 output.writeDouble(4.5);
9                 output.writeDouble(43.25);
10                output.writeDouble(3.2);
11            }
12
13            try (DataInputStream input =
14                new DataInputStream(new FileInputStream("test.dat"))) {
15                while (true)
16                    System.out.println(input.readDouble());
17            }
18        } catch (EOFException ex) {
19            System.out.println("All data were read");
20        } catch (IOException ex) {
21            ex.printStackTrace();
22        }
23    }
24 }
25 }
26 }

```

output stream
output
input stream
input
EOFException



```
4.5
43.25
3.2
All data were read
```

The program writes three double values to the file using `DataOutputStream` (lines 6–11) and reads the data using `DataInputStream` (lines 13–17). When reading past the end of the file, an `EOFException` is thrown. The exception is caught in line 19.

17.4.4 `BufferedInputStream/BufferedOutputStream`

`BufferedInputStream/BufferedOutputStream` can be used to speed up input and output by reducing the number of disk reads and writes. Using `BufferedInputStream`, the whole block of data on the disk is read into the buffer in the memory once. The individual data are then delivered to your program from the buffer, as shown in Figure 17.12a. Using `BufferedOutputStream`, the individual data are first written to the buffer in the memory. When the buffer is full, all data in the buffer are written to the disk once, as shown in Figure 17.12b.

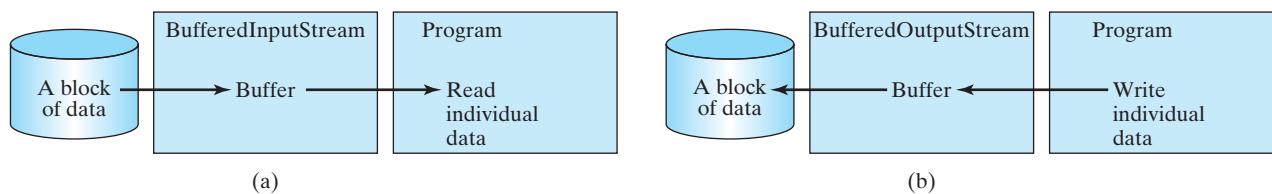


FIGURE 17.12 Buffer I/O places data in a buffer for fast processing.

`BufferedInputStream/BufferedOutputStream` does not contain new methods. All the methods in `BufferedInputStream/BufferedOutputStream` are inherited from the `InputStream/OutputStream` classes. `BufferedInputStream/BufferedOutputStream` manages a buffer behind the scene and automatically reads/writes data from/to disk on demand.

You can wrap a `BufferedInputStream/BufferedOutputStream` on any `InputStream/OutputStream` using the constructors shown in Figures 17.13 and 17.14.



FIGURE 17.13 `BufferedInputStream` buffers an input stream.



FIGURE 17.14 `BufferedOutputStream` buffers an output stream.

If no buffer size is specified, the default size is **512** bytes. You can improve the performance of the `TestDataStream` program in Listing 17.2 by adding buffers in the stream in lines 6–7 and lines 19–20, as follows:

```

DataOutputStream output = new DataOutputStream(
    new BufferedOutputStream(new FileOutputStream("temp.dat")));
DataInputStream input = new DataInputStream(
    new BufferedInputStream(new FileInputStream("temp.dat")));
  
```



Tip

You should always use buffered I/O to speed up input and output. For small files, you may not notice performance improvements. However, for large files—over 100 MB—you will see substantial improvements using buffered I/O.

- 17.8** Why do you have to declare to throw `IOException` in the method or use a try-catch block to handle `IOException` for Java I/O programs?
- 17.9** Why should you always close streams? How do you close streams?
- 17.10** The `read()` method in `InputStream` reads a byte. Why does it return an `int` instead of a `byte`? Find the abstract methods in `InputStream` and `OutputStream`.
- 17.11** Does `FileInputStream/FileOutputStream` introduce any new methods beyond the methods inherited from `InputStream/OutputStream`? How do you create a `FileInputStream/FileOutputStream`?
- 17.12** What will happen if you attempt to create an input stream on a nonexistent file? What will happen if you attempt to create an output stream on an existing file? Can you append data to an existing file?
- 17.13** How do you append data to an existing text file using `java.io.PrintWriter`?
- 17.14** Suppose a file contains an unspecified number of `double` values that were written to the file using the `writeDouble` method using a `DataOutputStream`, how do you write a program to read all these values? How do you detect the end of a file?
- 17.15** What is written to a file using `writeByte(91)` on a `FileOutputStream`?
- 17.16** How do you check the end of a file in an input stream (`FileInputStream`, `DataInputStream`)?
- 17.17** What is wrong in the following code?

```

import java.io.*;
public class Test {
  
```



Check Point

```

public static void main(String[] args) {
    try {
        FileInputStream fis = new FileInputStream("test.dat");
    }
    catch (IOException ex) {
        ex.printStackTrace();
    }
    catch (FileNotFoundException ex) {
        ex.printStackTrace();
    }
}
}

```

- 17.18** Suppose you run the following program on Windows using the default ASCII encoding after the program is finished, how many bytes are there in the file **t.txt**? Show the contents of each byte.

```

public class Test {
    public static void main(String[] args)
        throws java.io.IOException {
        try (java.io.PrintWriter output =
            new java.io.PrintWriter("t.txt")) {
            output.printf("%s", "1234");
            output.printf("%s", "5678");
            output.close();
        }
    }
}

```

- 17.19** After the following program is finished, how many bytes are there in the file **t.dat**? Show the contents of each byte.

```

import java.io.*;

public class Test {
    public static void main(String[] args) throws IOException {
        try (DataOutputStream output = new DataOutputStream(
            new FileOutputStream("t.dat"))) {
            output.writeInt(1234);
            output.writeInt(5678);
            output.close();
        }
    }
}

```

- 17.20** For each of the following statements on a **DataOutputStream output**, how many bytes are sent to the output?

```

output.writeChar('A');
output.writeChars("BC");
output.writeUTF("DEF");

```

- 17.21** What are the advantages of using buffered streams? Are the following statements correct?

```

BufferedInputStream input1 =
    new BufferedInputStream(new FileInputStream("t.dat"));

DataInputStream input2 = new DataInputStream(
    new BufferedInputStream(new FileInputStream("t.dat")));

DataOutputStream output = new DataOutputStream(
    new BufferedOutputStream(new FileOutputStream("t.dat")));

```

17.5 Case Study: Copying Files

This section develops a useful utility for copying files.

In this section, you will learn how to write a program that lets users copy files. The user needs to provide a source file and a target file as command-line arguments using the command:

java Copy source target

The program copies the source file to the target file and displays the number of bytes in the file. The program should alert the user if the source file does not exist or if the target file already exists. A sample run of the program is shown in Figure 17.15.



FIGURE 17.15 The program copies a file.

To copy the contents from a source file to a target file, it is appropriate to use an input stream to read bytes from the source file and an output stream to send bytes to the target file, regardless of the file's contents. The source file and the target file are specified from the command line. Create an **InputStream** for the source file and an **OutputStream** for the target file. Use the **read()** method to read a byte from the input stream, and then use the **write(b)** method to write the byte to the output stream. Use **BufferedInputStream** and **BufferedOutputStream** to improve the performance. Listing 17.4 gives the solution to the problem.

LISTING 17.4 Copy.java

```

1 import java.io.*;
2
3 public class Copy {
4     /** Main method
5      * @param args[0] for sourcefile
6      * @param args[1] for target file
7      */
8     public static void main(String[] args) throws IOException {
9         // Check command-line parameter usage
10        if (args.length != 2) {                                check usage
11            System.out.println(
12                "Usage: java Copy sourceFile targetfile");
13            System.exit(1);
14        }
15
16        // Check if source file exists
17        File sourceFile = new File(args[0]);                  source file
18        if (!sourceFile.exists()) {
19            System.out.println("Source file " + args[0]
20                + " does not exist");
21        }
22    }
23 }
```

```

21         System.exit(2);
22     }
23
24     // Check if target file exists
25     File targetFile = new File(args[1]);
26     if (targetFile.exists()) {
27         System.out.println("Target file " + args[1]
28             + " already exists");
29         System.exit(3);
30     }
31
32     try {
33         // Create an input stream
34         BufferedInputStream input =
35             new BufferedInputStream(new FileInputStream(sourceFile));
36
37         // Create an output stream
38         BufferedOutputStream output =
39             new BufferedOutputStream(new FileOutputStream(targetFile));
40     } {
41         // Continuously read a byte from input and write it to output
42         int r, numberBytesCopied = 0;
43         while ((r = input.read()) != -1) {
44             output.write((byte)r);
45             numberBytesCopied++;
46         }
47
48         // Display the file size
49         System.out.println(numberBytesCopied + " bytes copied");
50     }
51 }
52 }
```

target file

input stream

output stream

read
write

The program first checks whether the user has passed the two required arguments from the command line in lines 10–14.

The program uses the `File` class to check whether the source file and target file exist. If the source file does not exist (lines 18–22) or if the target file already exists (lines 25–30), the program ends.

An input stream is created using `BufferedInputStream` wrapped on `FileInputStream` in lines 34 and 35, and an output stream is created using `BufferedOutputStream` wrapped on `FileOutputStream` in lines 38 and 39.

The expression `((r = input.read()) != -1)` (line 43) reads a byte from `input.read()`, assigns it to `r`, and checks whether it is `-1`. The input value of `-1` signifies the end of a file. The program continuously reads bytes from the input stream and sends them to the output stream until all of the bytes have been read.



17.22 How does the program check if a file already exists?

17.23 How does the program detect the end of the file while reading data?

17.24 How does the program count the number of bytes read from the file?



17.6 Object I/O

`ObjectInputStream/ObjectOutputStream` classes can be used to read/write *Serializable* objects.

`DataInputStream/DataOutputStream` enables you to perform I/O for primitive-type values and strings. `ObjectInputStream/ObjectOutputStream` enables you to perform I/O



for objects in addition to primitive-type values and strings. Since `ObjectInputStream`/`ObjectOutputStream` contains all the functions of `DataInputStream`/`DataOutputStream`, you can replace `DataInputStream`/`DataOutputStream` completely with `ObjectInputStream`/`ObjectOutputStream`.

`ObjectInputStream` extends `InputStream` and implements `ObjectInput` and `ObjectStreamConstants`, as shown in Figure 17.16. `ObjectInput` is a subinterface of `DataInput` (`DataInput` is shown in Figure 17.9). `ObjectStreamConstants` contains the constants to support `ObjectInputStream`/`ObjectOutputStream`.

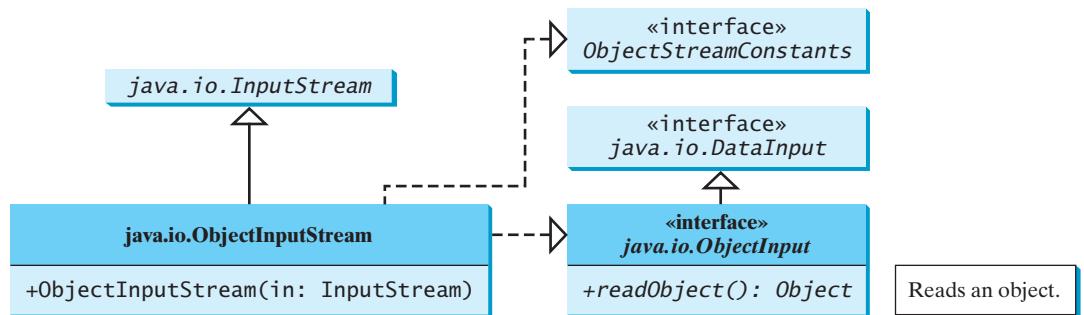


FIGURE 17.16 `ObjectInputStream` can read objects, primitive-type values, and strings.

`ObjectOutputStream` extends `OutputStream` and implements `ObjectOutput` and `ObjectStreamConstants`, as shown in Figure 17.17. `ObjectOutput` is a subinterface of `DataOutput` (`DataOutput` is shown in Figure 17.10).

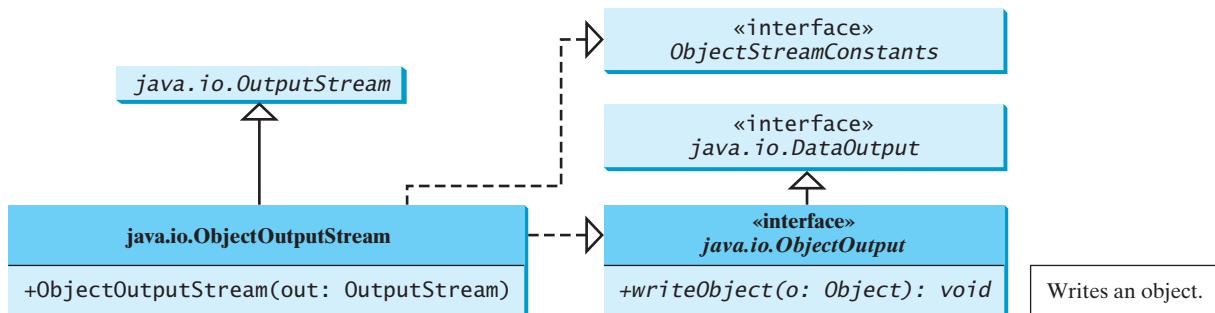


FIGURE 17.17 `ObjectOutputStream` can write objects, primitive-type values, and strings.

You can wrap an `ObjectInputStream`/`ObjectOutputStream` on any `InputStream`/`OutputStream` using the following constructors:

```

// Create an ObjectInputStream
public ObjectInputStream(InputStream in)

// Create an ObjectOutputStream
public ObjectOutputStream(OutputStream out)
  
```

Listing 17.5 writes student names, scores, and the current date to a file named `object.dat`.

LISTING 17.5 TestObjectOutputStream.java

```

1 import java.io.*;
2
3 public class TestObjectOutputStream {
  
```

```

4  public static void main(String[] args) throws IOException {
5      try { // Create an output stream for file object.dat
6          ObjectOutputStream output =
7              new ObjectOutputStream(new FileOutputStream("object.dat"));
8      } {
9          // Write a string, double value, and object to the file
10         output.writeUTF("John");
11         output.writeDouble(85.5);
12         output.writeObject(new java.util.Date());
13     }
14 }
15 }
```

output stream
output string
output object

An **ObjectOutputStream** is created to write data into the file **object.dat** in lines 6 and 7. A string, a double value, and an object are written to the file in lines 10–12. To improve performance, you may add a buffer in the stream using the following statement to replace lines 6 and 7:

```
ObjectOutputStream output = new ObjectOutputStream(
    new BufferedOutputStream(new FileOutputStream("object.dat")));
```

Multiple objects or primitives can be written to the stream. The objects must be read back from the corresponding **ObjectInputStream** with the same types and in the same order as they were written. Java's safe casting should be used to get the desired type. Listing 17.6 reads data from **object.dat**.

LISTING 17.6 TestObjectInputStream.java

```

1 import java.io.*;
2
3 public class TestObjectInputStream {
4     public static void main(String[] args)
5         throws ClassNotFoundException, IOException {
6     try { // Create an input stream for file object.dat
7         ObjectInputStream input =
8             new ObjectInputStream(new FileInputStream("object.dat"));
9     } {
10        // Read a string, double value, and object from the file
11        String name = input.readUTF();
12        double score = input.readDouble();
13        java.util.Date date = (java.util.Date)(input.readObject());
14        System.out.println(name + " " + score + " " + date);
15    }
16 }
17 }
```

input stream
input string
input object



John 85.5 Sun Dec 04 10:35:31 EST 2011

ClassNotFoundException

The **readObject()** method may throw **java.lang.ClassNotFoundException**, because when the JVM restores an object, it first loads the class for the object if the class has not been loaded. Since **ClassNotFoundException** is a checked exception, the **main** method declares to throw it in line 5. An **ObjectInputStream** is created to read input from **object.dat** in lines 7 and 8. You have to read the data from the file in the same order and format as they were written to the file. A string, a double value, and an object are read in lines 11–13. Since **readObject()** returns an **Object**, it is cast into **Date** and assigned to a **Date** variable in line 13.

17.6.1 The `Serializable` Interface

Not every object can be written to an output stream. Objects that can be so written are said to be *serializable*. A serializable object is an instance of the `java.io.Serializable` interface, so the object's class must implement `Serializable`.

serializable

The `Serializable` interface is a marker interface. Since it has no methods, you don't need to add additional code in your class that implements `Serializable`. Implementing this interface enables the Java serialization mechanism to automate the process of storing objects and arrays.

To appreciate this automation feature, consider what you otherwise need to do in order to store an object. Suppose you wish to store an `ArrayList` object. To do this you need to store all the elements in the list. Each element is an object that may contain other objects. As you can see, this would be a very tedious process. Fortunately, you don't have to go through it manually. Java provides a built-in mechanism to automate the process of writing objects. This process is referred as *object serialization*, which is implemented in `ObjectOutputStream`. In contrast, the process of reading objects is referred as *object deserialization*, which is implemented in `ObjectInputStream`.

serialization
deserialization

Many classes in the Java API implement `Serializable`. All the wrapper classes for primitive type values, `java.math.BigInteger`, `java.math.BigDecimal`, `java.lang.String`, `java.lang.StringBuilder`, `java.lang.StringBuffer`, `java.util.Date`, and `java.util.ArrayList` implement `java.io.Serializable`. Attempting to store an object that does not support the `Serializable` interface would cause a `NotSerializableException`.

NotSerializableException

When a serializable object is stored, the class of the object is encoded; this includes the class name and the signature of the class, the values of the object's instance variables, and the closure of any other objects referenced by the object. The values of the object's static variables are not stored.



Note

Nonserializable fields

If an object is an instance of `Serializable` but contains nonserializable instance data fields, can it be serialized? The answer is no. To enable the object to be serialized, mark these data fields with the `transient` keyword to tell the JVM to ignore them when writing the object to an object stream. Consider the following class:

```
public class C implements java.io.Serializable {
    private int v1;
    private static double v2;
    private transient A v3 = new A();
}

class A { } // A is not serializable
```

transient

When an object of the `C` class is serialized, only variable `v1` is serialized. Variable `v2` is not serialized because it is a static variable, and variable `v3` is not serialized because it is marked `transient`. If `v3` were not marked `transient`, a `java.io.NotSerializableException` would occur.



Note

Duplicate objects

If an object is written to an object stream more than once, will it be stored in multiple copies? No, it will not. When an object is written for the first time, a serial number is created for it. The JVM writes the complete contents of the object along with the serial number into the object stream. After the first time, only the serial number is stored if the

same object is written again. When the objects are read back, their references are the same since only one object is actually created in the memory.

17.6.2 Serializing Arrays

An array is serializable if all its elements are serializable. An entire array can be saved into a file using `writeObject` and later can be restored using `readObject`. Listing 17.7 stores an array of five `int` values and an array of three strings and reads them back to display on the console.

LISTING 17.7 TestObjectStreamForArray.java

```

1 import java.io.*;
2
3 public class TestObjectStreamForArray {
4     public static void main(String[] args)
5         throws ClassNotFoundException, IOException {
6         int[] numbers = {1, 2, 3, 4, 5};
7         String[] strings = {"John", "Susan", "Kim"};
8
9         try { // Create an output stream for file array.dat
10             ObjectOutputStream output = new ObjectOutputStream(new
11                 FileOutputStream("array.dat", true));
12         } {
13             // Write arrays to the object output stream
14             output.writeObject(numbers);
15             output.writeObject(strings);
16         }
17
18         try { // Create an input stream for file array.dat
19             ObjectInputStream input =
20                 new ObjectInputStream(new FileInputStream("array.dat"));
21         } {
22             int[] newNumbers = (int[])(input.readObject());
23             String[] newStrings = (String[])(input.readObject());
24
25             // Display arrays
26             for (int i = 0; i < newNumbers.length; i++)
27                 System.out.print(newNumbers[i] + " ");
28             System.out.println();
29
30             for (int i = 0; i < newStrings.length; i++)
31                 System.out.print(newStrings[i] + " ");
32         }
33     }
34 }
```

output stream

store array

input stream

restore array



```

1 2 3 4 5
John Susan Kim

```

Lines 14 and 15 write two arrays into file `array.dat`. Lines 22 and 23 read two arrays back in the same order they were written. Since `readObject()` returns `Object`, casting is used to cast the objects into `int[]` and `String[]`.



17.25 What types of objects can be stored using the `ObjectOutputStream`? What is the method for writing an object? What is the method for reading an object? What is the return type of the method that reads an object from `ObjectInputStream`?

- 17.26** If you serialize two objects of the same type, will they take the same amount of space? If not, give an example.
- 17.27** Is it true that any instance of `java.io.Serializable` can be successfully serialized? Are the static variables in an object serialized? How do you mark an instance variable not to be serialized?
- 17.28** Can you write an array to an `ObjectOutputStream`?
- 17.29** Is it true that `DataInputStream/DataOutputStream` can always be replaced by `ObjectInputStream/ObjectOutputStream`?
- 17.30** What will happen when you attempt to run the following code?

```
import java.io.*;

public class Test {
    public static void main(String[] args) throws IOException {
        try ( ObjectOutputStream output =
            new ObjectOutputStream(new FileOutputStream("object.dat")); ) {
            output.writeObject(new A());
        }
    }
}

class A implements Serializable {
    B b = new B();
}

class B {
```

17.7 Random-Access Files

Java provides the `RandomAccessFile` class to allow data to be read from and written to at any locations in the file.

All of the streams you have used so far are known as *read-only* or *write-only* streams. These streams are called *sequential streams*. A file that is opened using a sequential stream is called a *sequential-access file*. The contents of a sequential-access file cannot be updated. However, it is often necessary to modify files. Java provides the `RandomAccessFile` class to allow data to be read from and written to at any locations in a file. A file that is opened using the `RandomAccessFile` class is known as a *random-access file*.

The `RandomAccessFile` class implements the `DataInput` and `DataOutput` interfaces, as shown in Figure 17.18. The `DataInput` interface (see Figure 17.9) defines the methods for reading primitive-type values and strings (e.g., `readInt`, `readDouble`, `readChar`, `readBoolean`, `readUTF`) and the `DataOutput` interface (see Figure 17.10) defines the methods for writing primitive-type values and strings (e.g., `writeInt`, `writeDouble`, `writeChar`, `writeBoolean`, `writeUTF`).

When creating a `RandomAccessFile`, you can specify one of two modes: `r` or `rw`. Mode `r` means that the stream is read-only, and mode `rw` indicates that the stream allows both read and write. For example, the following statement creates a new stream, `raf`, that allows the program to read from and write to the file `test.dat`:

```
RandomAccessFile raf = new RandomAccessFile("test.dat", "rw");
```

If `test.dat` already exists, `raf` is created to access it; if `test.dat` does not exist, a new file named `test.dat` is created, and `raf` is created to access the new file. The method `raf.length()` returns the number of bytes in `test.dat` at any given time. If you append new data into the file, `raf.length()` increases.



read-only
write-only
sequential-access file

random-access file

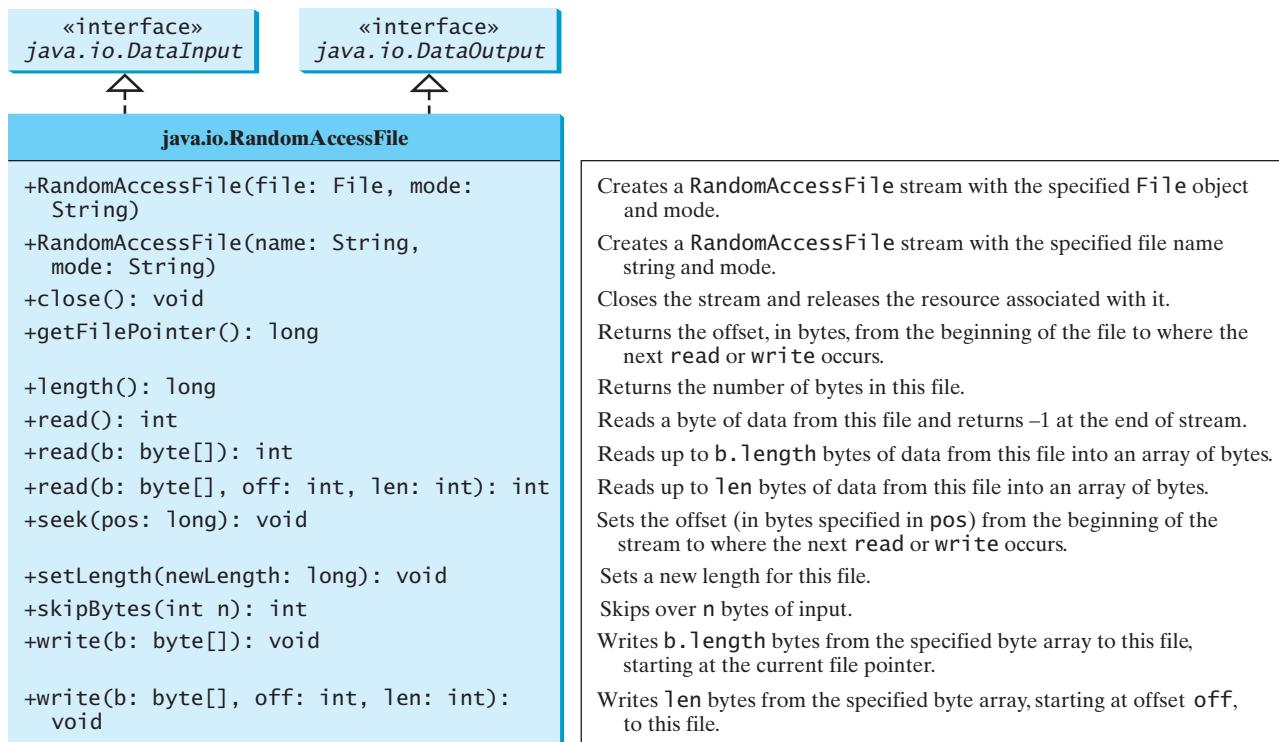


FIGURE 17.18 `RandomAccessFile` implements the `DataInput` and `DataOutput` interfaces with additional methods to support random access.



Tip

If the file is not intended to be modified, open it with the `r` mode. This prevents unintentional modification of the file.

file pointer

A random-access file consists of a sequence of bytes. A special marker called a *file pointer* is positioned at one of these bytes. A read or write operation takes place at the location of the file pointer. When a file is opened, the file pointer is set at the beginning of the file. When you read or write data to the file, the file pointer moves forward to the next data item. For example, if you read an `int` value using `readInt()`, the JVM reads 4 bytes from the file pointer, and now the file pointer is 4 bytes ahead of the previous location, as shown in Figure 17.19.

For a `RandomAccessFile raf`, you can use the `raf.seek(position)` method to move the file pointer to a specified position. `raf.seek(0)` moves it to the beginning of the file, and `raf.seek(raf.length())` moves it to the end of the file. Listing 17.8 demonstrates

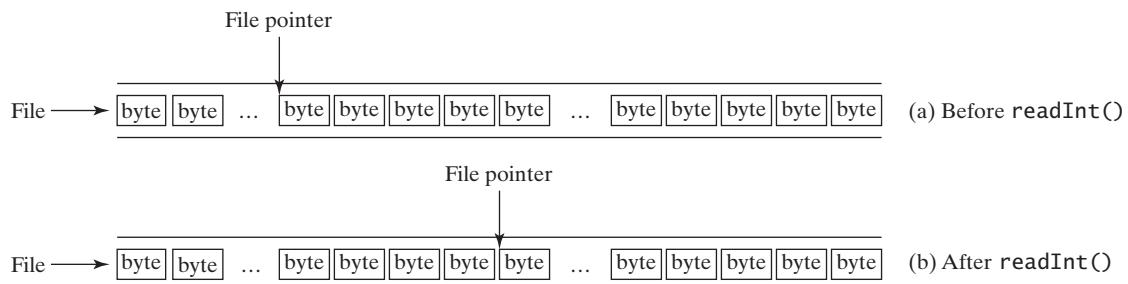


FIGURE 17.19 After an `int` value is read, the file pointer is moved 4 bytes ahead.

RandomAccessFile. A large case study of using **RandomAccessFile** to organize an address book is given in Supplement VI.D.

LISTING 17.8 TestRandomAccessFile.java

```

1 import java.io.*;
2
3 public class TestRandomAccessFile {
4     public static void main(String[] args) throws IOException {
5         try { // Create a random access file
6             RandomAccessFile inout = new RandomAccessFile("inout.dat", "rw"); RandomAccessFile
7         } {
8             // Clear the file to destroy the old contents if exists
9             inout.setLength(0); empty file
10
11            // Write new integers to the file
12            for (int i = 0; i < 200; i++)
13                inout.writeInt(i); write
14
15            // Display the current length of the file
16            System.out.println("Current file length is " + inout.length());
17
18            // Retrieve the first number
19            inout.seek(0); // Move the file pointer to the beginning move pointer
20            System.out.println("The first number is " + inout.readInt()); read
21
22            // Retrieve the second number
23            inout.seek(1 * 4); // Move the file pointer to the second number
24            System.out.println("The second number is " + inout.readInt());
25
26            // Retrieve the tenth number
27            inout.seek(9 * 4); // Move the file pointer to the tenth number
28            System.out.println("The tenth number is " + inout.readInt());
29
30            // Modify the eleventh number
31            inout.writeInt(555);
32
33            // Append a new number
34            inout.seek(inout.length()); // Move the file pointer to the end
35            inout.writeInt(999);
36
37            // Display the new length
38            System.out.println("The new length is " + inout.length());
39
40            // Retrieve the new eleventh number
41            inout.seek(10 * 4); // Move the file pointer to the eleventh number
42            System.out.println("The eleventh number is " + inout.readInt());
43        }
44    }
45 }
```

```

Current file length is 800
The first number is 0
The second number is 1
The tenth number is 9
The new length is 804
The eleventh number is 555

```



A `RandomAccessFile` is created for the file named `inout.dat` with mode `rw` to allow both read and write operations in line 6.

`inout.setLength(0)` sets the length to `0` in line 9. This, in effect, destroys the old contents of the file.

The `for` loop writes `200 int` values from `0` to `199` into the file in lines 12 and 13. Since each `int` value takes `4` bytes, the total length of the file returned from `inout.length()` is now `800` (line 16), as shown in the sample output.

Invoking `inout.seek(0)` in line 19 sets the file pointer to the beginning of the file. `inout.readInt()` reads the first value in line 20 and moves the file pointer to the next number. The second number is read in line 24.

`inout.seek(9 * 4)` (line 27) moves the file pointer to the tenth number. `inout.readInt()` reads the tenth number and moves the file pointer to the eleventh number in line 28. `inout.writeInt(555)` writes a new eleventh number at the current position (line 31). The previous eleventh number is destroyed.

`inout.seek(inout.length())` moves the file pointer to the end of the file (line 34). `inout.writeInt(999)` writes a `999` to the file (line 35). Now the length of the file is increased by `4`, so `inout.length()` returns `804` (line 38).

`inout.seek(10 * 4)` moves the file pointer to the eleventh number in line 41. The new eleventh number, `555`, is displayed in line 42.



- 17.31** Can `RandomAccessFile` streams read and write a data file created by `DataOutputStream`? Can `RandomAccessFile` streams read and write objects?
- 17.32** Create a `RandomAccessFile` stream for the file `address.dat` to allow the updating of student information in the file. Create a `DataOutputStream` for the file `address.dat`. Explain the differences between these two statements.
- 17.33** What happens if the file `test.dat` does not exist when you attempt to compile and run the following code?

```
import java.io.*;

public class Test {
    public static void main(String[] args) {
        try ( RandomAccessFile raf =
            new RandomAccessFile("test.dat", "r") ) {
            int i = raf.readInt();
        }
        catch (IOException ex) {
            System.out.println("IO exception");
        }
    }
}
```

KEY TERMS

binary I/O 678
deserialization 695
file pointer 698
random-access file 697

sequential-access file 697
serialization 695
stream 678
text I/O 678

CHAPTER SUMMARY

1. I/O can be classified into *text I/O* and *binary I/O*. Text I/O interprets data in sequences of characters. Binary I/O interprets data as raw binary values. How text is stored in a file depends on the encoding scheme for the file. Java automatically performs encoding and decoding for text I/O.
2. The `InputStream` and `OutputStream` classes are the roots of all binary I/O classes. `FileInputStream/FileOutputStream` associates a file for input/output. `BufferedInputStream/BufferedOutputStream` can be used to wrap any binary I/O stream to improve performance. `DataInputStream/DataOutputStream` can be used to read/write primitive values and strings.
3. `ObjectInputStream/ObjectOutputStream` can be used to read/write objects in addition to primitive values and strings. To enable object *serialization*, the object's defining class must implement the `java.io.Serializable` marker interface.
4. The `RandomAccessFile` class enables you to read and write data to a file. You can open a file with the `r` mode to indicate that it is read-only or with the `rw` mode to indicate that it is updateable. Since the `RandomAccessFile` class implements `DataInput` and `DataOutput` interfaces, many methods in `RandomAccessFile` are the same as those in `DataInputStream` and `DataOutputStream`.

Quiz

Answer the quiz for this chapter online at www.cs.armstrong.edu/liang/intro10e/quiz.html.

PROGRAMMING EXERCISES

MyProgrammingLab™

Section 17.3

- *17.1 (*Create a text file*) Write a program to create a file named **Exercise17_01.txt** if it does not exist. Append new data to it if it already exists. Write 100 integers created randomly into the file using text I/O. Integers are separated by a space.

Section 17.4

- *17.2 (*Create a binary data file*) Write a program to create a file named **Exercise17_02.dat** if it does not exist. Append new data to it if it already exists. Write 100 integers created randomly into the file using binary I/O.
- *17.3 (*Sum all the integers in a binary data file*) Suppose a binary data file named **Exercise17_03.dat** has been created and its data are created using `writeInt(int)` in `DataOutputStream`. The file contains an unspecified number of integers. Write a program to find the sum of the integers.
- *17.4 (*Convert a textfile into UTF*) Write a program that reads lines of characters from a text file and writes each line as a UTF-8 string into a binary file. Display the sizes of the text file and the binary file. Use the following command to run the program:

```
java Exercise17_04 Welcome.java Welcome.utf
```

Section 17.6

- *17.5 (*Store objects and arrays in a file*) Write a program that stores an array of the five `int` values 1, 2, 3, 4, and 5, a `Date` object for the current time, and the `double` value 5.5 into the file named `Exercise17_05.dat`.
- *17.6 (*Store Loan objects*) The `Loan` class in Listing 10.2 does not implement `Serializable`. Rewrite the `Loan` class to implement `Serializable`. Write a program that creates five `Loan` objects and stores them in a file named `Exercise17_06.dat`.
- *17.7 (*Restore objects from a file*) Suppose a file named `Exercise17_07.dat` has been created using the `ObjectOutputStream`. The file contains `Loan` objects. The `Loan` class in Listing 10.2 does not implement `Serializable`. Rewrite the `Loan` class to implement `Serializable`. Write a program that reads the `Loan` objects from the file and displays the total loan amount. Suppose you don't know how many `Loan` objects are there in the file, use `EOFException` to end the loop.

Section 17.7

- *17.8 (*Update count*) Suppose you wish to track how many times a program has been executed. You can store an `int` to count the file. Increase the count by 1 each time this program is executed. Let the program be `Exercise17_08` and store the count in `Exercise17_08.dat`.
- ***17.9 (*Address book*) Write a program that stores, retrieves, adds, and updates addresses as shown in Figure 17.20. Use a fixed-length string for storing each attribute in the address. Use random access file for reading and writing an address. Assume that the size of name, street, city, state, and zip is 32, 32, 20, 2, 5 bytes, respectively.



FIGURE 17.20 The application can store, retrieve, and update addresses from a file.

Comprehensive



- *17.10 (*Split files*) Suppose you want to back up a huge file (e.g., a 10-GB AVI file) to a CD-R. You can achieve it by splitting the file into smaller pieces and backing up these pieces separately. Write a utility program that splits a large file into smaller ones using the following command:

```
java Exercise17_10 SourceFile numberOfPieces
```

The command creates the files `SourceFile.1`, `SourceFile.2`, . . . , `SourceFile.n`, where `n` is `numberOfPieces` and the output files are about the same size.

- **17.11 (*Split files GUI*) Rewrite Exercise 17.10 with a GUI, as shown in Figure 17.21a.
- *17.12 (*Combine files*) Write a utility program that combines the files together into a new file using the following command:

```
java Exercise17_12 SourceFile1 . . . SourceFilen TargetFile
```

The command combines `SourceFile1`, . . . , and `SourceFilen` into `TargetFile`.

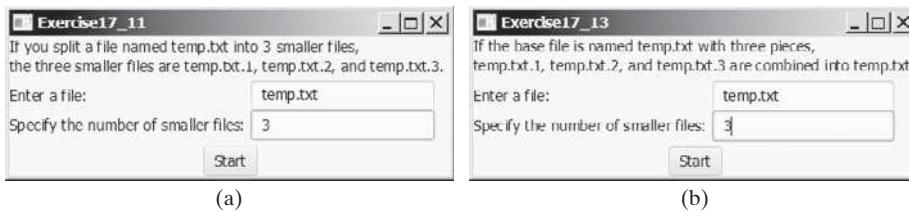


FIGURE 17.21 (a) The program splits a file. (b) The program combines files into a new file.

***17.13** (*Combine files GUI*) Rewrite Exercise 17.12 with a GUI, as shown in Figure 17.21b.

17.14 (*Encrypt files*) Encode the file by adding 5 to every byte in the file. Write a program that prompts the user to enter an input file name and an output file name and saves the encrypted version of the input file to the output file.

17.15 (*Decrypt files*) Suppose a file is encrypted using the scheme in Programming Exercise 17.14. Write a program to decode an encrypted file. Your program should prompt the user to enter an input file name for the encrypted file and an output file name for the unencrypted version of the input file.

17.16 (*Frequency of characters*) Write a program that prompts the user to enter the name of an ASCII text file and displays the frequency of the characters in the file.

****17.17** (*BitOutputStream*) Implement a class named **BitOutputStream**, as shown in Figure 17.22, for writing bits to an output stream. The **writeBit(char bit)** method stores the bit in a byte variable. When you create a **BitOutputStream**, the byte is empty. After invoking **writeBit('1')**, the byte becomes **00000001**. After invoking **writeBit("0101")**, the byte becomes **00010101**. The first three bits are not filled yet. When a byte is full, it is sent to the output stream. Now the byte is reset to empty. You must close the stream by invoking the **close()** method. If the byte is neither empty nor full, the **close()** method first fills the zeros to make a full 8 bits in the byte, and then outputs the byte and closes the stream. For a hint, see Programming Exercise 5.44. Write a test program that sends the bits **010000100100001001101** to the file named **Exercise17_17.dat**.

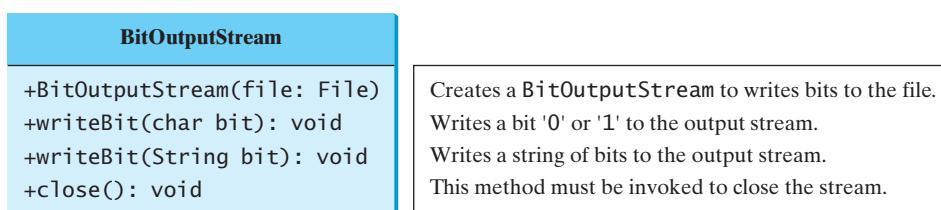


FIGURE 17.22 **BitOutputStream** outputs a stream of bits to a file.

***17.18** (*View bits*) Write the following method that displays the bit representation for the last byte in an integer:

```
public static String getBits(int value)
```

For a hint, see Programming Exercise 5.44. Write a program that prompts the user to enter a file name, reads bytes from the file, and displays each byte's binary representation.

***17.19** (*View hex*) Write a program that prompts the user to enter a file name, reads bytes from the file, and displays each byte's hex representation. (*Hint:* You can first convert the byte value into an 8-bit string, then convert the bit string into a two-digit hex string.)

****17.20** (*Binary editor*) Write a GUI application that lets the user enter a file name in the text field and press the *Enter* key to display its binary representation in a text area. The user can also modify the binary code and save it back to the file, as shown in Figure 17.23a.

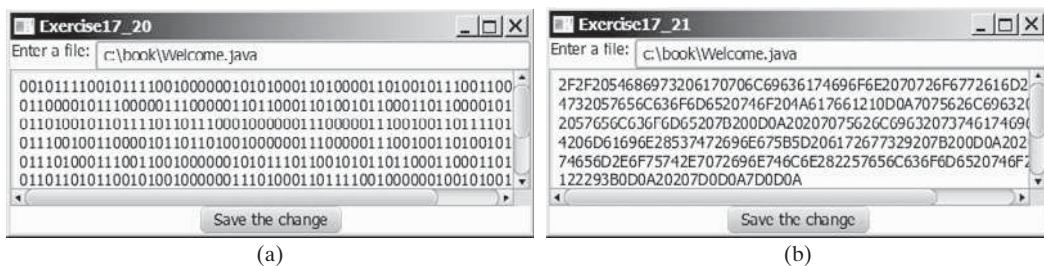


FIGURE 17.23 The programs enable the user to manipulate the contents of the file in (a) binary and (b) hex.

****17.21** (*Hex editor*) Write a GUI application that lets the user enter a file name in the text field and press the *Enter* key to display its hex representation in a text area. The user can also modify the hex code and save it back to the file, as shown in Figure 17.23b.

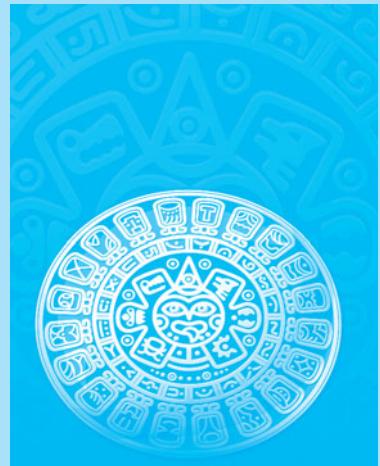
CHAPTER

18

RECUSION

Objectives

- To describe what a recursive method is and the benefits of using recursion (§18.1).
- To develop recursive methods for recursive mathematical functions (§§18.2–18.3).
- To explain how recursive method calls are handled in a call stack (§§18.2–18.3).
- To solve problems using recursion (§18.4).
- To use an overloaded helper method to design a recursive method (§18.5).
- To implement a selection sort using recursion (§18.5.1).
- To implement a binary search using recursion (§18.5.2).
- To get the directory size using recursion (§18.6).
- To solve the Tower of Hanoi problem using recursion (§18.7).
- To draw fractals using recursion (§18.8).
- To discover the relationship and difference between recursion and iteration (§18.9).
- To know tail-recursive methods and why they are desirable (§18.10).



18.1 Introduction



Recursion is a technique that leads to elegant solutions to problems that are difficult to program using simple loops.

search word problem

Suppose you want to find all the files under a directory that contain a particular word. How do you solve this problem? There are several ways to do so. An intuitive and effective solution is to use recursion by searching the files in the subdirectories recursively.

H-tree problem

H-trees, depicted in Figure 18.1, are used in a very large-scale integration (VLSI) design as a clock distribution network for routing timing signals to all parts of a chip with equal propagation delays. How do you write a program to display H-trees? A good approach is to use recursion.

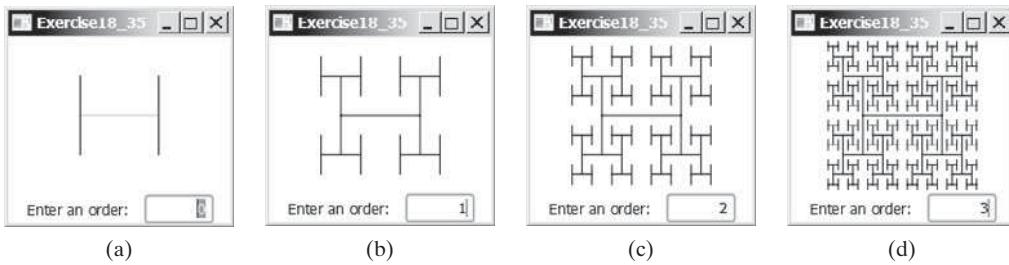


FIGURE 18.1 An H-tree can be displayed using recursion.

recursive method

To use recursion is to program using *recursive methods*—that is, to use methods that invoke themselves. Recursion is a useful programming technique. In some cases, it enables you to develop a natural, straightforward, simple solution to an otherwise difficult problem. This chapter introduces the concepts and techniques of recursive programming and illustrates with examples of how to “think recursively.”

18.2 Case Study: Computing Factorials



A recursive method is one that invokes itself.

Many mathematical functions are defined using recursion. Let’s begin with a simple example. The factorial of a number n can be recursively defined as follows:

$$\begin{aligned} 0! &= 1; \\ n! &= n \times (n - 1)!; \quad n > 0 \end{aligned}$$

How do you find $n!$ for a given n ? To find $1!$ is easy, because you know that $0!$ is 1 , and $1!$ is $1 \times 0!$. Assuming that you know $(n - 1)!$, you can obtain $n!$ immediately by using $n \times (n - 1)!$. Thus, the problem of computing $n!$ is reduced to computing $(n - 1)!$. When computing $(n - 1)!$, you can apply the same idea recursively until n is reduced to 0 .

Let `factorial(n)` be the method for computing $n!$. If you call the method with $n = 0$, it immediately returns the result. The method knows how to solve the simplest case, which is referred to as the *base case* or the *stopping condition*. If you call the method with $n > 0$, it reduces the problem into a subproblem for computing the factorial of $n - 1$. The *subproblem* is essentially the same as the original problem, but it is simpler or smaller. Because the subproblem has the same property as the original problem, you can call the method with a different argument, which is referred to as a *recursive call*.

The recursive algorithm for computing `factorial(n)` can be simply described as follows:

```
if (n == 0)
    return 1;
```

base case or stopping condition

recursive call

```

else
    return n * factorial(n - 1);

```

A recursive call can result in many more recursive calls, because the method keeps on dividing a subproblem into new subproblems. For a recursive method to terminate, the problem must eventually be reduced to a stopping case, at which point the method returns a result to its caller. The caller then performs a computation and returns the result to its own caller. This process continues until the result is passed back to the original caller. The original problem can now be solved by multiplying `n` by the result of `factorial(n - 1)`.

Listing 18.1 gives a complete program that prompts the user to enter a nonnegative integer and displays the factorial for the number.

LISTING 18.1 ComputeFactorial.java

```

1 import java.util.Scanner;
2
3 public class ComputeFactorial {
4     /** Main method */
5     public static void main(String[] args) {
6         // Create a Scanner
7         Scanner input = new Scanner(System.in);
8         System.out.print("Enter a nonnegative integer: ");
9         int n = input.nextInt();
10
11        // Display factorial
12        System.out.println("Factorial of " + n + " is " + factorial(n));
13    }
14
15    /** Return the factorial for the specified number */
16    public static long factorial(int n) {
17        if (n == 0) // Base case
18            return 1;                                base case
19        else
20            return n * factorial(n - 1); // Recursive call
21    }
22 }

```



```

Enter a nonnegative integer: 4 ↵Enter
Factorial of 4 is 24

```




```

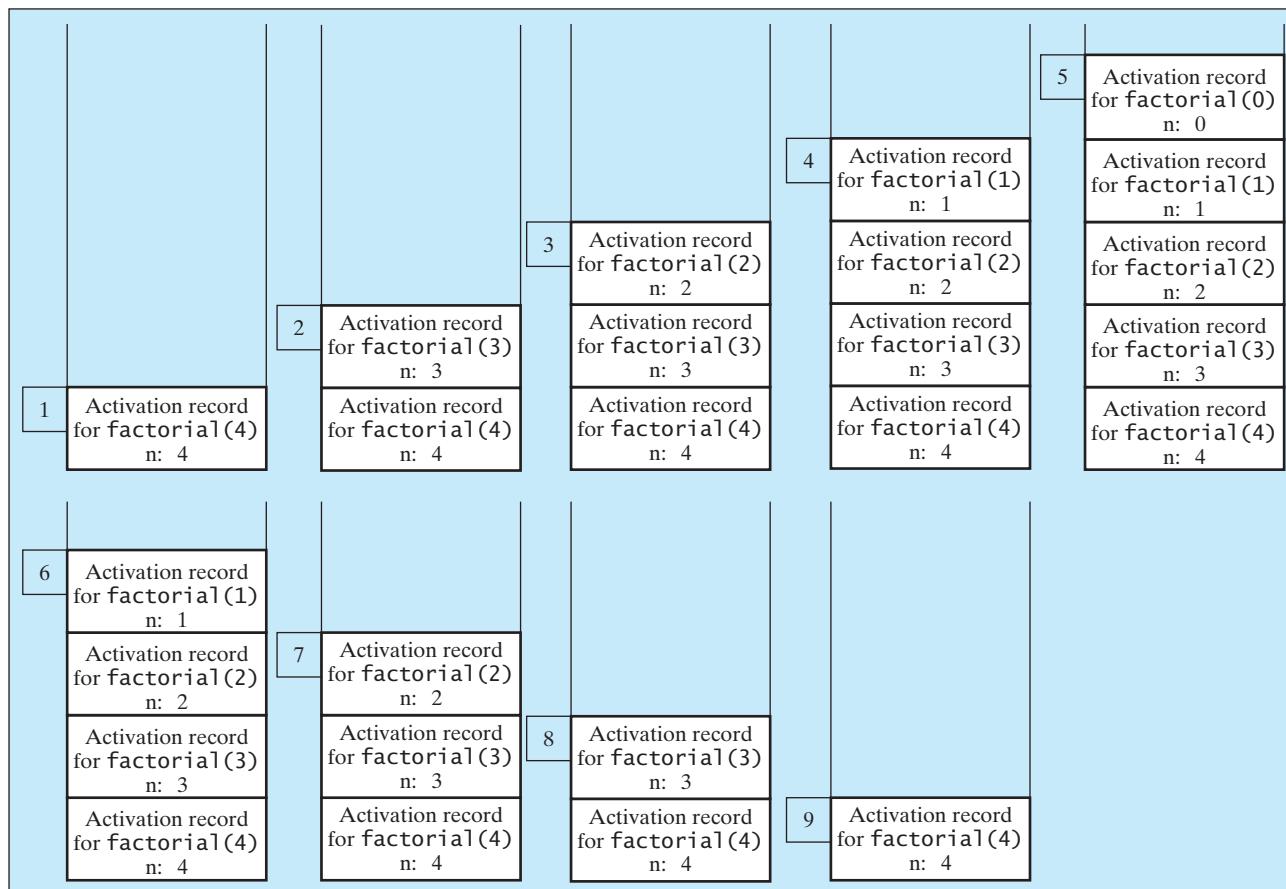
Enter a nonnegative integer: 10 ↵Enter
Factorial of 10 is 3628800

```



The `factorial` method (lines 16–21) is essentially a direct translation of the recursive mathematical definition for the factorial into Java code. The call to `factorial` is recursive because it calls itself. The parameter passed to `factorial` is decremented until it reaches the base case of `0`.

You see how to write a recursive method. How does recursion work behind the scenes? Figure 18.2 illustrates the execution of the recursive calls, starting with `n = 4`. The use of stack space for recursive calls is shown in Figure 18.3.

FIGURE 18.2 Invoking `factorial(4)` spawns recursive calls to `factorial`.FIGURE 18.3 When `factorial(4)` is being executed, the `factorial` method is called recursively, causing stack space to dynamically change.



Pedagogical Note

It is simpler and more efficient to implement the **factorial** method using a loop. However, we use the recursive **factorial** method here to demonstrate the concept of recursion. Later in this chapter, we will present some problems that are inherently recursive and are difficult to solve without using recursion.

If recursion does not reduce the problem in a manner that allows it to eventually converge into the base case or a base case is not specified, *infinite recursion* can occur. For example, suppose you mistakenly write the **factorial** method as follows:

infinite recursion

```
public static long factorial(int n) {
    return n * factorial(n - 1);
}
```

The method runs infinitely and causes a **StackOverflowError**.

direct recursion
indirect recursion



The example discussed in this section shows a recursive method that invokes itself. This is known as *direct recursion*. It is also possible to create *indirect recursion*. This occurs when method A invokes method B, which in turn invokes method A. There can even be several more methods involved in the recursion. For example, method A invokes method B, which invokes method C, which invokes method A.

18.1 What is a recursive method? What is an infinite recursion?

18.2 How many times is the **factorial** method in Listing 18.1 invoked for **factorial(6)**?

18.3 Show the output of the following programs and identify base cases and recursive calls.

```
public class Test {
    public static void main(String[] args) {
        System.out.println(
            "Sum is " + xMethod(5));
    }

    public static int xMethod(int n) {
        if (n == 1)
            return 1;
        else
            return n + xMethod(n - 1);
    }
}
```

```
public class Test {
    public static void main(String[] args) {
        xMethod(1234567);
    }

    public static void xMethod(int n) {
        if (n > 0) {
            System.out.print(n % 10);
            xMethod(n / 10);
        }
    }
}
```

18.4 Write a recursive mathematical definition for computing 2^n for a positive integer n .

18.5 Write a recursive mathematical definition for computing x^n for a positive integer n and a real number x .

18.6 Write a recursive mathematical definition for computing $1 + 2 + 3 + \dots + n$ for a positive integer n .



18.3 Case Study: Computing Fibonacci Numbers

In some cases, recursion enables you to create an intuitive, straightforward, simple solution to a problem.

The **factorial** method in the preceding section could easily be rewritten without using recursion. In this section, we show an example for creating an intuitive solution to a problem using recursion. Consider the well-known Fibonacci-series problem:

The series:	0 1 1 2 3 5 8 13 21 34 55 89 ...
indexes:	0 1 2 3 4 5 6 7 8 9 10 11

The Fibonacci series begins with **0** and **1**, and each subsequent number is the sum of the preceding two. The series can be recursively defined as:

```
fib(0) = 0;
fib(1) = 1;
fib(index) = fib(index - 2) + fib(index - 1); index >= 2
```

The Fibonacci series was named for Leonardo Fibonacci, a medieval mathematician, who originated it to model the growth of the rabbit population. It can be applied in numeric optimization and in various other areas.

How do you find **fib(index)** for a given **index**? It is easy to find **fib(2)**, because you know **fib(0)** and **fib(1)**. Assuming that you know **fib(index - 2)** and **fib(index - 1)**, you can obtain **fib(index)** immediately. Thus, the problem of computing **fib(index)** is reduced to computing **fib(index - 2)** and **fib(index - 1)**. When doing so, you apply the idea recursively until **index** is reduced to **0** or **1**.

The base case is **index = 0** or **index = 1**. If you call the method with **index = 0** or **index = 1**, it immediately returns the result. If you call the method with **index >= 2**, it divides the problem into two subproblems for computing **fib(index - 1)** and **fib(index - 2)** using recursive calls. The recursive algorithm for computing **fib(index)** can be simply described as follows:

```
if (index == 0)
    return 0;
else if (index == 1)
    return 1;
else
    return fib(index - 1) + fib(index - 2);
```

Listing 18.2 gives a complete program that prompts the user to enter an index and computes the Fibonacci number for that index.

LISTING 18.2 ComputeFibonacci.java

```
1 import java.util.Scanner;
2
3 public class ComputeFibonacci {
4     /** Main method */
5     public static void main(String[] args) {
6         // Create a Scanner
7         Scanner input = new Scanner(System.in);
8         System.out.print("Enter an index for a Fibonacci number: ");
9         int index = input.nextInt();
10
11        // Find and display the Fibonacci number
12        System.out.println("The Fibonacci number at index "
13            + index + " is " + fib(index));
14    }
15
16    /** The method for finding the Fibonacci number */
17    public static long fib(long index) {
18        if (index == 0) // Base case
19            return 0;
```

```
20     else if (index == 1) // Base case           base case
21         return 1;
22     else // Reduction and recursive calls      recursion
23         return fib(index - 1) + fib(index - 2);
24     }
25 }
```

```
Enter an index for a Fibonacci number: 1 ↵ Enter
The Fibonacci number at index 1 is 1
```



Enter an index for a Fibonacci number: 6 ↵ Enter
The Fibonacci number at index 6 is 8



Enter an index for a Fibonacci number: 7 ↵ Enter
The Fibonacci number at index 7 is 13



The program does not show the considerable amount of work done behind the scenes by the computer. Figure 18.4, however, shows the successive recursive calls for evaluating `fib(4)`. The original method, `fib(4)`, makes two recursive calls, `fib(3)` and `fib(2)`, and then returns `fib(3) + fib(2)`. But in what order are these methods called? In Java, operands are evaluated from left to right, so `fib(2)` is called after `fib(3)` is completely evaluated. The labels in Figure 18.4 show the order in which the methods are called.



FIGURE 18.4 Invoking `fib(4)` spawns recursive calls to `fib`.

As shown in Figure 18.4, there are many duplicated recursive calls. For instance, `fib(2)` is called twice, `fib(1)` three times, and `fib(0)` twice. In general, computing `fib(index)` requires roughly twice as many recursive calls as does computing `fib(index - 1)`. As you try larger index values, the number of calls substantially increases, as shown in Table 18.1.

TABLE 18.1 Number of Recursive Calls in `fib(index)`

index	2	3	4	10	20	30	40	50
# of calls	3	5	9	177	21891	2,692,537	331,160,281	2,075,316,483

**Pedagogical Note**

The recursive implementation of the `fib` method is very simple and straightforward, but it isn't efficient, since it requires more time and memory to run recursive methods. See Programming Exercise 18.2 for an efficient solution using loops. Though it is not practical, the recursive `fib` method is a good example of how to write recursive methods.

**18.7** Show the output of the following two programs:

```
public class Test {
    public static void main(String[] args) {
        xMethod(5);
    }

    public static void xMethod(int n) {
        if (n > 0) {
            System.out.print(n + " ");
            xMethod(n - 1);
        }
    }
}
```

```
public class Test {
    public static void main(String[] args) {
        xMethod(5);
    }

    public static void xMethod(int n) {
        if (n > 0) {
            xMethod(n - 1);
            System.out.print(n + " ");
        }
    }
}
```

18.8 What is wrong in the following method?

```
public class Test {
    public static void main(String[] args) {
        xMethod(1234567);
    }

    public static void xMethod(double n) {
        if (n != 0) {
            System.out.print(n);
            xMethod(n / 10);
        }
    }
}
```

```
public class Test {
    public static void main(String[] args) {
        Test test = new Test();
        System.out.println(test.toString());
    }

    public Test() {
        Test test = new Test();
    }
}
```

18.9 How many times is the `fib` method in Listing 18.2 invoked for `Fib(6)`?**18.4 Problem Solving Using Recursion**

If you think recursively, you can solve many problems using recursion.

recursion characteristics

if-else

- The method is implemented using an `if-else` or a `switch` statement that leads to different cases.

base cases

- One or more base cases (the simplest case) are used to stop recursion.

reduction

- Every recursive call reduces the original problem, bringing it increasingly closer to a base case until it becomes that case.

In general, to solve a problem using recursion, you break it into subproblems. Each subproblem is the same as the original problem but smaller in size. You can apply the same approach to each subproblem to solve it recursively.

Recursion is everywhere. It is fun to *think recursively*. Consider drinking coffee. You may think recursively describe the procedure recursively as follows:

```
public static void drinkCoffee(Cup cup) {
    if (!cup.isEmpty()) {
        cup.takeOneSip(); // Take one sip
        drinkCoffee(cup);
    }
}
```

Assume `cup` is an object for a cup of coffee with the instance methods `isEmpty()` and `takeOneSip()`. You can break the problem into two subproblems: one is to drink one sip of coffee and the other is to drink the rest of the coffee in the cup. The second problem is the same as the original problem but smaller in size. The base case for the problem is when the cup is empty.

Consider the problem of printing a message `n` times. You can break the problem into two subproblems: one is to print the message one time and the other is to print it `n - 1` times. The second problem is the same as the original problem but it is smaller in size. The base case for the problem is `n == 0`. You can solve this problem using recursion as follows:

```
public static void nPrintln(String message, int times) {
    if (times >= 1) {
        System.out.println(message);
        nPrintln(message, times - 1);
    } // The base case is times == 0
}
```

recursive call

Note that the `fib` method in the preceding section returns a value to its caller, but the `drinkCoffee` and `nPrintln` methods are `void` and they do not return a value.

If you *think recursively*, you can use recursion to solve many of the problems presented in earlier chapters of this book. Consider the palindrome problem in Listing 5.14. Recall that a string is a palindrome if it reads the same from the left and from the right. For example, “mom” and “dad” are palindromes, but “uncle” and “aunt” are not. The problem of checking whether a string is a palindrome can be divided into two subproblems:

- Check whether the first character and the last character of the string are equal.
- Ignore the two end characters and check whether the rest of the substring is a palindrome.

The second subproblem is the same as the original problem but smaller in size. There are two base cases: (1) the two end characters are not the same, and (2) the string size is `0` or `1`. In case 1, the string is not a palindrome; in case 2, the string is a palindrome. The recursive method for this problem can be implemented as shown in Listing 18.3.

LISTING 18.3 RecursivePalindromeUsingSubstring.java

```
1 public class RecursivePalindromeUsingSubstring {
2     public static boolean isPalindrome(String s) {
3         if (s.length() <= 1) // Base case
4             return true;
5         else if (s.charAt(0) != s.charAt(s.length() - 1)) // Base case
6             return false;
7         else
8             return isPalindrome(s.substring(1, s.length() - 1));
9     }
10
11    public static void main(String[] args) {
12        System.out.println("Is moon a palindrome? "
```

method header
base case
base case
recursive call

```

13      + isPalindrome("moon"));
14  System.out.println("Is noon a palindrome? "
15      + isPalindrome("noon"));
16  System.out.println("Is a a palindrome? " + isPalindrome("a"));
17  System.out.println("Is aba a palindrome? " +
18      isPalindrome("aba"));
19  System.out.println("Is ab a palindrome? " + isPalindrome("ab"));
20 }
21 }
```



```

Is moon a palindrome? false
Is noon a palindrome? true
Is a a palindrome? true
Is aba a palindrome? true
Is ab a palindrome? false
```

The **substring** method in line 8 creates a new string that is the same as the original string except without the first and last characters. Checking whether a string is a palindrome is equivalent to checking whether the substring is a palindrome if the two end characters in the original string are the same.



18.10 Describe the characteristics of recursive methods.

18.11 For the **isPalindrome** method in Listing 18.3, what are the base cases? How many times is this method called when invoking **isPalindrome("abdxcdxba")**?

18.12 Show the call stack for **isPalindrome("abcba")** using the method defined in Listing 18.3.



18.5 Recursive Helper Methods

Sometimes you can find a solution to the original problem by defining a recursive function to a problem similar to the original problem. This new method is called a recursive helper method. The original problem can be solved by invoking the recursive helper method.

The recursive **isPalindrome** method in Listing 18.3 is not efficient, because it creates a new string for every recursive call. To avoid creating new strings, you can use the low and high indices to indicate the range of the substring. These two indices must be passed to the recursive method. Since the original method is **isPalindrome(String s)**, you have to create the new method **isPalindrome(String s, int low, int high)** to accept additional information on the string, as shown in Listing 18.4.

LISTING 18.4 RecursivePalindrome.java

```

1  public class RecursivePalindrome {
2      public static boolean isPalindrome(String s) {
3          return isPalindrome(s, 0, s.length() - 1);
4      }
5
6      private static boolean isPalindrome(String s, int low, int high) {
7          if (high <= low) // Base case
8              return true;
9          else if (s.charAt(low) != s.charAt(high)) // Base case
10             return false;
11         else
12             return isPalindrome(s, low + 1, high - 1);
13     }
}
```

helper method
base case

base case

```

14
15 public static void main(String[] args) {
16     System.out.println("Is moon a palindrome? "
17         + isPalindrome("moon"));
18     System.out.println("Is noon a palindrome? "
19         + isPalindrome("noon"));
20     System.out.println("Is a a palindrome? " + isPalindrome("a"));
21     System.out.println("Is aba a palindrome? " + isPalindrome("aba"));
22     System.out.println("Is ab a palindrome? " + isPalindrome("ab"));
23 }
24 }
```

Two overloaded `isPalindrome` methods are defined. The first, `isPalindrome(String s)`, checks whether a string is a palindrome, and the second, `isPalindrome(String s, int low, int high)`, checks whether a substring `s(low..high)` is a palindrome. The first method passes the string `s` with `low = 0` and `high = s.length() - 1` to the second method. The second method can be invoked recursively to check a palindrome in an ever-shrinking substring. It is a common design technique in recursive programming to define a second method that receives additional parameters. Such a method is known as a *recursive helper method*.

recursive helper method

Helper methods are very useful in designing recursive solutions for problems involving strings and arrays. The sections that follow give two more examples.

18.5.1 Recursive Selection Sort

Selection sort was introduced in Section 7.11. Recall that it finds the smallest element in the list and swaps it with the first element. It then finds the smallest element remaining and swaps it with the first element in the remaining list, and so on until the remaining list contains only a single element. The problem can be divided into two subproblems:

- Find the smallest element in the list and swap it with the first element.
- Ignore the first element and sort the remaining smaller list recursively.

The base case is that the list contains only one element. Listing 18.5 gives the recursive sort method.

LISTING 18.5 RecursiveSelectionSort.java

```

1 public class RecursiveSelectionSort {
2     public static void sort(double[] list) {
3         sort(list, 0, list.length - 1); // Sort the entire list
4     }
5
6     private static void sort(double[] list, int low, int high) {    helper method
7         if (low < high) {                                         base case
8             // Find the smallest number and its index in list[low .. high]
9             int indexOfMin = low;
10            double min = list[low];
11            for (int i = low + 1; i <= high; i++) {
12                if (list[i] < min) {
13                    min = list[i];
14                    indexOfMin = i;
15                }
16            }
17
18            // Swap the smallest in list[low .. high] with list[low]
19            list[indexOfMin] = list[low];
20            list[low] = min;
21        }
22    }
23 }
```

```

recursive call    22      // Sort the remaining list[low+1 .. high]
23      sort(list, low + 1, high);
24  }
25 }
26 }
```

Two overloaded `sort` methods are defined. The first method, `sort(double[] list)`, sorts an array in `list[0..list.length - 1]` and the second method, `sort(double[] list, int low, int high)`, sorts an array in `list[low..high]`. The second method can be invoked recursively to sort an ever-shrinking subarray.



VideoNote
Binary search

18.5.2 Recursive Binary Search

Binary search was introduced in Section 7.10.2. For binary search to work, the elements in the array must be in increasing order. The binary search first compares the key with the element in the middle of the array. Consider the following three cases:

- Case 1: If the key is less than the middle element, recursively search for the key in the first half of the array.
- Case 2: If the key is equal to the middle element, the search ends with a match.
- Case 3: If the key is greater than the middle element, recursively search for the key in the second half of the array.

Case 1 and Case 3 reduce the search to a smaller list. Case 2 is a base case when there is a match. Another base case is that the search is exhausted without a match. Listing 18.6 gives a clear, simple solution for the binary search problem using recursion.

LISTING 18.6 Recursive Binary Search Method

```

helper method 1 public class RecursiveBinarySearch {
2   public static int recursiveBinarySearch(int[] list, int key) {
3     int low = 0;
4     int high = list.length - 1;
5     return recursiveBinarySearch(list, key, low, high);
6   }
7
base case 8   private static int recursiveBinarySearch(int[] list, int key,
9             int low, int high) {
10            if (low > high) // The list has been exhausted without a match
11              return -low - 1;
12
13            int mid = (low + high) / 2;
14            if (key < list[mid])
15              return recursiveBinarySearch(list, key, low, mid - 1);
16            else if (key == list[mid])
17              return mid;
18            else
19              return recursiveBinarySearch(list, key, mid + 1, high);
20          }
21      }
```

The first method finds a key in the whole list. The second method finds a key in the list with index from `low` to `high`.

The first `binarySearch` method passes the initial array with `low = 0` and `high = list.length - 1` to the second `binarySearch` method. The second method is invoked recursively to find the key in an ever-shrinking subarray.

- 18.13** Show the call stack for `isPalindrome("abcba")` using the method defined in Listing 18.4.
- 18.14** Show the call stack for `selectionSort(new double[]{2, 3, 5, 1})` using the method defined in Listing 18.5.
- 18.15** What is a recursive helper method?



18.6 Case Study: Finding the Directory Size

Recursive methods are efficient for solving problems with recursive structures.

The preceding examples can easily be solved without using recursion. This section presents a problem that is difficult to solve without using recursion. The problem is to find the size of a directory. The size of a directory is the sum of the sizes of all files in the directory. A directory d may contain subdirectories. Suppose a directory contains files f_1, f_2, \dots, f_m and subdirectories d_1, d_2, \dots, d_n , as shown in Figure 18.5.



VideoNote

Directory size

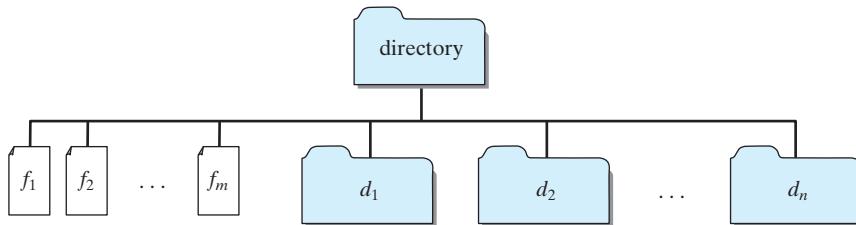


FIGURE 18.5 A directory contains files and subdirectories.

The size of the directory can be defined recursively as follows:

$$\text{size}(d) = \text{size}(f_1) + \text{size}(f_2) + \dots + \text{size}(f_m) + \text{size}(d_1) + \text{size}(d_2) + \dots + \text{size}(d_n)$$

The `File` class, introduced in Section 12.10, can be used to represent a file or a directory and obtain the properties for files and directories. Two methods in the `File` class are useful for this problem:

- The `length()` method returns the size of a file.
- The `listFiles()` method returns an array of `File` objects under a directory.

Listing 18.7 gives a program that prompts the user to enter a directory or a file and displays its size.

LISTING 18.7 DirectorySize.java

```

1 import java.io.File;
2 import java.util.Scanner;
3
4 public class DirectorySize {
5     public static void main(String[] args) {
6         // Prompt the user to enter a directory or a file
7         System.out.print("Enter a directory or a file: ");
8         Scanner input = new Scanner(System.in);
9         String directory = input.nextLine();
10
11        // Display the size
12        System.out.println(getSize(new File(directory)) + " bytes");      invoke method
13    }
  
```

```

14
getSize method      15  public static long getSize(File file) {
16      long size = 0; // Store the total size of all files
17
is directory?      18  if (file.isDirectory()) {
all subitems       19      File[] files = file.listFiles(); // All files and subdirectories
20      for (int i = 0; files != null && i < files.length; i++) {
recursive call     21          size += getSize(files[i]); // Recursive call
22      }
23  }
base case          24  else { // Base case
25      size += file.length();
26  }
27
28  return size;
29 }
30 }
```



Enter a directory or a file: c:\book



Enter a directory or a file: c:\book\Welcome.java



Enter a directory or a file: c:\book\NonExistentFile

testing all cases



Tip

To avoid mistakes, it is a good practice to test all cases. For example, you should test the program for an input of file, an empty directory, a nonexistent directory, and a nonexistent file.



18.16 What is the base case for the `getSize` method?

18.17 How does the program get all files and directories under a given directory?

18.18 How many times will the `getSize` method be invoked for a directory if the directory has three subdirectories and each subdirectory has four files?

18.19 Will the program work if the directory is empty (i.e., it does not contain any files)?

18.20 Will the program work if line 20 is replaced by the following code?

```
for (int i = 0; i < files.length; i++)
```

18.21 Will the program work if lines 20–21 is replaced by the following code?

```
for (File file: files)
    size += getSize(file); // Recursive call
```

18.7 Case Study: Tower of Hanoi

The Tower of Hanoi problem is a classic problem that can be solved easily using recursion, but it is difficult to solve otherwise.



The problem involves moving a specified number of disks of distinct sizes from one tower to another while observing the following rules:

- There are n disks labeled 1, 2, 3, . . . , n and three towers labeled A, B, and C.
- No disk can be on top of a smaller disk at any time.
- All the disks are initially placed on tower A.
- Only one disk can be moved at a time, and it must be the smallest disk on a tower.

The objective of the problem is to move all the disks from A to B with the assistance of C. For example, if you have three disks, the steps to move all of the disks from A to B are shown in Figure 18.6.



FIGURE 18.6 The goal of the Tower of Hanoi problem is to move disks from tower A to tower B without breaking the rules.

**Note**

The Tower of Hanoi is a classic computer-science problem, to which many websites are devoted. One of them worth looking at is www.cut-the-knot.com/recurrence/hanoi.shtml.

In the case of three disks, you can find the solution manually. For a larger number of disks, however—even for four—the problem is quite complex. Fortunately, the problem has an inherently recursive nature, which leads to a straightforward recursive solution.

The base case for the problem is $n = 1$. If $n == 1$, you could simply move the disk from A to B. When $n > 1$, you could split the original problem into the following three subproblems and solve them sequentially.

1. Move the first $n - 1$ disks from A to C recursively with the assistance of tower B, as shown in Step 1 in Figure 18.7.
2. Move disk n from A to B, as shown in Step 2 in Figure 18.7.
3. Move $n - 1$ disks from C to B recursively with the assistance of tower A, as shown in Step 3 in Figure 18.7.

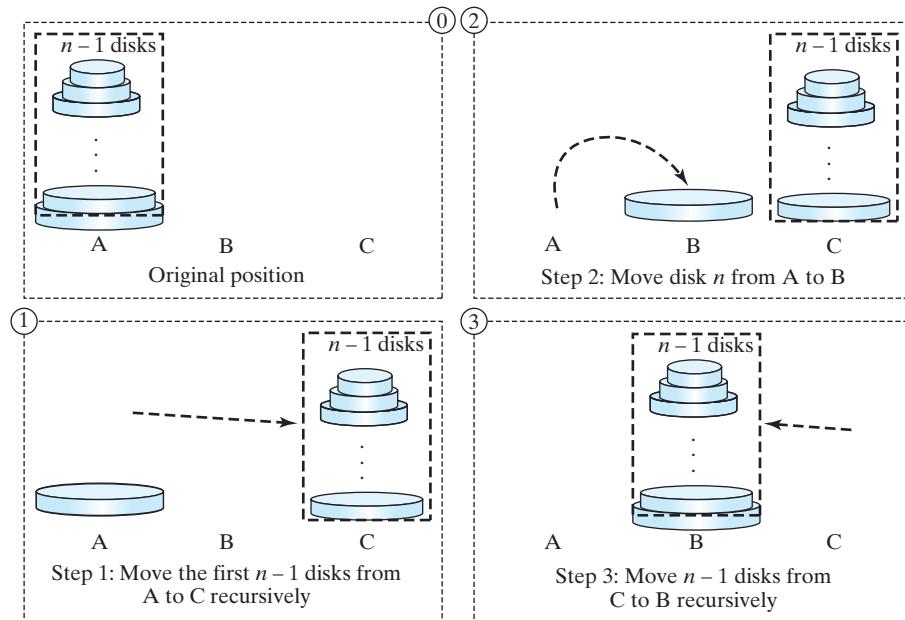


FIGURE 18.7 The Tower of Hanoi problem can be decomposed into three subproblems.

The following method moves n disks from the `fromTower` to the `toTower` with the assistance of the `auxTower`:

```
void moveDisks(int n, char fromTower, char toTower, char auxTower)
```

The algorithm for the method can be described as:

```
if (n == 1) // Stopping condition
    Move disk 1 from the fromTower to the toTower;
else {
    moveDisks(n - 1, fromTower, auxTower, toTower);
    Move disk n from the fromTower to the toTower;
    moveDisks(n - 1, auxTower, toTower, fromTower);
}
```

Listing 18.8 gives a program that prompts the user to enter the number of disks and invokes the recursive method `moveDisks` to display the solution for moving the disks.

LISTING 18.8 TowerOfHanoi.java

```

1 import java.util.Scanner;
2
3 public class TowerOfHanoi {
4     /** Main method */
5     public static void main(String[] args) {
6         // Create a Scanner
7         Scanner input = new Scanner(System.in);
8         System.out.print("Enter number of disks: ");
9         int n = input.nextInt();
10
11        // Find the solution recursively
12        System.out.println("The moves are:");
13        moveDisks(n, 'A', 'B', 'C');
14    }
15
16    /** The method for finding the solution to move n disks
17     * from fromTower to toTower with auxTower */
18    public static void moveDisks(int n, char fromTower,
19        char toTower, char auxTower) {
20        if (n == 1) // Stopping condition
21            System.out.println("Move disk " + n + " from " +
22                fromTower + " to " + toTower); base case
23        else {
24            moveDisks(n - 1, fromTower, auxTower, toTower);
25            System.out.println("Move disk " + n + " from " +
26                fromTower + " to " + toTower);
27            moveDisks(n - 1, auxTower, toTower, fromTower); recursion
28        }
29    }
30 }
```



Enter number of disks: 4

The moves are:

Move disk 1 from A to C
 Move disk 2 from A to B
 Move disk 1 from C to B
 Move disk 3 from A to C
 Move disk 1 from B to A
 Move disk 2 from B to C
 Move disk 1 from A to C
 Move disk 4 from A to B
 Move disk 1 from C to B
 Move disk 2 from C to A
 Move disk 1 from B to A
 Move disk 3 from C to B
 Move disk 1 from A to C
 Move disk 2 from A to B
 Move disk 1 from C to B

This problem is inherently recursive. Using recursion makes it possible to find a natural, simple solution. It would be difficult to solve the problem without using recursion.

Consider tracing the program for $n = 3$. The successive recursive calls are shown in Figure 18.8. As you can see, writing the program is easier than tracing the recursive calls. The system uses stacks to manage the calls behind the scenes. To some extent, recursion provides a level of abstraction that hides iterations and other details from the user.



FIGURE 18.8 Invoking `moveDisks(3, 'A', 'B', 'C')` spawns calls to `moveDisks` recursively.



18.22 How many times is the `moveDisks` method in Listing 18.8 invoked for `moveDisks(5, 'A', 'B', 'C')`?



18.8 Case Study: Fractals

Using recursion is ideal for displaying fractals, because fractals are inherently recursive.



Fractal (Sierpinski triangle)

A *fractal* is a geometrical figure, but unlike triangles, circles, and rectangles, fractals can be divided into parts, each of which is a reduced-size copy of the whole. There are many interesting examples of fractals. This section introduces a simple fractal, the *Sierpinski triangle*, named after a famous Polish mathematician.

A Sierpinski triangle is created as follows:

1. Begin with an equilateral triangle, which is considered to be a Sierpinski fractal of order (or level) **0**, as shown in Figure 18.9a.
2. Connect the midpoints of the sides of the triangle of order **0** to create a Sierpinski triangle of order **1** (Figure 18.9b).
3. Leave the center triangle intact. Connect the midpoints of the sides of the three other triangles to create a Sierpinski triangle of order **2** (Figure 18.9c).
4. You can repeat the same process recursively to create a Sierpinski triangle of order **3, 4, ..., n**, and so on (Figure 18.9d).

The problem is inherently recursive. How do you develop a recursive solution for it? Consider the base case when the order is **0**. It is easy to draw a Sierpinski triangle of order **0**. How do you draw a Sierpinski triangle of order **1**? The problem can be reduced to drawing three Sierpinski triangles of order **0**. How do you draw a Sierpinski triangle of order **2**? The problem can be reduced to drawing three Sierpinski triangles of order **1**, so the problem of



FIGURE 18.9 A Sierpinski triangle is a pattern of recursive triangles.

drawing a Sierpinski triangle of order n can be reduced to drawing three Sierpinski triangles of order $n - 1$.

Listing 18.9 gives a program that displays a Sierpinski triangle of any order, as shown in Figure 18.9. You can enter an order in a text field to display a Sierpinski triangle of the specified order.

LISTING 18.9 SierpinskiTriangle.java

```

1 import javafx.application.Application;
2 import javafx.geometry.Point2D;
3 import javafx.geometry.Pos;
4 import javafx.scene.Scene;
5 import javafx.scene.control.Label;
6 import javafx.scene.control.TextField;
7 import javafx.scene.layout.BorderPane;
8 import javafx.scene.layout.HBox;
9 import javafx.scene.layout.Pane;
10 import javafx.scene.paint.Color;
11 import javafx.scene.shape.Polygon;
12 import javafx.stage.Stage;
13
14 public class SierpinskiTriangle extends Application {
15     @Override // Override the start method in the Application class
16     public void start(Stage primaryStage) {
17         SierpinskiTrianglePane trianglePane = new SierpinskiTrianglePane();    recursive triangle pane
18         TextField tfOrder = new TextField();
19         tfOrder.setOnAction(

```

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```
listener for text field          20      e -> trianglePane.setOrder(Integer.parseInt(tfOrder.getText())));
21      tfOrder.setPrefColumnCount(4);
22      tfOrder.setAlignment(Pos.BOTTOM_RIGHT);
23
24      // Pane to hold label, text field, and a button
25      HBox hBox = new HBox(10);
26      hBox.getChildren().addAll(new Label("Enter an order: "), tfOrder);
27      hBox.setAlignment(Pos.CENTER);
28
29      BorderPane borderPane = new BorderPane();
30      borderPane.setCenter(trianglePane);
31      borderPane.setBottom(hBox);
32
33      // Create a scene and place it in the stage
34      Scene scene = new Scene(borderPane, 200, 210);
35      primaryStage.setTitle("SierpinskiTriangle"); // Set the stage title
36      primaryStage.setScene(scene); // Place the scene in the stage
37      primaryStage.show(); // Display the stage
38
39      scene.widthProperty().addListener(ov -> trianglePane.paint());
40      scene.heightProperty().addListener(ov -> trianglePane.paint());
41  }
42
43  /** Pane for displaying triangles */
44  static class SierpinskiTrianglePane extends Pane {
45      private int order = 0;
46
47      /** Set a new order */
48      public void setOrder(int order) {
49          this.order = order;
50          paint();
51      }
52
53      SierpinskiTrianglePane() {
54      }
55
56      protected void paint() {
57          // Select three points in proportion to the pane size
58          Point2D p1 = new Point2D(getWidth() / 2, 10);
59          Point2D p2 = new Point2D(10, getHeight() - 10);
60          Point2D p3 = new Point2D(getWidth() - 10, getHeight() - 10);
61
62          this.getChildren().clear(); // Clear the pane before redisplay
63
64          displayTriangles(order, p1, p2, p3);
65      }
66
67      private void displayTriangles(int order, Point2D p1,
68          Point2D p2, Point2D p3) {
69          if (order == 0) {
70              // Draw a triangle to connect three points
71              Polygon triangle = new Polygon();
72              triangle.getPoints().addAll(p1.getX(), p1.getY(), p2.getX(),
73                  p2.getY(), p3.getX(), p3.getY());
74              triangle.setStroke(Color.BLACK);
75              triangle.setFill(Color.WHITE);
76
77              this.getChildren().add(triangle);
78          } else {
79      }
```

```

80      // Get the midpoint on each edge in the triangle
81      Point2D p12 = p1.midpoint(p2);
82      Point2D p23 = p2.midpoint(p3);
83      Point2D p31 = p3.midpoint(p1);
84
85      // Recursively display three triangles
86      displayTriangles(order - 1, p1, p12, p31); top subtriangle
87      displayTriangles(order - 1, p12, p2, p23); left subtriangle
88      displayTriangles(order - 1, p31, p23, p3); right subtriangle
89  }
90 }
91 }
92 }
```

The initial triangle has three points set in proportion to the pane size (lines 58–60). If `order == 0`, the `displayTriangles(order, p1, p2, p3)` method displays a triangle that connects the three points `p1`, `p2`, and `p3` in lines 71–77, as shown in Figure 18.10a. Otherwise, it performs the following tasks:

displayTriangle method

1. Obtain the midpoint between `p1` and `p2` (line 81), the midpoint between `p2` and `p3` (line 82), and the midpoint between `p3` and `p1` (line 83), as shown in Figure 18.10b.
2. Recursively invoke `displayTriangles` with a reduced order to display three smaller Sierpinski triangles (lines 86–88). Note that each small Sierpinski triangle is structurally identical to the original big Sierpinski triangle except that the order of a small triangle is one less, as shown in Figure 18.10b.

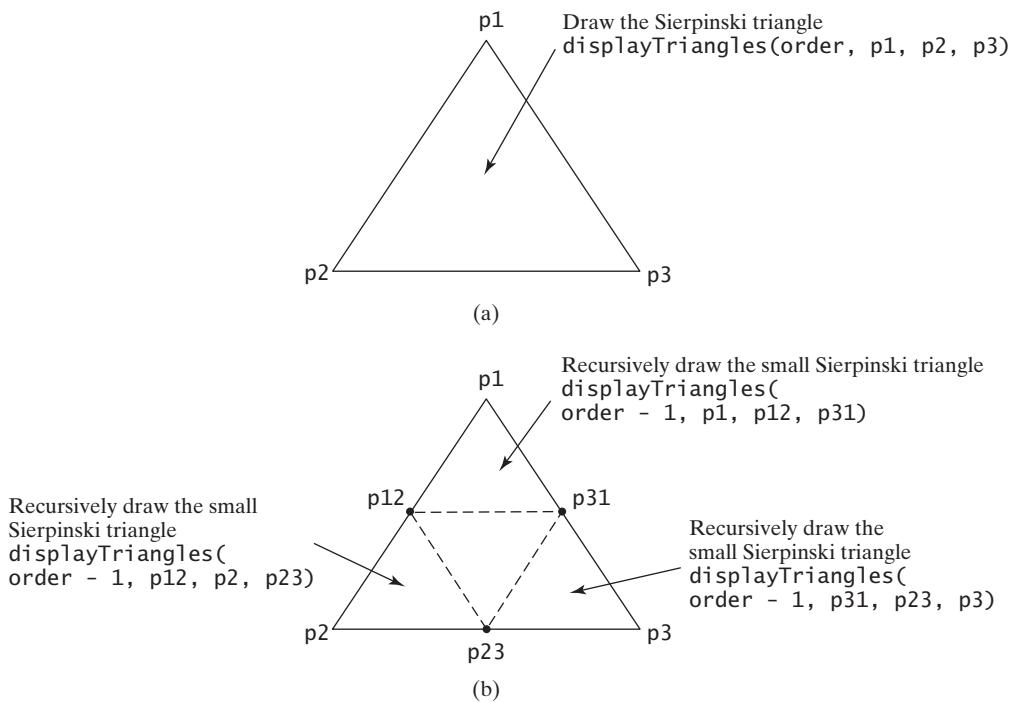


FIGURE 18.10 Drawing a Sierpinski triangle spawns calls to draw three small Sierpinski triangles recursively.

A Sierpinski triangle is displayed in a `SierpinskiTrianglePane`. The `order` property in the inner class `SierpinskiTrianglePane` specifies the order for the Sierpinski triangle. The `Point2D` class, introduced in Section 9.8, `The Point2D Class`, represents a point with

x- and y-coordinates. Invoking `p1.midpoint(p2)` returns a new `Point2D` object that is the midpoint between `p1` and `p2` (lines 81–83).



- 18.23** How do you obtain the midpoint between two points?
- 18.24** What is the base case for the `displayTriangles` method?
- 18.25** How many times is the `displayTriangles` method invoked for a Sierpinski triangle of order 0, order 1, order 2, and order n?
- 18.26** What happens if you enter a negative order? How do you fix this problem in the code?
- 18.27** Instead of drawing a triangle using a polygon, rewrite the code to draw a triangle by drawing three lines to connect the points in lines 71–77.



18.9 Recursion vs. Iteration

Recursion is an alternative form of program control. It is essentially repetition without a loop.

recursion overhead

When you use loops, you specify a loop body. The repetition of the loop body is controlled by the loop control structure. In recursion, the method itself is called repeatedly. A selection statement must be used to control whether to call the method recursively or not.

Recursion bears substantial overhead. Each time the program calls a method, the system must allocate memory for all of the method's local variables and parameters. This can consume considerable memory and requires extra time to manage the memory.

recursion advantages

Any problem that can be solved recursively can be solved nonrecursively with iterations. Recursion has some negative aspects: it uses up too much time and too much memory. Why, then, should you use it? In some cases, using recursion enables you to specify a clear, simple solution for an inherently recursive problem that would otherwise be difficult to obtain. Examples are the directory-size problem, the Tower of Hanoi problem, and the fractal problem, which are rather difficult to solve without using recursion.

recursion or iteration?

The decision whether to use recursion or iteration should be based on the nature of, and your understanding of, the problem you are trying to solve. The rule of thumb is to use whichever approach can best develop an intuitive solution that naturally mirrors the problem. If an iterative solution is obvious, use it. It will generally be more efficient than the recursive option.

StackOverflowError



Note

Recursive programs can run out of memory, causing a `StackOverflowError`.

performance concern



Tip

If you are concerned about your program's performance, avoid using recursion, because it takes more time and consumes more memory than iteration. In general, recursion can be used to solve the inherent recursive problems such as Tower of Hanoi, recursive directories, and Sierpinski triangles.



- 18.28** Which of the following statements are true?

- Any recursive method can be converted into a nonrecursive method.
- Recursive methods take more time and memory to execute than nonrecursive methods.
- Recursive methods are *always* simpler than nonrecursive methods.
- There is always a selection statement in a recursive method to check whether a base case is reached.

- 18.29** What is a cause for a stack-overflow exception?

18.10 Tail Recursion

A tail recursive method is efficient for reducing stack size.

A recursive method is said to be *tail recursive* if there are no pending operations to be performed on return from a recursive call, as illustrated in Figure 18.11a. However, method B in Figure 18.11b is not tail recursive because there are pending operations after a method call is returned.

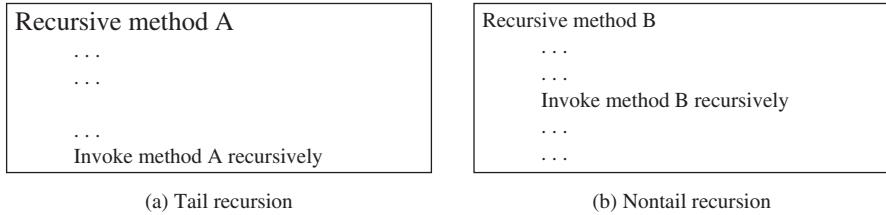


FIGURE 18.11 A tail-recursive method has no pending operations after a recursive call.

For example, the recursive `isPalindrome` method (lines 6–13) in Listing 18.4 is tail recursive because there are no pending operations after recursively invoking `isPalindrome` in line 12. However, the recursive `factorial` method (lines 16–21) in Listing 18.1 is not tail recursive, because there is a pending operation, namely multiplication, to be performed on return from each recursive call.

Tail recursion is desirable: because the method ends when the last recursive call ends, there is no need to store the intermediate calls in the stack. Compilers can optimize tail recursion to reduce stack size.

A nontail-recursive method can often be converted to a tail-recursive method by using auxiliary parameters. These parameters are used to contain the result. The idea is to incorporate the pending operations into the auxiliary parameters in such a way that the recursive call no longer has a pending operation. You can define a new auxiliary recursive method with the auxiliary parameters. This method may overload the original method with the same name but a different signature. For example, the `factorial` method in Listing 18.1 is written in a tail-recursive way in Listing 18.10.

LISTING 18.10 ComputeFactorialTailRecursion.java

```

1  public class ComputeFactorialTailRecursion {
2      /** Return the factorial for a specified number */
3      public static long factorial(int n) {
4          return factorial(n, 1); // Call auxiliary method
5      }
6
7      /** Auxiliary tail-recursive method for factorial */
8      private static long factorial(int n, int result) {
9          if (n == 0)
10              return result;
11          else
12              return factorial(n - 1, n * result); // Recursive call
13      }
14  }

```

original method
invoke auxiliary method

auxiliary method

recursive call

The first `factorial` method (line 3) simply invokes the second auxiliary method (line 4). The second method contains an auxiliary parameter `result` that stores the result for the factorial of `n`. This method is invoked recursively in line 12. There is no pending operation after

a call is returned. The final result is returned in line 10, which is also the return value from invoking `factorial(n, 1)` in line 4.



18.30 Identify tail-recursive methods in this chapter.

18.31 Rewrite the `fib` method in Listing 18.2 using tail recursion.

KEY TERMS

base case	706	recursive helper method	715
direct recursion	709	recursive method	706
indirect recursion	709	stopping condition	706
infinite recursion	709	tail recursion	727

CHAPTER SUMMARY

1. A *recursive method* is one that directly or indirectly invokes itself. For a recursive method to terminate, there must be one or more *base cases*.
2. *Recursion* is an alternative form of program control. It is essentially repetition without a loop control. It can be used to write simple, clear solutions for inherently recursive problems that would otherwise be difficult to solve.
3. Sometimes the original method needs to be modified to receive additional parameters in order to be invoked recursively. A *recursive helper method* can be defined for this purpose.
4. Recursion bears substantial overhead. Each time the program calls a method, the system must allocate memory for all of the method's local variables and parameters. This can consume considerable memory and requires extra time to manage the memory.
5. A recursive method is said to be *tail recursive* if there are no pending operations to be performed on return from a recursive call. Some compilers can optimize tail recursion to reduce stack size.

QUIZ

Answer the quiz for this chapter online at www.cs.armstrong.edu/liang/intro10e/quiz.html.

MyProgrammingLab™

PROGRAMMING EXERCISES

Sections 18.2–18.3

***18.1** (*Factorial*) Using the `BigInteger` class introduced in Section 10.9, you can find the factorial for a large number (e.g., `100!`). Implement the `factorial` method using recursion. Write a program that prompts the user to enter an integer and displays its factorial.

***18.2** (*Fibonacci numbers*) Rewrite the `fib` method in Listing 18.2 using iterations.

Hint: To compute `fib(n)` without recursion, you need to obtain `fib(n - 2)` and `fib(n - 1)` first. Let `f0` and `f1` denote the two previous Fibonacci

numbers. The current Fibonacci number would then be **f0 + f1**. The algorithm can be described as follows:

```
f0 = 0; // For fib(0)
f1 = 1; // For fib(1)

for (int i = 1; i <= n; i++) {
    currentFib = f0 + f1;
    f0 = f1;
    f1 = currentFib;
}
// After the loop, currentFib is fib(n)
```

Write a test program that prompts the user to enter an index and displays its Fibonacci number.

- *18.3** (*Compute greatest common divisor using recursion*) The **gcd(m, n)** can also be defined recursively as follows:

- If **m % n** is **0**, **gcd(m, n)** is **n**.
- Otherwise, **gcd(m, n)** is **gcd(n, m % n)**.

Write a recursive method to find the GCD. Write a test program that prompts the user to enter two integers and displays their GCD.

- 18.4** (*Sum series*) Write a recursive method to compute the following series:

$$m(i) = 1 + \frac{1}{2} + \frac{1}{3} + \dots + \frac{1}{i}$$

Write a test program that displays **m(i)** for **i = 1, 2, ..., 10**.

- 18.5** (*Sum series*) Write a recursive method to compute the following series:

$$m(i) = \frac{1}{3} + \frac{2}{5} + \frac{3}{7} + \frac{4}{9} + \frac{5}{11} + \frac{6}{13} + \dots + \frac{i}{2i+1}$$

Write a test program that displays **m(i)** for **i = 1, 2, ..., 10**.

- *18.6** (*Sum series*) Write a recursive method to compute the following series:

$$m(i) = \frac{1}{2} + \frac{2}{3} + \dots + \frac{i}{i+1}$$

Write a test program that displays **m(i)** for **i = 1, 2, ..., 10**.

- *18.7** (*Fibonacci series*) Modify Listing 18.2, ComputeFibonacci.java, so that the program finds the number of times the **fib** method is called. (*Hint:* Use a static variable and increment it every time the method is called.)

Section 18.4

- *18.8** (*Print the digits in an integer reversely*) Write a recursive method that displays an **int** value reversely on the console using the following header:

```
public static void reverseDisplay(int value)
```

For example, **reverseDisplay(12345)** displays **54321**. Write a test program that prompts the user to enter an integer and displays its reversal.

- *18.9** (*Print the characters in a string reversely*) Write a recursive method that displays a string reversely on the console using the following header:

```
public static void reverseDisplay(String value)
```

For example, `reverseDisplay("abcd")` displays `dcb`. Write a test program that prompts the user to enter a string and displays its reversal.

- *18.10** (*Occurrences of a specified character in a string*) Write a recursive method that finds the number of occurrences of a specified letter in a string using the following method header:

```
public static int count(String str, char a)
```

For example, `count("Welcome", 'e')` returns `2`. Write a test program that prompts the user to enter a string and a character, and displays the number of occurrences for the character in the string.

- *18.11** (*Sum the digits in an integer using recursion*) Write a recursive method that computes the sum of the digits in an integer. Use the following method header:

```
public static int sumDigits(long n)
```

For example, `sumDigits(234)` returns $2 + 3 + 4 = 9$. Write a test program that prompts the user to enter an integer and displays its sum.

Section 18.5

- **18.12** (*Print the characters in a string reversely*) Rewrite Programming Exercise 18.9 using a helper method to pass the substring `high` index to the method. The helper method header is:

```
public static void reverseDisplay(String value, int high)
```

- *18.13** (*Find the largest number in an array*) Write a recursive method that returns the largest integer in an array. Write a test program that prompts the user to enter a list of eight integers and displays the largest element.

- *18.14** (*Find the number of uppercase letters in a string*) Write a recursive method to return the number of uppercase letters in a string. Write a test program that prompts the user to enter a string and displays the number of uppercase letters in the string.

- *18.15** (*Occurrences of a specified character in a string*) Rewrite Programming Exercise 18.10 using a helper method to pass the substring `high` index to the method. The helper method header is:

```
public static int count(String str, char a, int high)
```

- *18.16** (*Find the number of uppercase letters in an array*) Write a recursive method to return the number of uppercase letters in an array of characters. You need to define the following two methods. The second one is a recursive helper method.

```
public static int count(char[] chars)
public static int count(char[] chars, int high)
```

Write a test program that prompts the user to enter a list of characters in one line and displays the number of uppercase letters in the list.

- *18.17** (*Occurrences of a specified character in an array*) Write a recursive method that finds the number of occurrences of a specified character in an array. You need to define the following two methods. The second one is a recursive helper method.

```
public static int count(char[] chars, char ch)
public static int count(char[] chars, char ch, int high)
```

Write a test program that prompts the user to enter a list of characters in one line, and a character, and displays the number of occurrences of the character in the list.

Sections 18.6–18.10

- *18.18 (*Tower of Hanoi*) Modify Listing 18.8, TowerOfHanoi.java, so that the program finds the number of moves needed to move n disks from tower A to tower B. (*Hint:* Use a static variable and increment it every time the method is called.)
- *18.19 (*Sierpinski triangle*) Revise Listing 18.9 to develop a program that lets the user use the + and – buttons to increase or decrease the current order by 1, as shown in Figure 18.12a. The initial order is 0. If the current order is 0, the *Decrease* button is ignored.

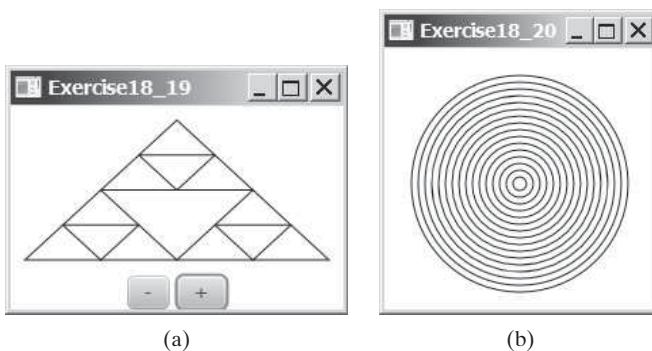


FIGURE 18.12 (a) Programming Exercise 18.19 uses the + and – buttons to increase or decrease the current order by 1. (b) Programming Exercise 18.20 draws ovals using a recursive method.

- *18.20 (*Display circles*) Write a Java program that displays ovals, as shown in Figure 18.12b. The circles are centered in the pane. The gap between two adjacent circles is 10 pixels, and the gap between the border of the pane and the largest circle is also 10.
- *18.21 (*Decimal to binary*) Write a recursive method that converts a decimal number into a binary number as a string. The method header is:

```
public static String dec2Bin(int value)
```

Write a test program that prompts the user to enter a decimal number and displays its binary equivalent.

- *18.22 (*Decimal to hex*) Write a recursive method that converts a decimal number into a hex number as a string. The method header is:

```
public static String dec2Hex(int value)
```

Write a test program that prompts the user to enter a decimal number and displays its hex equivalent.

- *18.23 (*Binary to decimal*) Write a recursive method that parses a binary number as a string into a decimal integer. The method header is:

```
public static int bin2Dec(String binaryString)
```

Write a test program that prompts the user to enter a binary string and displays its decimal equivalent.

- *18.24** (*Hex to decimal*) Write a recursive method that parses a hex number as a string into a decimal integer. The method header is:

```
public static int hex2Dec(String hexString)
```

Write a test program that prompts the user to enter a hex string and displays its decimal equivalent.

- **18.25** (*String permutation*) Write a recursive method to print all the permutations of a string. For example, for the string `abc`, the permutation is

```
abc
acb
bac
bca
cab
cba
```

(*Hint:* Define the following two methods. The second is a helper method.)

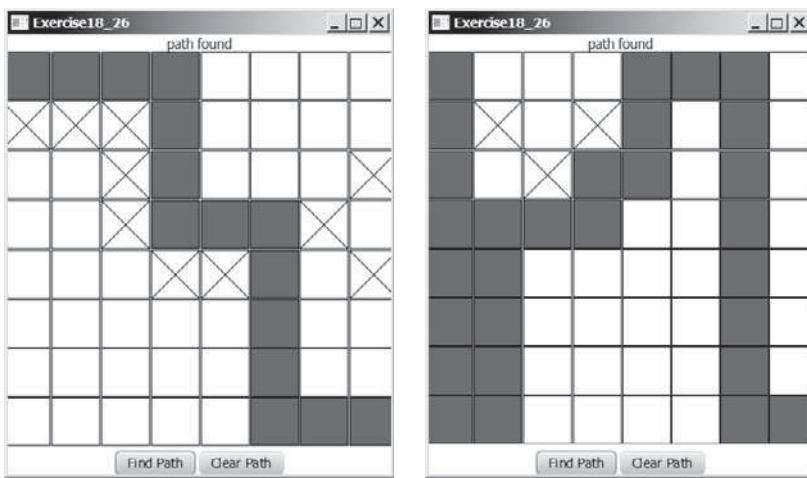
```
public static void displayPermutation(String s)
public static void displayPermutation(String s1, String s2)
```

The first method simply invokes `displayPermutation(" ", s)`. The second method uses a loop to move a character from `s2` to `s1` and recursively invokes it with a new `s1` and `s2`. The base case is that `s2` is empty and prints `s1` to the console.

Write a test program that prompts the user to enter a string and displays all its permutations.

- **18.26** (*Create a maze*) Write a program that will find a path in a maze, as shown in Figure 18.13a. The maze is represented by an 8×8 board. The path must meet the following conditions:

- The path is between the upper-left corner cell and the lower-right corner cell in the maze.



(a) Correct path

(b) Illegal path

FIGURE 18.13 The program finds a path from the upper-left corner to the bottom-right corner.

- The program enables the user to place or remove a mark on a cell. A path consists of adjacent unmarked cells. Two cells are said to be adjacent if they are horizontal or vertical neighbors, but not if they are diagonal neighbors.
- The path does not contain cells that form a square. The path in Figure 18.13b, for example, does not meet this condition. (The condition makes a path easy to identify on the board.)

****18.27** (*Koch snowflake fractal*) The text presented the Sierpinski triangle fractal. In this exercise, you will write a program to display another fractal, called the *Koch snowflake*, named after a famous Swedish mathematician. A Koch snowflake is created as follows:

- Begin with an equilateral triangle, which is considered to be the Koch fractal of order (or level) 0, as shown in Figure 18.14a.
- Divide each line in the shape into three equal line segments and draw an outward equilateral triangle with the middle line segment as the base to create a Koch fractal of order 1, as shown in Figure 18.14b.
- Repeat Step 2 to create a Koch fractal of order 2, 3, . . . , and so on, as shown in Figure 18.14c–d.

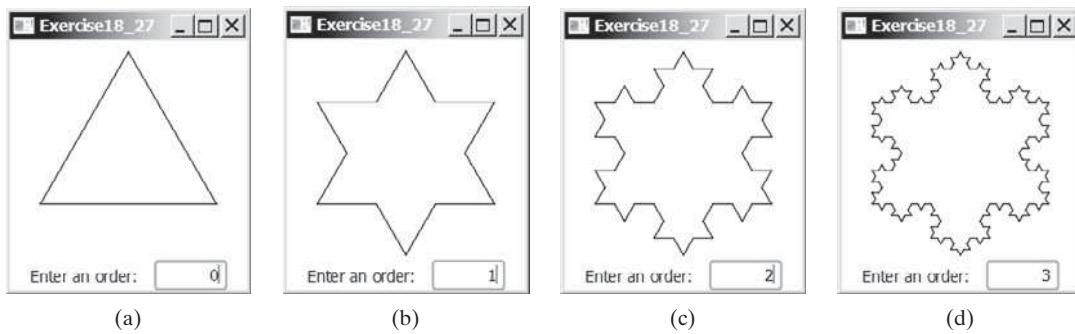


FIGURE 18.14 A Koch snowflake is a fractal starting with a triangle.

****18.28** (*Nonrecursive directory size*) Rewrite Listing 18.7, DirectorySize.java, without using recursion.

***18.29** (*Number of files in a directory*) Write a program that prompts the user to enter a directory and displays the number of the files in the directory.

****18.30** (*Find words*) Write a program that finds all occurrences of a word in all the files under a directory, recursively. Pass the parameters from the command line as follows:

```
java Exercise18_30 dirName word
```

****18.31** (*Replace words*) Write a program that replaces all occurrences of a word with a new word in all the files under a directory, recursively. Pass the parameters from the command line as follows:

```
java Exercise18_31 dirName oldWord newWord
```



VideoNote

Search a string in a directory

*****18.32** (*Game: Knight's Tour*) The Knight's Tour is an ancient puzzle. The objective is to move a knight, starting from any square on a chessboard, to every other square once, as shown in Figure 18.15a. Note that the knight makes only L-shaped moves (two spaces in one direction and one space in a perpendicular direction). As shown in Figure 18.15b, the knight can move to eight squares. Write

a program that displays the moves for the knight, as shown in Figure 18.15c. When you click a cell, the knight is placed at the cell. This cell will be starting point for the knight. Clicking the *Solve* button to display the path for a solution.



FIGURE 18.15 (a) A knight traverses all squares once. (b) A knight makes an L-shaped move. (c) A program displays a Knight’s Tour path.

(Hint: A brute-force approach for this problem is to move the knight from one square to another available square arbitrarily. Using such an approach, your program will take a long time to finish. A better approach is to employ some heuristics. A knight has two, three, four, six, or eight possible moves, depending on its location. Intuitively, you should attempt to move the knight to the least accessible squares first and leave those more accessible squares open, so there will be a better chance of success at the end of the search.)

*****18.33** (*Game: Knight’s Tour animation*) Write a program for the Knight’s Tour problem. Your program should let the user move a knight to any starting square and click the *Solve* button to animate a knight moving along the path, as shown in Figure 18.16.



FIGURE 18.16 A knight traverses along the path.

****18.34** (*Game: Eight Queens*) The Eight Queens problem is to find a solution to place a queen in each row on a chessboard such that no two queens can attack each other. Write a program to solve the Eight Queens problem using recursion and display the result as shown in Figure 18.17.

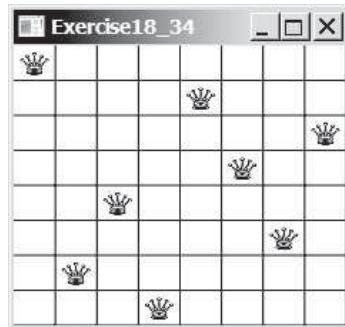


FIGURE 18.17 The program displays a solution to the Eight Queens problem.

****18.35** (*H-tree fractal*) An H-tree (introduced at the beginning of this chapter in Figure 18.1) is a fractal defined as follows:

1. Begin with a letter H. The three lines of the H are of the same length, as shown in Figure 18.1a.
2. The letter H (in its sans-serif form, H) has four endpoints. Draw an H centered at each of the four endpoints to an H-tree of order 1, as shown in Figure 18.1b. These Hs are half the size of the H that contains the four endpoints.
3. Repeat Step 2 to create an H-tree of order 2, 3, . . . , and so on, as shown in Figure 18.1c–d.

Write a program that draws an H-tree, as shown in Figure 18.1.

18.36 (*Sierpinski triangle*) Write a program that lets the user to enter the order and display the filled Sierpinski triangles as shown in Figure 18.18.

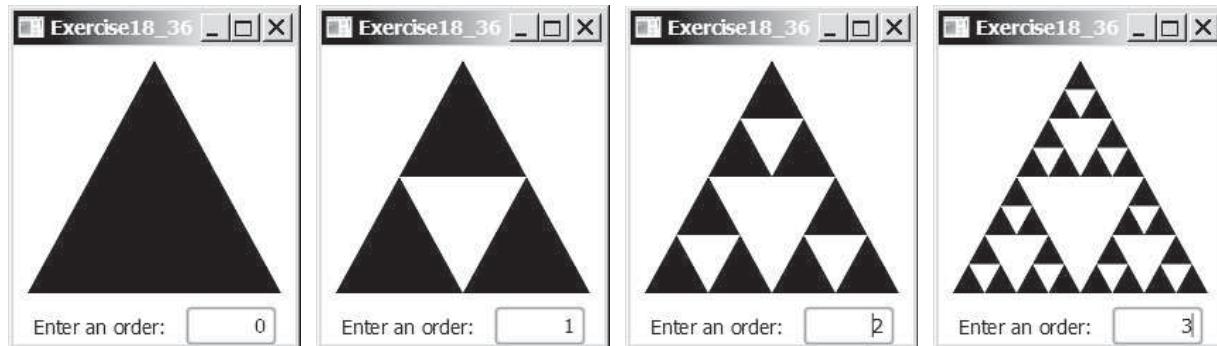
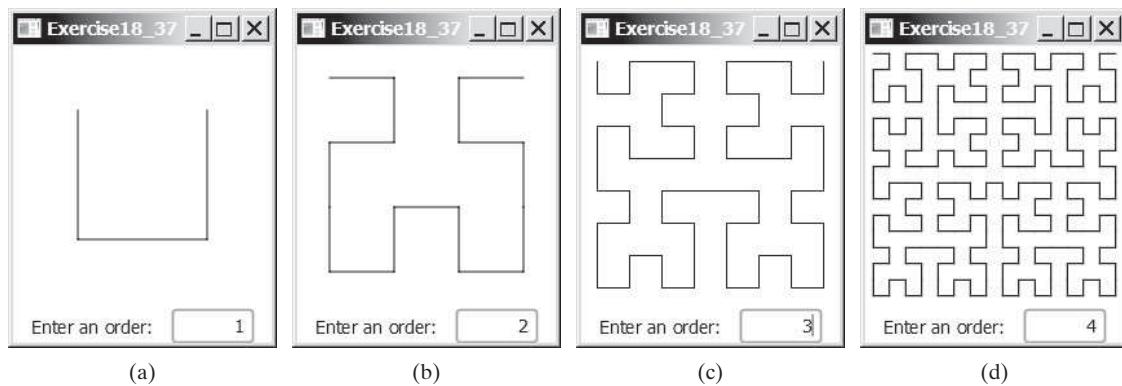
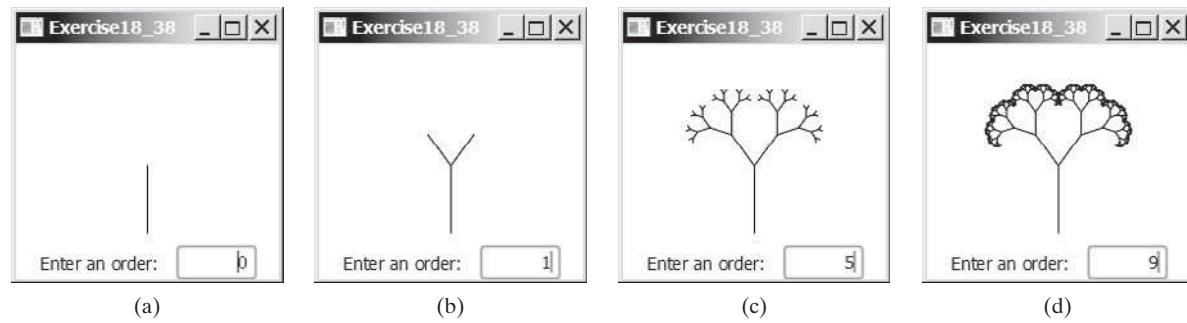


FIGURE 18.18 A filled Sierpinski triangle is displayed.

****18.37** (*Hilbert curve*) The Hilbert curve, first described by German mathematician David Hilbert in 1891, is a space-filling curve that visits every point in a square grid with a size of 2×2 , 4×4 , 8×8 , 16×16 , or any other power of 2. Write a program that displays a Hilbert curve for the specified order, as shown in Figure 18.19.

**FIGURE 18.19** A Hilbert curve with the specified order is drawn.

****18.38 (Recursive tree)** Write a program to display a recursive tree as shown in Figure 18.20.

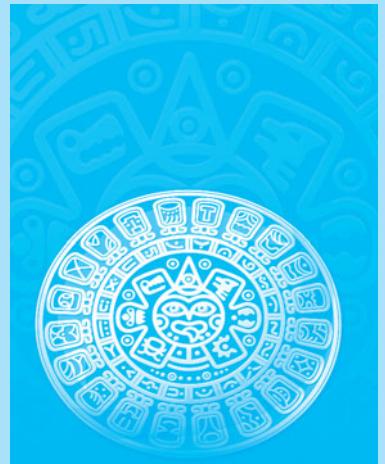
**FIGURE 18.20** A recursive tree with the specified depth is drawn.

****18.39 (Dragging the tree)** Revise Programming Exercise 18.38 to move the tree to where the mouse is dragged.

GENERICs

Objectives

- To describe the benefits of generics (§19.2).
- To use generic classes and interfaces (§19.2).
- To define generic classes and interfaces (§19.3).
- To explain why generic types can improve reliability and readability (§19.3).
- To define and use generic methods and bounded generic types (§19.4).
- To develop a generic sort method to sort an array of **Comparable** objects (§19.5).
- To use raw types for backward compatibility (§19.6).
- To explain why wildcard generic types are necessary (§19.7).
- To describe generic type erasure and list certain restrictions and limitations on generic types caused by type erasure (§19.8).
- To design and implement generic matrix classes (§19.9).



19.1 Introduction



what is generics?

why generics?

Generics enable you to detect errors at compile time rather than at runtime.

You have used a generic class `ArrayList` in Chapter 11 and generic interface `Comparable` in Chapter 13. *Generics* let you parameterize types. With this capability, you can define a class or a method with generic types that the compiler can replace with concrete types. For example, Java defines a generic `ArrayList` class for storing the elements of a generic type. From this generic class, you can create an `ArrayList` object for holding strings and an `ArrayList` object for holding numbers. Here, strings and numbers are concrete types that replace the generic type.

The key benefit of generics is to enable errors to be detected at compile time rather than at runtime. A generic class or method permits you to specify allowable types of objects that the class or method can work with. If you attempt to use an incompatible object, the compiler will detect that error.

This chapter explains how to define and use generic classes, interfaces, and methods and demonstrates how generics can be used to improve software reliability and readability. It can be intertwined with Chapter 13, Abstract Classes and Interfaces.

19.2 Motivations and Benefits



The motivation for using Java generics is to detect errors at compile time.

Java has allowed you to define generic classes, interfaces, and methods since JDK 1.5. Several interfaces and classes in the Java API were modified using generics. For example, prior to JDK 1.5 the `java.lang.Comparable` interface was defined as shown in Figure 19.1a, but since JDK 1.5 it is modified as shown in Figure 19.1b.

```
package java.lang;

public interface Comparable {
    public int compareTo(Object o)
}
```

(a) Prior to JDK 1.5

```
package java.lang;

public interface Comparable<T> {
    public int compareTo(T o)
}
```

(b) JDK 1.5

FIGURE 19.1 The `java.lang.Comparable` interface was modified in JDK 1.5 with a generic type

formal generic type
actual concrete type
generic instantiation

Here, `<T>` represents a *formal generic type*, which can be replaced later with an *actual concrete type*. Replacing a generic type is called a *generic instantiation*. By convention, a single capital letter such as `E` or `T` is used to denote a formal generic type.

To see the benefits of using generics, let us examine the code in Figure 19.2. The statement in Figure 19.2a declares that `c` is a reference variable whose type is `Comparable` and invokes the `compareTo` method to compare a `Date` object with a string. The code compiles fine, but it has a runtime error because a string cannot be compared with a date.

```
Comparable c = new Date();
System.out.println(c.compareTo("red"));
```

(a) Prior to JDK 1.5

```
Comparable<Date> c = new Date();
System.out.println(c.compareTo("red"));
```

(b) JDK 1.5

FIGURE 19.2 The new generic type detects possible errors at compile time.

The statement in Figure 19.2b declares that `c` is a reference variable whose type is `Comparable<Date>` and invokes the `compareTo` method to compare a `Date` object with a string. This code generates a compile error, because the argument passed to the `compareTo`

method must be of the **Date** type. Since the errors can be detected at compile time rather than at runtime, the generic type makes the program more reliable.

ArrayList was introduced in Section 11.11, The **ArrayList** Class. This class has been a generic class since JDK 1.5. Figure 19.3 shows the class diagram for **ArrayList** before and since JDK 1.5, respectively.

reliable

java.util.ArrayList	java.util.ArrayList<E>
<pre>+ArrayList() +add(o: Object): void +add(index: int, o: Object): void +clear(): void +contains(o: Object): boolean +get(index:int): Object +indexOf(o: Object): int +isEmpty(): boolean +lastIndexOf(o: Object): int +remove(o: Object): boolean +size(): int +remove(index: int): boolean +set(index: int, o: Object): Object</pre>	<pre>+ArrayList() +add(o: E): void +add(index: int, o: E): void +clear(): void +contains(o: Object): boolean +get(index:int): E +indexOf(o: Object): int +isEmpty(): boolean +lastIndexOf(o: Object): int +remove(o: Object): boolean +size(): int +remove(index: int): boolean +set(index: int, o: E): E</pre>

(a) *ArrayList* before JDK 1.5

(b) *ArrayList* since JDK 1.5

FIGURE 19.3 *ArrayList* is a generic class since JDK 1.5.

For example, the following statement creates a list for strings:

```
ArrayList<String> list = new ArrayList<>();
```

You can now add *only strings* into the list. For instance,

only strings allowed

```
list.add("Red");
```

If you attempt to add a nonstring, a compile error will occur. For example, the following statement is now illegal, because **list** can contain only strings.

```
list.add(new Integer(1));
```

Generic types must be reference types. You cannot replace a generic type with a primitive type such as **int**, **double**, or **char**. For example, the following statement is wrong:

generic reference type

```
ArrayList<int> intList = new ArrayList<>();
```

To create an **ArrayList** object for **int** values, you have to use:

```
ArrayList<Integer> intList = new ArrayList<>();
```

You can add an **int** value to **intList**. For example,

```
intList.add(5);
```

Java automatically wraps **5** into **new Integer(5)**. This is called *autoboxing*, as introduced in Section 10.8, Automatic Conversion between Primitive Types and Wrapper Class Types.

autoboxing

no casting needed

Casting is not needed to retrieve a value from a list with a specified element type, because the compiler already knows the element type. For example, the following statements create a list that contains strings, add strings to the list, and retrieve strings from the list.

```
1 ArrayList<String> list = new ArrayList<>();
2 list.add("Red");
3 list.add("White");
4 String s = list.get(0); // No casting is needed
```

autounboxing

Prior to JDK 1.5, without using generics, you would have had to cast the return value to **String** as:

```
String s = (String)(list.get(0)); // Casting needed prior to JDK 1.5
```

If the elements are of wrapper types, such as **Integer**, **Double**, and **Character**, you can directly assign an element to a primitive type variable. This is called *autounboxing*, as introduced in Section 10.8. For example, see the following code:

```
1 ArrayList<Double> list = new ArrayList<>();
2 list.add(5.5); // 5.5 is automatically converted to new Double(5.5)
3 list.add(3.0); // 3.0 is automatically converted to new Double(3.0)
4 Double doubleObject = list.get(0); // No casting is needed
5 double d = list.get(1); // Automatically converted to double
```

In lines 2 and 3, **5.5** and **3.0** are automatically converted into **Double** objects and added to **list**. In line 4, the first element in **list** is assigned to a **Double** variable. No casting is necessary, because **list** is declared for **Double** objects. In line 5, the second element in **list** is assigned to a **double** variable. The object in **list.get(1)** is automatically converted into a primitive type value.



19.1 Are there any compile errors in (a) and (b)?

```
ArrayList dates = new ArrayList();
dates.add(new Date());
dates.add(new String());
```

(a) Prior to JDK 1.5

```
ArrayList<Date> dates =
new ArrayList<>();
dates.add(new Date());
dates.add(new String());
```

(b) Since JDK 1.5

19.2 What is wrong in (a)? Is the code in (b) correct?

```
ArrayList dates = new ArrayList();
dates.add(new Date());
Date date = dates.get(0);
```

(a) Prior to JDK 1.5

```
ArrayList<Date> dates =
new ArrayList<>();
dates.add(new Date());
Date date = dates.get(0);
```

(b) Since JDK 1.5

19.3 What are the benefits of using generic types?

19.3 Defining Generic Classes and Interfaces



A generic type can be defined for a class or interface. A concrete type must be specified when using the class to create an object or using the class or interface to declare a reference variable.

Let us revise the stack class in Section 11.13, Case Study: A Custom Stack Class, to generalize the element type with a generic type. The new stack class, named **GenericStack**, is shown in Figure 19.4 and is implemented in Listing 19.1.

GenericStack<E>	
-list: java.util.ArrayList<E>	An array list to store elements.
+GenericStack()	Creates an empty stack.
+getSize(): int	Returns the number of elements in this stack.
+peek(): E	Returns the top element in this stack.
+pop(): E	Returns and removes the top element in this stack.
+push(o: E): void	Adds a new element to the top of this stack.
+isEmpty(): boolean	Returns true if the stack is empty.

FIGURE 19.4 The **GenericStack** class encapsulates the stack storage and provides the operations for manipulating the stack.

LISTING 19.1 GenericStack.java

```

1  public class GenericStack<E> {
2      private java.util.ArrayList<E> list = new java.util.ArrayList<>();
3
4      public int getSize() {
5          return list.size();
6      }
7
8      public E peek() {
9          return list.get(getSize() - 1);
10 }
11
12     public void push(E o) {
13         list.add(o);
14     }
15
16     public E pop() {
17         E o = list.get(getSize() - 1);
18         list.remove(getSize() - 1);
19         return o;
20     }
21
22     public boolean isEmpty() {
23         return list.isEmpty();
24     }
25
26     @Override
27     public String toString() {
28         return "stack: " + list.toString();
29     }
30 }
```

generic type E declared
generic array list

getSize

peek

push

pop

isEmpty

The following example creates a stack to hold strings and adds three strings to the stack:

```
GenericStack<String> stack1 = new GenericStack<>();
stack1.push("London");
stack1.push("Paris");
stack1.push("Berlin");
```

This example creates a stack to hold integers and adds three integers to the stack:

```
GenericStack<Integer> stack2 = new GenericStack<>();
stack2.push(1); // autoboxing 1 to new Integer(1)
stack2.push(2);
stack2.push(3);
```

benefits of using generic types

Instead of using a generic type, you could simply make the type element `Object`, which can accommodate any object type. However, using generic types can improve software reliability and readability, because certain errors can be detected at compile time rather than at runtime. For example, because `stack1` is declared `GenericStack<String>`, only strings can be added to the stack. It would be a compile error if you attempted to add an integer to `stack1`.

generic class constructor



Caution

To create a stack of strings, you use `new GenericStack<String>()` or `new GenericStack<>()`. This could mislead you into thinking that the constructor of `GenericStack` should be defined as

```
public GenericStack<E>()
```

This is wrong. It should be defined as

```
public GenericStack()
```

multiple generic parameters



Note

Occasionally, a generic class may have more than one parameter. In this case, place the parameters together inside the brackets, separated by commas—for example, `<E1, E2, E3>`.

inheritance with generics



Note

You can define a class or an interface as a subtype of a generic class or interface. For example, the `java.lang.String` class is defined to implement the `Comparable` interface in the Java API as follows:

```
public class String implements Comparable<String>
```



19.4 What is the generic definition for `java.lang.Comparable` in the Java API?

19.5 Since you create an instance of `ArrayList` of strings using `new ArrayList<String>()`, should the constructor in the `ArrayList` class be defined as

```
public ArrayList<E>()
```

19.6 Can a generic class have multiple generic parameters?

19.7 How do you declare a generic type in a class?

generic method



19.4 Generic Methods

A generic type can be defined for a static method.

You can define generic interfaces (e.g., the `Comparable` interface in Figure 19.1b) and classes (e.g., the `GenericStack` class in Listing 19.1). You can also use generic types to define generic methods. For example, Listing 19.2 defines a generic method `print` (lines 10–14) to print an array of objects. Line 6 passes an array of integer objects to invoke the generic `print` method. Line 7 invokes `print` with an array of strings.

LISTING 19.2 GenericMethodDemo.java

```

1  public class GenericMethodDemo {
2      public static void main(String[] args) {
3          Integer[] integers = {1, 2, 3, 4, 5};
4          String[] strings = {"London", "Paris", "New York", "Austin"};
5
6          GenericMethodDemo.<Integer>print(integers);
7          GenericMethodDemo.<String>print(strings);
8      }
9
10     public static <E> void print(E[] list) {           generic method
11         for (int i = 0; i < list.length; i++)
12             System.out.print(list[i] + " ");
13         System.out.println();
14     }
15 }
```

To declare a generic method, you place the generic type `<E>` immediately after the keyword `static` in the method header. For example,

```
public static <E> void print(E[] list)
```

To invoke a generic method, prefix the method name with the actual type in angle brackets. For example,

```
GenericMethodDemo.<Integer>print(integers);
GenericMethodDemo.<String>print(strings);
```

or simply invoke it as follows:

```
print(integers);
print(strings);
```

In the latter case, the actual type is not explicitly specified. The compiler automatically discovers the actual type.

A generic type can be specified as a subtype of another type. Such a generic type is called *bounded*. For example, Listing 19.3 revises the `equalArea` method in Listing 13.4, TestGeometricObject.java, to test whether two geometric objects have the same area. The bounded generic type `<E extends GeometricObject>` (line 7) specifies that `E` is a generic subtype of `GeometricObject`. You must invoke `equalArea` by passing two instances of `GeometricObject`.

bounded generic type

LISTING 19.3 BoundedTypeDemo.java

```

1  public class BoundedTypeDemo {
2      public static void main(String[] args) {
3          Rectangle rectangle = new Rectangle(2, 2);
4          Circle circle = new Circle(2);
5
6          System.out.println("Same area? " +
7              equalArea(rectangle, circle));
8      }
9
10     public static <E extends GeometricObject> boolean equalArea(       bounded generic type
11         E object1, E object2) {
12         return object1.getArea() == object2.getArea();
13     }
14 }
```

Rectangle in Listing 13.3
Circle in Listing 13.2

bounded generic type

generic class parameter vs.
generic method parameter



- 19.8** How do you declare a generic method? How do you invoke a generic method?
19.9 What is a bounded generic type?



19.5 Case Study: Sorting an Array of Objects

You can develop a generic method for sorting an array of Comparable objects.

This section presents a generic method for sorting an array of **Comparable** objects. The objects are instances of the **Comparable** interface, and they are compared using the **compareTo** method. To test the method, the program sorts an array of integers, an array of double numbers, an array of characters, and an array of strings. The program is shown in Listing 19.4.

LISTING 19.4 GenericSort.java

```

1  public class GenericSort {
2      public static void main(String[] args) {
3          // Create an Integer array
4          Integer[] intArray = {new Integer(2), new Integer(4),
5              new Integer(3)};
6
7          // Create a Double array
8          Double[] doubleArray = {new Double(3.4), new Double(1.3),
9              new Double(-22.1)};
10
11         // Create a Character array
12         Character[] charArray = {new Character('a'),
13             new Character('J'), new Character('r')};
14
15         // Create a String array
16         String[] stringArray = {"Tom", "Susan", "Kim"};
17
18         // Sort the arrays
19         sort(intArray);
20         sort(doubleArray);
21         sort(charArray);
22         sort(stringArray);
23
24         // Display the sorted arrays
25         System.out.print("Sorted Integer objects: ");
26         printList(intArray);
27         System.out.print("Sorted Double objects: ");
28         printList(doubleArray);
29         System.out.print("Sorted Character objects: ");
30         printList(charArray);
31         System.out.print("Sorted String objects: ");
32         printList(stringArray);
33     }
34 }
```

sort Integer objects
sort Double objects
sort Character objects
sort String objects

```

35  /** Sort an array of comparable objects */
36  public static <E extends Comparable<E>> void sort(E[] list) {           generic sort method
37      E currentMin;
38      int currentMinIndex;
39
40      for (int i = 0; i < list.length - 1; i++) {
41          // Find the minimum in the list[i+1..list.length-2]
42          currentMin = list[i];
43          currentMinIndex = i;
44
45          for (int j = i + 1; j < list.length; j++) {
46              if (currentMin.compareTo(list[j]) > 0) {                      compareTo
47                  currentMin = list[j];
48                  currentMinIndex = j;
49              }
50          }
51
52          // Swap list[i] with list[currentMinIndex] if necessary;
53          if (currentMinIndex != i) {
54              list[currentMinIndex] = list[i];
55              list[i] = currentMin;
56          }
57      }
58  }
59
60  /** Print an array of objects */
61  public static void printList(Object[] list) {
62      for (int i = 0; i < list.length; i++)
63          System.out.print(list[i] + " ");
64      System.out.println();
65  }
66 }
```

```

Sorted Integer objects: 2 3 4
Sorted Double objects: -22.1 1.3 3.4
Sorted Character objects: J a r
Sorted String objects: Kim Susan Tom

```



The algorithm for the `sort` method is the same as in Listing 7.8, SelectionSort.java. The `sort` method in that program sorts an array of `double` values. The `sort` method in this example can sort an array of any object type, provided that the objects are also instances of the `Comparable` interface. The generic type is defined as `<E extends Comparable<E>>` (line 36). This has two meanings. First, it specifies that `E` is a subtype of `Comparable`. Second, it specifies that the elements to be compared are of the `E` type as well.

The `sort` method uses the `compareTo` method to determine the order of the objects in the array (line 46). `Integer`, `Double`, `Character`, and `String` implement `Comparable`, so the objects of these classes can be compared using the `compareTo` method. The program creates arrays of `Integer` objects, `Double` objects, `Character` objects, and `String` objects (lines 4–16) and invoke the `sort` method to sort these arrays (lines 19–22).

19.10 Given `int[] list = {1, 2, -1}`, can you invoke `sort(list)` using the `sort` method in Listing 19.4?



19.11 Given `int[] list = {new Integer(1), new Integer(2), new Integer(-1)}`, can you invoke `sort(list)` using the `sort` method in Listing 19.4?



19.6 Raw Types and Backward Compatibility

A generic class or interface used without specifying a concrete type, called a *raw type*, enables backward compatibility with earlier versions of Java.

You can use a generic class without specifying a concrete type like this:

```
GenericStack stack = new GenericStack(); // raw type
```

This is roughly equivalent to

```
GenericStack<Object> stack = new GenericStack<Object>();
```

raw type
backward compatibility

A generic class such as `GenericStack` and `ArrayList` used without a type parameter is called a *raw type*. Using raw types allows for backward compatibility with earlier versions of Java. For example, a generic type has been used in `java.lang.Comparable` since JDK 1.5, but a lot of code still uses the raw type `Comparable`, as shown in Listing 19.5:

LISTING 19.5 Max.java

raw type

```
1 public class Max {
2     /** Return the maximum of two objects */
3     public static Comparable max(Comparable o1, Comparable o2) {
4         if (o1.compareTo(o2) > 0)
5             return o1;
6         else
7             return o2;
8     }
9 }
```

`Comparable o1` and `Comparable o2` are raw type declarations. Be careful: *raw types are unsafe*. For example, you might invoke the `max` method using

```
Max.max("Welcome", 23); // 23 is autoboxed into new Integer(23)
```

Xlint:unchecked

This would cause a runtime error, because you cannot compare a string with an integer object. The Java compiler displays a warning on line 3 when compiled with the option `-Xlint:unchecked`, as shown in Figure 19.5.

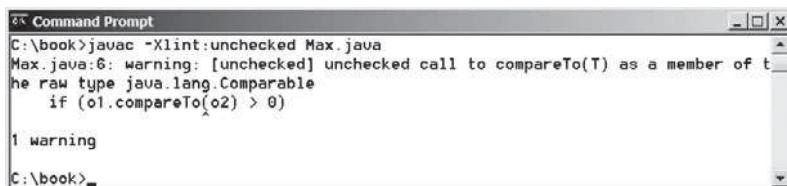


FIGURE 19.5 The unchecked warnings are displayed using the compiler option `-Xlint:unchecked`.

A better way to write the `max` method is to use a generic type, as shown in Listing 19.6.

LISTING 19.6 MaxUsingGenericType.java

bounded type

```
1 public class MaxUsingGenericType {
2     /** Return the maximum of two objects */
3     public static <E extends Comparable<E>> E max(E o1, E o2) {
4         if (o1.compareTo(o2) > 0)
5             return o1;
6         else
```

```

7     return o2;
8 }
9 }
```

If you invoke the `max` method using

```
// 23 is autoboxed into new Integer(23)
MaxUsingGenericType.max("Welcome", 23);
```

a compile error will be displayed, because the two arguments of the `max` method in `MaxUsingGenericType` must have the same type (e.g., two strings or two integer objects). Furthermore, the type `E` must be a subtype of `Comparable<E>`.

As another example, in the following code you can declare a raw type `stack` in line 1, assign `new GenericStack<String>` to it in line 2, and push a string and an integer object to the stack in lines 3 and 4.

```

1 GenericStack stack;
2 stack = new GenericStack<String>();
3 stack.push("Welcome to Java");
4 stack.push(new Integer(2));
```

However, line 4 is unsafe because the stack is intended to store strings, but an `Integer` object is added into the stack. Line 3 should be okay, but the compiler will show warnings for both line 3 and line 4, because it cannot follow the semantic meaning of the program. All the compiler knows is that `stack` is a raw type, and performing certain operations is unsafe. Therefore, warnings are displayed to alert potential problems.



Tip

Since raw types are unsafe, this book will not use them from here on.

19.12 What is a raw type? Why is a raw type unsafe? Why is the raw type allowed in Java?

19.13 What is the syntax to declare an `ArrayList` reference variable using the raw type and assign a raw type `ArrayList` object to it?



19.7 Wildcard Generic Types

You can use unbounded wildcards, bounded wildcards, or lower-bound wildcards to specify a range for a generic type.

What are wildcard generic types and why are they needed? Listing 19.7 gives an example to demonstrate the needs. The example defines a generic `max` method for finding the maximum in a stack of numbers (lines 12–22). The main method creates a stack of integer objects, adds three integers to the stack, and invokes the `max` method to find the maximum number in the stack.

LISTING 19.7 WildCardNeedDemo.java

```

1 public class WildCardNeedDemo {
2     public static void main(String[] args) {
3         GenericStack<Integer> intStack = new GenericStack<>();
4         intStack.push(1); // 1 is autoboxed into new Integer(1)
5         intStack.push(2);
6         intStack.push(-2);
7
8         System.out.print("The max number is " + max(intStack));
9     }
10 }
```

GenericStack<Integer>
type

```

11  /** Find the maximum in a stack of numbers */
12  public static double max(GenericStack<Number> stack) {
13      double max = stack.pop().doubleValue(); // Initialize max
14
15      while (!stack.isEmpty()) {
16          double value = stack.pop().doubleValue();
17          if (value > max)
18              max = value;
19      }
20
21      return max;
22  }
23 }

```

unbounded wildcard
bounded wildcard
lower-bound wildcard

The program in Listing 19.7 has a compile error in line 8 because `intStack` is not an instance of `GenericStack<Number>`. Thus, you cannot invoke `max(intStack)`.

The fact is that `Integer` is a subtype of `Number`, but `GenericStack<Integer>` is not a subtype of `GenericStack<Number>`. To circumvent this problem, use wildcard generic types. A wildcard generic type has three forms: `?` and `? extends T`, as well as `? super T`, where `T` is a generic type.

The first form, `?`, called an *unbounded wildcard*, is the same as `? extends Object`. The second form, `? extends T`, called a *bounded wildcard*, represents `T` or a subtype of `T`. The third form, `? super T`, called a *lower-bound wildcard*, denotes `T` or a supertype of `T`.

You can fix the error by replacing line 12 in Listing 19.7 as follows:

```
public static double max(GenericStack<? extends Number> stack) {
```

`<? extends Number>` is a wildcard type that represents `Number` or a subtype of `Number`, so it is legal to invoke `max(new GenericStack<Integer>())` or `max(new GenericStack<Double>())`.

Listing 19.8 shows an example of using the `?` wildcard in the `print` method that prints objects in a stack and empties the stack. `<?>` is a wildcard that represents any object type. It is equivalent to `<? extends Object>`. What happens if you replace `GenericStack<?>` with `GenericStack<Object>?` It would be wrong to invoke `print(intStack)`, because `intStack` is not an instance of `GenericStack<Object>`. Please note that `GenericStack<Integer>` is not a subtype of `GenericStack<Object>`, even though `Integer` is a subtype of `Object`.

LISTING 19.8 AnyWildCardDemo.java

```

1  public class AnyWildCardDemo {
2      public static void main(String[] args ) {
3          GenericStack<Integer> intStack = new GenericStack<>();
4          intStack.push(1); // 1 is autoboxed into new Integer(1)
5          intStack.push(2);
6          intStack.push(-2);
7
8          print(intStack);
9      }
10
11     /** Prints objects and empties the stack */
12     public static void print(GenericStack<?> stack) {
13         while (!stack.isEmpty()) {
14             System.out.print(stack.pop() + " ");
15         }
16     }
17 }

```

wildcard type

When is the wildcard `<? super T>` needed? Consider the example in Listing 19.9. The example creates a stack of strings in `stack1` (line 3) and a stack of objects in `stack2` (line 4), and invokes `add(stack1, stack2)` (line 8) to add the strings in `stack1` into `stack2`. `GenericStack<? super T>` is used to declare `stack2` in line 13. If `<? super T>` is replaced by `<T>`, a compile error will occur on `add(stack1, stack2)` in line 8, because `stack1`'s type is `GenericStack<String>` and `stack2`'s type is `GenericStack<Object>`. `<? super T>` represents type `T` or a supertype of `T`. `Object` is a supertype of `String`.

LISTING 19.9 SuperWildCardDemo.java

```

1  public class SuperWildCardDemo {
2      public static void main(String[] args) {
3          GenericStack<String> stack1 = new GenericStack<>();
4          GenericStack<Object> stack2 = new GenericStack<>();
5          stack2.push("Java");
6          stack2.push(2);
7          stack1.push("Sun");
8          add(stack1, stack2);
9          AnyWildCardDemo.print(stack2);
10     }
11
12    public static <T> void add(GenericStack<T> stack1,
13        GenericStack<? super T> stack2) { <? Super T> type
14        while (!stack1.isEmpty())
15            stack2.push(stack1.pop());
16    }
17 }
```

This program will also work if the method header in lines 12–13 is modified as follows:

```
public static <T> void add(GenericStack<? extends T> stack1,
    GenericStack<T> stack2)
```

The inheritance relationship involving generic types and wildcard types is summarized in Figure 19.6. In this figure, **A** and **B** represent classes or interfaces, and **E** is a generic type parameter.

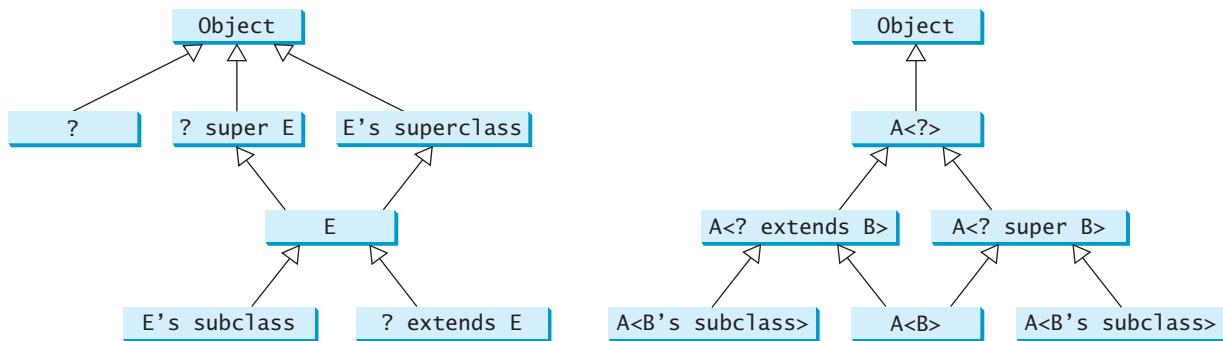


FIGURE 19.6 The relationship between generic types and wildcard types.

19.14 Is `GenericStack` the same as `GenericStack<Object>`?

19.15 What are an unbounded wildcard, a bounded wildcard, and a lower-bound wildcard?

19.16 What happens if lines 12–13 in Listing 19.9 are changed to



```
public static <T> void add(GenericStack<T> stack1,
    GenericStack<T> stack2)
```

19.17 What happens if lines 12–13 in Listing 19.9 are changed to

```
public static <T> void add(GenericStack<? extends T> stack1,
GenericStack<T> stack2)
```

19.8 Erasure and Restrictions on Generics



*The information on generics is used by the compiler but is not available at runtime.
This is called type erasure.*

type erasure

Generics are implemented using an approach called *type erasure*: The compiler uses the generic type information to compile the code, but erases it afterward. Thus, the generic information is not available at runtime. This approach enables the generic code to be backward compatible with the legacy code that uses raw types.

erase generics

The generics are present at compile time. Once the compiler confirms that a generic type is used safely, it converts the generic type to a raw type. For example, the compiler checks whether the following code in (a) uses generics correctly and then translates it into the equivalent code in (b) for runtime use. The code in (b) uses the raw type.

```
ArrayList<String> list = new ArrayList<>();
list.add("Oklahoma");
String state = list.get(0);
```

(a)

```
ArrayList list = new ArrayList();
list.add("Oklahoma");
String state = (String)(list.get(0));
```

(b)

replace generic type

When generic classes, interfaces, and methods are compiled, the compiler replaces the generic type with the **Object** type. For example, the compiler would convert the following method in (a) into (b).

```
public static <E> void print(E[] list) {
    for (int i = 0; i < list.length; i++)
        System.out.print(list[i] + " ");
    System.out.println();
}
```

(a)

```
public static void print(Object[] list) {
    for (int i = 0; i < list.length; i++)
        System.out.print(list[i] + " ");
    System.out.println();
}
```

(b)

replace bounded type

If a generic type is bounded, the compiler replaces it with the bounded type. For example, the compiler would convert the following method in (a) into (b).

```
public static <E extends GeometricObject>
boolean equalArea(
    E object1,
    E object2) {
    return object1.getArea() ==
        object2.getArea();
}
```

(a)

```
public static
boolean equalArea(
    GeometricObject object1,
    GeometricObject object2) {
    return object1.getArea() ==
        object2.getArea();
}
```

(b)

important fact

It is important to note that a generic class is shared by all its instances regardless of its actual concrete type. Suppose **list1** and **list2** are created as follows:

```
ArrayList<String> list1 = new ArrayList<>();
ArrayList<Integer> list2 = new ArrayList<>();
```

Although `ArrayList<String>` and `ArrayList<Integer>` are two types at compile time, only one `ArrayList` class is loaded into the JVM at runtime. `list1` and `list2` are both instances of `ArrayList`, so the following statements display `true`:

```
System.out.println(list1 instanceof ArrayList);
System.out.println(list2 instanceof ArrayList);
```

However, the expression `list1 instanceof ArrayList<String>` is wrong. Since `ArrayList<String>` is not stored as a separate class in the JVM, using it at runtime makes no sense.

Because generic types are erased at runtime, there are certain restrictions on how generic types can be used. Here are some of the restrictions:

Restriction 1: Cannot Use `new E()`

You cannot create an instance using a generic type parameter. For example, the following statement is wrong:

```
E object = new E();
```

no new E()

The reason is that `new E()` is executed at runtime, but the generic type `E` is not available at runtime.

Restriction 2: Cannot Use `new E[]`

You cannot create an array using a generic type parameter. For example, the following statement is wrong:

```
E[] elements = new E[capacity];
```

no new E[capacity]

You can circumvent this limitation by creating an array of the `Object` type and then casting it to `E[]`, as follows:

```
E[] elements = (E[])new Object[capacity];
```

However, casting to `(E[])` causes an unchecked compile warning. The warning occurs because the compiler is not certain that casting will succeed at runtime. For example, if `E` is `String` and `new Object[]` is an array of `Integer` objects, `(String[])(new Object[])` will cause a `ClassCastException`. This type of compile warning is a limitation of Java generics and is unavoidable.

unavoidable compile warning

Generic array creation using a generic class is not allowed, either. For example, the following code is wrong:

```
ArrayList<String>[] list = new ArrayList<String>[10];
```

You can use the following code to circumvent this restriction:

```
ArrayList<String>[] list = (ArrayList<String>[])new
ArrayList[10];
```

However, you will still get a compile warning.

Restriction 3: A Generic Type Parameter of a Class Is Not Allowed in a Static Context

Since all instances of a generic class have the same runtime class, the static variables and methods of a generic class are shared by all its instances. Therefore, it is illegal to refer to

a generic type parameter for a class in a static method, field, or initializer. For example, the following code is illegal:

```
public class Test<E> {
    public static void m(E o1) { // Illegal
    }

    public static E o1; // Illegal

    static {
        E o2; // Illegal
    }
}
```

Restriction 4: Exception Classes Cannot Be Generic

A generic class may not extend `java.lang.Throwable`, so the following class declaration would be illegal:

```
public class MyException<T> extends Exception {
```

Why? If it were allowed, you would have a `catch` clause for `MyException<T>` as follows:

```
try {
    ...
}
catch (MyException<T> ex) {
    ...
}
```

The JVM has to check the exception thrown from the `try` clause to see if it matches the type specified in a `catch` clause. This is impossible, because the type information is not present at runtime.



- 19.18** What is erasure? Why are Java generics implemented using erasure?
- 19.19** If your program uses `ArrayList<String>` and `ArrayList<Date>`, does the JVM load both of them?
- 19.20** Can you create an instance using `new EO` for a generic type `E`? Why?
- 19.21** Can a method that uses a generic class parameter be static? Why?
- 19.22** Can you define a custom generic exception class? Why?

19.9 Case Study: Generic Matrix Class



This section presents a case study on designing classes for matrix operations using generic types.

The addition and multiplication operations for all matrices are similar except that their element types differ. Therefore, you can design a superclass that describes the common operations shared by matrices of all types regardless of their element types, and you can define subclasses tailored to specific types of matrices. This case study gives implementations for two types: `int` and `Rational`. For the `int` type, the wrapper class `Integer` should be used to wrap an `int` value into an object, so that the object is passed in the methods for operations.

The class diagram is shown in Figure 19.7. The methods `addMatrix` and `multiplyMatrix` add and multiply two matrices of a generic type `E[][]`. The static method `printResult` displays the matrices, the operator, and their result. The methods `add`, `multiply`, and `zero` are abstract, because their implementations depend on the specific type of the array elements. For example, the `zero()` method returns `0` for the

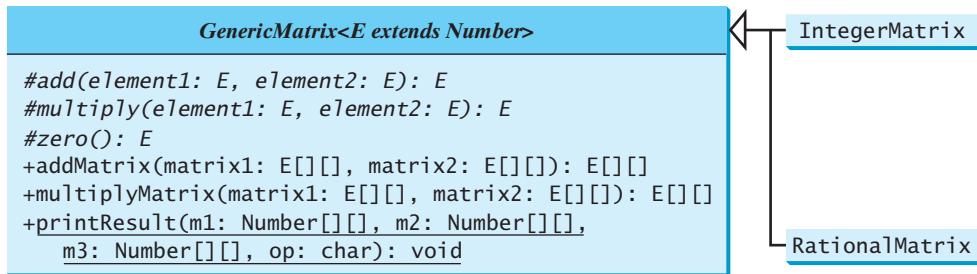


FIGURE 19.7 The `GenericMatrix` class is an abstract superclass for `IntegerMatrix` and `RationalMatrix`.

`Integer` type and `0/1` for the `Rational` type. These methods will be implemented in the subclasses in which the matrix element type is specified.

`IntegerMatrix` and `RationalMatrix` are concrete subclasses of `GenericMatrix`. These two classes implement the `add`, `multiply`, and `zero` methods defined in the `GenericMatrix` class.

Listing 19.10 implements the `GenericMatrix` class. `<E extends Number>` in line 1 specifies that the generic type is a subtype of `Number`. Three abstract methods—`add`, `multiply`, and `zero`—are defined in lines 3, 6, and 9. These methods are abstract because we cannot implement them without knowing the exact type of the elements. The `addMatrix` (lines 12–30) and `multiplyMatrix` (lines 33–57) methods implement the methods for adding and multiplying two matrices. All these methods must be nonstatic, because they use generic type `E` for the class. The `printResult` method (lines 60–84) is static because it is not tied to specific instances.

The matrix element type is a generic subtype of `Number`. This enables you to use an object of any subclass of `Number` as long as you can implement the abstract `add`, `multiply`, and `zero` methods in subclasses.

The `addMatrix` and `multiplyMatrix` methods (lines 12–57) are concrete methods. They are ready to use as long as the `add`, `multiply`, and `zero` methods are implemented in the subclasses.

The `addMatrix` and `multiplyMatrix` methods check the bounds of the matrices before performing operations. If the two matrices have incompatible bounds, the program throws an exception (lines 16, 36).

LISTING 19.10 GenericMatrix.java

```

1  public abstract class GenericMatrix<E extends Number> {
2      /** Abstract method for adding two elements of the matrices */
3      protected abstract E add(E o1, E o2);
4
5      /** Abstract method for multiplying two elements of the matrices */
6      protected abstract E multiply(E o1, E o2);
7
8      /** Abstract method for defining zero for the matrix element */
9      protected abstract E zero();
10
11     /** Add two matrices */
12     public E[][] addMatrix(E[][] matrix1, E[][] matrix2) {
13         // Check bounds of the two matrices
14         if ((matrix1.length != matrix2.length) ||
15             (matrix1[0].length != matrix2[0].length)) {
16             throw new RuntimeException(
17                 "The matrices do not have the same size");
18         }
19

```

bounded generic type
abstract method
abstract method
abstract method
add two matrices

```

20     E[][] result =
21         (E[][])new Number[matrix1.length][matrix1[0].length];
22
23     // Perform addition
24     for (int i = 0; i < result.length; i++) {
25         for (int j = 0; j < result[i].length; j++) {
26             result[i][j] = add(matrix1[i][j], matrix2[i][j]);
27         }
28
29     return result;
30 }
31
32 /** Multiply two matrices */
33 public E[][] multiplyMatrix(E[][] matrix1, E[][] matrix2) {
34     // Check bounds
35     if (matrix1[0].length != matrix2.length) {
36         throw new RuntimeException(
37             "The matrices do not have compatible size");
38     }
39
40     // Create result matrix
41     E[][] result =
42         (E[][])new Number[matrix1.length][matrix2[0].length];
43
44     // Perform multiplication of two matrices
45     for (int i = 0; i < result.length; i++) {
46         for (int j = 0; j < result[0].length; j++) {
47             result[i][j] = zero();
48
49             for (int k = 0; k < matrix1[0].length; k++) {
50                 result[i][j] = add(result[i][j],
51                     multiply(matrix1[i][k], matrix2[k][j]));
52             }
53         }
54     }
55
56     return result;
57 }
58
59 /** Print matrices, the operator, and their operation result */
60 public static void printResult(
61     Number[][] m1, Number[][] m2, Number[][] m3, char op) {
62     for (int i = 0; i < m1.length; i++) {
63         for (int j = 0; j < m1[0].length; j++) {
64             System.out.print(" " + m1[i][j]);
65
66             if (i == m1.length / 2)
67                 System.out.print(" " + op + " ");
68             else
69                 System.out.print("      ");
70
71             for (int j = 0; j < m2.length; j++)
72                 System.out.print(" " + m2[i][j]);
73
74             if (i == m1.length / 2)
75                 System.out.print(" = ");
76             else
77                 System.out.print("      ");
78
79             for (int j = 0; j < m3.length; j++)

```

multiply two matrices

display result

```

80         System.out.print(m3[i][j] + " ");
81     }
82     System.out.println();
83   }
84 }
85 }
```

Listing 19.11 implements the `IntegerMatrix` class. The class extends `GenericMatrix<Integer>` in line 1. After the generic instantiation, the `add` method in `GenericMatrix<Integer>` is now `Integer add(Integer o1, Integer o2)`. The `add`, `multiply`, and `zero` methods are implemented for `Integer` objects. These methods are still protected, because they are invoked only by the `addMatrix` and `multiplyMatrix` methods.

LISTING 19.11 IntegerMatrix.java

```

1 public class IntegerMatrix extends GenericMatrix<Integer> {
2   @Override /** Add two integers */
3   protected Integer add(Integer o1, Integer o2) {
4     return o1 + o2;
5   }
6
7   @Override /** Multiply two integers */
8   protected Integer multiply(Integer o1, Integer o2) {
9     return o1 * o2;
10  }
11
12  @Override /** Specify zero for an integer */
13  protected Integer zero() {
14    return 0;
15  }
16 }
```

extends generic type	
implement add	
	implement multiply
	implement zero

Listing 19.12 implements the `RationalMatrix` class. The `Rational` class was introduced in Listing 13.13 Rational.java. `Rational` is a subtype of `Number`. The `RationalMatrix` class extends `GenericMatrix<Rational>` in line 1. After the generic instantiation, the `add` method in `GenericMatrix<Rational>` is now `Rational add(Rational r1, Rational r2)`. The `add`, `multiply`, and `zero` methods are implemented for `Rational` objects. These methods are still protected, because they are invoked only by the `addMatrix` and `multiplyMatrix` methods.

LISTING 19.12 RationalMatrix.java

```

1 public class RationalMatrix extends GenericMatrix<Rational> {
2   @Override /** Add two rational numbers */
3   protected Rational add(Rational r1, Rational r2) {
4     return r1.add(r2);
5   }
6
7   @Override /** Multiply two rational numbers */
8   protected Rational multiply(Rational r1, Rational r2) {
9     return r1.multiply(r2);
10  }
11
12  @Override /** Specify zero for a Rational number */
13  protected Rational zero() {
14    return new Rational(0, 1);
15  }
16 }
```

extends generic type	
implement add	
	implement multiply
	implement zero

Listing 19.13 gives a program that creates two `Integer` matrices (lines 4–5) and an `IntegerMatrix` object (line 8), and adds and multiplies two matrices in lines 12 and 16.

LISTING 19.13 TestIntegerMatrix.java

```

1  public class TestIntegerMatrix {
2    public static void main(String[] args) {
3      // Create Integer arrays m1, m2
4      Integer[][] m1 = new Integer[][]{{1, 2, 3}, {4, 5, 6}, {1, 1, 1}};
5      Integer[][] m2 = new Integer[][]{{1, 1, 1}, {2, 2, 2}, {0, 0, 0}};
6
7      // Create an instance of IntegerMatrix
8      IntegerMatrix integerMatrix = new IntegerMatrix();
9
10     System.out.println("\nm1 + m2 is ");
11     GenericMatrix.printResult(
12       m1, m2, integerMatrix.addMatrix(m1, m2), '+');
13
14     System.out.println("\nm1 * m2 is ");
15     GenericMatrix.printResult(
16       m1, m2, integerMatrix.multiplyMatrix(m1, m2), '*');
17   }
18 }
```



```

m1 + m2 is
1 2 3      1 1 1      2 3 4
4 5 6  +  2 2 2  =  6 7 8
1 1 1      0 0 0      1 1 1

m1 * m2 is
1 2 3      1 1 1      5 5 5
4 5 6  *  2 2 2  =  14 14 14
1 1 1      0 0 0      3 3 3

```

Listing 19.14 gives a program that creates two `Rational` matrices (lines 4–10) and a `RationalMatrix` object (line 13) and adds and multiplies two matrices in lines 17 and 19.

LISTING 19.14 TestRationalMatrix.java

```

1  public class TestRationalMatrix {
2    public static void main(String[] args) {
3      // Create two Rational arrays m1 and m2
4      Rational[][] m1 = new Rational[3][3];
5      Rational[][] m2 = new Rational[3][3];
6      for (int i = 0; i < m1.length; i++) {
7        for (int j = 0; j < m1[0].length; j++) {
8          m1[i][j] = new Rational(i + 1, j + 5);
9          m2[i][j] = new Rational(i + 1, j + 6);
10         }
11
12      // Create an instance of RationalMatrix
13      RationalMatrix rationalMatrix = new RationalMatrix();
14
15      System.out.println("\nm1 + m2 is ");
16      GenericMatrix.printResult(
17        m1, m2, rationalMatrix.addMatrix(m1, m2), '+');
18
19      System.out.println("\nm1 * m2 is ");

```

```

20     GenericMatrix.printResult(
21         m1, m2, rationalMatrix.multiplyMatrix(m1, m2), '*');
22     }
23 }
```

multiply two matrices



```

m1 + m2 is
1/5 1/6 1/7      1/6 1/7 1/8      11/30 13/42 15/56
2/5 1/3 2/7 +   1/3 2/7 1/4 =   11/15 13/21 15/28
3/5 1/2 3/7      1/2 3/7 3/8      11/10 13/14 45/56

m1 * m2 is
1/5 1/6 1/7      1/6 1/7 1/8      101/630 101/735 101/840
2/5 1/3 2/7 *   1/3 2/7 1/4 =   101/315 202/735 101/420
3/5 1/2 3/7      1/2 3/7 3/8      101/210 101/245 101/280

```



- 19.23** Why are the `add`, `multiple`, and `zero` methods defined abstract in the `GenericMatrix` class?
- 19.24** How are the `add`, `multiple`, and `zero` methods implemented in the `IntegerMatrix` class?
- 19.25** How are the `add`, `multiple`, and `zero` methods implemented in the `RationalMatrix` class?
- 19.26** What would be wrong if the `printResult` method defined as follows?

```
public static void printResult(
    E[][] m1, E[][] m2, E[][] m3, char op)
```

Key Terms

actual concrete type	738	generic instantiation	738
bounded generic type	743	lower-bound wildcard	
bounded wildcard		(<code><? super E></code>)	748
(<code><? extends E></code>)	748	raw type	746
formal generic type	738	unbounded wildcard (<code><?></code>)	748

CHAPTER SUMMARY

1. *Generics* give you the capability to parameterize types. You can define a class or a method with generic types, which the compiler replaces with concrete types.
2. The key benefit of generics is to enable errors to be detected at compile time rather than at runtime.
3. A generic class or method permits you to specify allowable types of objects that the class or method can work with. If you attempt to use a class or method with an incompatible object, the compiler will detect the error.
4. A generic type defined in a class, interface, or a static method is called a *formal generic type*, which can be replaced later with an *actual concrete type*. Replacing a generic type is called a *generic instantiation*.

5. A generic class such as `ArrayList` used without a type parameter is called a *raw type*. Use of raw types is allowed for backward compatibility with the earlier versions of Java.
6. A wildcard generic type has three forms: `? extends T`, and `? super T`, where `T` is a generic type. The first form, `?`, called an *unbounded wildcard*, is the same as `? extends Object`. The second form, `? extends T`, called a *bounded wildcard*, represents `T` or a subtype of `T`. The third form, `? super T`, called a *lower-bound wildcard*, denotes `T` or a supertype of `T`.
7. Generics are implemented using an approach called *type erasure*. The compiler uses the generic type information to compile the code but erases it afterward, so the generic information is not available at runtime. This approach enables the generic code to be backward compatible with the legacy code that uses raw types.
8. You cannot create an instance using a generic type parameter.
9. You cannot create an array using a generic type parameter.
10. You cannot use a generic type parameter of a class in a static context.
11. Generic type parameters cannot be used in exception classes.

Quiz

Answer the quiz for this chapter online at www.cs.armstrong.edu/liang/intro10e/quiz.html.

MyProgrammingLab™

PROGRAMMING EXERCISES

- 19.1** (*Revising Listing 19.1*) Revise the `GenericStack` class in Listing 19.1 to implement it using an array rather than an `ArrayList`. You should check the array size before adding a new element to the stack. If the array is full, create a new array that doubles the current array size and copy the elements from the current array to the new array.
 - 19.2** (*Implement `GenericStack` using inheritance*) In Listing 19.1, `GenericStack` is implemented using composition. Define a new stack class that extends `ArrayList`. Draw the UML diagram for the classes and then implement `GenericStack`. Write a test program that prompts the user to enter five strings and displays them in reverse order.
 - 19.3** (*Distinct elements in `ArrayList`*) Write the following method that returns a new `ArrayList`. The new list contains the non-duplicate elements from the original list.
- ```
public static <E> ArrayList<E> removeDuplicates(ArrayList<E> list)
```
- 19.4** (*Generic linear search*) Implement the following generic method for linear search.
- ```
public static <E extends Comparable<E>>
    int linearSearch(E[] list, E key)
```
- 19.5** (*Maximum element in an array*) Implement the following method that returns the maximum element in an array.
- ```
public static <E extends Comparable<E>> E max(E[] list)
```

- 19.6** (*Maximum element in a two-dimensional array*) Write a generic method that returns the maximum element in a two-dimensional array.

```
public static <E extends Comparable<E>> E max(E[][] list)
```

- 19.7** (*Generic binary search*) Implement the following method using binary search.

```
public static <E extends Comparable<E>>
 int binarySearch(E[] list, E key)
```

- 19.8** (*Shuffle ArrayList*) Write the following method that shuffles an **ArrayList**:

```
public static <E> void shuffle(ArrayList<E> list)
```

- 19.9** (*Sort ArrayList*) Write the following method that sorts an **ArrayList**:

```
public static <E extends Comparable<E>>
 void sort(ArrayList<E> list)
```

- 19.10** (*Largest element in ArrayList*) Write the following method that returns the largest element in an **ArrayList**:

```
public static <E extends Comparable<E>> E max(ArrayList<E> list)
```

- 19.11** (*ComplexMatrix*) Use the **Complex** class introduced in Programming Exercise 13.17 to develop the **ComplexMatrix** class for performing matrix operations involving complex numbers. The **ComplexMatrix** class should extend the **GenericMatrix** class and implement the **add**, **multiple**, and **zero** methods. You need to modify **GenericMatrix** and replace every occurrence of **Number** by **Object**, because **Complex** is not a subtype of **Number**. Write a test program that creates the following two matrices and displays the result of addition and multiplication of the matrices by invoking the **printResult** method.

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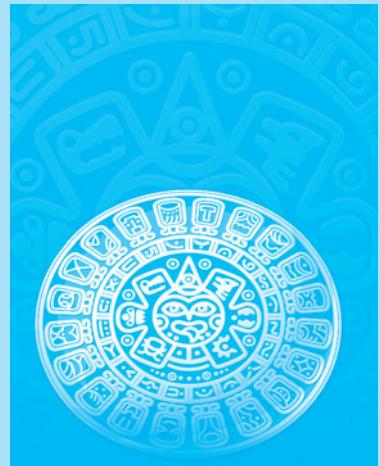
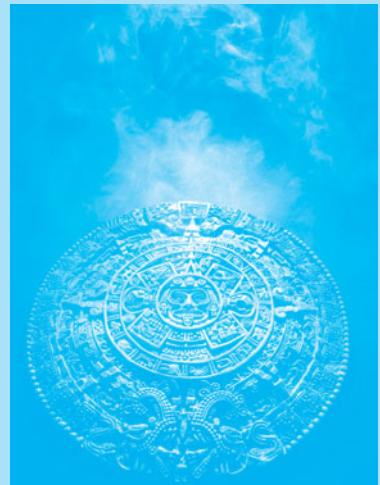
# CHAPTER

# 20

## LISTS, STACKS, QUEUES, AND PRIORITY QUEUES

### Objectives

- To explore the relationship between interfaces and classes in the Java Collections Framework hierarchy (§20.2).
- To use the common methods defined in the **Collection** interface for operating collections (§20.2).
- To use the **Iterator** interface to traverse the elements in a collection (§20.3).
- To use a foreach loop to traverse the elements in a collection (§20.3).
- To explore how and when to use **ArrayList** or **LinkedList** to store a list of elements (§20.4).
- To compare elements using the **Comparable** interface and the **Comparator** interface (§20.5).
- To use the static utility methods in the **Collections** class for sorting, searching, shuffling lists, and finding the largest and smallest element in collections (§20.6).
- To develop a multiple bouncing balls application using **ArrayList** (§20.7).
- To distinguish between **Vector** and **ArrayList** and to use the **Stack** class for creating stacks (§20.8).
- To explore the relationships among **Collection**, **Queue**, **LinkedList**, and **PriorityQueue** and to create priority queues using the **PriorityQueue** class (§20.9).
- To use stacks to write a program to evaluate expressions (§20.10).



## 20.1 Introduction



data structure

container

Java Collections Framework

*Choosing the best data structures and algorithms for a particular task is one of the keys to developing high-performance software.*

A *data structure* is a collection of data organized in some fashion. The structure not only stores data but also supports operations for accessing and manipulating the data.

In object-oriented thinking, a data structure, also known as a *container* or *container object*, is an object that stores other objects, referred to as data or elements. To define a data structure is essentially to define a class. The class for a data structure should use data fields to store data and provide methods to support such operations as search, insertion, and deletion. To create a data structure is therefore to create an instance from the class. You can then apply the methods on the instance to manipulate the data structure, such as inserting an element into or deleting an element from the data structure.

Section 11.11 introduced the **ArrayList** class, which is a data structure to store elements in a list. Java provides several more data structures that can be used to organize and manipulate data efficiently. These are commonly known as *Java Collections Framework*. We will introduce the applications of lists, vectors, stacks, queues, and priority queues in this chapter and sets and maps in the next chapter. The implementation of these data structures will be discussed in Chapters 24–27.

## 20.2 Collections



*The **Collection** interface defines the common operations for lists, vectors, stacks, queues, priority queues, and sets.*

collection

map

Set

List

Stack

Queue

PriorityQueue

The Java Collections Framework supports two types of containers:

- One for storing a collection of elements is simply called a *collection*.
- The other, for storing key/value pairs, is called a *map*.

Maps are efficient data structures for quickly searching an element using a key. We will introduce maps in the next chapter. Now we turn our attention to the following collections.

- **Sets** store a group of nonduplicate elements.
- **Lists** store an ordered collection of elements.
- **Stacks** store objects that are processed in a last-in, first-out fashion.
- **Queues** store objects that are processed in a first-in, first-out fashion.
- **PriorityQueues** store objects that are processed in the order of their priorities.

The common features of these collections are defined in the interfaces, and implementations are provided in concrete classes, as shown in Figure 20.1.



### Note

All the interfaces and classes defined in the Java Collections Framework are grouped in the **java.util** package.



### Design Guide

The design of the Java Collections Framework is an excellent example of using interfaces, abstract classes, and concrete classes. The interfaces define the framework. The abstract classes provide partial implementation. The concrete classes implement the interfaces with concrete data structures. Providing an abstract class that partially implements an interface makes it convenient for the user to write the code. The user can simply define



**FIGURE 20.1** A collection is a container that stores objects.

a concrete class that extends the abstract class rather implements all the methods in the interface. The abstract classes such as **AbstractCollection** are provided for convenience. For this reason, they are called *convenience abstract classes*.

convenience abstract class

The **Collection** interface is the root interface for manipulating a collection of objects. Its public methods are listed in Figure 20.2. The **AbstractCollection** class provides partial implementation for the **Collection** interface. It implements all the methods in **Collection** except the **add**, **size**, and **iterator** methods. These are implemented in appropriate concrete subclasses.

basic operations

The **Collection** interface provides the basic operations for adding and removing elements in a collection. The **add** method adds an element to the collection. The **addAll** method adds all the elements in the specified collection to this collection. The **remove** method removes an element from the collection. The **removeAll** method removes the elements from this collection that are present in the specified collection. The **retainAll** method retains the elements in this collection that are also present in the specified collection. All these methods return **boolean**. The return value is **true** if the collection is changed as a result of the method execution. The **clear()** method simply removes all the elements from the collection.



### Note

The methods **addAll**, **removeAll**, and **retainAll** are similar to the set union, difference, and intersection operations.

set operations

The **Collection** interface provides various query operations. The **size** method returns the number of elements in the collection. The **contains** method checks whether the collection contains the specified element. The **containsAll** method checks whether the collection contains all the elements in the specified collection. The **isEmpty** method returns **true** if the collection is empty.

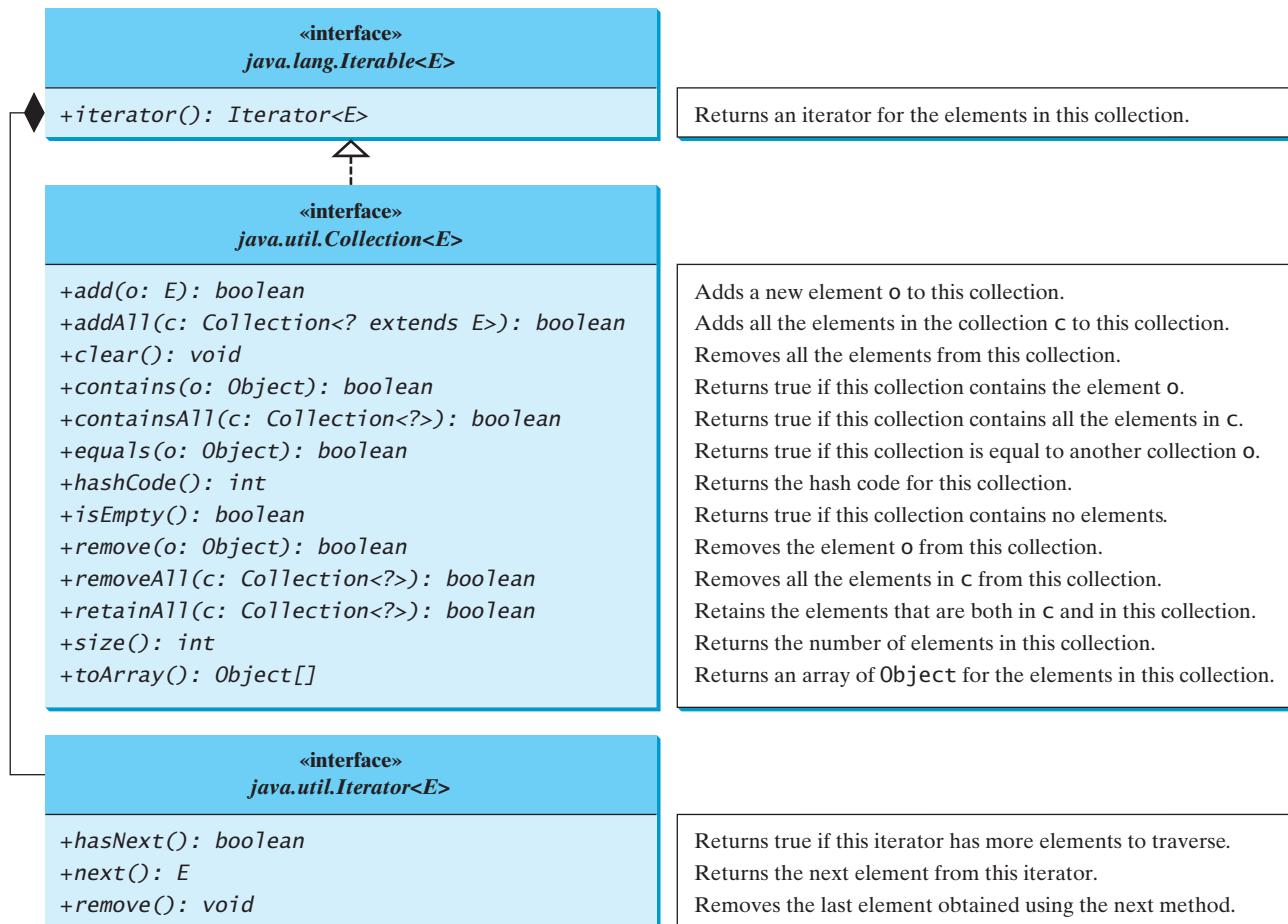
query operations

The **Collection** interface provides the **toArray()** method, which returns an array representation for the collection.



### Design Guide

Some of the methods in the **Collection** interface cannot be implemented in the concrete subclass. In this case, the method would throw **java.lang**



**FIGURE 20.2** The `Collection` interface contains the methods for manipulating the elements in a collection, and you can obtain an iterator object for traversing elements in the collection.

unsupported operations

.`UnsupportedOperationException`, a subclass of `RuntimeException`.

This is a good design that you can use in your project. If a method has no meaning in the subclass, you can implement it as follows:

```

public void someMethod() {
 throw new UnsupportedOperationException
 ("Method not supported");
}

```

Listing 20.1 gives an example to use the methods defined in the `Collection` interface.

### LISTING 20.1 TestCollection.java

```

1 import java.util.*;
2
3 public class TestCollection {
4 public static void main(String[] args) {
5 ArrayList<String> collection1 = new ArrayList<>();
6 collection1.add("New York");
7 collection1.add("Atlanta");
8 collection1.add("Dallas");
9 collection1.add("Madison");

```

create an array list  
add elements

```

10
11 System.out.println("A list of cities in collection1:");
12 System.out.println(collection1);
13
14 System.out.println("\nIs Dallas in collection1? "
15 + collection1.contains("Dallas")); contains?
16
17 collection1.remove("Dallas");
18 System.out.println("\n" + collection1.size() + size?
19 " cities are in collection1 now");
20
21 Collection<String> collection2 = new ArrayList<>();
22 collection2.add("Seattle");
23 collection2.add("Portland");
24 collection2.add("Los Angeles");
25 collection2.add("Atlanta");
26
27 System.out.println("\nA list of cities in collection2:");
28 System.out.println(collection2);
29
30 ArrayList<String> c1 = (ArrayList<String>)(collection1.clone()); clone
31 c1.addAll(collection2); addAll
32 System.out.println("\nCities in collection1 or collection2: ");
33 System.out.println(c1);
34
35 c1 = (ArrayList<String>)(collection1.clone());
36 c1.retainAll(collection2); retainAll
37 System.out.print("\nCities in collection1 and collection2: ");
38 System.out.println(c1);
39
40 c1 = (ArrayList<String>)(collection1.clone());
41 c1.removeAll(collection2); removeAll
42 System.out.print("\nCities in collection1, but not in 2: ");
43 System.out.println(c1);
44 }
45 }
```

```

A list of cities in collection1:
[New York, Atlanta, Dallas, Madison]
Is Dallas in collection1? true
3 cities are in collection1 now
A list of cities in collection2:
[Seattle, Portland, Los Angeles, Atlanta]
Cities in collection1 or collection2:
[New York, Atlanta, Madison, Seattle, Portland, Los Angeles, Atlanta]
Cities in collection1 and collection2: [Atlanta]
Cities in collection1, but not in 2: [New York, Madison]
```



The program creates a concrete collection object using `ArrayList` (line 5), and invokes the `Collection` interface's `contains` method (line 15), `remove` method (line 17), `size` method (line 18), `addAll` method (line 31), `retainAll` method (line 36), and `removeAll` method (line 41).

For this example, we use `ArrayList`. You can use any concrete class of `Collection` such as `HashSet`, `LinkedList`, `Vector`, and `Stack` to replace `ArrayList` to test these methods defined in the `Collection` interface.

The program creates a copy of an array list (lines 30, 35, 40). The purpose of this is to keep the original array list intact and use its copy to perform `addAll`, `retainAll`, and `removeAll` operations.

Cloneable  
Serializable



### Note

All the concrete classes in the Java Collections Framework implement the `java.lang.Cloneable` and `java.io.Serializable` interfaces except that `java.util.PriorityQueue` does not implement the `Cloneable` interface. Thus, all instances of `Cloneable` except priority queues can be cloned and all instances of `Cloneable` can be serialized.

#### 20.1 What is a data structure?

- 20.2 Describe the Java Collections Framework. List the interfaces, convenience abstract classes, and concrete classes under the `Collection` interface.
- 20.3 Can a collection object be cloned and serialized?
- 20.4 What method do you use to add all the elements from one collection to another collection?
- 20.5 When should a method throw an `UnsupportedOperationException`?



## 20.3 Iterators

*Each collection is `Iterable`. You can obtain its `Iterator` object to traverse all the elements in the collection.*

`Iterator` is a classic design pattern for walking through a data structure without having to expose the details of how data is stored in the data structure.

The `Collection` interface extends the `Iterable` interface. The `Iterable` interface defines the `iterator` method, which returns an iterator. The `Iterator` interface provides a uniform way for traversing elements in various types of collections. The `iterator()` method in the `Iterable` interface returns an instance of `Iterator`, as shown in Figure 20.2, which provides sequential access to the elements in the collection using the `next()` method. You can also use the `hasNext()` method to check whether there are more elements in the iterator, and the `remove()` method to remove the last element returned by the iterator.

Listing 20.2 gives an example that uses the iterator to traverse all the elements in an array list.

### LISTING 20.2 TestIterator.java

create an array list  
add elements

iterator  
hasNext()  
next()

```

1 import java.util.*;
2
3 public class TestIterator {
4 public static void main(String[] args) {
5 Collection<String> collection = new ArrayList<>();
6 collection.add("New York");
7 collection.add("Atlanta");
8 collection.add("Dallas");
9 collection.add("Madison");
10
11 Iterator<String> iterator = collection.iterator();
12 while (iterator.hasNext()) {
13 System.out.print(iterator.next().toUpperCase() + " ");
14 }
15 System.out.println();
16 }
17 }
```

NEW YORK ATLANTA DALLAS MADISON



The program creates a concrete collection object using `ArrayList` (line 5) and adds four strings into the list (lines 6–9). The program then obtains an iterator for the collection (line 11) and uses the iterator to traverse all the strings in the list and displays the strings in uppercase (lines 12–14).

**Tip**

You can simplify the code in lines 11–14 using a foreach loop without using an iterator, as follows:

```
for (String element: collection)
 System.out.print(element.toUpperCase() + " ");
```

This loop is read as “for each element in the collection, do the following.” The foreach loop can be used for arrays (see Section 7.2.7) as well as any instance of `Iterable`.

foreach loop

**20.6** How do you obtain an iterator from a collection object?

**20.7** What method do you use to obtain an element in the collection from an iterator?

**20.8** Can you use a foreach loop to traverse the elements in any instance of `Collection`?

**20.9** When using a foreach loop to traverse all elements in a collection, do you need to use the `next()` or `hasNext()` methods in an iterator?



Check Point



Key Point

## 20.4 Lists

The `List` interface extends the `Collection` interface and defines a collection for storing elements in a sequential order. To create a list, use one of its two concrete classes: `ArrayList` or `LinkedList`.

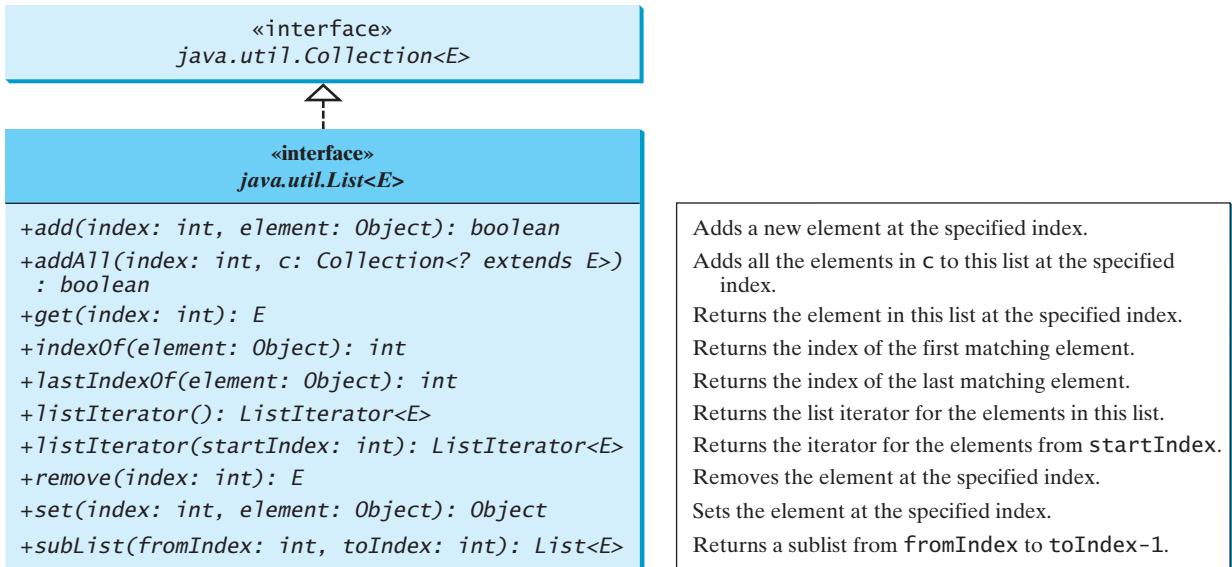
We used `ArrayList` to test the methods in the `Collection` interface in the preceding sections. Now we will examine `ArrayList` in more depth. We will also introduce another useful list, `LinkedList`, in this section.

### 20.4.1 The Common Methods in the `List` Interface

`ArrayList` and `LinkedList` are defined under the `List` interface. The `List` interface extends `Collection` to define an ordered collection with duplicates allowed. The `List` interface adds position-oriented operations, as well as a new list iterator that enables the user to traverse the list bidirectionally. The methods introduced in the `List` interface are shown in Figure 20.3.

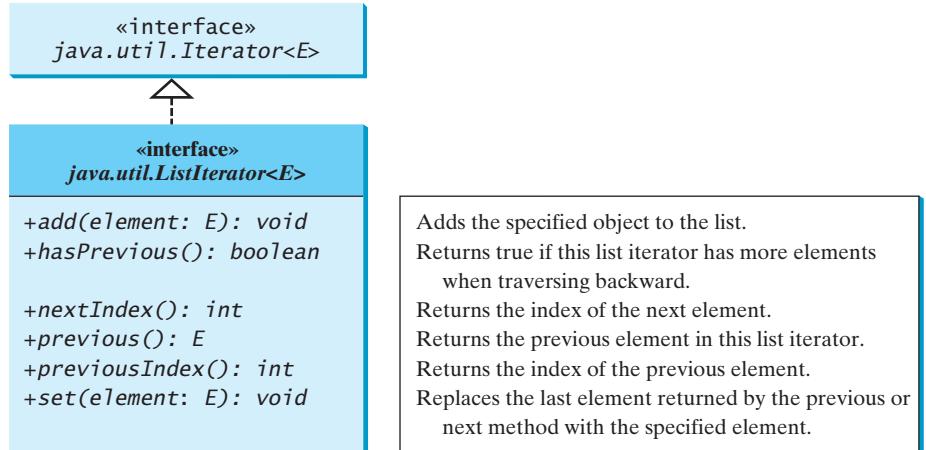
The `add(index, element)` method is used to insert an element at a specified index, and the `addAll(index, collection)` method to insert a collection of elements at a specified index. The `remove(index)` method is used to remove an element at the specified index from the list. A new element can be set at the specified index using the `set(index, element)` method.

The `indexOf(element)` method is used to obtain the index of the specified element’s first occurrence in the list, and the `lastIndexOf(element)` method to obtain the index of its last occurrence. A sublist can be obtained by using the `subList(fromIndex, toIndex)` method.



**FIGURE 20.3** The `List` interface stores elements in sequence and permits duplicates.

The `listIterator()` or `listIterator(startIndex)` method returns an instance of `ListIterator`. The `ListIterator` interface extends the `Iterator` interface to add bidirectional traversal of the list. The methods in `ListIterator` are listed in Figure 20.4.



**FIGURE 20.4** `ListIterator` enables traversal of a list bidirectionally.

The `add(element)` method inserts the specified element into the list. The element is inserted immediately before the next element that would be returned by the `next()` method defined in the `Iterator` interface, if any, and after the element that would be returned by the `previous()` method, if any. If the list doesn't contain any elements, the new element becomes the sole element in the list. The `set(element)` method can be used to replace the last element returned by the `next` method or the `previous` method with the specified element.

The `hasNext()` method defined in the `Iterator` interface is used to check whether the iterator has more elements when traversed in the forward direction, and the `hasPrevious()`

method to check whether the iterator has more elements when traversed in the backward direction.

The `next()` method defined in the `Iterator` interface returns the next element in the iterator, and the `previous()` method returns the previous element in the iterator. The `nextIndex()` method returns the index of the next element in the iterator, and the `previousIndex()` returns the index of the previous element in the iterator.

The `AbstractList` class provides a partial implementation for the `List` interface. The `AbstractSequentialList` class extends `AbstractList` to provide support for linked lists.

## 20.4.2 The `ArrayList` and `LinkedList` Classes

The `ArrayList` class and the `LinkedList` class are two concrete implementations of the `List` interface. `ArrayList` stores elements in an array. The array is dynamically created. If the capacity of the array is exceeded, a larger new array is created and all the elements from the current array are copied to the new array. `LinkedList` stores elements in a *linked list*. Which of the two classes you use depends on your specific needs. If you need to support random access through an index without inserting or removing elements at the beginning of the list, `ArrayList` offers the most efficient collection. If, however, your application requires the insertion or deletion of elements at the beginning of the list, you should choose `LinkedList`. A list can grow or shrink dynamically. Once it is created, an array is fixed. If your application does not require the insertion or deletion of elements, an array is the most efficient data structure.

`ArrayList` is a resizable-array implementation of the `List` interface. It also provides methods for manipulating the size of the array used internally to store the list, as shown in Figure 20.5. Each `ArrayList` instance has a capacity, which is the size of the array used to store the elements in the list. It is always at least as large as the list size. As elements are added to an `ArrayList`, its capacity grows automatically. An `ArrayList` does not automatically shrink. You can use the `trimToSize()` method to reduce the array capacity to the size of the list. An `ArrayList` can be constructed using its no-arg constructor, `ArrayList(Collection)`, or `ArrayList(initialCapacity)`.

ArrayList vs. LinkedList

linked list

trimToSize()

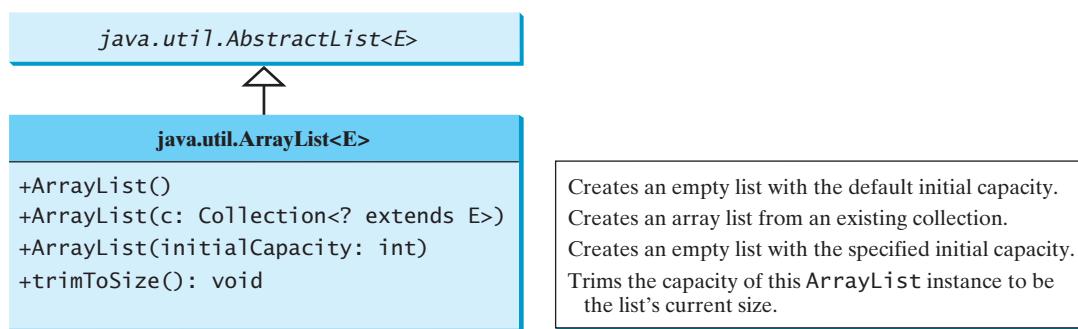


FIGURE 20.5 `ArrayList` implements `List` using an array.

`LinkedList` is a linked list implementation of the `List` interface. In addition to implementing the `List` interface, this class provides the methods for retrieving, inserting, and removing elements from both ends of the list, as shown in Figure 20.6. A `LinkedList` can be constructed using its no-arg constructor or `LinkedList(Collection)`.



**FIGURE 20.6** `LinkedList` provides methods for adding and inserting elements at both ends of the list.

Listing 20.3 gives a program that creates an array list filled with numbers and inserts new elements into specified locations in the list. The example also creates a linked list from the array list and inserts and removes elements from the list. Finally, the example traverses the list forward and backward.

### LISTING 20.3 TestArrayAndLinkedList.java

```

1 import java.util.*;
2
3 public class TestArrayAndLinkedList {
4 public static void main(String[] args) {
5 List<Integer> arrayList = new ArrayList<>();
6 arrayList.add(1); // 1 is autoboxed to new Integer(1)
7 arrayList.add(2);
8 arrayList.add(3);
9 arrayList.add(1);
10 arrayList.add(4);
11 arrayList.add(0, 10);
12 arrayList.add(3, 30);
13
14 System.out.println("A list of integers in the array list:");
15 System.out.println(arrayList);
16
array list
17 LinkedList<Object> linkedList = new LinkedList<>(arrayList);
18 linkedList.add(1, "red");
19 linkedList.removeLast();
20 linkedList.addFirst("green");
21
linked list
22 System.out.println("Display the linked list forward:");
23 ListIterator<Object> listIterator = linkedList.listIterator();
24 while (listIterator.hasNext()) {
25 System.out.print(listIterator.next() + " ");
26 }
27 System.out.println();
28
list iterator
29 System.out.println("Display the linked list backward:");
30 listIterator = linkedList.listIterator(linkedList.size());
31 while (listIterator.hasPrevious()) {
32 System.out.print(listIterator.previous() + " ");
33 }
34 }
35 }

```



```
A list of integers in the array list:
[10, 1, 2, 30, 3, 1, 4]
Display the linked list forward:
green 10 red 1 2 30 3 1
Display the linked list backward:
1 3 30 2 1 red 10 green
```

A list can hold identical elements. Integer 1 is stored twice in the list (lines 6, 9). `ArrayList` and `LinkedList` operate similarly. The critical difference between them pertains to internal implementation, which affects their performance. `ArrayList` is efficient for retrieving elements and `LinkedList` is efficient for inserting and removing elements at the beginning of the list. Both have the same performance for inserting and removing elements in the middle or at the end of the list.

The `get(i)` method is available for a linked list, but it is a time-consuming operation. Do not use it to traverse all the elements in a list as shown in (a). Instead you should use an iterator as shown in (b). Note that a `foreach` loop uses an iterator implicitly. You will know the reason when you learn how to implement a linked list in Chapter 24.

```
for (int i = 0; i < list.size(); i++) {
 process list.get(i);
}
```

(a) Very inefficient

```
for (ListElementType s: list) {
 process s;
}
```

(b) Efficient

**Tip**

Java provides the static `asList` method for creating a list from a variable-length list of arguments. Thus you can use the following code to create a list of strings and a list of integers:

```
List<String> list1 = Arrays.asList("red", "green", "blue");
List<Integer> list2 = Arrays.asList(10, 20, 30, 40, 50);
```

`Arrays.asList(T... a)`  
method



**20.10** How do you add and remove elements from a list? How do you traverse a list in both directions?

**20.11** Suppose that `list1` is a list that contains the strings `red`, `yellow`, and `green`, and that `list2` is another list that contains the strings `red`, `yellow`, and `blue`. Answer the following questions:

- What are `list1` and `list2` after executing `list1.addAll(list2)`?
- What are `list1` and `list2` after executing `list1.add(list2)`?
- What are `list1` and `list2` after executing `list1.removeAll(list2)`?
- What are `list1` and `list2` after executing `list1.remove(list2)`?
- What are `list1` and `list2` after executing `list1.retainAll(list2)`?
- What is `list1` after executing `list1.clear()`?

**20.12** What are the differences between `ArrayList` and `LinkedList`? Which list should you use to insert and delete elements at the beginning of a list?

**20.13** Are all the methods in `ArrayList` also in `LinkedList`? What methods are in `LinkedList` but not in `ArrayList`?

**20.14** How do you create a list from an array of objects?

## 20.5 The Comparator Interface



**Comparator** can be used to compare the objects of a class that doesn't implement **Comparable**.

You have learned how to compare elements using the **Comparable** interface (introduced in Section 13.6). Several classes in the Java API, such as **String**, **Date**, **Calendar**, **BigInteger**, **BigDecimal**, and all the numeric wrapper classes for the primitive types, implement the **Comparable** interface. The **Comparable** interface defines the **compareTo** method, which is used to compare two elements of the same class that implement the **Comparable** interface.

comparator

What if the elements' classes do not implement the **Comparable** interface? Can these elements be compared? You can define a *comparator* to compare the elements of different classes. To do so, define a class that implements the **java.util.Comparator<T>** interface and overrides its **compare** method.

```
public int compare(T element1, T element2)
```

Returns a negative value if **element1** is less than **element2**, a positive value if **element1** is greater than **element2**, and zero if they are equal.

The **GeometricObject** class was introduced in Section 13.2, Abstract Classes. The **GeometricObject** class does not implement the **Comparable** interface. To compare the objects of the **GeometricObject** class, you can define a comparator class, as shown in Listing 20.4.

### LISTING 20.4 GeometricObjectComparator.java

implements Comparator  
implements compare

```
1 import java.util.Comparator;
2
3 public class GeometricObjectComparator
4 implements Comparator<GeometricObject>, java.io.Serializable {
5 public int compare(GeometricObject o1, GeometricObject o2) {
6 double area1 = o1.getArea();
7 double area2 = o2.getArea();
8
9 if (area1 < area2)
10 return -1;
11 else if (area1 == area2)
12 return 0;
13 else
14 return 1;
15 }
16 }
```

Line 4 implements **Comparator<GeometricObject>**. Line 5 overrides the **compare** method to compare two geometric objects. The class also implements **Serializable**. It is generally a good idea for comparators to implement **Serializable**, as they may be used as ordering methods in serializable data structures. In order for the data structure to serialize successfully, the comparator (if provided) must implement **Serializable**.

Listing 20.5 gives a method that returns a larger object between two geometric objects. The objects are compared using the **GeometricObjectComparator**.

### LISTING 20.5 TestComparator.java

```
1 import java.util.Comparator;
2
3 public class TestComparator {
4 public static void main(String[] args) {
```

```

5 GeometricObject g1 = new Rectangle(5, 5);
6 GeometricObject g2 = new Circle(5);
7
8 GeometricObject g =
9 max(g1, g2, new GeometricObjectComparator()); invoke max
10
11 System.out.println("The area of the larger object is " +
12 g.getArea());
13}
14
15 public static GeometricObject max(GeometricObject g1,
16 GeometricObject g2, Comparator<GeometricObject> c) { the max method
17 if (c.compare(g1, g2) > 0) invoke compare
18 return g1;
19 else
20 return g2;
21 }
22 }
```

The area of the larger object is 78.53981633974483



The program creates a `Rectangle` and a `Circle` object in lines 5–6 (the `Rectangle` and `Circle` classes were defined in Section 13.2, Abstract Classes). They are all subclasses of `GeometricObject`. The program invokes the `max` method to obtain the geometric object with the larger area (lines 8–9).

The `GeometricObjectComparator` is created and passed to the `max` method (line 9) and this comparator is used in the `max` method to compare the geometric objects in line 17.



### Note

`Comparable` is used to compare the objects of the class that implement `Comparable`.

`Comparator` can be used to compare the objects of a class that doesn't implement `Comparable`.

Comparable vs. Comparator

Comparing elements using the `Comparable` interface is referred to as comparing using *natural order*, and comparing elements using the `Comparator` interface is referred to as comparing using *comparator*.

natural order  
using comparator

**20.15** What are the differences between the `Comparable` interface and the `Comparator` interface? In which package is `Comparable`, and in which package is `Comparator`?



**20.16** How do you define a class `A` that implements the `Comparable` interface? Are two instances of class `A` comparable? How do you define a class `B` that implements the `Comparator` interface and override the `compare` method to compare to objects of type `B1`? How do you invoke the `sort` method to sort a list of objects of the type `B1`?

## 20.6 Static Methods for Lists and Collections

The `Collections` class contains static methods to perform common operations in a collection and a list.



Section 11.12 introduced several static methods in the `Collections` class for array lists. The `Collections` class contains the `sort`, `binarySearch`, `reverse`, `shuffle`, `copy`, and `fill` methods for lists, and `max`, `min`, `disjoint`, and `frequency` methods for collections, as shown in Figure 20.7.

| java.util.Collections |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
|-----------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| List                  | +sort(list: List): void<br>+sort(list: List, c: Comparator): void<br>+binarySearch(list: List, key: Object): int<br>+binarySearch(list: List, key: Object, c: Comparator): int<br>+reverse(list: List): void<br>+reverseOrder(): Comparator<br>+shuffle(list: List): void<br>+shuffle(list: List, rmd: Random): void<br>+copy(des: List, src: List): void<br>+nCopies(n: int, o: Object): List<br>+fill(list: List, o: Object): void<br>+max(c: Collection): Object<br>+max(c: Collection, c: Comparator): Object<br>+min(c: Collection): Object<br>+min(c: Collection, c: Comparator): Object<br>+disjoint(c1: Collection, c2: Collection): boolean<br>+frequency(c: Collection, o: Object): int                                                                                                                                                                                                                                                        |
| Collection            | Sorts the specified list.<br>Sorts the specified list with the comparator.<br>Searches the key in the sorted list using binary search.<br>Searches the key in the sorted list using binary search with the comparator.<br>Reverses the specified list.<br>Returns a comparator with the reverse ordering.<br>Shuffles the specified list randomly.<br>Shuffles the specified list with a random object.<br>Copies from the source list to the destination list.<br>Returns a list consisting of $n$ copies of the object.<br>Fills the list with the object.<br>Returns the <code>max</code> object in the collection.<br>Returns the <code>max</code> object using the comparator.<br>Returns the <code>min</code> object in the collection.<br>Returns the <code>min</code> object using the comparator.<br>Returns true if $c1$ and $c2$ have no elements in common.<br>Returns the number of occurrences of the specified element in the collection. |

**FIGURE 20.7** The `Collections` class contains static methods for manipulating lists and collections.

sort list

You can sort the comparable elements in a list in its natural order with the `compareTo` method in the `Comparable` interface. You may also specify a comparator to sort elements. For example, the following code sorts strings in a list.

```
List<String> list = Arrays.asList("red", "green", "blue");
Collections.sort(list);
System.out.println(list);
```

The output is `[blue, green, red]`.

ascending order  
descending order

The preceding code sorts a list in ascending order. To sort it in descending order, you can simply use the `Collections.reverseOrder()` method to return a `Comparator` object that orders the elements in reverse of their natural order. For example, the following code sorts a list of strings in descending order.

```
List<String> list = Arrays.asList("yellow", "red", "green", "blue");
Collections.sort(list, Collections.reverseOrder());
System.out.println(list);
```

The output is `[yellow, red, green, blue]`.

binarySearch

You can use the `binarySearch` method to search for a key in a list. To use this method, the list must be sorted in increasing order. If the key is not in the list, the method returns  $-(\text{insertion point} + 1)$ . Recall that the insertion point is where the item would fall in the list if it were present. For example, the following code searches the keys in a list of integers and a list of strings.

```
List<Integer> list1 =
 Arrays.asList(2, 4, 7, 10, 11, 45, 50, 59, 60, 66);
System.out.println("(1) Index: " + Collections.binarySearch(list1, 7));
```

```
System.out.println("(2) Index: " + Collections.binarySearch(list1, 9));
List<String> list2 = Arrays.asList("blue", "green", "red");
System.out.println("(3) Index: " +
 Collections.binarySearch(list2, "red"));
System.out.println("(4) Index: " +
 Collections.binarySearch(list2, "cyan"));
```

The output of the preceding code is:

(1) Index: 2  
(2) Index: -4  
(3) Index: 2  
(4) Index: -2



You can use the **reverse** method to reverse the elements in a list. For example, the following code displays [blue, green, red, yellow].

```
List<String> list = Arrays.asList("yellow", "red", "green", "blue");
Collections.reverse(list);
System.out.println(list);
```

You can use the **shuffle(List)** method to randomly reorder the elements in a list. For example, the following code shuffles the elements in **list**.

```
List<String> list = Arrays.asList("yellow", "red", "green", "blue");
Collections.shuffle(list);
System.out.println(list);
```

You can also use the **shuffle(List, Random)** method to randomly reorder the elements in a list with a specified **Random** object. Using a specified **Random** object is useful to generate a list with identical sequences of elements for the same original list. For example, the following code shuffles the elements in **list**.

```
List<String> list1 = Arrays.asList("yellow", "red", "green", "blue");
List<String> list2 = Arrays.asList("yellow", "red", "green", "blue");
Collections.shuffle(list1, new Random(20));
Collections.shuffle(list2, new Random(20));
System.out.println(list1);
System.out.println(list2);
```

You will see that **list1** and **list2** have the same sequence of elements before and after the shuffling.

You can use the **copy(dest, src)** method to copy all the elements from a source list to a destination list on the same index. The destination list must be as long as the source list. If it is longer, the remaining elements in the source list are not affected. For example, the following code copies **list2** to **list1**.

```
List<String> list1 = Arrays.asList("yellow", "red", "green", "blue");
List<String> list2 = Arrays.asList("white", "black");
Collections.copy(list1, list2);
System.out.println(list1);
```

The output for `list1` is [white, black, green, blue]. The `copy` method performs a shallow copy: only the references of the elements from the source list are copied.

## nCopies

You can use the `nCopies(int n, Object o)` method to create an immutable list that consists of `n` copies of the specified object. For example, the following code creates a list with five `Calendar` objects.

```
List<GregorianCalendar> list1 = Collections.nCopies
(5, new GregorianCalendar(2005, 0, 1));
```

The list created from the `nCopies` method is immutable, so you cannot add, remove, or update elements in the list. All the elements have the same references.

## fill

You can use the `fill(List list, Object o)` method to replace all the elements in the list with the specified element. For example, the following code displays [black, black, black].

```
List<String> list = Arrays.asList("red", "green", "blue");
Collections.fill(list, "black");
System.out.println(list);
```

## max and min methods

You can use the `max` and `min` methods for finding the maximum and minimum elements in a collection. The elements must be comparable using the `Comparable` interface or the `Comparator` interface. For example, the following code displays the largest and smallest strings in a collection.

```
Collection<String> collection = Arrays.asList("red", "green", "blue");
System.out.println(Collections.max(collection));
System.out.println(Collections.min(collection));
```

## disjoint method

The `disjoint(collection1, collection2)` method returns `true` if the two collections have no elements in common. For example, in the following code, `disjoint(collection1, collection2)` returns `false`, but `disjoint(collection1, collection3)` returns `true`.

```
Collection<String> collection1 = Arrays.asList("red", "cyan");
Collection<String> collection2 = Arrays.asList("red", "blue");
Collection<String> collection3 = Arrays.asList("pink", "tan");
System.out.println(Collections.disjoint(collection1, collection2));
System.out.println(Collections.disjoint(collection1, collection3));
```

## frequency method

The `frequency(collection, element)` method finds the number of occurrences of the element in the collection. For example, `frequency(collection, "red")` returns 2 in the following code.

```
Collection<String> collection = Arrays.asList("red", "cyan", "red");
System.out.println(Collections.frequency(collection, "red"));
```



**20.17** Are all the methods in the `Collections` class static?

**20.18** Which of the following static methods in the `Collections` class are for lists, and which are for collections?

sort, binarySearch, reverse, shuffle, max, min, disjoint, frequency

**20.19** Show the output of the following code:

```
import java.util.*;
public class Test {
 public static void main(String[] args) {
```

```

List<String> list =
 Arrays.asList("yellow", "red", "green", "blue");
Collections.reverse(list);
System.out.println(list);

List<String> list1 =
 Arrays.asList("yellow", "red", "green", "blue");
List<String> list2 = Arrays.asList("white", "black");
Collections.copy(list1, list2);
System.out.println(list1);

Collection<String> c1 = Arrays.asList("red", "cyan");
Collection<String> c2 = Arrays.asList("red", "blue");
Collection<String> c3 = Arrays.asList("pink", "tan");
System.out.println(Collections.disjoint(c1, c2));
System.out.println(Collections.disjoint(c1, c3));

Collection<String> collection =
 Arrays.asList("red", "cyan", "red");
System.out.println(Collections.frequency(collection, "red"));
}
}

```

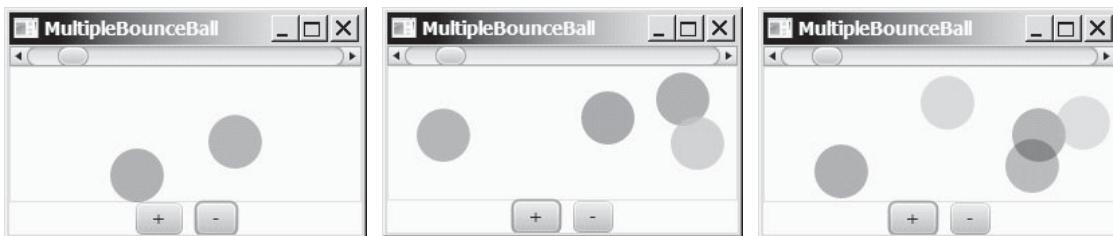
- 20.20** Which method can you use to sort the elements in an [ArrayList](#) or a [LinkedList](#)?  
 Which method can you use to sort an array of strings?
- 20.21** Which method can you use to perform binary search for elements in an [ArrayList](#) or a [LinkedList](#)? Which method can you use to perform binary search for an array of strings?
- 20.22** Write a statement to find the largest element in an array of comparable objects.

## 20.7 Case Study: Bouncing Balls

*This section presents a program that displays bouncing balls and enables the user to add and remove balls.*



Section 15.12 presents a program that displays one bouncing ball. This section presents a program that displays multiple bouncing balls. You can use two buttons to suspend and resume the movement of the balls, a scroll bar to control the ball speed, and the + or – button add or remove a ball, as shown in Figure 20.8.



**FIGURE 20.8** Pressing the + or – button adds or removes a ball.

The example in Section 15.12 only had to store one ball. How do you store the multiple balls in this example? The `Pane's getChildren()` method returns an `ObservableList<Node>`, a subtype of `List<Node>`, for storing the nodes in the pane. Initially, the list is empty. When a new ball is created, add it to the end of the list. To remove a ball, simply remove the last one in the list.

Each ball has its state: the *x*-, *y*-coordinates, color, and direction to move. You can define a class named `Ball` that extends `javafx.scene.shape.Circle`. The *x*-, *y*-coordinates and the color are already defined in `Circle`. When a ball is created, it starts from the upper-left corner and moves downward to the right. A random color is assigned to a new ball.

The `MultipleBallPane` class is responsible for displaying the ball and the `MultipleBounceBall` class places the control components and implements the control. The relationship of these classes is shown in Figure 20.9. Listing 20.6 gives the program.

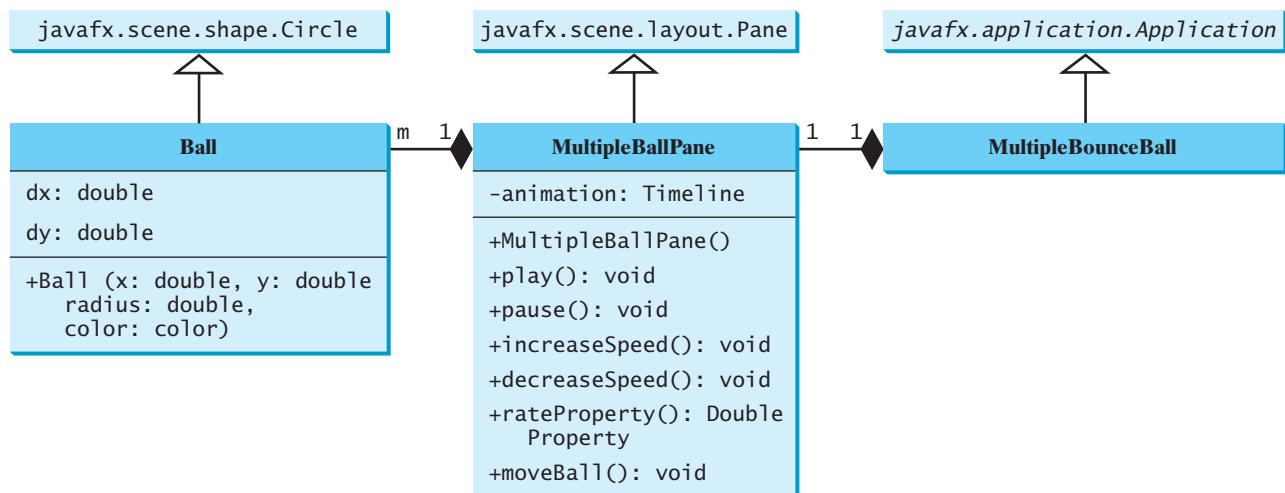


FIGURE 20.9 `MultipleBounceBall` contains `MultipleBallPane`, and `MultipleBallPane` contains `Ball`.

### LISTING 20.6 MultipleBounceBall.java

```

1 import javafx.animation.KeyFrame;
2 import javafx.animation.Timeline;
3 import javafx.application.Application;
4 import javafx.beans.property.DoubleProperty;
5 import javafx.geometry.Pos;
6 import javafx.scene.Node;
7 import javafx.stage.Stage;
8 import javafx.scene.Scene;
9 import javafx.scene.control.Button;
10 import javafx.scene.control.ScrollBar;
11 import javafx.scene.layout.BorderPane;
12 import javafx.scene.layout.HBox;
13 import javafx.scene.layout.Pane;
14 import javafx.scene.paint.Color;
15 import javafx.scene.shape.Circle;
16 import javafx.util.Duration;
17
18 public class MultipleBounceBall extends Application {
19 @Override // Override the start method in the Application class
20 public void start(Stage primaryStage) {
21 MultipleBallPane ballPane = new MultipleBallPane();
22 ballPane.setStyle("-fx-border-color: yellow");
23
24 Button btAdd = new Button("+");

```

create a ball pane  
set ball pane border  
create buttons

```

25 Button btSubtract = new Button("-");
26 HBox hBox = new HBox(10);
27 hBox.getChildren().addAll(btAdd, btSubtract); add buttons to HBox
28 hBox.setAlignment(Pos.CENTER);
29
30 // Add or remove a ball
31 btAdd.setOnAction(e -> ballPane.add());
32 btSubtract.setOnAction(e -> ballPane.subtract()); add a ball
33 remove a ball
33
34 // Pause and resume animation
35 ballPane.setOnMousePressed(e -> ballPane.pause());
36 ballPane.setOnMouseReleased(e -> ballPane.play()); pause animation
37 resume animation
37
38 // Use a scroll bar to control animation speed
39 ScrollBar sbSpeed = new ScrollBar();
40 sbSpeed.setMax(20);
41 sbSpeed.setValue(10);
42 ballPane.rateProperty().bind(sbSpeed.valueProperty()); bind animation rate
43
44 BorderPane pane = new BorderPane();
45 pane.setCenter(ballPane);
46 pane.setTop(sbSpeed);
47 pane.setBottom(hBox);
48
49 // Create a scene and place the pane in the stage
50 Scene scene = new Scene(pane, 250, 150);
51 primaryStage.setTitle("MultipleBounceBall"); // Set the stage title
52 primaryStage.setScene(scene); // Place the scene in the stage
53 primaryStage.show(); // Display the stage
54 }
55
56 private class MultipleBallPane extends Pane {
57 private Timeline animation;
58
59 public MultipleBallPane() {
60 // Create an animation for moving the ball
61 animation = new Timeline(
62 new KeyFrame(Duration.millis(50), e -> moveBall()));
63 animation.setCycleCount(Timeline.INDEFINITE);
64 animation.play(); // Start animation
65 }
66
67 public void add() {
68 Color color = new Color(Math.random(),
69 Math.random(), Math.random(), 0.5);
70 getChildren().add(new Ball(30, 30, 20, color)); add a ball to pane
71 }
72
73 public void subtract() {
74 if (getChildren().size() > 0) {
75 getChildren().remove(getChildren().size() - 1); remove a ball
76 }
77 }
78
79 public void play() {
80 animation.play();
81 }
82
83 public void pause() {

```

```

84 animation.pause();
85 }
86
87 public void increaseSpeed() {
88 animation.setRate(animation.getRate() + 0.1);
89 }
90
91 public void decreaseSpeed() {
92 animation.setRate(
93 animation.getRate() > 0 ? animation.getRate() - 0.1 : 0);
94 }
95
96 public DoubleProperty rateProperty() {
97 return animation.rateProperty();
98 }
99
100 protected void moveBall() {
101 for (Node node: this.getChildren()) {
102 Ball ball = (Ball)node;
103 // Check boundaries
104 if (ball.getCenterX() < ball.getRadius() ||
105 ball.getCenterX() > getWidth() - ball.getRadius()) {
106 ball.dx *= -1; // Change ball move direction
107 }
108 if (ball.getCenterY() < ball.getRadius() ||
109 ball.getCenterY() > getHeight() - ball.getRadius()) {
110 ball.dy *= -1; // Change ball move direction
111 }
112 // Adjust ball position
113 ball.setCenterX(ball.dx + ball.getCenterX());
114 ball.setCenterY(ball.dy + ball.getCenterY());
115 }
116 }
117 }
118
119
120 class Ball extends Circle {
121 private double dx = 1, dy = 1;
122
123 Ball(double x, double y, double radius, Color color) {
124 super(x, y, radius);
125 setFill(color); // Set ball color
126 }
127 }
128 }
```

move all balls

change x direction

change y direction

adjust ball positions

declare dx and dy

create a ball

The `add()` method creates a new ball with a random color and adds it to the pane (line 70). The pane stores all the balls in a list. The `subtract()` method removes the last ball in the list (line 75).

When the user clicks the + button, a new ball is added to the pane (line 31). When the user clicks the – button, the last ball in the array list is removed (line 32).

The `moveBall()` method in the `MultipleBallPane` class gets every ball in the pane's list and adjusts the balls' positions (lines 114–115).



**20.23** What is the return value from invoking `pane.getChildren()` for a pane?

- 20.24** How do you modify the code in the [MultipleBallApp](#) program to remove the first ball in the list when the button is clicked?
- 20.25** How do you modify the code in the [MultipleBallApp](#) program so that each ball will get a random radius between 10 and 20?

## 20.8 Vector and Stack Classes

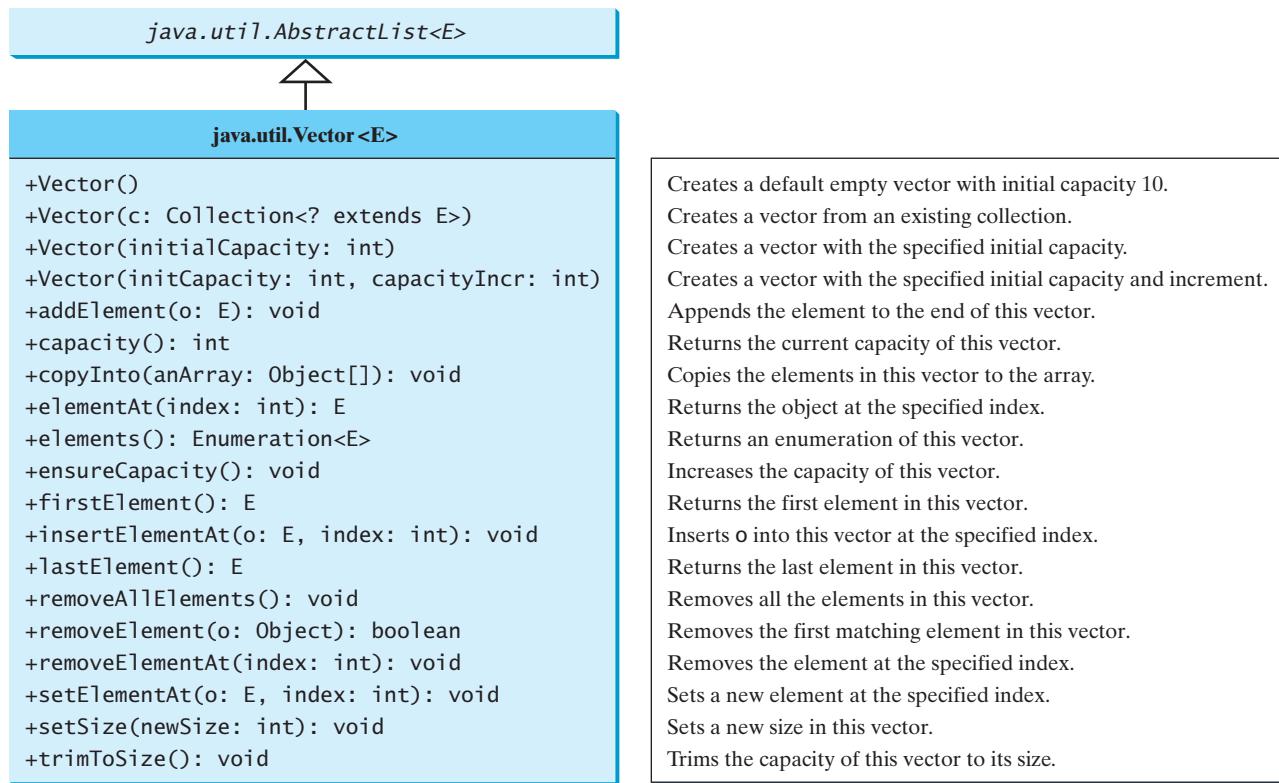
**Vector** is a subclass of [AbstractList](#), and **Stack** is a subclass of **Vector** in the Java API.



The Java Collections Framework was introduced in Java 2. Several data structures were supported earlier, among them the **Vector** and **Stack** classes. These classes were redesigned to fit into the Java Collections Framework, but all their old-style methods are retained for compatibility.

**Vector** is the same as [ArrayList](#), except that it contains synchronized methods for accessing and modifying the vector. Synchronized methods can prevent data corruption when a vector is accessed and modified by two or more threads concurrently. We will discuss synchronization in Chapter 30, Multithreading and Parallel Programming. For the many applications that do not require synchronization, using [ArrayList](#) is more efficient than using **Vector**.

The **Vector** class extends the [AbstractList](#) class. It also has the methods contained in the original **Vector** class defined prior to Java 2, as shown in Figure 20.10.



**FIGURE 20.10** Starting in Java 2, the **Vector** class extends [AbstractList](#) and also retains all the methods in the original **Vector** class.

Most of the methods in the `Vector` class listed in the UML diagram in Figure 20.10 are similar to the methods in the `List` interface. These methods were introduced before the Java Collections Framework. For example, `addElement(Object element)` is the same as the `add(Object element)` method, except that the `addElement` method is synchronized. Use the `ArrayList` class if you don't need synchronization. It works much faster than `Vector`.



### Note

The `elements()` method returns an `Enumeration`. The `Enumeration` interface was introduced prior to Java 2 and was superseded by the `Iterator` interface.



### Note

`Vector` is widely used in Java legacy code because it was the Java resizable array implementation before Java 2.

In the Java Collections Framework, `Stack` is implemented as an extension of `Vector`, as illustrated in Figure 20.11.



**FIGURE 20.11** The `Stack` class extends `Vector` to provide a last-in, first-out data structure.

The `Stack` class was introduced prior to Java 2. The methods shown in Figure 20.11 were used before Java 2. The `empty()` method is the same as `isEmpty()`. The `peek()` method looks at the element at the top of the stack without removing it. The `pop()` method removes the top element from the stack and returns it. The `push(Object element)` method adds the specified element to the stack. The `search(Object element)` method checks whether the specified element is in the stack.



- 20.26** How do you create an instance of `Vector`? How do you add or insert a new element into a vector? How do you remove an element from a vector? How do you find the size of a vector?
- 20.27** How do you create an instance of `Stack`? How do you add a new element to a stack? How do you remove an element from a stack? How do you find the size of a stack?
- 20.28** Does Listing 20.1, `TestCollection.java`, compile and run if all the occurrences of `ArrayList` are replaced by `LinkedList`, `Vector`, or `Stack`?

## 20.9 Queues and Priority Queues

*In a priority queue, the element with the highest priority is removed first.*

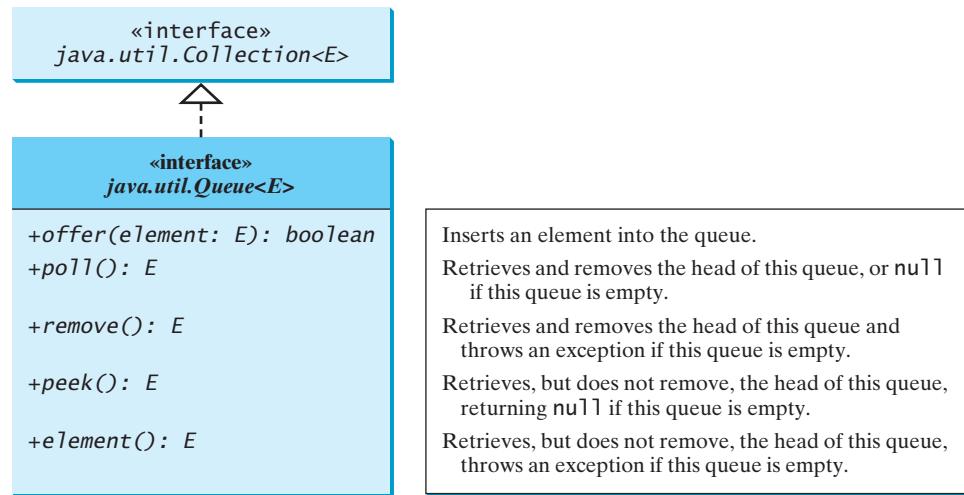
A *queue* is a first-in, first-out data structure. Elements are appended to the end of the queue and are removed from the beginning of the queue. In a *priority queue*, elements are assigned priorities. When accessing elements, the element with the highest priority is removed first. This section introduces queues and priority queues in the Java API.



queue  
priority queue

### 20.9.1 The Queue Interface

The **Queue** interface extends **java.util.Collection** with additional insertion, extraction, and inspection operations, as shown in Figure 20.12.



**FIGURE 20.12** The **Queue** interface extends **Collection** to provide additional insertion, extraction, and inspection operations.

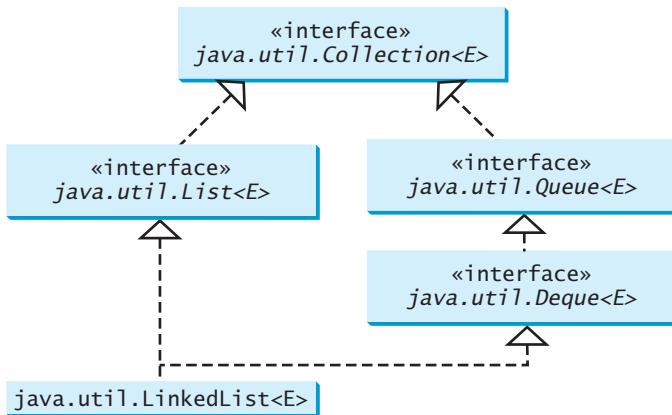
The **offer** method is used to add an element to the queue. This method is similar to the **add** method in the **Collection** interface, but the **offer** method is preferred for queues. The **poll** and **remove** methods are similar, except that **poll()** returns **null** if the queue is empty, whereas **remove()** throws an exception. The **peek** and **element** methods are similar, except that **peek()** returns **null** if the queue is empty, whereas **element()** throws an exception.

queue operations

### 20.9.2 Deque and LinkedList

The **LinkedList** class implements the **Deque** interface, which extends the **Queue** interface, as shown in Figure 20.13. Therefore, you can use **LinkedList** to create a queue. **LinkedList** is ideal for queue operations because it is efficient for inserting and removing elements from both ends of a list.

**Deque** supports element insertion and removal at both ends. The name *deque* is short for “double-ended queue” and is usually pronounced “deck.” The **Deque** interface extends **Queue** with additional methods for inserting and removing elements from both ends of the queue. The methods **addFirst(e)**, **removeFirst()**, **addLast(e)**, **removeLast()**, **getFirst()**, and **getLast()** are defined in the **Deque** interface.

FIGURE 20.13 `LinkedList` implements `List` and `Deque`.

Listing 20.7 shows an example of using a queue to store strings. Line 4 creates a queue using `LinkedList`. Four strings are added to the queue in lines 5–8. The `size()` method defined in the `Collection` interface returns the number of elements in the queue (line 10). The `remove()` method retrieves and removes the element at the head of the queue (line 11).

### LISTING 20.7 TestQueue.java

creates a queue  
inserts an element

queue size  
remove element

```

1 public class TestQueue {
2 public static void main(String[] args) {
3 java.util.Queue<String> queue = new java.util.LinkedList<>();
4 queue.offer("Oklahoma");
5 queue.offer("Indiana");
6 queue.offer("Georgia");
7 queue.offer("Texas");
8
9 while (queue.size() > 0)
10 System.out.print(queue.remove() + " ");
11 }
12 }
```



Oklahoma Indiana Georgia Texas

PriorityQueue class

The `PriorityQueue` class implements a priority queue, as shown in Figure 20.14. By default, the priority queue orders its elements according to their natural ordering using `Comparable`. The element with the least value is assigned the highest priority and thus is removed from the queue first. If there are several elements with the same highest priority, the tie is broken arbitrarily. You can also specify an ordering using `Comparator` in the constructor `PriorityQueue(initialCapacity, comparator)`.

Listing 20.8 shows an example of using a priority queue to store strings. Line 5 creates a priority queue for strings using its no-arg constructor. This priority queue orders the strings using their natural order, so the strings are removed from the queue in increasing order. Lines 16–17 create a priority queue using the comparator obtained from `Collections.reverseOrder()`, which orders the elements in reverse order, so the strings are removed from the queue in decreasing order.



FIGURE 20.14 The **PriorityQueue** class implements a priority queue.

### LISTING 20.8 PriorityQueueDemo.java

```

1 import java.util.*;
2
3 public class PriorityQueueDemo {
4 public static void main(String[] args) {
5 PriorityQueue<String> queue1 = new PriorityQueue<>();
6 queue1.offer("Oklahoma");
7 queue1.offer("Indiana");
8 queue1.offer("Georgia");
9 queue1.offer("Texas");
10
11 System.out.println("Priority queue using Comparable:");
12 while (queue1.size() > 0) {
13 System.out.print(queue1.remove() + " ");
14 }
15
16 PriorityQueue<String> queue2 = new PriorityQueue(
17 4, Collections.reverseOrder());
18 queue2.offer("Oklahoma");
19 queue2.offer("Indiana");
20 queue2.offer("Georgia");
21 queue2.offer("Texas");
22
23 System.out.println("\nPriority queue using Comparator:");
24 while (queue2.size() > 0) {
25 System.out.print(queue2.remove() + " ");
26 }
27 }
28 }

```

a default queue  
inserts an element

a queue with comparator

```

Priority queue using Comparable:
Georgia Indiana Oklahoma Texas
Priority queue using Comparator:
Texas Oklahoma Indiana Georgia

```



- 20.29** Is **java.util.Queue** a subinterface of **java.util.Collection**, **java.util.Set**, or **java.util.List**? Does **LinkedList** implement **Queue**?



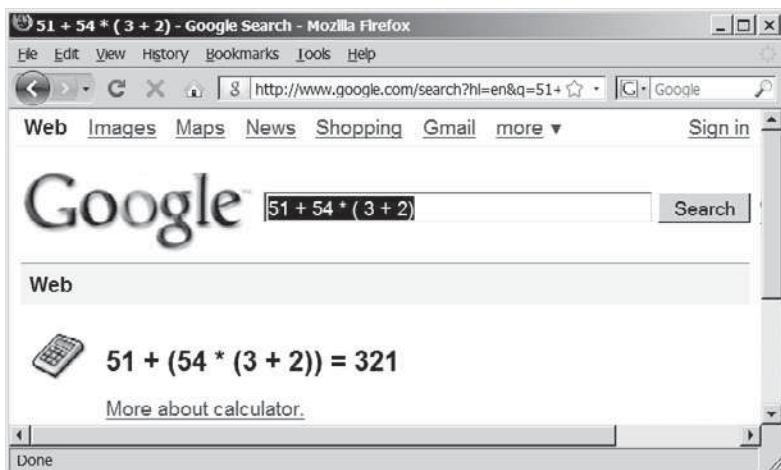
- 20.30** How do you create a priority queue for integers? By default, how are elements ordered in a priority queue? Is the element with the least value assigned the highest priority in a priority queue?
- 20.31** How do you create a priority queue that reverses the natural order of the elements?

## 20.10 Case Study: Evaluating Expressions



*Stacks can be used to evaluate expressions.*

Stacks and queues have many applications. This section gives an application that uses stacks to evaluate expressions. You can enter an arithmetic expression from Google to evaluate the expression, as shown in Figure 20.15.



**FIGURE 20.15** You can evaluate an arithmetic expression using a Google search engine.

compound expression

How does Google evaluate an expression? This section presents a program that evaluates a *compound expression* with multiple operators and parentheses (e.g.,  $(15 + 2) * 34 - 2$ ). For simplicity, assume that the operands are integers and the operators are of four types:  $+$ ,  $-$ ,  $*$ , and  $/$ .

process an operator

The problem can be solved using two stacks, named **operandStack** and **operatorStack**, for storing operands and operators, respectively. Operands and operators are pushed into the stacks before they are processed. When an *operator is processed*, it is popped from **operatorStack** and applied to the first two operands from **operandStack** (the two operands are popped from **operandStack**). The resultant value is pushed back to **operandStack**.

The algorithm proceeds in two phases:

### Phase 1: Scanning the expression

The program scans the expression from left to right to extract operands, operators, and the parentheses.

- 1.1. If the extracted item is an operand, push it to **operandStack**.
- 1.2. If the extracted item is a  $+$  or  $-$  operator, process all the operators at the top of **operatorStack** and push the extracted operator to **operatorStack**.
- 1.3. If the extracted item is a  $*$  or  $/$  operator, process the  $*$  or  $/$  operators at the top of **operatorStack** and push the extracted operator to **operatorStack**.

- 1.4. If the extracted item is a `C` symbol, push it to `operatorStack`.
- 1.5. If the extracted item is a `)` symbol, repeatedly process the operators from the top of `operatorStack` until seeing the `C` symbol on the stack.

### Phase 2: Clearing the stack

Repeatedly process the operators from the top of `operatorStack` until `operatorStack` is empty.

Table 20.1 shows how the algorithm is applied to evaluate the expression `(1 + 2) * 4 - 3`.

**TABLE 20.1** Evaluating an expression

| Expression      | Scan | Action    | operandStack | operatorStack |
|-----------------|------|-----------|--------------|---------------|
| $(1 + 2)*4 - 3$ | (    | Phase 1.4 |              | (             |
|                 | ↑    |           |              |               |
| $(1 + 2)*4 - 3$ | 1    | Phase 1.1 | 1            | (             |
|                 | ↑    |           |              |               |
| $(1 + 2)*4 - 3$ | +    | Phase 1.2 | 1            | + (           |
|                 | ↑    |           |              |               |
| $(1 + 2)*4 - 3$ | 2    | Phase 1.1 | 2<br>1       | (             |
|                 | ↑    |           |              |               |
| $(1 + 2)*4 - 3$ | )    | Phase 1.5 | 3            |               |
|                 | ↑    |           |              |               |
| $(1 + 2)*4 - 3$ | *    | Phase 1.3 | 3            | *             |
|                 | ↑    |           |              |               |
| $(1 + 2)*4 - 3$ | 4    | Phase 1.1 | 4<br>3       | *             |
|                 | ↑    |           |              |               |
| $(1 + 2)*4 - 3$ | -    | Phase 1.2 | 12           | -             |
|                 | ↑    |           |              |               |
| $(1 + 2)*4 - 3$ | 3    | Phase 1.1 | 3<br>12      | -             |
|                 | ↑    |           |              |               |
| $(1 + 2)*4 - 3$ | none | Phase 2   | 9            |               |
|                 | ↑    |           |              |               |

Listing 20.9 gives the program, and Figure 20.16 shows some sample output.

```
Command Prompt
c:\book>java EvaluateExpression "(1 + 3 * 3 - 2) * (12 / 6 * 5)"
80

c:\book>java EvaluateExpression "(1 + 3 * 3 - 2) * (12 / 6 * 5) +
Wrong expression: (1 + 3 * 3 - 2) * (12 / 6 * 5) +

c:\book>java EvaluateExpression "(1 + 2) * 4 - 3"
9

c:\book>
```

**FIGURE 20.16** The program takes an expression as command-line arguments.

**LISTING 20.9 EvaluateExpression.java**

```

1 import java.util.Stack;
2
3 public class EvaluateExpression {
4 public static void main(String[] args) {
5 // Check number of arguments passed
6 if (args.length != 1) {
7 System.out.println(
8 "Usage: java EvaluateExpression \"expression\"");
9 System.exit(1);
10 }
11
12 try {
13 System.out.println(evaluateExpression(args[0]));
14 }
15 catch (Exception ex) {
16 System.out.println("Wrong expression: " + args[0]);
17 }
18 }
19
20 /** Evaluate an expression */
21 public static int evaluateExpression(String expression) {
22 // Create operandStack to store operands
23 Stack<Integer> operandStack = new Stack<>();
24
25 // Create operatorStack to store operators
26 Stack<Character> operatorStack = new Stack<>();
27
28 // Insert blanks around (,), +, -, /, and *
29 expression = insertBlanks(expression);
30
31 // Extract operands and operators
32 String[] tokens = expression.split(" ");
33
34 // Phase 1: Scan tokens
35 for (String token: tokens) {
36 if (token.length() == 0) // Blank space
37 continue; // Back to the while loop to extract the next token
38 else if (token.charAt(0) == '+' || token.charAt(0) == '-') {
39 // Process all +, -, *, / in the top of the operator stack
40 while (!operatorStack.isEmpty() &&
41 (operatorStack.peek() == '+' ||
42 operatorStack.peek() == '-' ||
43 operatorStack.peek() == '*' ||
44 operatorStack.peek() == '/')) {
45 processAnOperator(operandStack, operatorStack);
46 }
47
48 // Push the + or - operator into the operator stack
49 operatorStack.push(token.charAt(0));
50 }
51 else if (token.charAt(0) == '*' || token.charAt(0) == '/') {
52 // Process all *, / in the top of the operator stack
53 while (!operatorStack.isEmpty() &&
54 (operatorStack.peek() == '*' ||
55 operatorStack.peek() == '/')) {
56 processAnOperator(operandStack, operatorStack);
57 }
58 }
}

```

check usage

evaluate expression

exception

operandStack

operatorStack

prepare for extraction

extract tokens

process tokens

+ or - scanned

\* or / scanned

```

59 // Push the * or / operator into the operator stack
60 operatorStack.push(token.charAt(0));
61 }
62 else if (token.trim().charAt(0) == '(') { (scanned
63 operatorStack.push('('); // Push '(' to stack
64 }
65 else if (token.trim().charAt(0) == ')') {) scanned
66 // Process all the operators in the stack until seeing ')'
67 while (operatorStack.peek() != '(') {
68 processAnOperator(operandStack, operatorStack);
69 }
70
71 operatorStack.pop(); // Pop the ')' symbol from the stack
72 }
73 else { // An operand scanned
74 // Push an operand to the stack
75 operandStack.push(new Integer(token)); an operand scanned
76 }
77 }
78
79 // Phase 2: Process all the remaining operators in the stack
80 while (!operatorStack.isEmpty()) { clear operatorStack
81 processAnOperator(operandStack, operatorStack);
82 }
83
84 // Return the result
85 return operandStack.pop(); return result
86 }
87
88 /** Process one operator: Take an operator from operatorStack and
89 * apply it on the operands in the operandStack */
90 public static void processAnOperator(
91 Stack<Integer> operandStack, Stack<Character> operatorStack) {
92 char op = operatorStack.pop();
93 int op1 = operandStack.pop();
94 int op2 = operandStack.pop();
95 if (op == '+') process +
96 operandStack.push(op2 + op1);
97 else if (op == '-') process -
98 operandStack.push(op2 - op1);
99 else if (op == '*') process *
100 operandStack.push(op2 * op1);
101 else if (op == '/') process /
102 operandStack.push(op2 / op1);
103 }
104
105 public static String insertBlanks(String s) { insert blanks
106 String result = "";
107
108 for (int i = 0; i < s.length(); i++) {
109 if (s.charAt(i) == '(' || s.charAt(i) == ')' ||
110 s.charAt(i) == '+' || s.charAt(i) == '-' ||
111 s.charAt(i) == '*' || s.charAt(i) == '/')
112 result += " " + s.charAt(i) + " ";
113 else
114 result += s.charAt(i);
115 }
116
117 return result;
118 }
119 }
```

You can use the `GenericStack` class provided by the book or the `java.util.Stack` class defined in the Java API for creating stacks. This example uses the `java.util.Stack` class. The program will work if it is replaced by `GenericStack`.

The program takes an expression as a command-line argument in one string.

The `evaluateExpression` method creates two stacks, `operandStack` and `operatorStack` (lines 23, 26), and extracts operands, operators, and parentheses delimited by space (lines 29–32). The `insertBlanks` method is used to ensure that operands, operators, and parentheses are separated by at least one blank (line 29).

The program scans each token in the `for` loop (lines 35–77). If a token is empty, skip it (line 37). If a token is an operand, push it to `operandStack` (line 75). If a token is a `+` or `-` operator (line 38), process all the operators from the top of `operatorStack`, if any (lines 40–46), and push the newly scanned operator into the stack (line 49). If a token is a `*` or `/` operator (line 51), process all the `*` and `/` operators from the top of `operatorStack`, if any (lines 53–57), and push the newly scanned operator to the stack (line 60). If a token is a `(` symbol (line 62), push it into `operatorStack`. If a token is a `)` symbol (line 65), process all the operators from the top of `operatorStack` until seeing the `)` symbol (lines 67–69) and pop the `)` symbol from the stack.

After all tokens are considered, the program processes the remaining operators in `operatorStack` (lines 80–82).

The `processAnOperator` method (lines 90–103) processes an operator. The method pops the operator from `operatorStack` (line 92) and pops two operands from `operandStack` (lines 93–94). Depending on the operator, the method performs an operation and pushes the result of the operation back to `operandStack` (lines 96, 98, 100, 102).



- 20.32** Can the `EvaluateExpression` program evaluate the following expressions "`1+2`", "`1 + 2`", "`(1) + 2`", "`((1)) + 2`", and "`(1 + 2)`"?
- 20.33** Show the change of the contents in the stacks when evaluating "`3 + (4 + 5) * (3 + 5) + 4 * 5`" using the `EvaluateExpression` program.
- 20.34** If you enter an expression "`4 + 5 5 5`", the program will display 10. How do you fix this problem?

## KEY TERMS

---

|                            |     |                |     |
|----------------------------|-----|----------------|-----|
| collection                 | 762 | linked list    | 769 |
| comparator                 | 772 | list           | 762 |
| convenience abstract class | 762 | priority queue | 783 |
| data structure             | 762 | queue          | 762 |

## CHAPTER SUMMARY

---

1. The Java Collections Framework supports *sets*, *lists*, *queues*, and *maps*. They are defined in the interfaces `Set`, `List`, `Queue`, and `Map`.
2. A *list* stores an ordered *collection* of elements.
3. All the concrete classes except `PriorityQueue` in the Java Collections Framework implement the `Cloneable` and `Serializable` interfaces. Thus, their instances can be cloned and serialized.

4. To allow duplicate elements to be stored in a collection, you need to use a list. A list not only can store duplicate elements but also allows the user to specify where they are stored. The user can access elements by an index.
5. Two types of lists are supported: `ArrayList` and `LinkedList`. `ArrayList` is a resizable-array implementation of the `List` interface. All the methods in `ArrayList` are defined in `List`. `LinkedList` is a *linked-list* implementation of the `List` interface. In addition to implementing the `List` interface, this class provides the methods for retrieving, inserting, and removing elements from both ends of the list.
6. `Comparator` can be used to compare the objects of a class that doesn't implement `Comparable`.
7. The `Vector` class extends the `AbstractList` class. Starting with Java 2, `Vector` has been the same as `ArrayList`, except that the methods for accessing and modifying the vector are synchronized. The `Stack` class extends the `Vector` class and provides several methods for manipulating the stack.
8. The `Queue` interface represents a queue. The `PriorityQueue` class implements `Queue` for a *priority queue*.

## Quiz

Answer the quiz for this chapter online at [www.cs.armstrong.edu/liang/intro10e/quiz.html](http://www.cs.armstrong.edu/liang/intro10e/quiz.html).

## PROGRAMMING EXERCISES

MyProgrammingLab™

### Sections 20.2–20.7

- \*20.1** (*Display words in ascending alphabetical order*) Write a program that reads words from a text file and displays all the words (duplicates allowed) in ascending alphabetical order. The words must start with a letter. The text file is passed as a command-line argument.
- \*20.2** (*Store numbers in a linked list*) Write a program that lets the user enter numbers from a graphical user interface and displays them in a text area, as shown in Figure 20.17a. Use a linked list to store the numbers. Do not store duplicate numbers. Add the buttons *Sort*, *Shuffle*, and *Reverse* to sort, shuffle, and reverse the list.



FIGURE 20.17 (a) The numbers are stored in a list and displayed in the text area. (b) The colliding balls are combined.

**\*20.3** (*Guessing the capitals*) Rewrite Programming Exercise 8.37 to store the pairs of states and capitals so that the questions are displayed randomly.

**\*20.4** (*Sort points in a plane*) Write a program that meets the following requirements:

- Define a class named **Point** with two data fields **x** and **y** to represent a point's *x*- and *y*-coordinates. Implement the **Comparable** interface for comparing the points on *x*-coordinates. If two points have the same *x*-coordinates, compare their *y*-coordinates.
- Define a class named **CompareY** that implements **Comparator<Point>**. Implement the **compare** method to compare two points on their *y*-coordinates. If two points have the same *y*-coordinates, compare their *x*-coordinates.
- Randomly create 100 points and apply the **Arrays.sort** method to display the points in increasing order of their *x*-coordinates and in increasing order of their *y*-coordinates, respectively.

**\*\*\*20.5** (*Combine colliding bouncing balls*) The example in Section 20.7 displays multiple bouncing balls. Extend the example to detect collisions. Once two balls collide, remove the later ball that was added to the pane and add its radius to the other ball, as shown in Figure 20.17b. Use the *Suspend* button to suspend the animation and the *Resume* button to resume the animation. Add a mouse pressed handler that removes a ball when the mouse is pressed on the ball.

**20.6** (*Use iterators on linked lists*) Write a test program that stores 5 million integers in a linked list and test the time to traverse the list using an **iterator** vs. using the **get(index)** method.

**\*\*\*20.7** (*Game: hangman*) Programming Exercise 7.35 presents a console version of the popular hangman game. Write a GUI program that lets a user play the game. The user guesses a word by entering one letter at a time, as shown in Figure 20.18. If the user misses seven times, a hanging man swings. Once a word is finished, the user can press the *Enter* key to continue to guess another word.

**\*\*20.8** (*Game: lottery*) Revise Programming Exercise 3.15 to add an additional \$2,000 award if two digits from the user input are in the lottery number. (*Hint:* Sort the three digits in the lottery number and three digits in the user input into two lists, and use the **Collection's containsAll** method to check whether the two digits in the user input are in the lottery number.)

### Sections 20.8–20.10

**\*\*\*20.9** (*Remove the largest ball first*) Modify Listing 20.6, *MultipleBallApp.java* to assign a random radius between 2 and 20 when a ball is created. When the – button is clicked, one of largest balls is removed.

**20.10** (*Perform set operations on priority queues*) Create two priority queues, `{"George", "Jim", "John", "Blake", "Kevin", "Michael"}` and `{"George", "Katie", "Kevin", "Michelle", "Ryan"}`, and find their union, difference, and intersection.

**\*20.11** (*Match grouping symbols*) A Java program contains various pairs of grouping symbols, such as:

- Parentheses: `(` and `)`
- Braces: `{` and `}`
- Brackets: `[` and `]`

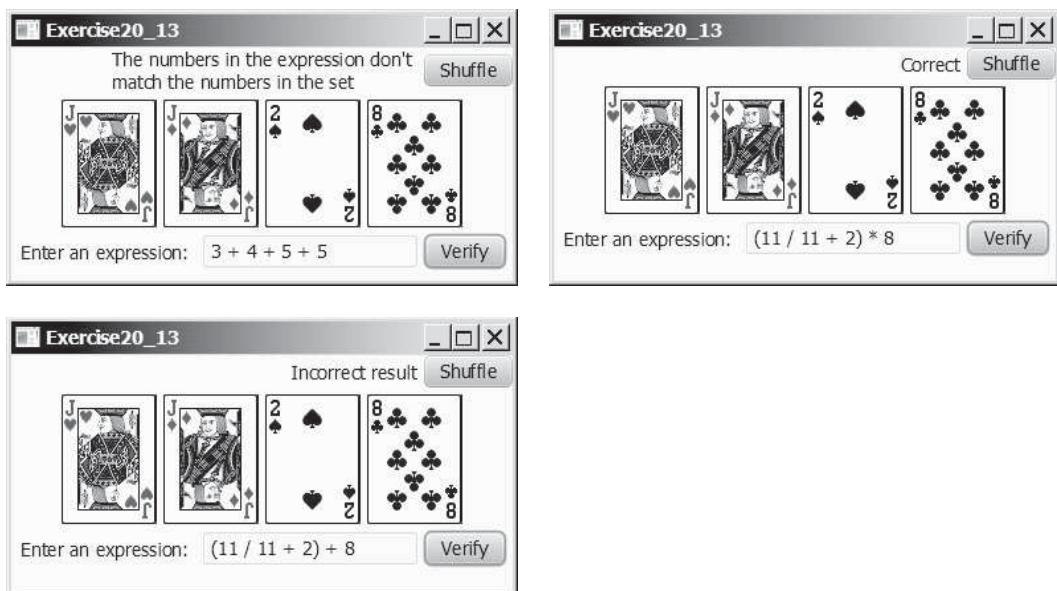
Note that the grouping symbols cannot overlap. For example, `(a{b})` is illegal. Write a program to check whether a Java source-code file has correct pairs of grouping symbols. Pass the source-code file name as a command-line argument.



FIGURE 20.18 The program displays a hangman game.

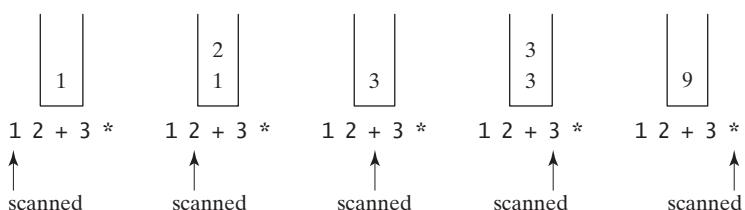
**20.12** (*Clone PriorityQueue*) Define `MyPriorityQueue` class that extends `PriorityQueue` to implement the `Cloneable` interface and implement the `clone()` method to clone a priority queue.

**\*\*20.13** (*Game: the 24-point card game*) The 24-point game is to pick any 4 cards from 52 cards, as shown in Figure 20.19. Note that the Jokers are excluded. Each card represents a number. An Ace, King, Queen, and Jack represent **1**, **13**, **12**, and **11**, respectively. You can click the *Shuffle* button to get four new cards. Enter an expression that uses the four numbers from the four selected cards. Each number must be used once and only once. You can use the operators (addition, subtraction, multiplication, and division) and parentheses in the expression. The expression must evaluate to **24**. After entering the expression, click the *Verify* button to check whether the numbers in the expression are currently selected and whether the result of the expression is correct. Display the verification in a label before the *Verify* button. Assume that images are stored in files named **1.png**, **2.png**, . . . , **52.png**, in the order of spades, hearts, diamonds, and clubs. So, the first 13 images are for spades 1, 2, 3, . . . , and 13.



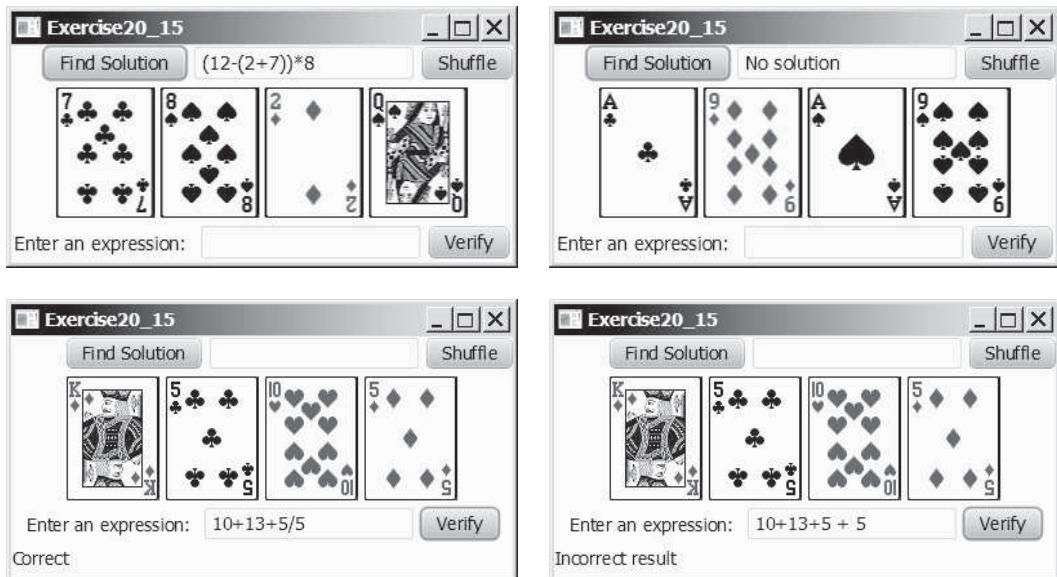
**FIGURE 20.19** The user enters an expression consisting of the numbers in the cards and clicks the Verify button to check the answer.

**\*\*20.14** (*Postfix notation*) Postfix notation is a way of writing expressions without using parentheses. For example, the expression **(1 + 2) \* 3** would be written as **1 2 + 3 \***. A postfix expression is evaluated using a stack. Scan a postfix expression from left to right. A variable or constant is pushed into the stack. When an operator is encountered, apply the operator with the top two operands in the stack and replace the two operands with the result. The following diagram shows how to evaluate **1 2 + 3 \***.



Write a program to evaluate postfix expressions. Pass the expression as a command-line argument in one string.

- \*\*\*20.15** (*Game: the 24-point card game*) Improve Programming Exercise 20.13 to enable the computer to display the expression if one exists, as shown in Figure 20.20. Otherwise, report that the expression does not exist. Place the label for verification result at the bottom of UI. The expression must use all four cards and evaluates to 24.



**FIGURE 20.20** The program can automatically find a solution if one exists.

- \*\*20.16** (*Convert infix to postfix*) Write a method that converts an infix expression into a postfix expression using the following header:

```
public static String infixToPostfix(String expression)
```

For example, the method should convert the infix expression **(1 + 2) \* 3** to **1 2 + 3 \*** and **2 \* (1 + 3)** to **2 1 3 + \***.

- \*\*\*20.17** (*Game: the 24-point card game*) This exercise is a variation of the 24-point card game described in Programming Exercise 20.13. Write a program to check whether there is a 24-point solution for the four specified numbers. The program lets the user enter four values, each between **1** and **13**, as shown in Figure 20.21. The user can then click the *Solve* button to display the solution or display "No solution" if none exist.



**FIGURE 20.21** The user enters four numbers and the program finds a solution.

- \*20.18** (*Directory size*) Listing 20.7, DirectorySize.java, gives a recursive method for finding a directory size. Rewrite this method without using recursion. Your

program should use a queue to store the subdirectories under a directory. The algorithm can be described as follows:

```
long getSize(File directory) {
 long size = 0;
 add directory to the queue;

 while (queue is not empty) {
 Remove an item from the queue into t;
 if (t is a file)
 size += t.length();
 else
 add all the files and subdirectories under t into the
 queue;
 }

 return size;
}
```

**\*\*\*20.19** (*Game: solution ratio for 24-point game*) When you pick four cards from a deck of 52 cards for the 24-point game introduced in Programming Exercise 20.13, the four cards may not have a 24-point solution. What is the number of all possible picks of four cards from 52 cards? Among all possible picks, how many of them have 24-point solutions? What is the success ratio—that is, (number of picks with solutions)/ (number of all possible picks of four cards)? Write a program to find these answers.

**\*20.20** (*Directory size*) Rewrite Programming Exercise 18.28 using a stack instead of a queue.

**\*20.21** (*Use Comparator*) Write the following generic method using selection sort and a comparator.

```
public static <E> void selectionSort(E[] list,
 Comparator<? super E> comparator)
```

Write a test program that creates an array of 10 **GeometricObjects** and invokes this method using the **GeometricObjectComparator** introduced in Listing 20.4 to sort the elements. Display the sorted elements. Use the following statement to create the array.

```
GeometricObject[] list = {new Circle(5), new Rectangle(4, 5),
 new Circle(5.5), new Rectangle(2.4, 5), new Circle(0.5),
 new Rectangle(4, 65), new Circle(4.5), new Rectangle(4.4, 1),
 new Circle(6.5), new Rectangle(4, 5)};
```

**\*20.22** (*Nonrecursive Tower of Hanoi*) Implement the **moveDisks** method in Listing 18.8 using a stack instead of using recursion.

**\*\*20.23** (*Evaluate expression*) Modify Listing 20.9 EvaluateExpression.java to add operators **^** for exponent and **%** for modulus. For example, **3 ^ 2** is **9** and **3 % 2** is **1**. The **^** operator has the highest precedence and the **%** operator has the same precedence as the **\*** and **/** operators. Your program should prompt the user to enter an expression. Here is a sample run of the program:



|                                                                                       |                                      |
|---------------------------------------------------------------------------------------|--------------------------------------|
| Enter an expression: (5 * 2 ^ 3 + 2 * 3 % 2) * 4<br>(5 * 2 ^ 3 + 2 * 3 % 2) * 4 = 160 | <input type="button" value="Enter"/> |
|---------------------------------------------------------------------------------------|--------------------------------------|

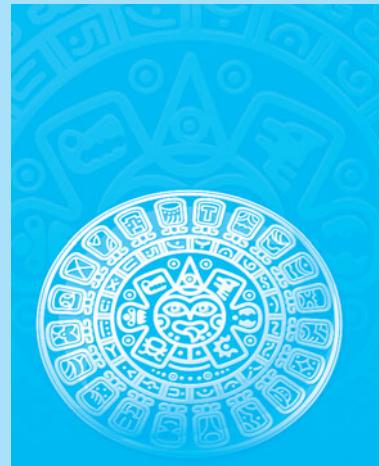
# CHAPTER

# 21

## SETS AND MAPS

### Objectives

- To store unordered, nonduplicate elements using a set (§21.2).
- To explore how and when to use **HashSet** (§21.2.1), **LinkedHashSet** (§21.2.2), or **TreeSet** (§21.2.3) to store a set of elements.
- To compare the performance of sets and lists (§21.3).
- To use sets to develop a program that counts the keywords in a Java source file (§21.4).
- To tell the differences between **Collection** and **Map** and describe when and how to use **HashMap**, **LinkedHashMap**, or **TreeMap** to store values associated with keys (§21.5).
- To use maps to develop a program that counts the occurrence of the words in a text (§21.6).
- To obtain singleton sets, lists, and maps, and unmodifiable sets, lists, and maps, using the static methods in the **Collections** class (§21.7).



## 21.1 Introduction



*A set is an efficient data structure for storing and processing nonduplicate elements. A map is like a dictionary that provides a quick lookup to retrieve a value using a key.*

why set?

why map?

The “**No-Fly**” list is a list, created and maintained by the U.S. government’s Terrorist Screening Center, of people who are not permitted to board a commercial aircraft for travel in or out of the United States. Suppose we need to write a program that checks whether a person is on the No-Fly list. You can use a list to store names in the No-Fly list. However, a more efficient data structure for this application is a *set*.

Suppose your program also needs to store detailed information about terrorists in the No-Fly list. The detailed information such as gender, height, weight, and nationality can be retrieved using the name as the key. A *map* is an efficient data structure for such a task.

This chapter introduces sets and maps in the Java Collections Framework.

## 21.2 Sets



*You can create a set using one of its three concrete classes: **HashSet**, **LinkedHashSet**, or **TreeSet**.*

set  
no duplicates

AbstractSet

hash set

load factor

hashCode()

The **Set** interface extends the **Collection** interface, as shown in Figure 20.1. It does not introduce new methods or constants, but it stipulates that an instance of **Set** contains no duplicate elements. The concrete classes that implement **Set** must ensure that no duplicate elements can be added to the set. That is, no two elements **e1** and **e2** can be in the set such that **e1.equals(e2)** is **true**.

The **AbstractSet** class extends **AbstractCollection** and partially implements **Set**. The **AbstractSet** class provides concrete implementations for the **equals** method and the **hashCode** method. The hash code of a set is the sum of the hash codes of all the elements in the set. Since the **size** method and **iterator** method are not implemented in the **AbstractSet** class, **AbstractSet** is an abstract class.

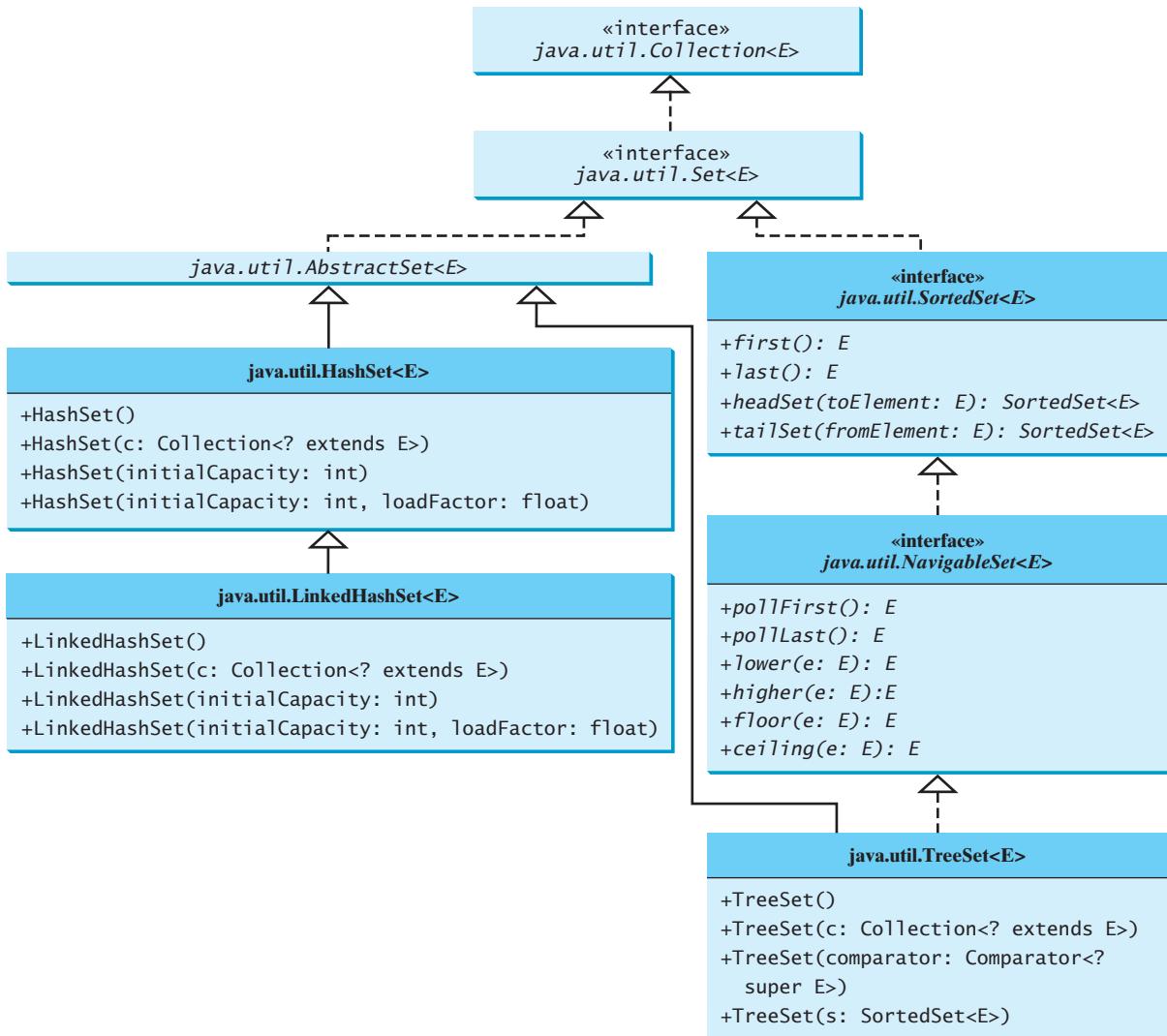
Three concrete classes of **Set** are **HashSet**, **LinkedHashSet**, and **TreeSet**, as shown in Figure 21.1.

### 21.2.1 HashSet

The **HashSet** class is a concrete class that implements **Set**. You can create an empty *hash set* using its no-arg constructor or create a hash set from an existing collection. By default, the initial capacity is **16** and the load factor is **0.75**. If you know the size of your set, you can specify the initial capacity and load factor in the constructor. Otherwise, use the default setting. The load factor is a value between **0.0** and **1.0**.

The *load factor* measures how full the set is allowed to be before its capacity is increased. When the number of elements exceeds the product of the capacity and load factor, the capacity is automatically doubled. For example, if the capacity is **16** and load factor is **0.75**, the capacity will be doubled to **32** when the size reaches **12** ( $16 * 0.75 = 12$ ). A higher load factor decreases the space costs but increases the search time. Generally, the default load factor **0.75** is a good trade-off between time and space costs. We will discuss more on the load factor in Chapter 27, Hashing.

A **HashSet** can be used to store *duplicate-free* elements. For efficiency, objects added to a hash set need to implement the **hashCode** method in a manner that properly disperses the hash code. Recall that **hashCode** is defined in the **Object** class. The hash codes of two objects must be the same if the two objects are equal. Two unequal objects may have the same hash code, but you should implement the **hashCode** method to avoid too many such cases. Most of the classes in the Java API implement the **hashCode** method. For example, the **hashCode** in the **Integer** class returns its **int** value. The **hashCode** in the **Character** class returns the Unicode of the character. The **hashCode** in the **String** class returns  $s_0 * 31^{(n-1)} + s_1 * 31^{(n-2)} + \dots + s_{n-1}$ , where  $s_i$  is **s.charAt(i)**.



**FIGURE 21.1** The Java Collections Framework provides three concrete set classes.

Listing 21.1 gives a program that creates a hash set to store strings and uses a foreach loop to traverse the elements in the set.

### LISTING 21.1 TestHashSet.java

```

1 import java.util.*;
2
3 public class TestHashSet {
4 public static void main(String[] args) {
5 // Create a hash set
6 Set<String> set = new HashSet<>(); create a set
7
8 // Add strings to the set
9 set.add("London");
10 set.add("Paris");
11 set.add("New York");
12 set.add("San Francisco");
13 set.add("Beijing"); add element

```

traverse elements

```

14 set.add("New York");
15
16 System.out.println(set);
17
18 // Display the elements in the hash set
19 for (String s: set) {
20 System.out.print(s.toUpperCase() + " ");
21 }
22 }
23 }
```



[San Francisco, New York, Paris, Beijing, London]  
SAN FRANCISCO NEW YORK PARIS BEIJING LONDON

The strings are added to the set (lines 9–14). **New York** is added to the set more than once, but only one string is stored, because a set does not allow duplicates.

As shown in the output, the strings are not stored in the order in which they are inserted into the set. There is no particular order for the elements in a hash set. To impose an order on them, you need to use the **LinkedHashSet** class, which is introduced in the next section.

Recall that the **Collection** interface extends the **Iterable** interface, so the elements in a set are iterable. A foreach loop is used to traverse all the elements in the set (lines 19–21).

Since a set is an instance of **Collection**, all methods defined in **Collection** can be used for sets. Listing 21.2 gives an example that applies the methods in the **Collection** interface on sets.

### LISTING 21.2 TestMethodsInCollection.java

create a set

```

1 public class TestMethodsInCollection {
2 public static void main(String[] args) {
3 // Create set1
4 java.util.Set<String> set1 = new java.util.HashSet<>();
5
6 // Add strings to set1
7 set1.add("London");
8 set1.add("Paris");
9 set1.add("New York");
10 set1.add("San Francisco");
11 set1.add("Beijing");
12
13 System.out.println("set1 is " + set1);
14 System.out.println(set1.size() + " elements in set1");
15
16 // Delete a string from set1
17 set1.remove("London");
18 System.out.println("\nset1 is " + set1);
19 System.out.println(set1.size() + " elements in set1");
20
21 // Create set2
22 java.util.Set<String> set2 = new java.util.HashSet<>();
23
24 // Add strings to set2
25 set2.add("London");
26 set2.add("Shanghai");
27 set2.add("Paris");
28 System.out.println("\nset2 is " + set2);
29 System.out.println(set2.size() + " elements in set2");
```

add element

get size

remove element

create a set

add element

```

30
31 System.out.println("\nIs Taipei in set2? "
32 + set2.contains("Taipei"));
33
34 set1.addAll(set2);
35 System.out.println("\nAfter adding set2 to set1, set1 is "
36 + set1);
37
38 set1.removeAll(set2);
39 System.out.println("After removing set2 from set1, set1 is "
40 + set1);
41
42 set1.retainAll(set2);
43 System.out.println("After removing common elements in set2 "
44 + "from set1, set1 is " + set1);
45 }
46 }
```

contains element?

addAll

removeAll

retainAll

set1 is [San Francisco, New York, Paris, Beijing, London]  
 5 elements in set1



set1 is [San Francisco, New York, Paris, Beijing]  
 4 elements in set1

set2 is [Shanghai, Paris, London]  
 3 elements in set2

Is Taipei in set2? false

After adding set2 to set1, set1 is  
 [San Francisco, New York, Shanghai, Paris, Beijing, London]

After removing set2 from set1, set1 is  
 [San Francisco, New York, Beijing]

After removing common elements in set2 from set1, set1 is []

The program creates two sets (lines 4, 22). The **size()** method returns the number of the elements in a set (line 14). Line 17

```
set1.remove("London");
```

removes **London** from **set1**.

The **contains** method (line 32) checks whether an element is in the set.

Line 34

```
set1.addAll(set2);
```

adds **set2** to **set1**. Therefore, **set1** becomes **[San Francisco, New York, Shanghai, Paris, Beijing, London]**.

Line 38

```
set1.removeAll(set2);
```

removes **set2** from **set1**. Thus, **set1** becomes **[San Francisco, New York, Beijing]**.

Line 42

```
set1.retainAll(set2);
```

retains the common elements in `set1`. Since `set1` and `set2` have no common elements, `set1` becomes empty.

### 21.2.2 `LinkedHashSet`

`LinkedHashSet` extends `HashSet` with a linked-list implementation that supports an ordering of the elements in the set. The elements in a `HashSet` are not ordered, but the elements in a `LinkedHashSet` can be retrieved in the order in which they were inserted into the set. A `LinkedHashSet` can be created by using one of its four constructors, as shown in Figure 21.1. These constructors are similar to the constructors for `HashSet`.

Listing 21.3 gives a test program for `LinkedHashSet`. The program simply replaces `HashSet` by `LinkedHashSet` in Listing 21.1.

linked hash set

create linked hash set

add element

display elements

#### LISTING 21.3 `TestLinkedHashSet.java`

```

1 import java.util.*;
2
3 public class TestLinkedHashSet {
4 public static void main(String[] args) {
5 // Create a hash set
6 Set<String> set = new LinkedHashSet<>();
7
8 // Add strings to the set
9 set.add("London");
10 set.add("Paris");
11 set.add("New York");
12 set.add("San Francisco");
13 set.add("Beijing");
14 set.add("New York");
15
16 System.out.println(set);
17
18 // Display the elements in the hash set
19 for (Object element: set)
20 System.out.print(element.toLowerCase() + " ");
21 }
22 }
```



[London, Paris, New York, San Francisco, Beijing]  
london paris new york san francisco beijing

A `LinkedHashSet` is created in line 6. As shown in the output, the strings are stored in the order in which they are inserted. Since `LinkedHashSet` is a set, it does not store duplicate elements.

The `LinkedHashSet` maintains the order in which the elements are inserted. To impose a different order (e.g., increasing or decreasing order), you can use the `TreeSet` class, which is introduced in the next section.



#### Tip

If you don't need to maintain the order in which the elements are inserted, use `HashSet`, which is more efficient than `LinkedHashSet`.

### 21.2.3 `TreeSet`

`SortedSet` is a subinterface of `Set`, which guarantees that the elements in the set are sorted. Additionally, it provides the methods `first()` and `last()` for returning the first and last elements in the set, and `headSet(toElement)` and `tailSet(fromElement)` for returning

a portion of the set whose elements are less than `toElement` and greater than or equal to `fromElement`, respectively.

`NavigableSet` extends `SortedSet` to provide navigation methods `lower(e)`, `floor(e)`, `ceiling(e)`, and `higher(e)` that return elements respectively less than, less than or equal, greater than or equal, and greater than a given element and return `null` if there is no such element. The `pollFirst()` and `pollLast()` methods remove and return the first and last element in the tree set, respectively.

`TreeSet` implements the `SortedSet` interface. To create a `TreeSet`, use a constructor, as shown in Figure 21.1. You can add objects into a *tree set* as long as they can be compared with each other.

As discussed in Section 20.5, the elements can be compared in two ways: using the `Comparable` interface or the `Comparator` interface.

Listing 21.4 gives an example of ordering elements using the `Comparable` interface. The preceding example in Listing 21.3 displays all the strings in their insertion order. This example rewrites the preceding example to display the strings in alphabetical order using the `TreeSet` class.

### LISTING 21.4 TestTreeSet.java

```

1 import java.util.*;
2
3 public class TestTreeSet {
4 public static void main(String[] args) {
5 // Create a hash set
6 Set<String> set = new HashSet<>(); create hash set
7
8 // Add strings to the set
9 set.add("London");
10 set.add("Paris");
11 set.add("New York");
12 set.add("San Francisco");
13 set.add("Beijing");
14 set.add("New York");
15
16 TreeSet<String> treeSet = new TreeSet<>(set); create tree set
17 System.out.println("Sorted tree set: " + treeSet);
18
19 // Use the methods in SortedSet interface
20 System.out.println("first(): " + treeSet.first()); display elements
21 System.out.println("last(): " + treeSet.last());
22 System.out.println("headSet(\"New York\"): " +
23 treeSet.headSet("New York"));
24 System.out.println("tailSet(\"New York\"): " +
25 treeSet.tailSet("New York"));
26
27 // Use the methods in NavigableSet interface
28 System.out.println("lower(\"P\"): " + treeSet.lower("P"));
29 System.out.println("higher(\"P\"): " + treeSet.higher("P"));
30 System.out.println("floor(\"P\"): " + treeSet.floor("P"));
31 System.out.println("ceiling(\"P\"): " + treeSet.ceiling("P"));
32 System.out.println("pollFirst(): " + treeSet.pollFirst());
33 System.out.println("pollLast(): " + treeSet.pollLast());
34 System.out.println("New tree set: " + treeSet);
35 }
36 }
```

```

Sorted tree set: [Beijing, London, New York, Paris, San Francisco]
first(): Beijing
last(): San Francisco
```



```

headSet("New York"): [Beijing, London]
tailSet("New York"): [New York, Paris, San Francisco]
lower("P"): New York
higher("P"): Paris
floor("P"): New York
ceiling("P"): Paris
pollFirst(): Beijing
pollLast(): San Francisco
New tree set: [London, New York, Paris]

```

The example creates a hash set filled with strings, then creates a tree set for the same strings. The strings are sorted in the tree set using the `compareTo` method in the `Comparable` interface.

The elements in the set are sorted once you create a `TreeSet` object from a `HashSet` object using `new TreeSet<String>(set)` (line 16). You may rewrite the program to create an instance of `TreeSet` using its no-arg constructor, and add the strings into the `TreeSet` object.

`treeSet.first()` returns the first element in `treeSet` (line 20), and `treeSet.last()` returns the last element in `treeSet` (line 21). `treeSet.headSet("New York")` returns the elements in `treeSet` before New York (lines 22–23). `treeSet.tailSet("New York")` returns the elements in `treeSet` after New York, including New York (lines 24–25).

`treeSet.lower("P")` returns the largest element less than P in `treeSet` (line 28). `treeSet.higher("P")` returns the smallest element greater than P in `treeSet` (line 29). `treeSet.floor("P")` returns the largest element less than or equal to P in `treeSet` (line 30). `treeSet.ceiling("P")` returns the smallest element greater than or equal to P in `treeSet` (line 31). `treeSet.pollFirst()` removes the first element in `treeSet` and returns the removed element (line 32). `treeSet.pollLast()` removes the last element in `treeSet` and returns the removed element (line 33).



### Note

All the concrete classes in Java Collections Framework (see Figure 20.1) have at least two constructors. One is the no-arg constructor that constructs an empty collection. The other constructs instances from a collection. Thus the `TreeSet` class has the constructor `TreeSet(Collection c)` for constructing a `TreeSet` from a collection `c`. In this example, `new TreeSet<>(set)` creates an instance of `TreeSet` from the collection `set`.



### Tip

If you don't need to maintain a sorted set when updating a set, you should use a hash set, because it takes less time to insert and remove elements in a hash set. When you need a sorted set, you can create a tree set from the hash set.

If you create a `TreeSet` using its no-arg constructor, the `compareTo` method is used to compare the elements in the set, assuming that the class of the elements implements the `Comparable` interface. To use a comparator, you have to use the constructor `TreeSet(Comparator comparator)` to create a sorted set that uses the `compare` method in the comparator to order the elements in the set.

Listing 21.5 gives a program that demonstrates how to sort elements in a tree set using the `Comparator` interface.

### LISTING 21.5 TestTreeSetWithComparator.java

```

1 import java.util.*;
2

```

```

3 public class TestTreeSetWithComparator {
4 public static void main(String[] args) {
5 // Create a tree set for geometric objects using a comparator
6 Set<GeometricObject> set =
7 new TreeSet<>(new GeometricObjectComparator()); tree set
8 set.add(new Rectangle(4, 5));
9 set.add(new Circle(40));
10 set.add(new Circle(40));
11 set.add(new Rectangle(4, 1));
12
13 // Display geometric objects in the tree set
14 System.out.println("A sorted set of geometric objects");
15 for (GeometricObject element: set) display elements
16 System.out.println("area = " + element.getArea());
17 }
18 }
```

A sorted set of geometric objects  
area = 4.0  
area = 20.0  
area = 5021.548245743669



The **GeometricObjectComparator** class is defined in Listing 20.4. The program creates a tree set of geometric objects using the **GeometricObjectComparator** for comparing the elements in the set (lines 6–7).

The **Circle** and **Rectangle** classes were defined in Section 13.2, Abstract Classes. They are all subclasses of **GeometricObject**. They are added to the set (lines 8–11).

Two circles of the same radius are added to the tree set (lines 9–10), but only one is stored, because the two circles are equal and the set does not allow duplicates.



- 21.1** How do you create an instance of **Set**? How do you insert a new element in a set? How do you remove an element from a set? How do you find the size of a set?
- 21.2** If two objects **o1** and **o2** are equal, what is **o1.equals(o2)** and **o1.hashCode() == o2.hashCode()**?
- 21.3** What are the differences between **HashSet**, **LinkedHashSet**, and **TreeSet**?
- 21.4** How do you traverse the elements in a set?
- 21.5** How do you sort the elements in a set using the **compareTo** method in the **Comparable** interface? How do you sort the elements in a set using the **Comparator** interface? What would happen if you added an element that could not be compared with the existing elements in a tree set?
- 21.6** Suppose that **set1** is a set that contains the strings **red**, **yellow**, and **green**, and that **set2** is another set that contains the strings **red**, **yellow**, and **blue**. Answer the following questions:
  - What are in **set1** and **set2** after executing **set1.addAll(set2)**?
  - What are in **set1** and **set2** after executing **set1.add(set2)**?
  - What are in **set1** and **set2** after executing **set1.removeAll(set2)**?
  - What are in **set1** and **set2** after executing **set1.remove(set2)**?
  - What are in **set1** and **set2** after executing **set1.retainAll(set2)**?
  - What is in **set1** after executing **set1.clear()**?

**21.7** Show the output of the following code:

```
import java.util.*;

public class Test {
 public static void main(String[] args) {
 LinkedHashSet<String> set1 = new LinkedHashSet<>();
 set1.add("New York");
 LinkedHashSet<String> set2 = set1;
 LinkedHashSet<String> set3 =
 (LinkedHashSet<String>)(set1.clone());
 set1.add("Atlanta");
 System.out.println("set1 is " + set1);
 System.out.println("set2 is " + set2);
 System.out.println("set3 is " + set3);
 }
}
```

**21.8** Show the output of the following code:

```
import java.util.*;
import java.io.*;

public class Test {
 public static void main(String[] args) throws Exception {
 ObjectOutputStream output = new ObjectOutputStream(
 new FileOutputStream("c:\\test.dat"));
 LinkedHashSet<String> set1 = new LinkedHashSet<>();
 set1.add("New York");
 LinkedHashSet<String> set2 =
 (LinkedHashSet<String>)set1.clone();
 set1.add("Atlanta");
 output.writeObject(set1);
 output.writeObject(set2);
 output.close();

 ObjectInputStream input = new ObjectInputStream(
 new FileInputStream("c:\\test.dat"));
 set1 = (LinkedHashSet<String>)input.readObject();
 set2 = (LinkedHashSet<String>)input.readObject();
 System.out.println(set1);
 System.out.println(set2);
 output.close();
 }
}
```

**21.9** What will the output be if lines 6–7 in Listing 21.5 is replaced by the following code:

```
Set<GeometricObject> set = new HashSet<>();
```

## 21.3 Comparing the Performance of Sets and Lists



*Sets are more efficient than lists for storing nonduplicate elements. Lists are useful for accessing elements through the index.*

The elements in a list can be accessed through the index. However, sets do not support indexing, because the elements in a set are unordered. To traverse all elements in a set, use a foreach loop. We now conduct an interesting experiment to test the performance of sets and lists. Listing 21.6 gives a program that shows the execution time of (1) testing whether an element

is in a hash set, linked hash set, tree set, array list, and linked list, and (2) removing elements from a hash set, linked hash set, tree set, array list, and linked list.

### LISTING 21.6 SetListPerformanceTest.java

```

1 import java.util.*;
2
3 public class SetListPerformanceTest {
4 static final int N = 50000;
5
6 public static void main(String[] args) {
7 // Add numbers 0, 1, 2, ..., N - 1 to the array list
8 List<Integer> list = new ArrayList<>();
9 for (int i = 0; i < N; i++)
10 list.add(i);
11 Collections.shuffle(list); // Shuffle the array list
12
13 // Create a hash set, and test its performance
14 Collection<Integer> set1 = new HashSet<>(list);
15 System.out.println("Member test time for hash set is " +
16 getTestTime(set1) + " milliseconds");
17 System.out.println("Remove element time for hash set is " +
18 getRemoveTime(set1) + " milliseconds");
19
20 // Create a linked hash set, and test its performance
21 Collection<Integer> set2 = new LinkedHashSet<>(list);
22 System.out.println("Member test time for linked hash set is " +
23 getTestTime(set2) + " milliseconds");
24 System.out.println("Remove element time for linked hash set is " +
25 getRemoveTime(set2) + " milliseconds");
26
27 // Create a tree set, and test its performance
28 Collection<Integer> set3 = new TreeSet<>(list);
29 System.out.println("Member test time for tree set is " +
30 getTestTime(set3) + " milliseconds");
31 System.out.println("Remove element time for tree set is " +
32 getRemoveTime(set3) + " milliseconds");
33
34 // Create an array list, and test its performance
35 Collection<Integer> list1 = new ArrayList<>(list);
36 System.out.println("Member test time for array list is " +
37 getTestTime(list1) + " milliseconds");
38 System.out.println("Remove element time for array list is " +
39 getRemoveTime(list1) + " milliseconds");
40
41 // Create a linked list, and test its performance
42 Collection<Integer> list2 = new LinkedList<>(list);
43 System.out.println("Member test time for linked list is " +
44 getTestTime(list2) + " milliseconds");
45 System.out.println("Remove element time for linked list is " +
46 getRemoveTime(list2) + " milliseconds");
47 }
48
49 public static long getTestTime(Collection<Integer> c) {
50 long startTime = System.currentTimeMillis();
51
52 // Test if a number is in the collection
53 for (int i = 0; i < N; i++)
54 c.contains((int)(Math.random() * 2 * N));
55
56 return System.currentTimeMillis() - startTime;
57 }
58
59
```

create test data

shuffle

a hash set

a linked hash set

a tree set

an array list

a linked list

start time

test membership

return execution time

```

57 }
58
59 public static long getRemoveTime(Collection<Integer> c) {
60 long startTime = System.currentTimeMillis();
61
62 for (int i = 0; i < N; i++)
63 c.remove(i);
64
65 return System.currentTimeMillis() - startTime;
66 }
67 }
```

remove from container

return execution time



```

Member test time for hash set is 20 milliseconds
Remove element time for hash set is 27 milliseconds
Member test time for linked hash set is 27 milliseconds
Remove element time for linked hash set is 26 milliseconds
Member test time for tree set is 47 milliseconds
Remove element time for tree set is 34 milliseconds
Member test time for array list is 39802 milliseconds
Remove element time for array list is 16196 milliseconds
Member test time for linked list is 52197 milliseconds
Remove element time for linked list is 14870 milliseconds
```

sets are better

The program creates a list for numbers from **0** to **N-1** (for **N = 50000**) (lines 8–10) and shuffles the list (line 11). From this list, the program creates a hash set (line 14), a linked hash set (line 21), a tree set (line 28), an array list (line 35), and a linked list (line 42). The program obtains the execution time for testing whether a number is in the hash set (line 16), linked hash set (line 23), tree set (line 30), array list (line 37), and linked list (line 44), and obtains the execution time for removing the elements from the hash set (line 18), linked hash set (line 25), tree set (line 32), array list (line 39), and linked list (line 46).

The **getTestTime** method invokes the **contains** method to test whether a number is in the container (line 54) and the **getRemoveTime** method invokes the **remove** method to remove an element from the container (line 63).

As these runtimes illustrate, sets are much more efficient than lists for testing whether an element is in a set or a list. Therefore, the No-Fly list should be implemented using a set instead of a list, because it is much faster to test whether an element is in a set than in a list.

You may wonder why sets are more efficient than lists. The questions will be answered in Chapters 24 and 27 when we introduce the implementations of lists and sets.



- 21.10** Suppose you need to write a program that stores unordered non-duplicate elements, what data structure should you use?
- 21.11** Suppose you need to write a program that stores non-duplicate elements in the order of insertion, what data structure should you use?
- 21.12** Suppose you need to write a program that stores non-duplicate elements in increasing order of the element values, what data structure should you use?
- 21.13** Suppose you need to write a program that stores a fixed number of the elements (possibly duplicates), what data structure should you use?
- 21.14** Suppose you need to write a program that stores the elements in a list with frequent operations to add and insert elements at the end of the list, what data structure should you use?
- 21.15** Suppose you need to write a program that stores the elements in a list with frequent operations to add and insert elements at the beginning of the list, what data structure should you use?

## 21.4 Case Study: Counting Keywords

This section presents an application that counts the number of the keywords in a Java source file.



For each word in a Java source file, we need to determine whether the word is a keyword. To handle this efficiently, store all the keywords in a `HashSet` and use the `contains` method to test if a word is in the keyword set. Listing 21.7 gives this program.

### LISTING 21.7 CountKeywords.java

```

1 import java.util.*;
2 import java.io.*;
3
4 public class CountKeywords {
5 public static void main(String[] args) throws Exception {
6 Scanner input = new Scanner(System.in);
7 System.out.print("Enter a Java source file: ");
8 String filename = input.nextLine();
9
10 File file = new File(filename);
11 if (file.exists()) {
12 System.out.println("The number of keywords in " + filename
13 + " is " + countKeywords(file));
14 }
15 else {
16 System.out.println("File " + filename + " does not exist");
17 }
18 }
19
20 public static int countKeywords(File file) throws Exception {
21 // Array of all Java keywords + true, false and null
22 String[] keywordString = {"abstract", "assert", "boolean",
23 "break", "byte", "case", "catch", "char", "class", "const",
24 "continue", "default", "do", "double", "else", "enum",
25 "extends", "for", "final", "finally", "float", "goto",
26 "if", "implements", "import", "instanceof", "int",
27 "interface", "long", "native", "new", "package", "private",
28 "protected", "public", "return", "short", "static",
29 "strictfp", "super", "switch", "synchronized", "this",
30 "throw", "throws", "transient", "try", "void", "volatile",
31 "while", "true", "false", "null"};
32
33 Set<String> keywordSet =
34 new HashSet<>(Arrays.asList(keywordString));
35 int count = 0;
36
37 Scanner input = new Scanner(file);
38
39 while (input.hasNext()) {
40 String word = input.next();
41 if (keywordSet.contains(word))
42 count++;
43 }
44
45 return count;
46 }
47 }
```

enter a filename

file exists?

count keywords

keywords

keyword set

is a keyword?



```
Enter a Java source file: c:\Welcome.java ↵Enter
The number of keywords in c:\Welcome.java is 5
```



```
Enter a Java source file: c:\TTT.java ↵Enter
File c:\TTT.java does not exist
```

The program prompts the user to enter a Java source filename (line 7) and reads the filename (line 8). If the file exists, the `countKeywords` method is invoked to count the keywords in the file (line 13).

The `countKeywords` method creates an array of strings for the keywords (lines 22–31) and creates a hash set from this array (lines 33–34). It then reads each word from the file and tests if the word is in the set (line 41). If so, the program increases the count by 1 (line 42).

You may rewrite the program to use a `LinkedHashSet`, `TreeSet`, `ArrayList`, or `LinkedList` to store the keywords. However, using a `HashSet` is the most efficient for this program.



### 21.16 Will the `CountKeywords` program work if lines 33–34 are changed to

```
Set<String> keywordSet =
 new LinkedHashSet<>(Arrays.asList(keywordString));
```

### 21.17 Will the `CountKeywords` program work if lines 33–34 are changed to

```
List<String> keywordSet =
 new ArrayList<>(Arrays.asList(keywordString));
```

## 21.5 Maps



*You can create a map using one of its three concrete classes: `HashMap`, `LinkedHashMap`, or `TreeMap`.*

map

A *map* is a container object that stores a collection of key/value pairs. It enables fast retrieval, deletion, and updating of the pair through the key. A map stores the values along with the keys. The keys are like indexes. In `List`, the indexes are integers. In `Map`, the keys can be any objects. A map cannot contain duplicate keys. Each key maps to one value. A key and its corresponding value form an entry stored in a map, as shown in Figure 21.2a. Figure 21.2b shows a map in which each entry consists of a Social Security number as the key and a name as the value.

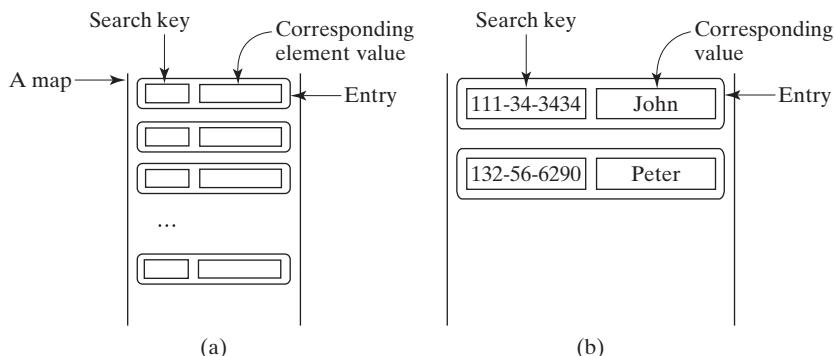
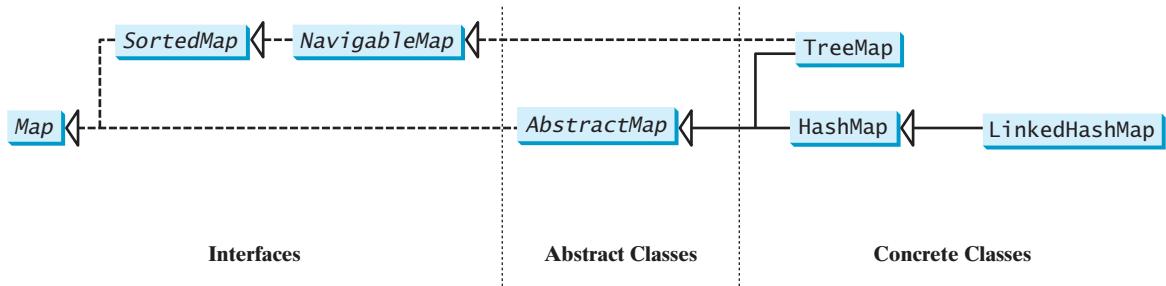


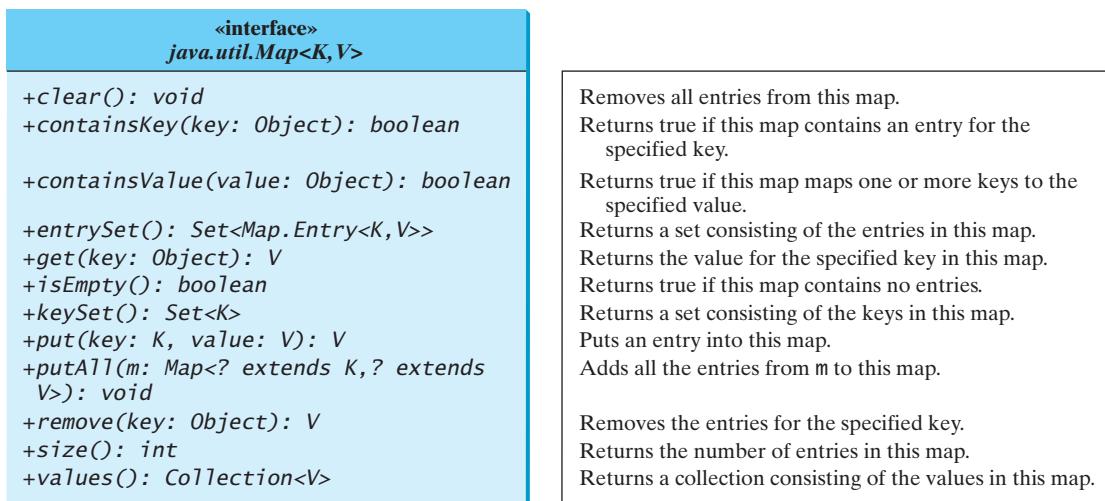
FIGURE 21.2 The entries consisting of key/value pairs are stored in a map.

There are three types of maps: **HashMap**, **LinkedHashMap**, and **TreeMap**. The common features of these maps are defined in the **Map** interface. Their relationship is shown in Figure 21.3.



**FIGURE 21.3** A map stores key/value pairs.

The **Map** interface provides the methods for querying, updating, and obtaining a collection of values and a set of keys, as shown in Figure 21.4.



**FIGURE 21.4** The **Map** interface maps keys to values.

The *update methods* include **clear**, **put**, **putAll**, and **remove**. The **clear()** method removes all entries from the map. The **put(K key, V value)** method adds an entry for the specified key and value in the map. If the map formerly contained an entry for this key, the old value is replaced by the new value and the old value associated with the key is returned. The **putAll(Map m)** method adds all entries in m to this map. The **remove(Object key)** method removes the entry for the specified key from the map.

The *query methods* include **containsKey**, **containsValue**, **isEmpty**, and **size**. The **containsKey(Object key)** method checks whether the map contains an entry for the specified key. The **containsValue(Object value)** method checks whether the map contains an entry for this value. The **isEmpty()** method checks whether the map contains any entries. The **size()** method returns the number of entries in the map.

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keySet()  
values()  
entrySet()

You can obtain a set of the keys in the map using the `keySet()` method, and a collection of the values in the map using the `values()` method. The `entrySet()` method returns a set of entries. The entries are instances of the `Map.Entry<K, V>` interface, where `Entry` is an inner interface for the `Map` interface, as shown in Figure 21.5. Each entry in the set is a key/value pair in the underlying map.



FIGURE 21.5 The `Map.Entry` interface operates on an entry in the map.

AbstractMap  
concrete implementations

The `AbstractMap` class is a convenience abstract class that implements all the methods in the `Map` interface except the `entrySet()` method.

The `HashMap`, `LinkedHashMap`, and `TreeMap` classes are three *concrete implementations* of the `Map` interface, as shown in Figure 21.6.

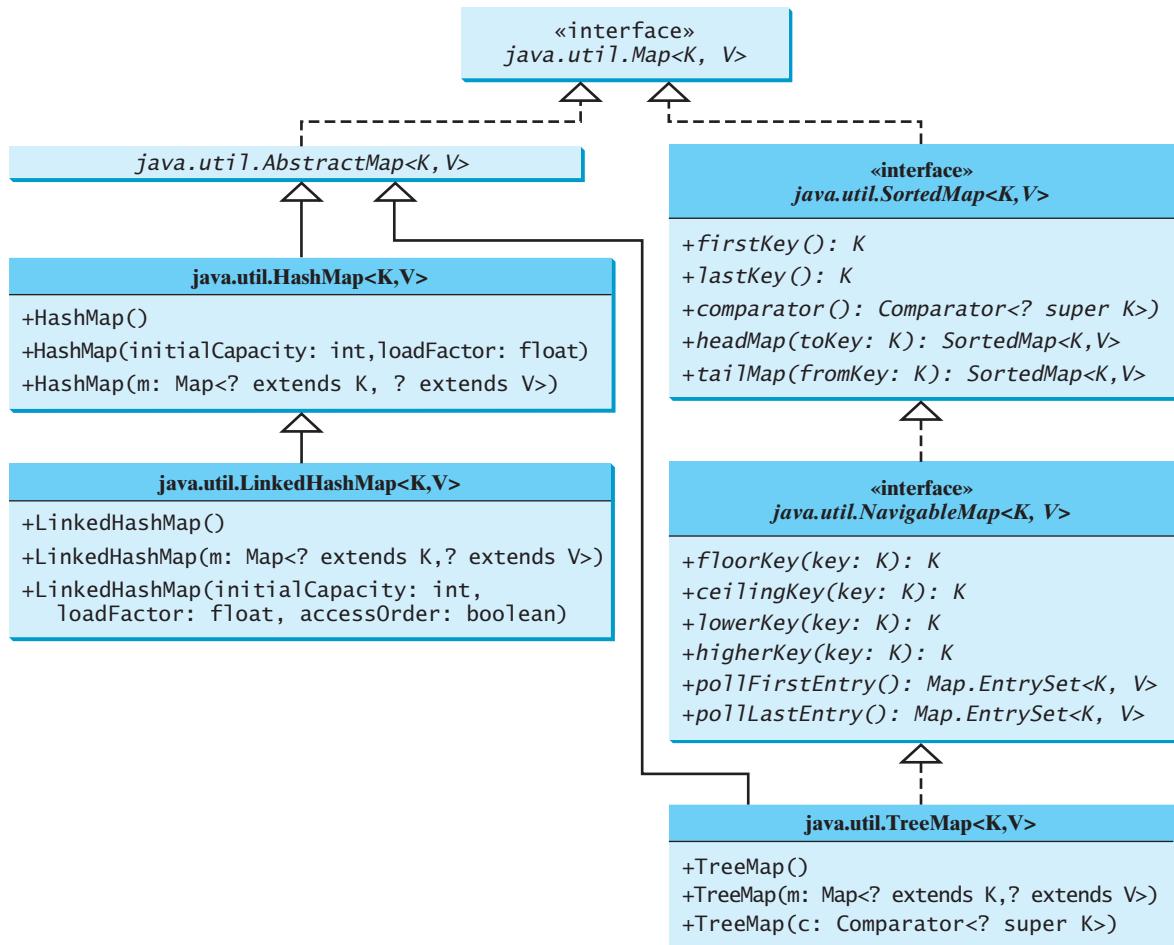


FIGURE 21.6 The Java Collections Framework provides three concrete map classes.

The **HashMap** class is efficient for locating a value, inserting an entry, and deleting an entry. **LinkedHashMap** extends **HashMap** with a linked-list implementation that supports an ordering of the entries in the map. The entries in a **HashMap** are not ordered, but the entries in a **LinkedHashMap** can be retrieved either in the order in which they were inserted into the map (known as the *insertion order*) or in the order in which they were last accessed, from least recently to most recently accessed (*access order*). The no-arg constructor constructs a **LinkedHashMap** with the insertion order. To construct a **LinkedHashMap** with the access order, use **LinkedHashMap(initialCapacity, loadFactor, true)**.

The **TreeMap** class is efficient for traversing the keys in a sorted order. The keys can be sorted using the **Comparable** interface or the **Comparator** interface. If you create a **TreeMap** using its no-arg constructor, the **compareTo** method in the **Comparable** interface is used to compare the keys in the map, assuming that the class for the keys implements the **Comparable** interface. To use a comparator, you have to use the **TreeMap(Comparator comparator)** constructor to create a sorted map that uses the **compare** method in the comparator to order the entries in the map based on the keys.

**SortedMap** is a subinterface of **Map**, which guarantees that the entries in the map are sorted. Additionally, it provides the methods **firstKey()** and **lastKey()** for returning the first and last keys in the map, and **headMap(toKey)** and **tailMap(fromKey)** for returning a portion of the map whose keys are less than **toKey** and greater than or equal to **fromKey**, respectively.

**NavigableMap** extends **SortedMap** to provide the navigation methods **lowerKey(key)**, **floorKey(key)**, **ceilingKey(key)**, and **higherKey(key)** that return keys respectively less than, less than or equal, greater than or equal, and greater than a given key and return **null** if there is no such key. The **pollFirstEntry()** and **pollLastEntry()** methods remove and return the first and last entry in the tree map, respectively.



### Note

Prior to Java 2, **java.util.Hashtable** was used for mapping keys with values.

**Hashtable** was redesigned to fit into the Java Collections Framework with all its methods retained for compatibility. **Hashtable** implements the **Map** interface and is used in the same way as **HashMap**, except that the update methods in **Hashtable** are synchronized.

Listing 21.8 gives an example that creates a *hash map*, a *linked hash map*, and a *tree map* for mapping students to ages. The program first creates a hash map with the student's name as its key and the age as its value. The program then creates a tree map from the hash map and displays the entries in ascending order of the keys. Finally, the program creates a linked hash map, adds the same entries to the map, and displays the entries.

### LISTING 21.8 TestMap.java

```

1 import java.util.*;
2
3 public class TestMap {
4 public static void main(String[] args) {
5 // Create a HashMap
6 Map<String, Integer> hashMap = new HashMap<>();
7 hashMap.put("Smith", 30);
8 hashMap.put("Anderson", 31);
9 hashMap.put("Lewis", 29);
10 hashMap.put("Cook", 29);
11
12 System.out.println("Display entries in HashMap");
13 System.out.println(hashMap + "\n");
14
15 // Create a TreeMap from the preceding HashMap
16 Map<String, Integer> treeMap =

```

HashMap  
LinkedHashMap

insertion order  
access order

TreeMap

SortedMap

NavigableMap

Hashtable

hash map  
linked hash map  
tree map

create map  
add entry

tree map

linked hash map

```

17 new TreeMap<>(hashMap);
18 System.out.println("Display entries in ascending order of key");
19 System.out.println(treeMap);
20
21 // Create a LinkedHashMap
22 Map<String, Integer> linkedHashMap =
23 new LinkedHashMap<>(16, 0.75f, true);
24 linkedHashMap.put("Smith", 30);
25 linkedHashMap.put("Anderson", 31);
26 linkedHashMap.put("Lewis", 29);
27 linkedHashMap.put("Cook", 29);
28
29 // Display the age for Lewis
30 System.out.println("\nThe age for " + "Lewis is " +
31 linkedHashMap.get("Lewis"));
32
33 System.out.println("Display entries in LinkedHashMap");
34 System.out.println(linkedHashMap);
35 }
36 }
```



Display entries in HashMap  
{Cook=29, Smith=30, Lewis=29, Anderson=31}

Display entries in ascending order of key  
{Anderson=31, Cook=29, Lewis=29, Smith=30}

The age for Lewis is 29  
Display entries in LinkedHashMap  
{Smith=30, Anderson=31, Cook=29, Lewis=29}

As shown in the output, the entries in the **HashMap** are in random order. The entries in the **TreeMap** are in increasing order of the keys. The entries in the **LinkedHashMap** are in the order of their access, from least recently accessed to most recently.

All the concrete classes that implement the **Map** interface have at least two constructors. One is the no-arg constructor that constructs an empty map, and the other constructs a map from an instance of **Map**. Thus, **new TreeMap<String, Integer>(hashMap)** (lines 16–17) constructs a tree map from a hash map.

You can create an insertion-ordered or access-ordered linked hash map. An access-ordered linked hash map is created in lines 22–21. The most recently accessed entry is placed at the end of the map. The entry with the key **Lewis** is last accessed in line 31, so it is displayed last in line 34.



### Tip

If you don't need to maintain an order in a map when updating it, use a **HashMap**.

When you need to maintain the insertion order or access order in the map, use a **LinkedHashMap**. When you need the map to be sorted on keys, use a **TreeMap**.



**21.18** How do you create an instance of **Map**? How do you add an entry to a map consisting of a key and a value? How do you remove an entry from a map? How do you find the size of a map? How do you traverse entries in a map?

**21.19** Describe and compare **HashMap**, **LinkedHashMap**, and **TreeMap**.

**21.20** Show the output of the following code:

```
public class Test {
 public static void main(String[] args) {
 Map<String, String> map = new LinkedHashMap<>();
 map.put("123", "John Smith");
 map.put("111", "George Smith");
 map.put("123", "Steve Yao");
 map.put("222", "Steve Yao");
 System.out.println("(1) " + map);
 System.out.println("(2) " + new TreeMap<String, String>(map));
 }
}
```

## 21.6 Case Study: Occurrences of Words

*This case study writes a program that counts the occurrences of words in a text and displays the words and their occurrences in alphabetical order of the words.*



The program uses a **TreeMap** to store an entry consisting of a word and its count. For each word, check whether it is already a key in the map. If not, add an entry to the map with the word as the key and value 1. Otherwise, increase the value for the word (key) by 1 in the map. Assume the words are case insensitive; e.g., **Good** is treated the same as **good**.

Listing 21.9 gives the solution to the problem.

### LISTING 21.9 CountOccurrenceOfWords.java

```
1 import java.util.*;
2
3 public class CountOccurrenceOfWords {
4 public static void main(String[] args) {
5 // Set text in a string
6 String text = "Good morning. Have a good class. " +
7 "Have a good visit. Have fun!";
8
9 // Create a TreeMap to hold words as key and count as value
10 Map<String, Integer> map = new TreeMap<>();tree map
11
12 String[] words = text.split("[\n\t\r.,;:!?\t\f]");split string
13 for (int i = 0; i < words.length; i++) {
14 String key = words[i].toLowerCase();
15
16 if (key.length() > 0) {
17 if (!map.containsKey(key)) {
18 map.put(key, 1);add entry
19 }
20 else {
21 int value = map.get(key);
22 value++;
23 map.put(key, value);update entry
24 }
25 }
26 }
27
28 // Get all entries into a set
29 Set<Map.Entry<String, Integer>> entrySet = map.entrySet();entry set
30 }
```

```

31 // Get key and value from each entry
32 for (Map.Entry<String, Integer> entry: entrySet)
33 System.out.println(entry.getValue() + "\t" + entry.getKey());
34 }
35 }

```



|         |   |
|---------|---|
| a       | 2 |
| class   | 1 |
| fun     | 1 |
| good    | 3 |
| have    | 3 |
| morning | 1 |
| visit   | 1 |

The program creates a **TreeMap** (line 10) to store pairs of words and their occurrence counts. The words serve as the keys. Since all values in the map must be stored as objects, the count is wrapped in an **Integer** object.

The program extracts a word from a text using the **split** method (line 12) in the **String** class (see Section 10.10.4). For each word extracted, the program checks whether it is already stored as a key in the map (line 17). If not, a new pair consisting of the word and its initial count (1) is stored in the map (line 18). Otherwise, the count for the word is incremented by 1 (lines 21–23).

The program obtains the entries of the map in a set (line 29), and traverses the set to display the count and the key in each entry (lines 32–33).

Since the map is a tree map, the entries are displayed in increasing order of words. To display them in ascending order of the occurrence counts, see Programming Exercise 21.8.

Now sit back and think how you would write this program without using map. Your new program would be longer and more complex. You will find that map is a very efficient and powerful data structure for solving problems such as this.



**21.21** Will the **CountOccurrenceOfWords** program work if line 10 is changed to

```
Map<String, int> map = new TreeMap<>();
```

**21.22** Will the **CountOccurrenceOfWords** program work if line 17 is changed to

```
if (map.get(key) == null) {
```

**21.23** Will the **CountOccurrenceOfWords** program work if lines 32–33 are changed to

```
for (String key: map)
 System.out.println(key + "\t" + map.getValue(key));
```

## 21.7 Singleton and Unmodifiable Collections and Maps



*You can create singleton sets, lists, and maps and unmodifiable sets, lists, and maps using the static methods in the **Collections** class.*

The **Collections** class contains the static methods for lists and collections. It also contains the methods for creating immutable singleton sets, lists, and maps, and for creating read-only sets, lists, and maps, as shown in Figure 21.7.

The **Collections** class defines three constants—**EMPTY\_SET**, **EMPTY\_LIST**, and **EMPTY\_MAP**—for an empty set, an empty list, and an empty map. These collections are immutable. The class also provides the **singleton(Object o)** method for creating an immutable set containing only a single item, the **singaporeList(Object o)** method for creating

| java.util.Collections                                           |                                                            |
|-----------------------------------------------------------------|------------------------------------------------------------|
| <code>+singleton(o: Object): Set</code>                         | Returns an immutable set containing the specified object.  |
| <code>+singletonList(o: Object): List</code>                    | Returns an immutable list containing the specified object. |
| <code>+singletonMap(key: Object, value: Object): Map</code>     | Returns an immutable map with the key and value pair.      |
| <code>+unmodifiableCollection(c: Collection): Collection</code> | Returns a read-only view of the collection.                |
| <code>+unmodifiableList(list: List): List</code>                | Returns a read-only view of the list.                      |
| <code>+unmodifiableMap(m: Map): Map</code>                      | Returns a read-only view of the map.                       |
| <code>+unmodifiableSet(s: Set): Set</code>                      | Returns a read-only view of the set.                       |
| <code>+unmodifiableSortedMap(s: SortedMap): SortedMap</code>    | Returns a read-only view of the sorted map.                |
| <code>+unmodifiableSortedSet(s: SortedSet): SortedSet</code>    | Returns a read-only view of the sorted set.                |

FIGURE 21.7 The `Collections` class contains the static methods for creating singleton and read-only sets, lists, and maps.

an immutable list containing only a single item, and the `singlentonMap(Object key, Object value)` method for creating an immutable map containing only a single entry.

The `Collections` class also provides six static methods for returning *read-only views* for collections: `unmodifiableCollection(Collection c)`, `unmodifiableList(List list)`, `unmodifiableMap(Map m)`, `unmodifiableSet(Set set)`, `unmodifiableSortedMap(SortedMap m)`, and `unmodifiableSortedSet(SortedSet s)`. This type of view is like a reference to the actual collection. But you cannot modify the collection through a read-only view. Attempting to modify a collection through a read-only view will cause an `UnsupportedOperationException`.

#### 21.24 What is wrong in the following code?

```
Set<String> set = Collections.singleton("Chicago");
set.add("Dallas");
```



#### 21.25 What happens when you run the following code?

```
List list = Collections.unmodifiableList(Arrays.asList("Chicago",
 "Boston"));
list.remove("Dallas");
```

## Key Terms

|                     |                    |
|---------------------|--------------------|
| hash map 813        | set 798            |
| hash set 798        | read-only view 817 |
| linked hash map 813 | tree map 813       |
| linked hash set 802 | tree set 803       |
| map 810             |                    |

## CHAPTER SUMMARY

1. A set stores nonduplicate elements. To allow duplicate elements to be stored in a collection, you need to use a list.
2. A *map* stores key/value pairs. It provides a quick lookup for a value using a key.
3. Three types of sets are supported: `HashSet`, `LinkedHashSet`, and `TreeSet`. `HashSet` stores elements in an unpredictable order. `LinkedHashSet` stores elements in the order

they were inserted. **TreeSet** stores elements sorted. All the methods in **HashSet**, **LinkedHashSet**, and **TreeSet** are inherited from the **Collection** interface.

4. The **Map** interface maps keys to the elements. The keys are like indexes. In **List**, the indexes are integers. In **Map**, the keys can be any objects. A map cannot contain duplicate keys. Each key can map to at most one value. The **Map** interface provides the methods for querying, updating, and obtaining a collection of values and a set of keys.
5. Three types of maps are supported: **HashMap**, **LinkedHashMap**, and **TreeMap**. **HashMap** is efficient for locating a value, inserting an entry, and deleting an entry. **LinkedHashMap** supports ordering of the entries in the map. The entries in a **HashMap** are not ordered, but the entries in a **LinkedHashMap** can be retrieved either in the order in which they were inserted into the map (known as the *insertion order*) or in the order in which they were last accessed, from least recently accessed to most recently (*access order*). **TreeMap** is efficient for traversing the keys in a sorted order. The keys can be sorted using the **Comparable** interface or the **Comparator** interface.

## Quiz

---

Answer the quiz for this chapter online at [www.cs.armstrong.edu/liang/intro10e/quiz.html](http://www.cs.armstrong.edu/liang/intro10e/quiz.html).

MyProgrammingLab™

## PROGRAMMING EXERCISES

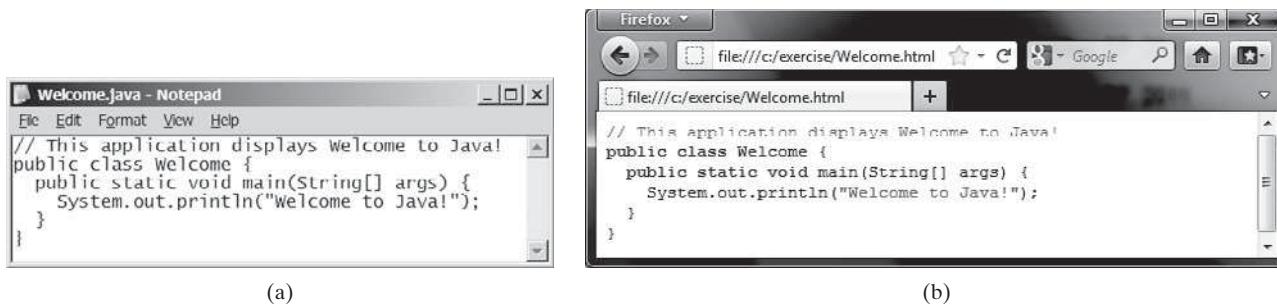
---

### Sections 21.2–21.4

- 21.1** (*Perform set operations on hash sets*) Create two linked hash sets `{"George", "Jim", "John", "Blake", "Kevin", "Michael"}` and `{"George", "Katie", "Kevin", "Michelle", "Ryan"}` and find their union, difference, and intersection. (You can clone the sets to preserve the original sets from being changed by these set methods.)
- 21.2** (*Display nonduplicate words in ascending order*) Write a program that reads words from a text file and displays all the nonduplicate words in ascending order. The text file is passed as a command-line argument.
- \*\*21.3** (*Count the keywords in Java source code*) Revise the program in Listing 21.7. If a keyword is in a comment or in a string, don't count it. Pass the Java file name from the command line. Assume that the Java source code is correct and line comments and paragraph comments do not overlap.
- \*21.4** (*Count consonants and vowels*) Write a program that prompts the user to enter a text file name and displays the number of vowels and consonants in the file. Use a set to store the vowels **A**, **E**, **I**, **O**, and **U**.
- \*\*\*21.5** (*Syntax highlighting*) Write a program that converts a Java file into an HTML file. In the HTML file, the keywords, comments, and literals are displayed in bold navy, green, and blue, respectively. Use the command line to pass a Java file and an HTML file. For example, the following command

```
java Exercise21_05 Welcome.java Welcome.html
```

converts **Welcome.java** into **Welcome.html**. Figure 21.8a shows a Java file. The corresponding HTML file is shown in Figure 21.8b.



**FIGURE 21.8** The Java code in plain text in (a) is displayed in HTML with syntax highlighted in (b).

## Sections 21.5–21.7

- \*21.6** (*Count the occurrences of numbers entered*) Write a program that reads an unspecified number of integers and finds the one that has the most occurrences. The input ends when the input is 0. For example, if you entered 2 3 4 0 3 5 4 –3 3 3 2 0, the number 3 occurred most often. If not one but several numbers have the most occurrences, all of them should be reported. For example, since 9 and 3 appear twice in the list 9 30 3 9 3 2 4, both occurrences should be reported.
- \*\*21.7** (*Revise Listing 21.9, CountOccurrenceOfWords.java*) Rewrite Listing 21.9 to display the words in ascending order of occurrence counts.  
*(Hint:* Create a class named **WordOccurrence** that implements the **Comparable** interface. The class contains two fields, **word** and **count**. The **compareTo** method compares the counts. For each pair in the hash set in Listing 21.9, create an instance of **WordOccurrence** and store it in an array list. Sort the array list using the **Collections.sort** method. What would be wrong if you stored the instances of **WordOccurrence** in a tree set?)
- \*\*21.8** (*Count the occurrences of words in a text file*) Rewrite Listing 21.9 to read the text from a text file. The text file is passed as a command-line argument. Words are delimited by whitespace characters, punctuation marks ( , ; : ? ), quotation marks (" "), and parentheses. Count words in case-insensitive fashion (e.g., consider **Good** and **good** to be the same word). The words must start with a letter. Display the output in alphabetical order of words, with each word preceded by its occurrence count.
- \*\*21.9** (*Guess the capitals using maps*) Rewrite Programming Exercise 8.37 to store pairs of each state and its capital in a map. Your program should prompt the user to enter a state and should display the capital for the state.
- \*21.10** (*Count the occurrences of each keyword*) Rewrite Listing 21.7 CountKeywords.java to read in a Java source code file and count the occurrence of each keyword in the file, but don't count the keyword if it is in a comment or in a string literal.
- \*\*21.11** (*Baby name popularity ranking*) Use the data files from Programming Exercise 12.31 to write a program that enables the user to select a year, gender, and enter a name to display the ranking of the name for the selected year and gender, as shown in Figure 21.9. To achieve the best efficiency, create two arrays for boy's names and girl's names, respectively. Each array has 10 elements for 10 years. Each element is a map that stores a name and its ranking in a pair with the name as the key. Assume the data files are stored at [www.cs.armstrong.edu/liang/data/babynamesranking2001.txt](http://www.cs.armstrong.edu/liang/data/babynamesranking2001.txt), . . . , and [www.cs.armstrong.edu/liang/data/babynamesranking2010.txt](http://www.cs.armstrong.edu/liang/data/babynamesranking2010.txt).

The figure shows three separate windows of the 'Exercise21\_11' application. Each window has a title bar, minimize, maximize, and close buttons.

- Window 1:** 'Select a year:' dropdown set to 2004, 'Boy or girl?' dropdown set to Male, 'Enter a name:' input field contains 'Michael'. A 'Find Ranking' button is below. Below the window, text says 'Boy name Michael is ranked #2 in year 2004'.
- Window 2:** 'Select a year:' dropdown set to 2007, 'Boy or girl?' dropdown set to Female, 'Enter a name:' input field contains 'Michelle'. A 'Find Ranking' button is below. Below the window, text says 'Girl name Michelle is ranked #94 in year 2007'.
- Window 3:** 'Select a year:' dropdown set to 2001, 'Boy or girl?' dropdown set to Female, 'Enter a name:' input field contains 'Samantha'. A 'Find Ranking' button is below. Below the window, text says 'Girl name Samantha is ranked #7 in year 2001'.

FIGURE 21.9 The user selects a year and gender, enters a name, and clicks the Find Ranking button to display the ranking.

- \*\*21.12** (*Name for both genders*) Write a program that prompts the user to enter one of the filenames described in Programming Exercise 12.31 and displays the names that are used for both genders in the file. Use sets to store names and find common names in two sets. Here is a sample run:



```
Enter a file name for baby name ranking: babynamesranking2001.txt ↵Enter
69 names used for both genders
They are Tyler Ryan Christian ...
```

- \*\*21.13** (*Baby name popularity ranking*) Revise Programming Exercise 21.11 to prompt the user to enter year, gender, and name and display the ranking for the name. Prompt the user to enter another inquiry or exit the program. Here is a sample run:



```
Enter the year: 2010 ↵Enter
Enter the gender: M ↵Enter
Enter the name: Javier ↵Enter
Boy name Javier is ranked #190 in year 2010
Enter another inquiry? Y ↵Enter
Enter the year: 2001 ↵Enter
Enter the gender: F ↵Enter
Enter the name: Emily ↵Enter
Girl name Emily is ranked #1 in year 2001
Enter another inquiry? N ↵Enter
```

- \*\*21.14** (*Web crawler*) Rewrite Listing 12.18, WebCrawler.java, to improve the performance by using appropriate new data structures for `List` and `List`.

- \*\*21.15** (*Addition quiz*) Rewrite Programming Exercise 11.16 to store the answers in a set rather than a list.

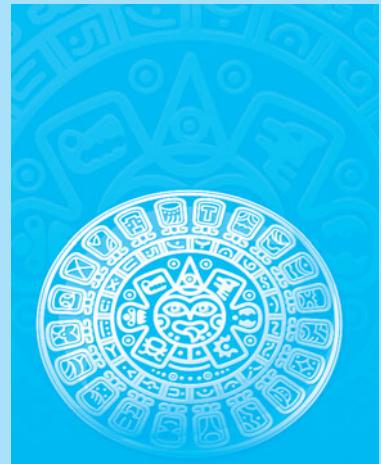
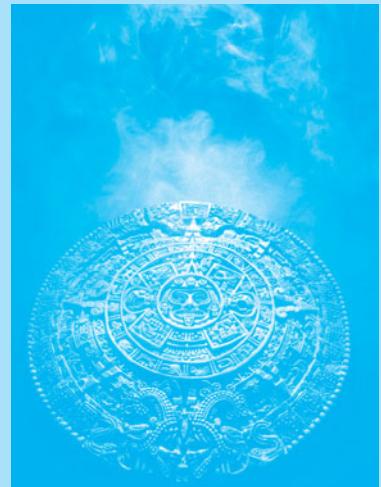
# CHAPTER

# 22

## DEVELOPING EFFICIENT ALGORITHMS

### Objectives

- To estimate algorithm efficiency using the Big  $O$  notation (§22.2).
- To explain growth rates and why constants and nondominating terms can be ignored in the estimation (§22.2).
- To determine the complexity of various types of algorithms (§22.3).
- To analyze the binary search algorithm (§22.4.1).
- To analyze the selection sort algorithm (§22.4.2).
- To analyze the Tower of Hanoi algorithm (§22.4.3).
- To describe common growth functions (constant, logarithmic, log-linear, quadratic, cubic, exponential) (§22.4.4).
- To design efficient algorithms for finding Fibonacci numbers using dynamic programming (§22.5).
- To find the GCD using Euclid's algorithm (§22.6).
- To find prime numbers using the sieve of Eratosthenes (§22.7).
- To design efficient algorithms for finding the closest pair of points using the divide-and-conquer approach (§22.8).
- To solve the Eight Queens problem using the backtracking approach (§22.9).
- To design efficient algorithms for finding a convex hull for a set of points (§22.10).



## 22.1 Introduction



*Algorithm design is to develop a mathematical process for solving a problem.  
Algorithm analysis is to predict the performance of an algorithm.*

The preceding two chapters introduced classic data structures (lists, stacks, queues, priority queues, sets, and maps) and applied them to solve problems. This chapter will use a variety of examples to introduce common algorithmic techniques (dynamic programming, divide-and-conquer, and backtracking) for developing efficient algorithms. Later in the book, we will introduce efficient algorithms in Chapters 23–29. Before introducing developing efficient algorithms, we need to address the question on how to measure algorithm efficiency.

## 22.2 Measuring Algorithm Efficiency Using Big O Notation



*The Big O notation obtains a function for measuring algorithm time complexity based on the input size. You can ignore multiplicative constants and nondominating terms in the function.*

what is algorithm efficiency?

Suppose two algorithms perform the same task, such as search (linear search vs. binary search). Which one is better? To answer this question, you might implement these algorithms and run the programs to get execution time. But there are two problems with this approach:

- First, many tasks run concurrently on a computer. The execution time of a particular program depends on the system load.
- Second, the execution time depends on specific input. Consider, for example, linear search and binary search. If an element to be searched happens to be the first in the list, linear search will find the element quicker than binary search.

growth rates

It is very difficult to compare algorithms by measuring their execution time. To overcome these problems, a theoretical approach was developed to analyze algorithms independent of computers and specific input. This approach approximates the effect of a change on the size of the input. In this way, you can see how fast an algorithm's execution time increases as the input size increases, so you can compare two algorithms by examining their *growth rates*.

Big O notation

Consider linear search. The linear search algorithm compares the key with the elements in the array sequentially until the key is found or the array is exhausted. If the key is not in the array, it requires  $n$  comparisons for an array of size  $n$ . If the key is in the array, it requires  $n/2$  comparisons on average. The algorithm's execution time is proportional to the size of the array. If you double the size of the array, you will expect the number of comparisons to double. The algorithm grows at a linear rate. The growth rate has an order of magnitude of  $n$ . Computer scientists use the Big O notation to represent the “order of magnitude.” Using this notation, the complexity of the linear search algorithm is  $O(n)$ , pronounced as “*order of n*.” We call an algorithm with a time complexity of  $O(n)$  a linear algorithm, and it exhibits a linear growth rate.

best-case input  
worst-case input

For the same input size, an algorithm's execution time may vary, depending on the input. An input that results in the shortest execution time is called the *best-case input*, and an input that results in the longest execution time is the *worst-case input*. Best-case analysis and worst-case analysis are to analyze the algorithms for their best-case input and worst-case input. Best-case and worst-case analysis are not representative, but worst-case analysis is very useful. You can be assured that the algorithm will never be slower than the worst case. An *average-case analysis* attempts to determine the average amount of time among all possible inputs of the same size. Average-case analysis is ideal, but difficult to perform, because for many problems it is hard to determine the relative probabilities and distributions of various input instances. Worst-case analysis is easier to perform, so the analysis is generally conducted for the worst case.

average-case analysis

The linear search algorithm requires  $n$  comparisons in the worst case and  $n/2$  comparisons in the average case if you are nearly always looking for something known to be in the list. Using the Big  $O$  notation, both cases require  $O(n)$  time. The multiplicative constant ( $1/2$ ) can be omitted. Algorithm analysis is focused on growth rate. The multiplicative constants have no impact on growth rates. The growth rate for  $n/2$  or  $100n$  is the same as for  $n$ , as illustrated in Table 22.1. Therefore,  $O(n) = O(n/2) = O(100n)$ .

ignore multiplicative constants

**TABLE 22.1 Growth Rates**

| $n \backslash f(n)$ | $n$ | $n/2$ | $100n$          |
|---------------------|-----|-------|-----------------|
| 100                 | 100 | 50    | 10000           |
| 200                 | 200 | 100   | 20000           |
|                     | 2   | 2     | 2               |
|                     |     |       | $f(200)/f(100)$ |

Consider the algorithm for finding the maximum number in an array of  $n$  elements. To find the maximum number if  $n$  is 2, it takes one comparison; if  $n$  is 3, two comparisons. In general, it takes  $n - 1$  comparisons to find the maximum number in a list of  $n$  elements. Algorithm analysis is for large input size. If the input size is small, there is no significance in estimating an algorithm's efficiency. As  $n$  grows larger, the  $n$  part in the expression  $n - 1$  dominates the complexity. The Big  $O$  notation allows you to ignore the nondominating part (e.g.,  $-1$  in the expression  $n - 1$ ) and highlight the important part (e.g.,  $n$  in the expression  $n - 1$ ). Therefore, the complexity of this algorithm is  $O(n)$ .

large input size

The Big  $O$  notation estimates the execution time of an algorithm in relation to the input size. If the time is not related to the input size, the algorithm is said to take *constant time* with the notation  $O(1)$ . For example, a method that retrieves an element at a given index in an array takes constant time, because the time does not grow as the size of the array increases.

ignore nondominating terms

The following mathematical summations are often useful in algorithm analysis:

constant time

useful summations

$$1 + 2 + 3 + \dots + (n - 2) + (n - 1) = \frac{n(n - 1)}{2} = O(n^2)$$

$$1 + 2 + 3 + \dots + (n - 1) + n = \frac{n(n + 1)}{2} = O(n^2)$$

$$a^0 + a^1 + a^2 + a^3 + \dots + a^{(n-1)} + a^n = \frac{a^{n+1} - 1}{a - 1} = O(a^n)$$

$$2^0 + 2^1 + 2^2 + 2^3 + \dots + 2^{(n-1)} + 2^n = \frac{2^{n+1} - 1}{2 - 1} = 2^{n+1} - 1 = O(2^n)$$



### Note

*Time complexity* is a measure of execution time using the Big-O notation. Similarly, you can also measure *space complexity* using the Big-O notation. *Space complexity* measures the amount of memory space used by an algorithm. The space complexity for most algorithms presented in the book is  $O(n)$ . i.e., they exhibit linear growth rate to the input size. For example, the space complexity for linear search is  $O(n)$ .

time complexity  
space complexity

**22.1** Why is a constant factor ignored in the Big  $O$  notation? Why is a nondominating term ignored in the Big  $O$  notation?



**22.2** What is the order of each of the following functions?

$$\frac{(n^2 + 1)^2}{n}, \frac{(n^2 + \log^2 n)^2}{n}, n^3 + 100n^2 + n, 2^n + 100n^2 + 45n, n2^n + n^2 2^n$$



## 22.3 Examples: Determining Big O

*This section gives several examples of determining Big O for repetition, sequence, and selection statements.*

### Example 1

Consider the time complexity for the following loop:

```
for (int i = 1; i <= n; i++) {
 k = k + 5;
}
```

It is a constant time,  $c$ , for executing

```
k = k + 5;
```

Since the loop is executed  $n$  times, the time complexity for the loop is

$$T(n) = (\text{a constant } c)*n = O(n).$$

The theoretical analysis predicts the performance of the algorithm. To see how this algorithm performs, we run the code in Listing 22.1 to obtain the execution time for  $n = 1000000$ ,  $10000000$ ,  $100000000$ , and  $1000000000$ .

### LISTING 22.1 PerformanceTest.java

```
1 public class PerformanceTest {
2 public static void main(String[] args) {
3 getTime(1000000);
4 getTime(10000000);
5 getTime(100000000);
6 getTime(1000000000);
7 }
8
9 public static void getTime (long n) {
10 long startTime = System.currentTimeMillis();
11 long k = 0;
12 for (int i = 1; i <= n; i++) {
13 k = k + 5;
14 }
15 long endTime = System.currentTimeMillis();
16 System.out.println("Execution time for n = " + n
17 + " is " + (endTime - startTime) + " milliseconds");
18 }
19 }
```



```
Execution time for n = 1000000 is 6 milliseconds
Execution time for n = 10000000 is 61 milliseconds
Execution time for n = 100000000 is 610 milliseconds
Execution time for n = 1000000000 is 6048 milliseconds
```

Our analysis predicts a linear time complexity for this loop. As shown in the sample output, when the input size increases 10 times, the runtime increases roughly 10 times. The execution confirms to the prediction.

### Example 2

What is the time complexity for the following loop?

```
for (int i = 1; i <= n; i++) {
 for (int j = 1; j <= n; j++) {
```

```

 k = k + i + j;
}
}

```

It is a constant time,  $c$ , for executing

```
k = k + i + j;
```

The outer loop executes  $n$  times. For each iteration in the outer loop, the inner loop is executed  $n$  times. Thus, the time complexity for the loop is

$$T(n) = (\text{a constant } c) * n * n = O(n^2)$$

An algorithm with the  $O(n^2)$  time complexity is called a *quadratic algorithm* and it exhibits a quadratic growth rate. The quadratic algorithm grows quickly as the problem size increases. If you double the input size, the time for the algorithm is quadrupled. Algorithms with a nested loop are often quadratic.

quadratic time

### Example 3

Consider the following loop:

```

for (int i = 1; i <= n; i++) {
 for (int j = 1; j <= i; j++) {
 k = k + i + j;
 }
}

```

The outer loop executes  $n$  times. For  $i = 1, 2, \dots$ , the inner loop is executed one time, two times, and  $n$  times. Thus, the time complexity for the loop is

$$\begin{aligned}
T(n) &= c + 2c + 3c + 4c + \dots + nc \\
&= cn(n + 1)/2 \\
&= (c/2)n^2 + (c/2)n \\
&= O(n^2)
\end{aligned}$$

### Example 4

Consider the following loop:

```

for (int i = 1; i <= n; i++) {
 for (int j = 1; j <= 20; j++) {
 k = k + i + j;
 }
}

```

The inner loop executes 20 times, and the outer loop  $n$  times. Therefore, the time complexity for the loop is

$$T(n) = 20 * c * n = O(n)$$

### Example 5

Consider the following sequences:

```

for (int j = 1; j <= 10; j++) {
 k = k + 4;
}

for (int i = 1; i <= n; i++) {

```

```

for (int j = 1; j <= 20; j++) {
 k = k + i + j;
}
}

```

The first loop executes 10 times, and the second loop  $20 * n$  times. Thus, the time complexity for the loop is

$$T(n) = 10*c + 20*c*n = O(n)$$

### Example 6

Consider the following selection statement:

```

if (list.contains(e)) {
 System.out.println(e);
}
else
 for (Object t: list) {
 System.out.println(t);
}

```

Suppose the list contains  $n$  elements. The execution time for `list.contains(e)` is  $O(n)$ . The loop in the `else` clause takes  $O(n)$  time. Hence, the time complexity for the entire statement is

$$\begin{aligned} T(n) &= \text{if test time} + \text{worst-case time (if clause, else clause)} \\ &= O(n) + O(n) = O(n) \end{aligned}$$

### Example 7

Consider the computation of  $a^n$  for an integer  $n$ . A simple algorithm would multiply  $a$   $n$  times, as follows:

```

result = 1;
for (int i = 1; i <= n; i++)
 result *= a;

```

The algorithm takes  $O(n)$  time. Without loss of generality, assume  $n = 2^k$ . You can improve the algorithm using the following scheme:

```

result = a;
for (int i = 1; i <= k; i++)
 result = result * result;

```

The algorithm takes  $O(\log n)$  time. For an arbitrary  $n$ , you can revise the algorithm and prove that the complexity is still  $O(\log n)$ . (See Checkpoint Question 22.7.)

omit base



#### Note

For simplicity, since  $O(\log n) = O(\log_2 n) = O(\log_a n)$ , the constant base is omitted.



### 22.3 Count the number of iterations in the following loops.

```

int count = 1;
while (count < 30) {
 count = count * 2;
}

```

(a)

```

int count = 15;
while (count < 30) {
 count = count * 3;
}

```

(b)

```
int count = 1;
while (count < n) {
 count = count * 2;
}
```

(c)

```
int count = 15;
while (count < n) {
 count = count * 3;
}
```

(d)

- 22.4** How many stars are displayed in the following code if  $n$  is 10? How many if  $n$  is 20?  
Use the Big  $O$  notation to estimate the time complexity.

```
for (int i = 0; i < n; i++) {
 System.out.print('*');
```

(a)

```
for (int i = 0; i < n; i++) {
 for (int j = 0; j < n; j++) {
 System.out.print('*');
 }
}
```

(b)

```
for (int k = 0; k < n; k++) {
 for (int i = 0; i < n; i++) {
 for (int j = 0; j < n; j++) {
 System.out.print('*');
 }
 }
}
```

(c)

```
for (int k = 0; k < 10; k++) {
 for (int i = 0; i < n; i++) {
 for (int j = 0; j < n; j++) {
 System.out.print('*');
 }
 }
}
```

(d)

- 22.5** Use the Big  $O$  notation to estimate the time complexity of the following methods:

```
public static void mA(int n) {
 for (int i = 0; i < n; i++) {
 System.out.print(Math.random());
 }
}
```

(a)

```
public static void mB(int n) {
 for (int i = 0; i < n; i++) {
 for (int j = 0; j < i; j++) {
 System.out.print(Math.random());
 }
 }
}
```

(b)

```
public static void mC(int[] m) {
 for (int i = 0; i < m.length; i++) {
 System.out.print(m[i]);
 }

 for (int i = m.length - 1; i >= 0;)
 {
 System.out.print(m[i]);
 i--;
 }
}
```

(c)

```
public static void mD(int[] m) {
 for (int i = 0; i < m.length; i++) {
 for (int j = 0; j < i; j++) {
 System.out.print(m[i] * m[j]);
 }
 }
}
```

(d)

- 22.6** Design an  $O(n)$  time algorithm for computing the sum of numbers from  $n1$  to  $n2$  for ( $n1 < n2$ ). Can you design an  $O(1)$  for performing the same task?
- 22.7** Example 7 in Section 22.3 assumes  $n = 2^k$ . Revise the algorithm for an arbitrary  $n$  and prove that the complexity is still  $O(\log n)$ .



## 22.4 Analyzing Algorithm Time Complexity

*This section analyzes the complexity of several well-known algorithms: binary search, selection sort, and Tower of Hanoi.*



binary search animation on the Companion Website

### 22.4.1 Analyzing Binary Search

The binary search algorithm presented in Listing 7.7, `BinarySearch.java`, searches for a key in a sorted array. Each iteration in the algorithm contains a fixed number of operations, denoted by  $c$ . Let  $T(n)$  denote the time complexity for a binary search on a list of  $n$  elements. Without loss of generality, assume  $n$  is a power of 2 and  $k = \log n$ . Since a binary search eliminates half of the input after two comparisons,

$$\begin{aligned} T(n) &= T\left(\frac{n}{2}\right) + c = T\left(\frac{n}{2^2}\right) + c + c = T\left(\frac{n}{2^k}\right) + kc \\ &= T(1) + c \log n = 1 + (\log n)c \\ &= O(\log n) \end{aligned}$$

logarithmic time

Ignoring constants and nondominating terms, the complexity of the binary search algorithm is  $O(\log n)$ . An algorithm with the  $O(\log n)$  time complexity is called a *logarithmic algorithm* and it exhibits a logarithmic growth rate. The base of the log is 2, but the base does not affect a logarithmic growth rate, so it can be omitted. The logarithmic algorithm grows slowly as the problem size increases. In the case of binary search, each time you double the array size, at most one more comparison will be required. If you square the input size of any logarithmic time algorithm, you only double the time of execution. So a logarithmic-time algorithm is very efficient.



selection sort animation on the Companion Website

### 22.4.2 Analyzing Selection Sort

The selection sort algorithm presented in Listing 7.8, `SelectionSort.java`, finds the smallest element in the list and swaps it with the first element. It then finds the smallest element remaining and swaps it with the first element in the remaining list, and so on until the remaining list contains only one element left to be sorted. The number of comparisons is  $n - 1$  for the first iteration,  $n - 2$  for the second iteration, and so on. Let  $T(n)$  denote the complexity for selection sort and  $c$  denote the total number of other operations such as assignments and additional comparisons in each iteration. Thus,

$$\begin{aligned} T(n) &= (n - 1) + c + (n - 2) + c + \dots + 2 + c + 1 + c \\ &= \frac{(n - 1)(n - 1 + 1)}{2} + c(n - 1) = \frac{n^2}{2} - \frac{n}{2} + cn - c \\ &= O(n^2) \end{aligned}$$

Therefore, the complexity of the selection sort algorithm is  $O(n^2)$ .

### 22.4.3 Analyzing the Tower of Hanoi Problem

The Tower of Hanoi problem presented in Listing 18.8, `TowerOfHanoi.java`, recursively moves  $n$  disks from tower A to tower B with the assistance of tower C as follows:

1. Move the first  $n - 1$  disks from A to C with the assistance of tower B.

2. Move disk  $n$  from A to B.
3. Move  $n - 1$  disks from C to B with the assistance of tower A.

The complexity of this algorithm is measured by the number of moves. Let  $T(n)$  denote the number of moves for the algorithm to move  $n$  disks from tower A to tower B with  $T(1) = 1$ . Thus,

$$\begin{aligned}
 T(n) &= T(n - 1) + 1 + T(n - 1) \\
 &= 2T(n - 1) + 1 \\
 &= 2(2T(n - 2) + 1) + 1 \\
 &= 2(2(2T(n - 3) + 1) + 1) + 1 \\
 &= 2^{n-1}T(1) + 2^{n-2} + \dots + 2 + 1 \\
 &= 2^{n-1} + 2^{n-2} + \dots + 2 + 1 = (2^n - 1) = O(2^n)
 \end{aligned}$$

An algorithm with  $O(2^n)$  time complexity is called an *exponential algorithm*, and it exhibits an exponential growth rate. As the input size increases, the time for the exponential algorithm grows exponentially. Exponential algorithms are not practical for large input size. Suppose the disk is moved at a rate of 1 per second. It would take  $2^{32}/(365 * 24 * 60 * 60) = 136$  years to move 32 disks and  $2^{64}/(365 * 24 * 60 * 60) = 585$  billion years to move 64 disks.

$O(2^n)$   
exponential time

#### 22.4.4 Common Recurrence Relations

*Recurrence relations* are a useful tool for analyzing algorithm complexity. As shown in the preceding examples, the complexity for binary search, selection sort, and the Tower of Hanoi is  $T(n) = T\left(\frac{n}{2}\right) + O(1)$ ,  $T(n) = T(n - 1) + O(n)$ , and  $T(n) = 2T(n - 1) + O(1)$ , respectively. Table 22.2 summarizes the common recurrence relations.

**TABLE 22.2** Common Recurrence Functions

| Recurrence Relation                 | Result               | Example                       |
|-------------------------------------|----------------------|-------------------------------|
| $T(n) = T(n/2) + O(1)$              | $T(n) = O(\log n)$   | Binary search, Euclid's GCD   |
| $T(n) = T(n - 1) + O(1)$            | $T(n) = O(n)$        | Linear search                 |
| $T(n) = 2T(n/2) + O(1)$             | $T(n) = O(n)$        | Checkpoint Question 22.20     |
| $T(n) = 2T(n/2) + O(n)$             | $T(n) = O(n \log n)$ | Merge sort (Chapter 23)       |
| $T(n) = T(n - 1) + O(n)$            | $T(n) = O(n^2)$      | Selection sort                |
| $T(n) = 2T(n - 1) + O(1)$           | $T(n) = O(2^n)$      | Tower of Hanoi                |
| $T(n) = T(n - 1) + T(n - 2) + O(1)$ | $T(n) = O(2^n)$      | Recursive Fibonacci algorithm |

#### 22.4.5 Comparing Common Growth Functions

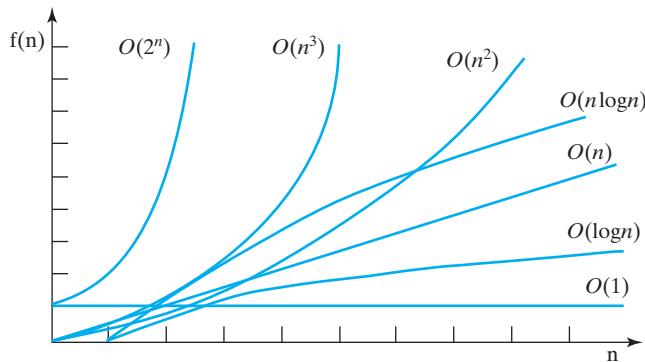
The preceding sections analyzed the complexity of several algorithms. Table 22.3 lists some common growth functions and shows how growth rates change as the input size doubles from  $n = 25$  to  $n = 50$ .

**TABLE 22.3** Change of Growth Rates

| Function      | Name             | $n = 25$           | $n = 50$              | $f(50)/f(25)$      |
|---------------|------------------|--------------------|-----------------------|--------------------|
| $O(1)$        | Constant time    | 1                  | 1                     | 1                  |
| $O(\log n)$   | Logarithmic time | 4.64               | 5.64                  | 1.21               |
| $O(n)$        | Linear time      | 25                 | 50                    | 2                  |
| $O(n \log n)$ | Log-linear time  | 116                | 282                   | 2.43               |
| $O(n^2)$      | Quadratic time   | 625                | 2,500                 | 4                  |
| $O(n^3)$      | Cubic time       | 15,625             | 125,000               | 8                  |
| $O(2^n)$      | Exponential time | $3.36 \times 10^7$ | $1.27 \times 10^{15}$ | $3.35 \times 10^7$ |

These functions are ordered as follows, as illustrated in Figure 22.1.

$$O(1) < O(\log n) < O(n) < O(n \log n) < O(n^2) < O(n^3) < O(2^n)$$



**FIGURE 22.1** As the size  $n$  increases, the function grows.



**22.8** Put the following growth functions in order:

$$\frac{5n^3}{4032}, 44 \log n, 10n \log n, 500, 2n^2, \frac{2^n}{45}, 3n$$

**22.9** Estimate the time complexity for adding two  $n \times m$  matrices, and for multiplying an  $n \times m$  matrix by an  $m \times k$  matrix.

**22.10** Describe an algorithm for finding the occurrence of the max element in an array. Analyze the complexity of the algorithm.

**22.11** Describe an algorithm for removing duplicates from an array. Analyze the complexity of the algorithm.

**22.12** Analyze the following sorting algorithm:

```
for (int i = 0; i < list.length - 1; i++) {
 if (list[i] > list[i + 1]) {
 swap list[i] with list[i + 1];
 i = -1;
 }
}
```

**22.13** Analyze the complexity for computing a polynomial  $f(x)$  of degree  $n$  for a given  $x$  value using a brute-force approach and the Horner's approach, respectively. A brute-force approach is to compute each term in the polynomial and add them together. The Horner's approach was introduced in Section 6.7.

$$f(x) = a_n x^n + a_{n-1} x^{n-1} + a_{n-2} x^{n-2} + \dots + a_1 x^1 + a_0$$

## 22.5 Finding Fibonacci Numbers Using Dynamic Programming

This section analyzes and designs an efficient algorithm for finding Fibonacci numbers using dynamic programming.



Section 18.3, Case Study: Computing Fibonacci Numbers, gave a recursive method for finding the Fibonacci number, as follows:

```
/** The method for finding the Fibonacci number */
public static long fib(long index) {
 if (index == 0) // Base case
 return 0;
 else if (index == 1) // Base case
 return 1;
 else // Reduction and recursive calls
 return fib(index - 1) + fib(index - 2);
}
```

We can now prove that the complexity of this algorithm is  $O(2^n)$ . For convenience, let the index be  $n$ . Let  $T(n)$  denote the complexity for the algorithm that finds  $\text{fib}(n)$  and  $c$  denote the constant time for comparing the index with 0 and 1; that is,  $T(1)$  and  $T(0)$  are  $c$ . Thus,

$$\begin{aligned} T(n) &= T(n - 1) + T(n - 2) + c \\ &\leq 2T(n - 1) + c \\ &\leq 2(2T(n - 2) + c) + c \\ &= 2^2T(n - 2) + 2c + c \end{aligned}$$

Similar to the analysis of the Tower of Hanoi problem, we can show that  $T(n)$  is  $O(2^n)$ .

However, this algorithm is not efficient. Is there an efficient algorithm for finding a Fibonacci number? The trouble with the recursive **fib** method is that the method is invoked redundantly with the same arguments. For example, to compute **fib(4)**, **fib(3)** and **fib(2)** are invoked. To compute **fib(3)**, **fib(2)** and **fib(1)** are invoked. Note that **fib(2)** is redundantly invoked. We can improve it by avoiding repeatedly calling of the **fib** method with the same argument. Note that a new Fibonacci number is obtained by adding the preceding two numbers in the sequence. If you use the two variables **f0** and **f1** to store the two preceding numbers, the new number, **f2**, can be immediately obtained by adding **f0** with **f1**. Now you should update **f0** and **f1** by assigning **f1** to **f0** and assigning **f2** to **f1**, as shown in Figure 22.2.

|                   | <b>f0</b> | <b>f1</b> | <b>f2</b> |   |   |   |   |    |    |    |    |        |
|-------------------|-----------|-----------|-----------|---|---|---|---|----|----|----|----|--------|
| Fibonacci series: | 0         | 1         | 1         | 2 | 3 | 5 | 8 | 13 | 21 | 34 | 55 | 89 ... |
| indices:          | 0         | 1         | 2         | 3 | 4 | 5 | 6 | 7  | 8  | 9  | 10 | 11     |
|                   | <b>f0</b> | <b>f1</b> | <b>f2</b> |   |   |   |   |    |    |    |    |        |
| Fibonacci series: | 0         | 1         | 1         | 2 | 3 | 5 | 8 | 13 | 21 | 34 | 55 | 89 ... |
| indices:          | 0         | 1         | 2         | 3 | 4 | 5 | 6 | 7  | 8  | 9  | 10 | 11     |
|                   | <b>f0</b> | <b>f1</b> | <b>f2</b> |   |   |   |   |    |    |    |    |        |
| Fibonacci series: | 0         | 1         | 1         | 2 | 3 | 5 | 8 | 13 | 21 | 34 | 55 | 89 ... |
| indices:          | 0         | 1         | 2         | 3 | 4 | 5 | 6 | 7  | 8  | 9  | 10 | 11     |

FIGURE 22.2 Variables **f0**, **f1**, and **f2** store three consecutive Fibonacci numbers in the series.

The new method is implemented in Listing 22.2.

### LISTING 22.2 ImprovedFibonacci.java

```

1 import java.util.Scanner;
2
3 public class ImprovedFibonacci {
4 /** Main method */
5 public static void main(String args[]) {
6 // Create a Scanner
7 Scanner input = new Scanner(System.in);
8 System.out.print("Enter an index for the Fibonacci number: ");
9 int index = input.nextInt();
10
11 // Find and display the Fibonacci number
12 System.out.println(
13 "Fibonacci number at index " + index + " is " + fib(index));
14 }
15
16 /** The method for finding the Fibonacci number */
17 public static long fib(long n) {
18 long f0 = 0; // For fib(0)
19 long f1 = 1; // For fib(1)
20 long f2 = 1; // For fib(2)
21
22 if (n == 0)
23 return f0;
24 else if (n == 1)
25 return f1;
26 else if (n == 2)
27 return f2;
28
29 for (int i = 3; i <= n; i++) {
30 f0 = f1;
31 f1 = f2;
32 f2 = f0 + f1;
33 }
34
35 return f2;
36 }
37 }

```

update f0, f1, f2



Enter an index for the Fibonacci number: 6  ↵ Enter

$O(n)$

dynamic programming

Obviously, the complexity of this new algorithm is  $O(n)$ . This is a tremendous improvement over the recursive  $O(2^n)$  algorithm.

The algorithm for computing Fibonacci numbers presented here uses an approach known as *dynamic programming*. Dynamic programming is the process of solving subproblems, then combining the solutions of the subproblems to obtain an overall solution. This naturally leads to a recursive solution. However, it would be inefficient to use recursion, because the



Enter an index for the Fibonacci number: 7  ↵ Enter

subproblems overlap. The key idea behind dynamic programming is to solve each subproblem only once and store the results for subproblems for later use to avoid redundant computing of the subproblems.

**22.14** What is dynamic programming? Give an example of dynamic programming.

**22.15** Why is the recursive Fibonacci algorithm inefficient, but the nonrecursive Fibonacci algorithm efficient?



## 22.6 Finding Greatest Common Divisors Using Euclid's Algorithm

*This section presents several algorithms in the search for an efficient algorithm for finding the greatest common divisor of two integers.*

The greatest common divisor (GCD) of two integers is the largest number that can evenly divide both integers. Listing 5.9, GreatestCommonDivisor.java, presented a brute-force algorithm for finding the greatest common divisor of two integers `m` and `n`. *Brute force* refers to an algorithmic approach that solves a problem in the simplest or most direct or obvious way. As a result, such an algorithm can end up doing far more work to solve a given problem than a cleverer or more sophisticated algorithm might do. On the other hand, a brute-force algorithm is often easier to implement than a more sophisticated one and, because of this simplicity, sometimes it can be more efficient.

The brute-force algorithm checks whether `k` (for `k = 2, 3, 4`, and so on) is a common divisor for `n1` and `n2`, until `k` is greater than `n1` or `n2`. The algorithm can be described as follows:

```
public static int gcd(int m, int n) {
 int gcd = 1;

 for (int k = 2; k <= m && k <= n; k++) {
 if (m % k == 0 && n % k == 0)
 gcd = k;
 }

 return gcd;
}
```

Assuming  $m \geq n$ , the complexity of this algorithm is obviously  $O(n)$ .

Is there a better algorithm for finding the GCD? Rather than searching a possible divisor from `1` up, it is more efficient to search from `n` down. Once a divisor is found, the divisor is the GCD. Therefore, you can improve the algorithm using the following loop:

```
for (int k = n; k >= 1; k--) {
 if (m % k == 0 && n % k == 0) {
 gcd = k;
 break;
 }
}
```

This algorithm is better than the preceding one, but its worst-case time complexity is still  $O(n)$ .

A divisor for a number `n` cannot be greater than `n / 2`, so you can further improve the algorithm using the following loop:

```
for (int k = m / 2; k >= 1; k--) {
 if (m % k == 0 && n % k == 0) {
 gcd = k;
```



GCD

brute force

assume  $m \geq n$

$O(n)$

improved solutions

```
 break;
}
```

However, this algorithm is incorrect, because  $n$  can be a divisor for  $m$ . This case must be considered. The correct algorithm is shown in Listing 22.3.

**LISTING 22.3** GCD.java

```
1 import java.util.Scanner;
2
3 public class GCD {
4 /** Find GCD for integers m and n */
5 public static int gcd(int m, int n) {
6 int gcd = 1;
7
8 if (m % n == 0) return n;
9
10 for (int k = n / 2; k >= 1; k--) {
11 if (m % k == 0 && n % k == 0) {
12 gcd = k;
13 break;
14 }
15 }
16
17 return gcd;
18 }
19
20 /** Main method */
21 public static void main(String[] args) {
22 // Create a Scanner
23 Scanner input = new Scanner(System.in);
24
25 // Prompt the user to enter two integers
26 System.out.print("Enter first integer: ");
27 int m = input.nextInt();
28 System.out.print("Enter second integer: ");
29 int n = input.nextInt();
30
31 System.out.println("The greatest common divisor for " + m +
32 " and " + n + " is " + gcd(m, n));
33 }
34}
```



```
Enter first integer: 2525 ↴Enter
Enter second integer: 125 ↴Enter
The greatest common divisor for 2525 and 125 is 25
```



```
Enter first integer: 3 ↴Enter
Enter second integer: 3 ↴Enter
The greatest common divisor for 3 and 3 is 3
```

$O(n)$

Assuming  $m \geq n$ , the **for** loop is executed at most  $n/2$  times, which cuts the time by half from the previous algorithm. The time complexity of this algorithm is still  $O(n)$ , but practically, it is much faster than the algorithm in Listing 5.9.

**Note**

The Big O notation provides a good theoretical estimate of algorithm efficiency. However, two algorithms of the same time complexity are not necessarily equally efficient. As shown in the preceding example, both algorithms in Listings 5.9 and 22.3 have the same complexity, but in practice the one in Listing 22.3 is obviously better.

practical consideration

Euclid's algorithm

A more efficient algorithm for finding the GCD was discovered by Euclid around 300 B.C. This is one of the oldest known algorithms. It can be defined recursively as follows:

Let  $\text{gcd}(m, n)$  denote the GCD for integers  $m$  and  $n$ :

- If  $m \% n$  is 0,  $\text{gcd}(m, n)$  is  $n$ .
- Otherwise,  $\text{gcd}(m, n)$  is  $\text{gcd}(n, m \% n)$ .

It is not difficult to prove the correctness of this algorithm. Suppose  $m \% n = r$ . Thus,  $m = qn + r$ , where  $q$  is the quotient of  $m / n$ . Any number that is divisible by  $m$  and  $n$  must also be divisible by  $r$ . Therefore,  $\text{gcd}(m, n)$  is the same as  $\text{gcd}(n, r)$ , where  $r = m \% n$ . The algorithm can be implemented as in Listing 22.4.

**LISTING 22.4 GCDEuclid.java**

```

1 import java.util.Scanner;
2
3 public class GCDEuclid {
4 /** Find GCD for integers m and n */
5 public static int gcd(int m, int n) {
6 if (m % n == 0) base case
7 return n;
8 else
9 return gcd(n, m % n); reduction
10 }
11
12 /** Main method */
13 public static void main(String[] args) {
14 // Create a Scanner
15 Scanner input = new Scanner(System.in);
16
17 // Prompt the user to enter two integers
18 System.out.print("Enter first integer: ");
19 int m = input.nextInt(); input
20 System.out.print("Enter second integer: ");
21 int n = input.nextInt(); input
22
23 System.out.println("The greatest common divisor for " + m +
24 " and " + n + " is " + gcd(m, n));
25 }
26 }
```

Enter first integer: 2525 ↵Enter  
 Enter second integer: 125 ↵Enter  
 The greatest common divisor for 2525 and 125 is 25



Enter first integer: 3 ↵Enter  
 Enter second integer: 3 ↵Enter  
 The greatest common divisor for 3 and 3 is 3



best case  
average case  
worst case

In the best case when  $m \% n$  is 0, the algorithm takes just one step to find the GCD. It is difficult to analyze the average case. However, we can prove that the worst-case time complexity is  $O(\log n)$ .

Assuming  $m \geq n$ , we can show that  $m \% n < m / 2$ , as follows:

- If  $n \leq m / 2$ ,  $m \% n < m / 2$ , since the remainder of  $m$  divided by  $n$  is always less than  $n$ .
- If  $n > m / 2$ ,  $m \% n = m - n < m / 2$ . Therefore,  $m \% n < m / 2$ .

Euclid's algorithm recursively invokes the `gcd` method. It first calls `gcd(m, n)`, then calls `gcd(n, m % n)`, and `gcd(m % n, n % (m % n))`, and so on, as follows:

$$\begin{aligned} & \text{gcd}(m, n) \\ &= \text{gcd}(n, m \% n) \\ &= \text{gcd}(m \% n, n \% (m \% n)) \\ &= \dots \end{aligned}$$

Since  $m \% n < m / 2$  and  $n \% (m \% n) < n / 2$ , the argument passed to the `gcd` method is reduced by half after every two iterations. After invoking `gcd` two times, the second parameter is less than  $n/2$ . After invoking `gcd` four times, the second parameter is less than  $n/4$ . After invoking `gcd` six times, the second parameter is less than  $\frac{n}{2^3}$ . Let  $k$  be the number of times the `gcd` method is invoked. After invoking `gcd`  $k$  times, the second parameter is less than  $\frac{n}{2^{(k/2)}}$ , which is greater than or equal to 1. That is,

$$\frac{n}{2^{(k/2)}} \geq 1 \Rightarrow n \geq 2^{(k/2)} \Rightarrow \log n \geq k/2 \Rightarrow k \leq 2 \log n$$

Therefore,  $k \leq 2 \log n$ . So the time complexity of the `gcd` method is  $O(\log n)$ .

The worst case occurs when the two numbers result in the most divisions. It turns out that two successive Fibonacci numbers will result in the most divisions. Recall that the Fibonacci series begins with 0 and 1, and each subsequent number is the sum of the preceding two numbers in the series, such as:

0 1 1 2 3 5 8 13 21 34 55 89 ...

The series can be recursively defined as

```
fib(0) = 0;
fib(1) = 1;
fib(index) = fib(index - 2) + fib(index - 1); index >= 2
```

For two successive Fibonacci numbers `fib(index)` and `fib(index - 1)`,

```
gcd(fib(index), fib(index - 1))
= gcd(fib(index - 1), fib(index - 2))
= gcd(fib(index - 2), fib(index - 3))
= gcd(fib(index - 3), fib(index - 4))
= ...
= gcd(fib(2), fib(1))
= 1
```

For example,

```
gcd(21, 13)
= gcd(13, 8)
= gcd(8, 5)
= gcd(5, 3)
```

```
= gcd(3, 2)
= gcd(2, 1)
= 1
```

Therefore, the number of times the `gcd` method is invoked is the same as the index. We can prove that  $\text{index} \leq 1.44 \log n$ , where  $n = \text{fib}(\text{index} - 1)$ . This is a tighter bound than  $\text{index} \leq 2 \log n$ .

Table 22.4 summarizes the complexity of three algorithms for finding the GCD.

**TABLE 22.4 Comparisons of GCD Algorithms**

| Algorithm    | Complexity  | Description                                 |
|--------------|-------------|---------------------------------------------|
| Listing 5.9  | $O(n)$      | Brute-force, checking all possible divisors |
| Listing 22.3 | $O(n)$      | Checking half of all possible divisors      |
| Listing 22.4 | $O(\log n)$ | Euclid's algorithm                          |

- 22.16** Prove that the following algorithm for finding the GCD of the two integers `m` and `n` is incorrect.



```
int gcd = 1;
for (int k = Math.min(Math.sqrt(n), Math.sqrt(m)); k >= 1; k--) {
 if (m % k == 0 && n % k == 0) {
 gcd = k;
 break;
 }
}
```

## 22.7 Efficient Algorithms for Finding Prime Numbers

This section presents several algorithms in the search for an efficient algorithm for finding prime numbers.



A \$150,000 award awaits the first individual or group who discovers a prime number with at least 100,000,000 decimal digits ([w2.eff.org/awards/coop-prime-rules.php](http://w2.eff.org/awards/coop-prime-rules.php)).

Can you design a fast algorithm for finding prime numbers?

An integer greater than `1` is *prime* if its only positive divisor is `1` or itself. For example, `2`, `3`, `5`, and `7` are prime numbers, but `4`, `6`, `8`, and `9` are not.

How do you determine whether a number `n` is prime? Listing 5.15 presented a brute-force algorithm for finding prime numbers. The algorithm checks whether `2`, `3`, `4`, `5`, ..., or `n - 1` is divisible by `n`. If not, `n` is prime. This algorithm takes  $O(n)$  time to check whether `n` is prime. Note that you need to check only whether `2`, `3`, `4`, `5`, ..., and  $n/2$  is divisible by `n`. If not, `n` is prime. This algorithm is slightly improved, but it is still of  $O(n)$ .

In fact, we can prove that if `n` is not a prime, `n` must have a factor that is greater than `1` and less than or equal to  $\sqrt{n}$ . Here is the proof. Since `n` is not a prime, there exist two numbers `p` and `q` such that `n = pq` with  $1 < p \leq q$ . Note that  $n = \sqrt{n} \sqrt{n}$ . `p` must be less than or equal to  $\sqrt{n}$ . Hence, you need to check only whether `2`, `3`, `4`, `5`, ..., or  $\sqrt{n}$  is divisible by `n`. If not, `n` is prime. This significantly reduces the time complexity of the algorithm to  $O(\sqrt{n})$ .

Now consider the algorithm for finding all the prime numbers up to `n`. A straightforward implementation is to check whether `i` is prime for  $i = 2, 3, 4, \dots, n$ . The program is given in Listing 22.5.

**LISTING 22.5** PrimeNumbers.java

```

1 import java.util.Scanner;
2
3 public class PrimeNumbers {
4 public static void main(String[] args) {
5 Scanner input = new Scanner(System.in);
6 System.out.print("Find all prime numbers <= n, enter n: ");
7 int n = input.nextInt();
8
9 final int NUMBER_PER_LINE = 10; // Display 10 per line
10 int count = 0; // Count the number of prime numbers
11 int number = 2; // A number to be tested for primeness
12
13 System.out.println("The prime numbers are:");
14
15 // Repeatedly find prime numbers
16 while (number <= n) {
17 // Assume the number is prime
18 boolean isPrime = true; // Is the current number prime?
19
20 // Test if number is prime
21 for (int divisor = 2; divisor <= (int)(Math.sqrt(number));
22 divisor++) {
23 if (number % divisor == 0) { // If true, number is not prime
24 isPrime = false; // Set isPrime to false
25 break; // Exit the for loop
26 }
27 }
28
29 // Print the prime number and increase the count
30 if (isPrime) {
31 count++; // Increase the count
32
33 if (count % NUMBER_PER_LINE == 0) {
34 // Print the number and advance to the new line
35 System.out.printf("%7d\n", number);
36 }
37 else
38 System.out.printf("%7d", number);
39 }
40
41 // Check if the next number is prime
42 number++;
43 }
44
45 System.out.println("\n" + count +
46 " prime(s) less than or equal to " + n);
47 }
48 }

```

check prime

increase count

check next number



```

Find all prime numbers <= n, enter n: 1000 ↵ Enter
The prime numbers are:
 2 3 5 7 11 13 17 19 23 29
 31 37 41 43 47 53 59 61 67 71
 ...
 ...
168 prime(s) less than or equal to 1000

```

The program is not efficient if you have to compute `Math.sqrt(number)` for every iteration of the `for` loop (line 21). A good compiler should evaluate `Math.sqrt(number)` only once for the entire `for` loop. To ensure this happens, you can explicitly replace line 21 with the following two lines:

```
1 int squareRoot = (int)(Math.sqrt(number));
2 for (int divisor = 2; divisor <= squareRoot; divisor++) {
```

In fact, there is no need to actually compute `Math.sqrt(number)` for every `number`. You need look only for the perfect squares such as **4, 9, 16, 25, 36, 49**, and so on. Note that for all the numbers between **36** and **48**, inclusively, their `(int)(Math.sqrt(number))` is **6**. With this insight, you can replace the code in lines 16–26 with the following:

```
...
1 int squareRoot = 1;
2
3 // Repeatedly find prime numbers
4 while (number <= n) {
5 // Assume the number is prime
6 boolean isPrime = true; // Is the current number prime?
7
8 if (squareRoot * squareRoot < number) squareRoot++;
9
10 // Test if number is prime
11 for (int divisor = 2; divisor <= squareRoot; divisor++) {
12 if (number % divisor == 0) { // If true, number is not prime
13 isPrime = false; // Set isPrime to false
14 break; // Exit the for loop
15 }
16 }
17
18}
```

Now we turn our attention to analyzing the complexity of this program. Since it takes  $\sqrt{i}$  steps in the `for` loop (lines 21–27) to check whether number  $i$  is prime, the algorithm takes  $\sqrt{2} + \sqrt{3} + \sqrt{4} + \dots + \sqrt{n}$  steps to find all the prime numbers less than or equal to  $n$ . Observe that

$$\sqrt{2} + \sqrt{3} + \sqrt{4} + \dots + \sqrt{n} \leq n\sqrt{n}$$

Therefore, the time complexity for this algorithm is  $O(n\sqrt{n})$ .

To determine whether  $i$  is prime, the algorithm checks whether **2, 3, 4, 5, ..., and  $\sqrt{i}$**  are divisible by  $i$ . This algorithm can be further improved. In fact, you need to check only whether the prime numbers from **2** to  $\sqrt{i}$  are possible divisors for  $i$ .

We can prove that if  $i$  is not prime, there must exist a prime number  $p$  such that  $i = pq$  and  $p \leq q$ . Here is the proof. Assume that  $i$  is not prime; let  $p$  be the smallest factor of  $i$ .  $p$  must be prime, otherwise,  $p$  has a factor  $k$  with  $2 \leq k < p$ .  $k$  is also a factor of  $i$ , which contradicts that  $p$  be the smallest factor of  $i$ . Therefore, if  $i$  is not prime, you can find a prime number from **2** to  $\sqrt{i}$  that is divisible by  $i$ . This leads to a more efficient algorithm for finding all prime numbers up to **n**, as shown in Listing 22.6.

## LISTING 22.6 EfficientPrimeNumbers.java

```
1 import java.util.Scanner;
2
3 public class EfficientPrimeNumbers {
4 public static void main(String[] args) {
5 Scanner input = new Scanner(System.in);
6 System.out.print("Find all prime numbers <= n, enter n: ");
```

```

7 int n = input.nextInt();
8
9 // A list to hold prime numbers
10 java.util.List<Integer> list =
11 new java.util.ArrayList<>();
12
13 final int NUMBER_PER_LINE = 10; // Display 10 per line
14 int count = 0; // Count the number of prime numbers
15 int number = 2; // A number to be tested for primeness
16 int squareRoot = 1; // Check whether number <= squareRoot
17
18 System.out.println("The prime numbers are \n");
19
20 // Repeatedly find prime numbers
21 while (number <= n) {
22 // Assume the number is prime
23 boolean isPrime = true; // Is the current number prime?
24
25 if (squareRoot * squareRoot < number) squareRoot++;
26
27 // Test whether number is prime
28 for (int k = 0; k < list.size()
29 && list.get(k) <= squareRoot; k++) {
30 if (number % list.get(k) == 0) { // If true, not prime
31 isPrime = false; // Set isPrime to false
32 break; // Exit the for loop
33 }
34 }
35
36 // Print the prime number and increase the count
37 if (isPrime) {
38 count++; // Increase the count
39 list.add(number); // Add a new prime to the list
40 if (count % NUMBER_PER_LINE == 0) {
41 // Print the number and advance to the new line
42 System.out.println(number);
43 }
44 else
45 System.out.print(number + " ");
46 }
47
48 // Check whether the next number is prime
49 number++;
50 }
51
52 System.out.println("\n" + count +
53 " prime(s) less than or equal to " + n);
54}
55

```

check prime

increase count

check next number



Find all prime numbers <= n, enter n: 1000

The prime numbers are:

|    |    |    |    |    |    |    |    |    |    |
|----|----|----|----|----|----|----|----|----|----|
| 2  | 3  | 5  | 7  | 11 | 13 | 17 | 19 | 23 | 29 |
| 31 | 37 | 41 | 43 | 47 | 53 | 59 | 61 | 67 | 71 |

...

...

168 prime(s) less than or equal to 1000

Let  $\pi(i)$  denote the number of prime numbers less than or equal to  $i$ . The primes under 20 are 2, 3, 5, 7, 11, 13, 17, and 19. Therefore,  $\pi(2)$  is 1,  $\pi(3)$  is 2,  $\pi(6)$  is 3, and  $\pi(20)$  is 8.

It has been proved that  $\pi(i)$  is approximately  $\frac{i}{\log i}$  (see [primes.utm.edu/howmany.shtml](http://primes.utm.edu/howmany.shtml)).

For each number  $i$ , the algorithm checks whether a prime number less than or equal to  $\sqrt{i}$  is divisible by  $i$ . The number of the prime numbers less than or equal to  $\sqrt{i}$  is

$$\frac{\sqrt{i}}{\log \sqrt{i}} = \frac{2\sqrt{i}}{\log i}$$

Thus, the complexity for finding all prime numbers up to  $n$  is

$$\frac{2\sqrt{2}}{\log 2} + \frac{2\sqrt{3}}{\log 3} + \frac{2\sqrt{4}}{\log 4} + \frac{2\sqrt{5}}{\log 5} + \frac{2\sqrt{6}}{\log 6} + \frac{2\sqrt{7}}{\log 7} + \frac{2\sqrt{8}}{\log 8} + \dots + \frac{2\sqrt{n}}{\log n}$$

Since  $\frac{\sqrt{i}}{\log i} < \frac{\sqrt{n}}{\log n}$  for  $i < n$  and  $n \geq 16$ ,

$$\frac{2\sqrt{2}}{\log 2} + \frac{2\sqrt{3}}{\log 3} + \frac{2\sqrt{4}}{\log 4} + \frac{2\sqrt{5}}{\log 5} + \frac{2\sqrt{6}}{\log 6} + \frac{2\sqrt{7}}{\log 7} + \frac{2\sqrt{8}}{\log 8} + \dots + \frac{2\sqrt{n}}{\log n} < \frac{2n\sqrt{n}}{\log n}$$

Therefore, the complexity of this algorithm is  $O\left(\frac{n\sqrt{n}}{\log n}\right)$ .

This algorithm is another example of dynamic programming. The algorithm stores the results of the subproblems in the array list and uses them later to check whether a new number is prime.

dynamic programming

Is there any algorithm better than  $O\left(\frac{n\sqrt{n}}{\log n}\right)$ ? Let us examine the well-known Eratosthenes algorithm for finding prime numbers. Eratosthenes (276–194 b.c.) was a Greek mathematician who devised a clever algorithm, known as the *Sieve of Eratosthenes*, for finding all prime numbers  $\leq n$ . His algorithm is to use an array named **primes** of  $n$  Boolean values. Initially, all elements in **primes** are set **true**. Since the multiples of 2 are not prime, set **primes[2 \* i]** to **false** for all  $2 \leq i \leq n/2$ , as shown in Figure 22.3. Since we don't care about **primes[0]** and **primes[1]**, these values are marked  $\times$  in the figure.

Sieve of Eratosthenes

|         | primes array |          |     |     |   |     |   |   |   |     |    |     |    |    |    |     |    |     |    |    |    |     |    |    |    |    |    |    |
|---------|--------------|----------|-----|-----|---|-----|---|---|---|-----|----|-----|----|----|----|-----|----|-----|----|----|----|-----|----|----|----|----|----|----|
| index   | 0            | 1        | 2   | 3   | 4 | 5   | 6 | 7 | 8 | 9   | 10 | 11  | 12 | 13 | 14 | 15  | 16 | 17  | 18 | 19 | 20 | 21  | 22 | 23 | 24 | 25 | 26 | 27 |
| initial | $\times$     | T        | T   | T   | T | T   | T | T | T | T   | T  | T   | T  | T  | T  | T   | T  | T   | T  | T  | T  | T   | T  | T  | T  | T  | T  |    |
| $k=2$   | $\times$     | $\times$ | T   | T   | F | T   | F | T | F | T   | F  | T   | F  | T  | F  | T   | F  | T   | F  | T  | F  | T   | F  | T  | F  | T  | F  |    |
| $k=3$   | $\times$     | $\times$ | T   | T   | F | T   | F | T | F | F   | F  | T   | F  | T  | F  | F   | T  | F   | T  | F  | F  | F   | T  | F  | T  | F  | F  |    |
| $k=5$   | $\times$     | $\times$ | (T) | (T) | F | (T) | F | F | F | (T) | F  | (T) | F  | F  | F  | (T) | F  | (T) | F  | F  | F  | (T) | F  | F  | F  | F  | F  |    |

FIGURE 22.3 The values in **primes** are changed with each prime number **k**.

Since the multiples of 3 are not prime, set **primes[3 \* i]** to **false** for all  $3 \leq i \leq n/3$ . Because the multiples of 5 are not prime, set **primes[5 \* i]** to **false** for all  $5 \leq i \leq n/5$ . Note that you don't need to consider the multiples of 4, because the multiples of 4 are also the multiples of 2, which have already been considered. Similarly, multiples of 6, 8, and 9 need not be considered. You only need to consider the multiples of a prime number  $k = 2, 3, 5, 7, 11, \dots$ , and set the corresponding element in **primes** to **false**. Afterward, if **primes[i]** is

still true, then `i` is a prime number. As shown in Figure 22.3, 2, 3, 5, 7, 11, 13, 17, 19, and 23 are prime numbers. Listing 22.7 gives the program for finding the prime numbers using the Sieve of Eratosthenes algorithm.

### LISTING 22.7 SieveOfEratosthenes.java

```

1 import java.util.Scanner;
2
3 public class SieveOfEratosthenes {
4 public static void main(String[] args) {
5 Scanner input = new Scanner(System.in);
6 System.out.print("Find all prime numbers <= n, enter n: ");
7 int n = input.nextInt();
8
sieve
9 boolean[] primes = new boolean[n + 1]; // Prime number sieve
10
11 // Initialize primes[i] to true
12 for (int i = 0; i < primes.length; i++) {
13 primes[i] = true;
14 }
15
16 for (int k = 2; k <= n / k; k++) {
17 if (primes[k]) {
18 for (int i = k; i <= n / k; i++) {
19 primes[k * i] = false; // k * i is not prime
20 }
21 }
22 }
23
24 int count = 0; // Count the number of prime numbers found so far
25 // Print prime numbers
26 for (int i = 2; i < primes.length; i++) {
27 if (primes[i]) {
28 count++;
29 if (count % 10 == 0)
30 System.out.printf("%7d\n", i);
31 else
32 System.out.printf("%7d", i);
33 }
34 }
35
36 System.out.println("\n" + count +
37 " prime(s) less than or equal to " + n);
38 }
39 }
```



Find all prime numbers <= n, enter n: 1000

The prime numbers are:

|    |    |    |    |    |    |    |    |    |    |
|----|----|----|----|----|----|----|----|----|----|
| 2  | 3  | 5  | 7  | 11 | 13 | 17 | 19 | 23 | 29 |
| 31 | 37 | 41 | 43 | 47 | 53 | 59 | 61 | 67 | 71 |

...

...

168 prime(s) less than or equal to 1000

Note that `k <= n / k` (line 16). Otherwise, `k * i` would be greater than `n` (line 19). What is the time complexity of this algorithm?

For each prime number  $k$  (line 17), the algorithm sets `primes[k * i]` to `false` (line 19). This is performed  $n / k - k + 1$  times in the `for` loop (line 18). Thus, the complexity for finding all prime numbers up to  $n$  is

$$\begin{aligned} & \frac{n}{2} - 2 + 1 + \frac{n}{3} - 3 + 1 + \frac{n}{5} - 5 + 1 + \frac{n}{7} - 7 + 1 + \frac{n}{11} - 11 + 1 \dots \\ &= O\left(\frac{n}{2} + \frac{n}{3} + \frac{n}{5} + \frac{n}{7} + \frac{n}{11} + \dots\right) < O(n\pi(n)) \\ &= O\left(n \frac{\sqrt{n}}{\log n}\right) \end{aligned}$$

The number of items in  
the series is  $\pi(n)$ .

This upper bound  $O\left(\frac{n\sqrt{n}}{\log n}\right)$  is very loose. The actual time complexity is much better than  $O\left(\frac{n\sqrt{n}}{\log n}\right)$ . The Sieve of Eratosthenes algorithm is good for a small  $n$  such that the array `primes` can fit in the memory.

Table 22.5 summarizes the complexity of these three algorithms for finding all prime numbers up to  $n$ .

**TABLE 22.5 Comparisons of Prime-Number Algorithms**

| Algorithm    | Complexity                               | Description                                 |
|--------------|------------------------------------------|---------------------------------------------|
| Listing 5.15 | $O(n^2)$                                 | Brute-force, checking all possible divisors |
| Listing 22.5 | $O(n\sqrt{n})$                           | Checking divisors up to $\sqrt{n}$          |
| Listing 22.6 | $O\left(\frac{n\sqrt{n}}{\log n}\right)$ | Checking prime divisors up to $\sqrt{n}$    |
| Listing 22.7 | $O\left(\frac{n\sqrt{n}}{\log n}\right)$ | Sieve of Eratosthenes                       |

**22.17** Prove that if  $n$  is not prime, there must exist a prime number  $p$  such that  $p \leq \sqrt{n}$  and  $p$  is a factor of  $n$ .



**22.18** Describe how the sieve of Eratosthenes is used to find the prime numbers.

## 22.8 Finding the Closest Pair of Points Using Divide-and-Conquer

*This section presents efficient algorithms for finding the closest pair of points using divide-and-conquer.*



Given a set of points, the closest-pair problem is to find the two points that are nearest to each other. As shown in Figure 22.4, a line is drawn to connect the two nearest points in the closest-pair animation.



Section 8.6, Case Study: Finding the Closest Pair, presented a brute-force algorithm for finding the closest pair of points. The algorithm computes the distances between all pairs of points and finds the one with the minimum distance. Clearly, the algorithm takes  $O(n^2)$  time. Can we design a more efficient algorithm?

closest-pair animation on Companion Website



**FIGURE 22.4** The closet-pair animation draws a line to connect the closest pair of points dynamically as points are added and removed interactively.

divide-and-conquer

We will use an approach called *divide-and-conquer* to solve this problem. The approach divides the problem into subproblems, solves the subproblems, then combines the solutions of the subproblems to obtain the solution for the entire problem. Unlike the dynamic programming approach, the subproblems in the divide-and-conquer approach don't overlap. A subproblem is like the original problem with a smaller size, so you can apply recursion to solve the problem. In fact, all the solutions for recursive problems follow the divide-and-conquer approach.

Listing 22.8 describes how to solve the closest pair problem using the divide-and-conquer approach.

### LISTING 22.8 Algorithm for Finding the Closest Pair

Step 1: Sort the points in increasing order of  $x$ -coordinates. For the points with the same  $x$ -coordinates, sort on  $y$ -coordinates. This results in a sorted list  $S$  of points.

Step 2: Divide  $S$  into two subsets,  $S_1$  and  $S_2$ , of equal size using the midpoint in the sorted list. Let the midpoint be in  $S_1$ . Recursively find the closest pair in  $S_1$  and  $S_2$ . Let  $d_1$  and  $d_2$  denote the distance of the closest pairs in the two subsets, respectively.

Step 3: Find the closest pair between a point in  $S_1$  and a point in  $S_2$  and denote their distance as  $d_3$ . The closest pair is the one with the distance  $\min(d_1, d_2, d_3)$ .

Selection sort takes  $O(n^2)$  time. In Chapter 23 we will introduce merge sort and heap sort. These sorting algorithms take  $O(n \log n)$  time. Step 1 can be done in  $O(n \log n)$  time.

Step 3 can be done in  $O(n)$  time. Let  $d = \min(d_1, d_2)$ . We already know that the closest-pair distance cannot be larger than  $d$ . For a point in  $S_1$  and a point in  $S_2$  to form the closest pair in  $S$ , the left point must be in **stripL** and the right point in **stripR**, as illustrated in Figure 22.5a.

For a point  $p$  in **stripL**, you need only consider a right point within the  $d \times 2d$  rectangle, as shown in 22.5b. Any right point outside the rectangle cannot form the closest pair with  $p$ . Since the closest-pair distance in  $S_2$  is greater than or equal to  $d$ , there can be at most six points in the rectangle. Thus, for each point in **stripL**, at most six points in **stripR** need to be considered.

For each point  $p$  in **stripL**, how do you locate the points in the corresponding  $d \times 2d$  rectangle area in **stripR**? This can be done efficiently if the points in **stripL** and **stripR** are sorted in increasing order of their  $y$ -coordinates. Let **pointsOrderedOnY** be the list of the points sorted in increasing order of  $y$ -coordinates. **pointsOrderedOnY** can be obtained beforehand in the algorithm. **stripL** and **stripR** can be obtained from **pointsOrderedOnY** in Step 3 as shown in Listing 22.9.

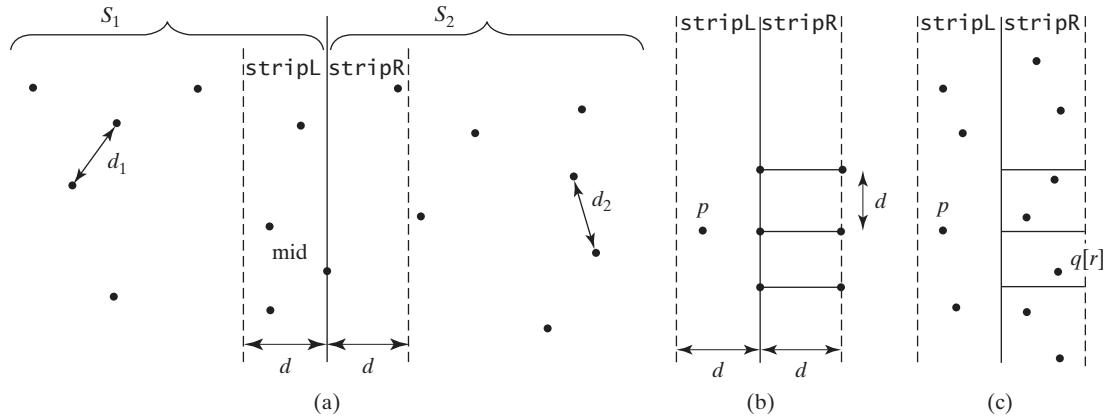


FIGURE 22.5 The midpoint divides the points into two sets of equal size.

### LISTING 22.9 Algorithm for Obtaining **stripL** and **stripR**

```

1 for each point p in pointsOrderedOnY
2 if (p is in S1 and mid.x - p.x <= d)
3 append p to stripL;
4 else if (p is in S2 and p.x - mid.x <= d)
5 append p to stripR;

```

stripL  
stripR

Let the points in **stripL** and **stripR** be  $\{p_0, p_1, \dots, p_k\}$  and  $\{q_0, q_1, \dots, q_l\}$ , as shown in Figure 22.5c. The closest pair between a point in **stripL** and a point in **stripR** can be found using the algorithm described in Listing 22.10.

### LISTING 22.10 Algorithm for Finding the Closest Pair in Step 3

```

1 d = min(d1, d2);
2 r = 0; // r is the index of a point in stripR
3 for (each point p in stripL) {
4 // Skip the points in stripR below p.y - d
5 while (r < stripR.length && q[r].y <= p.y - d)
6 r++;
7
8 let r1 = r;
9 while (r1 < stripR.length && |q[r1].y - p.y| <= d) {
10 // Check if (p, q[r1]) is a possible closest pair
11 if (distance(p, q[r1]) < d) {
12 d = distance(p, q[r1]);
13 (p, q[r1]) is now the current closest pair;
14 }
15
16 r1 = r1 + 1;
17 }
18 }

```

update closest pair

The points in **stripL** are considered from  $p_0, p_1, \dots, p_k$  in this order. For a point **p** in **stripL**, skip the points in **stripR** that are below **p.y - d** (lines 5–6). Once a point is skipped, it will no longer be considered. The **while** loop (lines 9–17) checks whether **(p, q[r1])** is a possible closest pair. There are at most six such **q[r1]** pairs, because the distance between two points in **stripR** cannot be less than **d**. So the complexity for finding the closest pair in Step 3 is  $O(n)$ .

Note that Step 1 in Listing 22.8 is performed only once to presort the points. Assume that all the points are presorted. Let  $T(n)$  denote the time complexity for this algorithm. Thus,

$$\begin{array}{c} \text{Step 2} \quad \text{Step 3} \\ \downarrow \quad \downarrow \\ T(n) = 2T(n/2) + O(n) = O(n \log n) \end{array}$$

Therefore, the closest pair of points can be found in  $O(n \log n)$  time. The complete implementation of this algorithm is left as an exercise (see Programming Exercise 22.7).



**22.19** What is the divide-and-conquer approach? Give an example.

**22.20** What is the difference between divide-and-conquer and dynamic programming?

**22.21** Can you design an algorithm for finding the minimum element in a list using divide-and-conquer? What is the complexity of this algorithm?



## 22.9 Solving the Eight Queens Problem Using Backtracking

*This section solves the Eight Queens problem using the backtracking approach.*

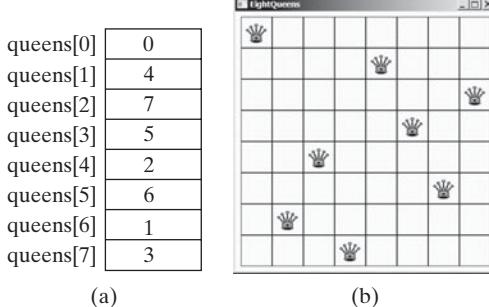
backtracking

The Eight Queens problem is to find a solution to place a queen in each row on a chessboard such that no two queens can attack each other. The problem can be solved using recursion (See Programming Exercise 18.34). In this section, we will introduce a common algorithm design technique called *backtracking* for solving this problem. The backtracking approach searches for a candidate solution incrementally, abandoning that option as soon as it determines that the candidate cannot possibly be a valid solution, and then looks for a new candidate.

You can use a two-dimensional array to represent a chessboard. However, since each row can have only one queen, it is sufficient to use a one-dimensional array to denote the position of the queen in the row. Thus, you can define the `queens` array as:

```
int[] queens = new int[8];
```

Assign `j` to `queens[i]` to denote that a queen is placed in row `i` and column `j`. Figure 22.6a shows the contents of the `queens` array for the chessboard in Figure 22.6b.



**FIGURE 22.6** `queens[i]` denotes the position of the queen in row `i`.

search algorithm

The search starts from the first row with  $k = 0$ , where  $k$  is the index of the current row being considered. The algorithm checks whether a queen can be possibly placed in the  $j$ th column in the row for  $j = 0, 1, \dots, 7$ , in this order. The search is implemented as follows:

- If successful, it continues to search for a placement for a queen in the next row. If the current row is the last row, a solution is found.
- If not successful, it backtracks to the previous row and continues to search for a new placement in the next column in the previous row.
- If the algorithm backtracks to the first row and cannot find a new placement for a queen in this row, no solution can be found.



Eight Queens animation on the Companion Website

To see how the algorithm works, go to [www.cs.armstrong.edu/liang/animation/EightQueensAnimation.html](http://www.cs.armstrong.edu/liang/animation/EightQueensAnimation.html).

Listing 22.11 gives the program that displays a solution for the Eight Queens problem.

## LISTING 22.11 EightQueens.java

```
1 import javafx.application.Application;
2 import javafx.geometry.Pos;
3 import javafx.stage.Stage;
4 import javafx.scene.Scene;
5 import javafx.scene.control.Label;
6 import javafx.scene.image.Image;
7 import javafx.scene.image.ImageView;
8 import javafx.scene.layout.GridPane;
9
10 public class EightQueens extends Application {
11 public static final int SIZE = 8; // The size of the chess board
12 // queens are placed at (i, queens[i])
13 // -1 indicates that no queen is currently placed in the ith row
14 // Initially, place a queen at (0, 0) in the 0th row
15 private int[] queens = {-1, -1, -1, -1, -1, -1, -1, -1}; queen positions
16
17 @Override // Override the start method in the Application class
18 public void start(Stage primaryStage) {
19 search(); // Search for a solution search for solution
20
21 // Display chess board
22 GridPane chessBoard = new GridPane();
23 chessBoard.setAlignment(Pos.CENTER);
24 Label[][] labels = new Label[SIZE][SIZE];
25 for (int i = 0; i < SIZE; i++) {
26 for (int j = 0; j < SIZE; j++) { create cells
27 chessBoard.add(labels[i][j] = new Label(), j, i);
28 labels[i][j].setStyle("-fx-border-color: black");
29 labels[i][j].setPrefSize(55, 55);
30 }
31
32 // Display queens
33 Image image = new Image("image/queen.jpg");
34 for (int i = 0; i < SIZE; i++) set queen image
35 labels[i][queens[i]].setGraphic(new ImageView(image));
36
37 // Create a scene and place it in the stage
38 Scene scene = new Scene(chessBoard, 55 * SIZE, 55 * SIZE);
39 primaryStage.setTitle("EightQueens"); // Set the stage title
40 primaryStage.setScene(scene); // Place the scene in the stage
41 primaryStage.show(); // Display the stage
42 }
43
44 /** Search for a solution */
45 private boolean search() {
46 // k - 1 indicates the number of queens placed so far
47 // We are looking for a position in the kth row to place a queen
48 int k = 0;
49 while (k >= 0 && k < SIZE) {
50 // Find a position to place a queen in the kth row
51 int j = findPosition(k); find a column
52 if (j < 0) {
53 queens[k] = -1;
54 k--; // back track to the previous row backtrack
55 } else {
```

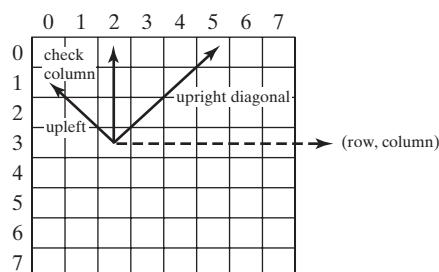
```
place a queen
search the next row

56 queens[k] = j;
57 k++;
58 }
59 }
60
61 if (k == -1)
62 return false; // No solution
63 else
64 return true; // A solution is found
65 }
66
67 public int findPosition(int k) {
68 int start = queens[k] + 1; // Search for a new placement
69
70 for (int j = start; j < SIZE; j++) {
71 if (isValid(k, j))
72 return j; // (k, j) is the place to put the queen now
73 }
74
75 return -1;
76 }
77
78 /** Return true if a queen can be placed at (row, column) */
79 public boolean isValid(int row, int column) {
80 for (int i = 1; i <= row; i++)
81 if (queens[row - i] == column) // Check column
82 || queens[row - i] == column - i // Check upleft diagonal
83 || queens[row - i] == column + i) // Check upright diagonal
84 return false; // There is a conflict
85 return true; // No conflict
86 }
87 }
```

The program invokes `search()` (line 19) to search for a solution. Initially, no queens are placed in any rows (line 15). The search now starts from the first row with `k = 0` (line 48) and finds a place for the queen (line 51). If successful, place it in the row (line 56) and consider the next row (line 57). If not successful, backtrack to the previous row (lines 53–54).

The `findPosition(k)` method searches for a possible position to place a queen in row `k` starting from `queen[k] + 1` (line 68). It checks whether a queen can be placed at `start`, `start + 1`, ..., and `7`, in this order (lines 70–73). If possible, return the column index (line 72); otherwise, return `-1` (line 75).

The `isValid(row, column)` method is called to check whether placing a queen at the specified position causes a conflict with the queens placed earlier (line 71). It ensures that no queen is placed in the same column (line 81), in the upper-left diagonal (line 82), or in the upper-right diagonal (line 83), as shown in Figure 22.7.



**FIGURE 22.7** Invoking `isValid(row, column)` checks whether a queen can be placed at  $(\text{row}, \text{column})$ .

**22.22** What is backtracking? Give an example.

**22.23** If you generalize the Eight Queens problem to the  $n$ -Queens problem in an  $n$ -by- $n$  chessboard, what will be the complexity of the algorithm?



## 22.10 Computational Geometry: Finding a Convex Hull

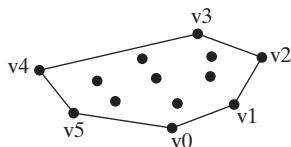
This section presents efficient geometric algorithms for finding a convex hull for a set of points.



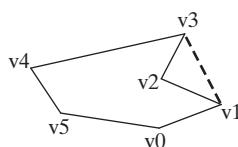
Computational geometry is to study the algorithms for geometrical problems. It has applications in computer graphics, games, pattern recognition, image processing, robotics, geographical information systems, and computer-aided design and manufacturing. Section 22.8 presented a geometrical algorithm for finding the closest pair of points. This section introduces geometrical algorithms for finding a convex hull.

Given a set of points, a *convex hull* is the smallest convex polygon that encloses all these points, as shown in Figure 22.8a. A polygon is convex if every line connecting two vertices is inside the polygon. For example, the vertices  $v_0, v_1, v_2, v_3, v_4$ , and  $v_5$  in Figure 22.8a form a convex polygon, but not in Figure 22.8b, because the line that connects  $v_3$  and  $v_1$  is not inside the polygon.

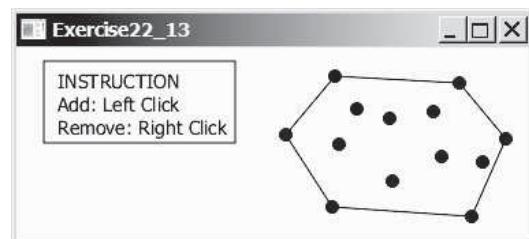
convex hull



(a) A convex hull



(b) A nonconvex polygon



(c) Convex hull animation

**FIGURE 22.8** A convex hull is the smallest convex polygon that contains a set of points.

A convex hull has many applications in game programming, pattern recognition, and image processing. Before we introduce the algorithms, it is helpful to get acquainted with the concept using an interactive tool from [www.cs.armstrong.edu/liang/animation/ConvexHull.html](http://www.cs.armstrong.edu/liang/animation/ConvexHull.html), as shown in Figure 22.8c. This tool allows you to add and remove points and displays the convex hull dynamically.



convex hull animation on the Companion Website

Many algorithms have been developed to find a convex hull. This section introduces two popular algorithms: the gift-wrapping algorithm and Graham's algorithm.

### 22.10.1 Gift-Wrapping Algorithm

An intuitive approach, called the *gift-wrapping algorithm*, works as shown in Listing 22.12:

#### LISTING 22.12 Finding a Convex Hull Using Gift-Wrapping Algorithm

Step 1: Given a list of points  $S$ , let the points in  $S$  be labeled  $s_0, s_1, \dots, s_k$ . Select the rightmost lowest point  $s_0$ . As shown in Figure 22.9a,  $h_0$  is such a point. Add  $h_0$  to list  $H$ . ( $H$  is initially empty.  $H$  will hold all points in the convex hull after the algorithm is finished.) Let  $t_0$  be  $h_0$ .



**FIGURE 22.9** (a)  $h_0$  is the rightmost lowest point in  $S$ . (b) Step 2 finds point  $t_1$ . (c) A convex hull is expanded repeatedly. (d) A convex hull is found when  $t_1$  becomes  $h_0$ .

```

Step 2: Let t_1 be s_0 .
For every point p in S ,
 if p is on the right side of the direct line from t_0 to t_1 , then
 let t_1 be p .
(After Step 2, no points lie on the right side of the direct line from t_0 to t_1 , as shown in Figure 22.9b.)
Step 3: If t_1 is h_0 (see Figure 22.9d), the points in H form a convex
hull for S . Otherwise, add t_1 to H , let t_0 be t_1 , and go back to Step 2
(see Figure 22.9c).

```

correctness of the algorithm

time complexity of the algorithm

The convex hull is expanded incrementally. The correctness is supported by the fact that no points lie on the right side of the direct line from  $t_0$  to  $t_1$  after Step 2. This ensures that every line segment with two points in  $S$  falls inside the polygon.

Finding the rightmost lowest point in Step 1 can be done in  $O(n)$  time. Whether a point is on the left side of a line, right side, or on the line can be determined in  $O(1)$  time (see Programming Exercise 3.32). Thus, it takes  $O(n)$  time to find a new point  $t_1$  in Step 2. Step 2 is repeated  $h$  times, where  $h$  is the size of the convex hull. Therefore, the algorithm takes  $O(hn)$  time. In the worst-case,  $h$  is  $n$ .

The implementation of this algorithm is left as an exercise (see Programming Exercise 22.9).

### 22.10.2 Graham's Algorithm

A more efficient algorithm was developed by Ronald Graham in 1972, as shown in Listing 22.13.

#### LISTING 22.13 Finding a Convex Hull Using Graham's Algorithm

Step 1: Given a list of points  $S$ , select the rightmost lowest point and name it  $p_0$ . As shown in Figure 22.10a,  $p_0$  is such a point.



**FIGURE 22.10** (a)  $p_0$  is the rightmost lowest point in  $S$ . (b) Points are sorted by their angles. (c–d) A convex hull is discovered incrementally.

Step 2: Sort the points in  $S$  angularly along the  $x$ -axis with  $p_0$  as the center, as shown in Figure 22.10b. If there is a tie and two points have the same angle, discard the one that is closer to  $p_0$ . The points in  $S$  are now sorted as  $p_0, p_1, p_2, \dots, p_{n-1}$ .

**Step 3:** Push  $p_0$ ,  $p_1$ , and  $p_2$  into stack  $H$ . (After the algorithm finishes,  $H$  contains all the points in the convex hull.)

**Step 4:**

```
i = 3;
while (i < n) {
 Let t_1 and t_2 be the top first and second element in stack H ;
 if (p_i is on the left side of the direct line from t_2 to t_1) {
 Push p_i to H ;
 i++; // Consider the next point in S .
 }
 else
 Pop the top element off stack H .
}
```

**Step 5:** The points in  $H$  form a convex hull.

The convex hull is discovered incrementally. Initially,  $p_0$ ,  $p_1$ , and  $p_2$  form a convex hull. Consider  $p_3$ .  $p_3$  is outside of the current convex hull since points are sorted in increasing order of their angles. If  $p_3$  is strictly on the left side of the line from  $p_1$  to  $p_2$  (see Figure 22.10c), push  $p_3$  into  $H$ . Now  $p_0$ ,  $p_1$ ,  $p_2$ , and  $p_3$  form a convex hull. If  $p_3$  is on the right side of the line from  $p_1$  to  $p_2$  (see Figure 22.10d), pop  $p_2$  out of  $H$  and push  $p_3$  into  $H$ . Now  $p_0$ ,  $p_1$ , and  $p_3$  form a convex hull and  $p_2$  is inside of this convex hull. You can prove by induction that all the points in  $H$  in Step 5 form a convex hull for all the points in the input list  $S$ .

Finding the rightmost lowest point in Step 1 can be done in  $O(n)$  time. The angles can be computed using trigonometry functions. However, you can sort the points without actually computing their angles. Observe that  $p_2$  would make a greater angle than  $p_1$  if and only if  $p_2$  lies on the left side of the line from  $p_0$  to  $p_1$ . Whether a point is on the left side of a line can be determined in  $O(1)$  time, as shown in Programming Exercise 3.32. Sorting in Step 2 can be done in  $O(n \log n)$  time using the merge-sort or heap-sort algorithms that will be introduced in Chapter 23. Step 4 can be done in  $O(n)$  time. Therefore, the algorithm takes  $O(n \log n)$  time.

The implementation of this algorithm is left as an exercise (see Programming Exercise 22.11).

correctness of the algorithm

time complexity of the algorithm



**22.24** What is a convex hull?

**22.25** Describe the gift-wrapping algorithm for finding a convex hull. Should list  $H$  be implemented using an [ArrayList](#) or a [LinkedList](#)?

**22.26** Describe Graham's algorithm for finding a convex hull. Why does the algorithm use a stack to store the points in a convex hull?

## KEY TERMS

|                             |     |                              |     |
|-----------------------------|-----|------------------------------|-----|
| average-case analysis       | 822 | dynamic programming approach | 832 |
| backtracking approach       | 846 | exponential time             | 829 |
| best-case input             | 822 | growth rate                  | 822 |
| Big $O$ notation            | 822 | logarithmic time             | 828 |
| brute force                 | 833 | quadratic time               | 825 |
| constant time               | 823 | space complexity             | 823 |
| convex hull                 | 849 | time complexity              | 823 |
| divide-and-conquer approach | 844 | worst-case input             | 822 |

## CHAPTER SUMMARY

- The *Big O notation* is a theoretical approach for analyzing the performance of an algorithm. It estimates how fast an algorithm's execution time increases as the input size increases, which enables you to compare two algorithms by examining their *growth rates*.

2. An input that results in the shortest execution time is called the *best-case* input and one that results in the longest execution time is called the *worst-case* input. Best case and worst case are not representative, but worst-case analysis is very useful. You can be assured that the algorithm will never be slower than the worst case.
3. An *average-case analysis* attempts to determine the average amount of time among all possible input of the same size. Average-case analysis is ideal, but difficult to perform, because for many problems it is hard to determine the relative probabilities and distributions of various input instances.
4. If the time is not related to the input size, the algorithm is said to take *constant time* with the notation  $O(1)$ .
5. Linear search takes  $O(n)$  time. An algorithm with the  $O(n)$  time complexity is called a *linear algorithm* and it exhibits a linear growth rate. Binary search takes  $O(\log n)$  time. An algorithm with the  $O(\log n)$  time complexity is called a *logarithmic algorithm*, and it exhibits a logarithmic growth rate.
6. The worst-time complexity for selection sort is  $O(n^2)$ . An algorithm with the  $O(n^2)$  time complexity is called a *quadratic algorithm*, and it exhibits a quadratic growth rate.
7. The time complexity for the Tower of Hanoi problem is  $O(2^n)$ . An algorithm with the  $O(2^n)$  time complexity is called an *exponential algorithm*, and it exhibits an exponential growth rate.
8. A Fibonacci number at a given index can be found in  $O(n)$  time using dynamic programming.
9. Dynamic programming is the process of solving subproblems, then combining the solutions of the subproblems to obtain an overall solution. The key idea behind dynamic programming is to solve each subproblem only once and store the results for subproblems for later use to avoid redundant computing of the subproblems.
10. Euclid's GCD algorithm takes  $O(\log n)$  time.
11. All prime numbers less than or equal to  $n$  can be found in  $O\left(\frac{n\sqrt{n}}{\log n}\right)$  time.
12. The closest pair can be found in  $O(n \log n)$  time using the *divide-and-conquer approach*.
13. The divide-and-conquer approach divides the problem into subproblems, solves the subproblems, then combines the solutions of the subproblems to obtain the solution for the entire problem. Unlike the dynamic programming approach, the subproblems in the divide-and-conquer approach don't overlap. A subproblem is like the original problem with a smaller size, so you can apply recursion to solve the problem.
14. The Eight Queens problem can be solved using backtracking.
15. The backtracking approach searches for a candidate solution incrementally, abandoning that option as soon as it determines that the candidate cannot possibly be a valid solution, and then looks for a new candidate.
16. A *convex hull* for a set of points can be found in  $O(n^2)$  time using the gift-wrapping algorithm and in  $O(n \log n)$  time using the Graham's algorithm.

## Quiz

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Answer the quiz for this chapter online at [www.cs.armstrong.edu/liang/intro10e/test.html](http://www.cs.armstrong.edu/liang/intro10e/test.html).

### PROGRAMMING EXERCISES

---

MyProgrammingLab™

- \*22.1** (*Maximum consecutive increasingly ordered substring*) Write a program that prompts the user to enter a string and displays the maximum consecutive increasingly ordered substring. Analyze the time complexity of your program. Here is a sample run:

```
Enter a string:abcabcdgabxy ↵ Enter
abcdg
```



```
Enter a string: abcabcdgabmnsxy ↵ Enter
abmnsxy
```



- \*\*22.2** (*Maximum increasingly ordered subsequence*) Write a program that prompts the user to enter a string and displays the maximum increasingly ordered subsequence of characters. Analyze the time complexity of your program. Here is a sample run:

```
Enter a string: Welcome ↵ Enter
WeLo
```



- \*22.3** (*Pattern matching*) Write a program that prompts the user to enter two strings and tests whether the second string is a substring of the first string. *Suppose the neighboring characters in the string are distinct.* (Don't use the `indexOf` method in the `String` class.) Analyze the time complexity of your algorithm. Your algorithm needs to be at least **O(n)** time. Here is a sample run of the program:

```
Enter a string s1: Welcome to Java ↵ Enter
Enter a string s2: come ↵ Enter
matched at index 3
```



- \*22.4** (*Pattern matching*) Write a program that prompts the user to enter two strings and tests whether the second string is a substring of the first string. (Don't use the `indexOf` method in the `String` class.) Analyze the time complexity of your algorithm. Here is a sample run of the program:

```
Enter a string s1: Mississippi ↵ Enter
Enter a string s2: sip ↵ Enter
matched at index 6
```



- \*22.5** (*Same-number subsequence*) Write an  $O(n)$  program that prompts the user to enter a sequence of integers ending with 0 and finds the longest subsequence with the same number. Here is a sample run of the program:



```
Enter a series of numbers ending with 0:
2 4 4 8 8 8 8 2 4 4 0 ↵Enter
The longest same number sequence starts at index 3 with 4 values of 8
```

- \*22.6** (*Execution time for GCD*) Write a program that obtains the execution time for finding the GCD of every two consecutive Fibonacci numbers from the index 40 to index 45 using the algorithms in Listings 22.3 and 22.4. Your program should print a table like this:

|                        | 40 | 41 | 42 | 43 | 44 | 45 |
|------------------------|----|----|----|----|----|----|
| Listing 22.3 GCD       |    |    |    |    |    |    |
| Listing 22.4 GCDEuclid |    |    |    |    |    |    |

(Hint: You can use the following code template to obtain the execution time.)

```
long startTime = System.currentTimeMillis();
perform the task;
long endTime = System.currentTimeMillis();
long executionTime = endTime - startTime;
```

- \*\*22.7** (*Closest pair of points*) Section 22.8 introduced an algorithm for finding the closest pair of points using a divide-and-conquer approach. Implement the algorithm to meet the following requirements:

- Define the classes **Point** and **CompareY** in the same way as in Programming Exercise 20.4.
- Define a class named **Pair** with the data fields **p1** and **p2** to represent two points, and a method named **getDistance()** that returns the distance between the two points.
- Implement the following methods:

```
/** Return the distance of the closest pair of points */
public static Pair getClosestPair(double[][] points)

/** Return the distance of the closest pair of points */
public static Pair getClosestPair(Point[] points)

/** Return the distance of the closest pair of points
 * in pointsOrderedOnX[low..high]. This is a recursive
 * method. pointsOrderedOnX and pointsOrderedOnY are
 * not changed in the subsequent recursive calls.
 */
public static Pair distance(Point[] pointsOrderedOnX,
 int low, int high, Point[] pointsOrderedOnY)
```

```
/** Compute the distance between two points p1 and p2 */
public static double distance(Point p1, Point p2)

/** Compute the distance between points (x1, y1) and (x2, y2) */
public static double distance(double x1, double y1,
 double x2, double y2)
```

- \*\*22.8** (All prime numbers up to 10,000,000,000) Write a program that finds all prime numbers up to 10,000,000,000. There are approximately 455,052,511 such prime numbers. Your program should meet the following requirements:

- Your program should store the prime numbers in a binary data file, named **PrimeNumbers.dat**. When a new prime number is found, the number is appended to the file.
- To find whether a new number is prime, your program should load the prime numbers from the file to an array of the **long** type of size **10000**. If no number in the array is a divisor for the new number, continue to read the next **10000** prime numbers from the data file, until a divisor is found or all numbers in the file are read. If no divisor is found, the new number is prime.
- Since this program takes a long time to finish, you should run it as a batch job from a UNIX machine. If the machine is shut down and rebooted, your program should resume by using the prime numbers stored in the binary data file rather than start over from scratch.

- \*\*22.9** (Geometry: gift-wrapping algorithm for finding a convex hull) Section 22.10.1 introduced the gift-wrapping algorithm for finding a convex hull for a set of points. Assume that the Java's coordinate system is used for the points. Implement the algorithm using the following method:

```
/** Return the points that form a convex hull */
public static ArrayList<Point2D> getConvexHull(double[][] s)
```

**Point2D** is defined in Section 9.6.

Write a test program that prompts the user to enter the set size and the points and displays the points that form a convex hull. Here is a sample run:

```
How many points are in the set? 6 ↵ Enter
Enter 6 points: 1 2.4 2.5 2 1.5 34.5 5.5 6 6 2.4 5.5 9 ↵ Enter
The convex hull is
(1.5, 34.5) (5.5, 9.0) (6.0, 2.4) (2.5, 2.0) (1.0, 2.4)
```



- 22.10** (Number of prime numbers) Programming Exercise 22.8 stores the prime numbers in a file named **PrimeNumbers.dat**. Write a program that finds the number of prime numbers that are less than or equal to 10, 100, 1,000, 10,000, 100,000, 1,000,000, 10,000,000, 100,000,000, 100,000,000, 1,000,000,000, and 10,000,000,000. Your program should read the data from **PrimeNumbers.dat**.

- \*\*22.11** (*Geometry: Graham's algorithm for finding a convex hull*) Section 22.10.2 introduced Graham's algorithm for finding a convex hull for a set of points. Assume that the Java's coordinate system is used for the points. Implement the algorithm using the following method:

```
/** Return the points that form a convex hull */
public static ArrayList<MyPoint> getConvexHull(double[][] s)

MyPoint is a static inner class defined as follows:
private static class MyPoint implements Comparable<MyPoint> {
 double x, y;

 MyPoint(double x, double y) {
 this.x = x; this.y = y;
 }

 public void setRightMostLowestPoint(MyPoint p) {
 rightMostLowestPoint = p;
 }

 @Override
 public int compareTo(MyPoint o) {
 // Implement it to compare this point with point o
 // angularly along the x-axis with rightMostLowestPoint
 // as the center, as shown in Figure 22.10b. By implementing
 // the Comparable interface, you can use the Array.sort
 // method to sort the points to simplify coding.
 }
}
```

Write a test program that prompts the user to enter the set size and the points and displays the points that form a convex hull. Here is a sample run:



How many points are in the set? 6 ↵Enter  
 Enter 6 points: 1 2.4 2.5 2 1.5 34.5 5.5 6 6 2.4 5.5 9 ↵Enter  
 The convex hull is  
 (1.5, 34.5) (5.5, 9.0) (6.0, 2.4) (2.5, 2.0) (1.0, 2.4)

- \*22.12** (*Last 100 prime numbers*) Programming Exercise 22.8 stores the prime numbers in a file named **PrimeNumbers.dat**. Write an efficient program that reads the last 100 numbers in the file. (*Hint:* Don't read all numbers from the file. Skip all numbers before the last 100 numbers in the file.)

- \*\*22.13** (*Geometry: convex hull animation*) Programming Exercise 22.11 finds a convex hull for a set of points entered from the console. Write a program that enables the user to add/remove points by clicking the left/right mouse button, and displays a convex hull, as shown in Figure 22.8c.

- \*22.14** (*Execution time for prime numbers*) Write a program that obtains the execution time for finding all the prime numbers less than 8,000,000, 10,000,000,

12,000,000, 14,000,000, 16,000,000, and 18,000,000 using the algorithms in Listings 22.5–22.7. Your program should print a table like this:

|              | 8000000 | 10000000 | 12000000 | 14000000 | 16000000 | 18000000 |
|--------------|---------|----------|----------|----------|----------|----------|
| Listing 22.5 |         |          |          |          |          |          |
| Listing 22.6 |         |          |          |          |          |          |
| Listing 22.7 |         |          |          |          |          |          |

- \*\*22.15** (*Geometry: non-cross polygon*) Write a program that enables the user to add/remove points by clicking the left/right mouse button, and displays a non-crossed polygon that links all the points, as shown in Figure 22.11a. A polygon is crossed if two or more sides intersect, as shown in Figure 22.11b. Use the following algorithm to construct a polygon from a set of points.



**FIGURE 22.11** (a) Programming Exercise22.15 displays a non-crossed polygon for a set of points. (b) Two or more sides intersect in a crossed polygon.

Step 1: Given a set of points  $S$ , select the rightmost lowest point  $p_0$  in the set  $S$ .

Step 2: Sort the points in  $S$  angularly along the  $x$ -axis with  $p_0$  as the center. If there is a tie and two points have the same angle, the one that is closer to  $p_0$  is considered greater. The points in  $S$  are now sorted as  $p_0, p_1, p_2, \dots, p_{n-1}$ .

Step 3: The sorted points form a non-cross polygon.

- \*\*22.16** (*Linear search animation*) Write a program that animates the linear search algorithm. Create an array that consists of 20 distinct numbers from 1 to 20 in a random order. The array elements are displayed in a histogram, as shown in Figure 22.12. You need to enter a search key in the text field. Clicking the *Step* button causes the program to perform one comparison in the algorithm and repaints the histogram with a bar indicating the search position. This button also freezes the text field to prevent its value from being changed. When the algorithm is finished, display the status in the label at the top of the border pane to inform the user. Clicking the *Reset* button creates a new random array for a new start. This button also makes the text field editable.



FIGURE 22.12 The program animates a linear search.

**\*\*22.17** (*Closest-pair animation*) Write a program that enables the user to add/remove points by clicking the left/right mouse button, and displays a line that connects the pair of nearest points, as shown in Figure 22.4.

**\*\*22.18** (*Binary search animation*) Write a program that animates the binary search algorithm. Create an array with numbers from 1 to 20 in this order. The array elements are displayed in a histogram, as shown in Figure 22.13. You need to enter a search key in the text field. Clicking the *Step* button causes the program to perform one comparison in the algorithm. Use a light-gray color to paint the bars for the numbers in the current search range and use a black color to paint the a bar indicating the middle number in the search range. The *Step* button also freezes the text field to prevent its value from being changed. When the algorithm is finished, display the status in a label at the top of a border pane. Clicking the *Reset* button enables a new search to start. This button also makes the text field editable.



FIGURE 22.13 The program animates a binary search.

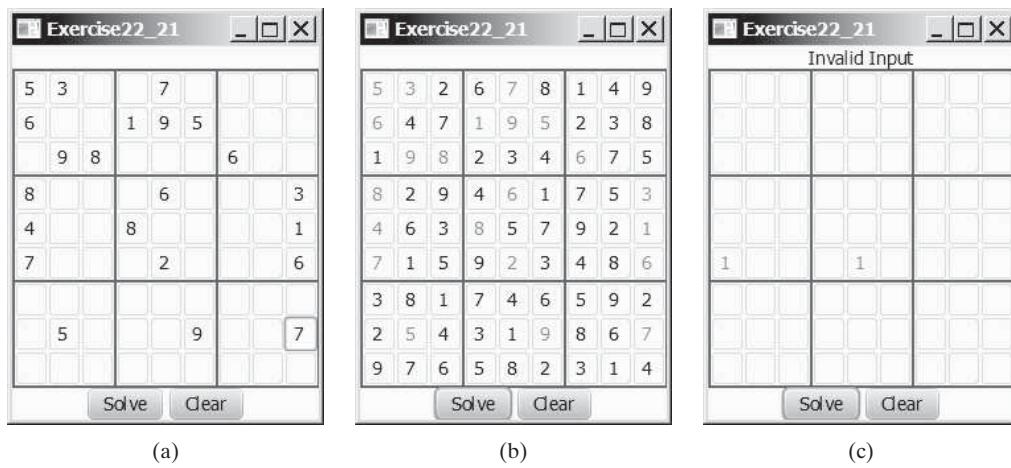
**\*22.19** (*Largest block*) The problem for finding a largest block is described in Programming Exercise 8.35. Design a dynamic programming algorithm for solving this problem in  $O(n^2)$  time. Write a test program that displays a 10-by-10 square matrix, as shown in Figure 22.14a. Each element in the matrix is 0 or 1, randomly generated with a click of the *Refresh* button. Display each number centered in a text field. *Use a text field for each entry. Allow the user to change the entry value.* Click the *Find Largest Block* button to find a largest square submatrix that consists of 1s. Highlight the numbers in the block, as shown in Figure 22.14b. See [www.cs.armstrong.edu/liang/animation/FindLargestBlock.html](http://www.cs.armstrong.edu/liang/animation/FindLargestBlock.html) for an interactive test.



**FIGURE 22.14** The program finds the largest block of 1s.

**\*\*\*22.20** (*Game: multiple Sudoku solutions*) The complete solution for the Sudoku problem is given in Supplement VI.A. A Sudoku problem may have multiple solutions. Modify Sudoku.java in Supplement VI.A to display the total number of the solutions. Display two solutions if multiple solutions exist.

**\*\*\*22.21** (*Game: Sudoku*) The complete solution for the Sudoku problem is given in Supplement VI.C. Write a program that lets the user enter the input from the text fields, as shown in Figure 22.15a. Clicking the *Solve* button displays the result, as shown in Figure 22.15b–c.

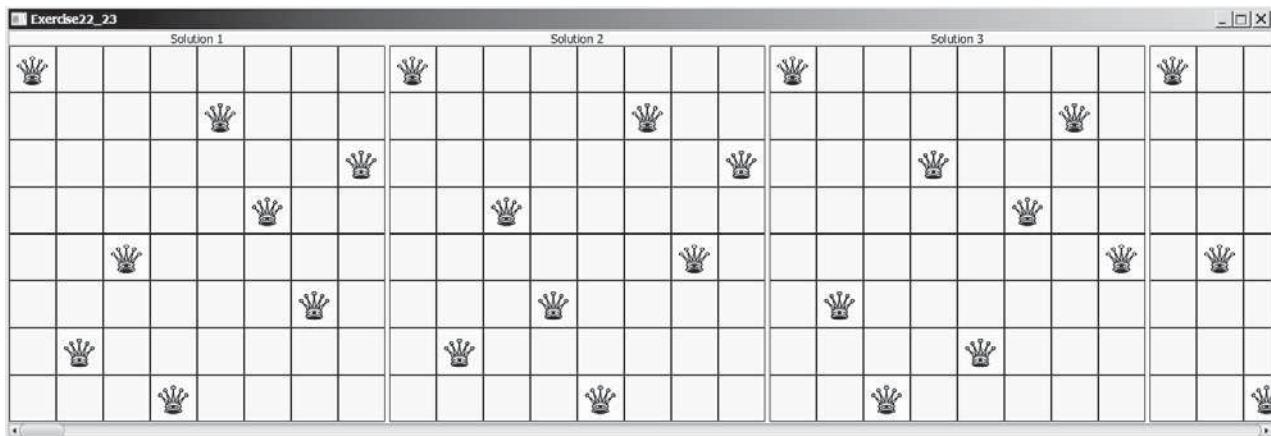


**FIGURE 22.15** The program solves the Sudoku problem.

**\*\*\*22.22** (*Game: recursive Sudoku*) Write a recursive solution for the Sudoku problem.

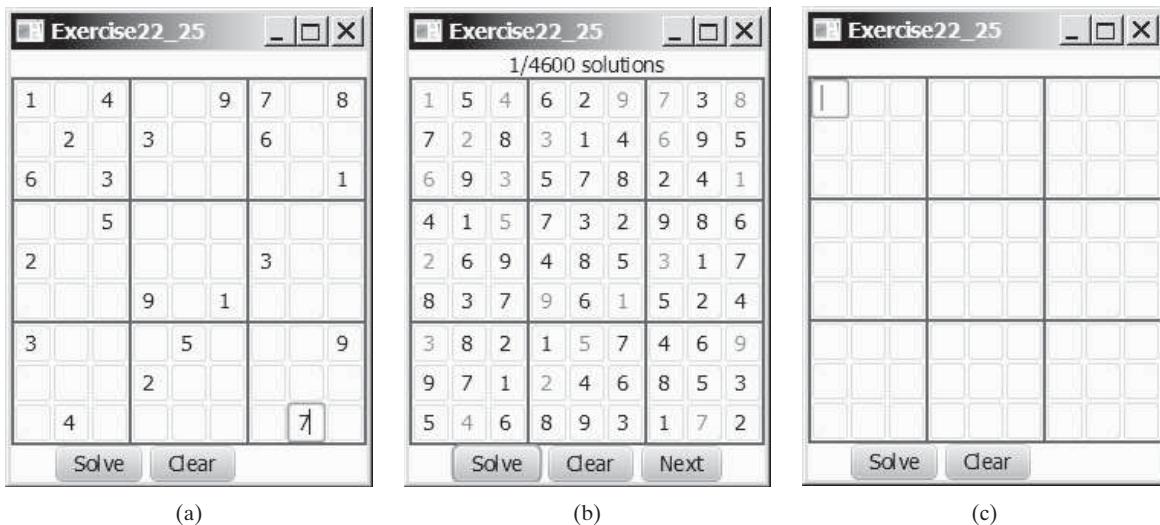
**\*\*\*22.23** (*Game: multiple Eight Queens solution*) Write a program to display all possible solutions for the Eight Queens puzzle in a scroll pane, as shown in Figure 22.16. For each solution, put a label to denote the solution number. (*Hint:* Place all solution panes into an **HBox** and place this one pane into a **ScrollPane**.)

**\*\*22.24** (*Find the smallest number*) Write a method that uses the divide-and-conquer approach to find the smallest number in a list.



**FIGURE 22.16** All solutions are placed in a scroll pane.

**\*\*\*22.25** (*Game: Sudoku*) Revise Programming Exercise 22.21 to display all solutions for the Sudoku game, as shown in Figure 22.17a. When you click the *Solve* button, the program stores all solutions in an **ArrayList**. Each element in the list is a two-dimensional 9-by-9 grid. If the program has multiple solutions, the *Next* button appears as shown in Figure 22.17b. You can click the *Next* button to display the next solution and also a label to show the solution count. When the *Clear* button is clicked, the cells are cleared and the *Next* button is hidden as shown in Figure 22.17c.

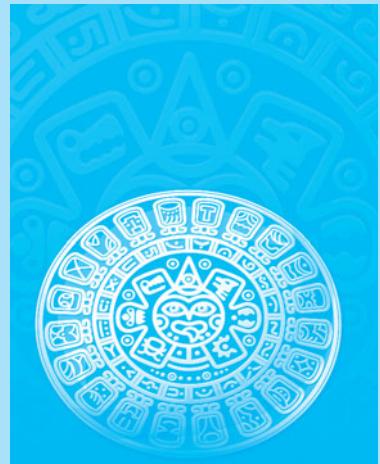


**FIGURE 22.17** The program can display multiple Sudoku solutions.

# SORTING

## Objectives

- To study and analyze time complexity of various sorting algorithms (§§23.2–23.7).
- To design, implement, and analyze insertion sort (§23.2).
- To design, implement, and analyze bubble sort (§23.3).
- To design, implement, and analyze merge sort (§23.4).
- To design, implement, and analyze quick sort (§23.5).
- To design and implement a binary heap (§23.6).
- To design, implement, and analyze heap sort (§23.6).
- To design, implement, and analyze bucket sort and radix sort (§23.7).
- To design, implement, and analyze external sort for files that have a large amount of data (§23.8).



## 23.1 Introduction



*Sorting algorithms are good examples for studying algorithm design and analysis.*

When presidential candidate Barack Obama visited Google in 2007, Google CEO Eric Schmidt asked Obama the most efficient way to sort a million 32-bit integers ([www.youtube.com/watch?v=k4RRi\\_ntQc8](http://www.youtube.com/watch?v=k4RRi_ntQc8)). Obama answered that the bubble sort would be the wrong way to go. Was he right? We will examine different sorting algorithms in this chapter and see if he was correct.

why study sorting?

Sorting is a classic subject in computer science. There are three reasons to study sorting algorithms.

- First, sorting algorithms illustrate many creative approaches to problem solving, and these approaches can be applied to solve other problems.
- Second, sorting algorithms are good for practicing fundamental programming techniques using selection statements, loops, methods, and arrays.
- Third, sorting algorithms are excellent examples to demonstrate algorithm performance.

what data to sort?

The data to be sorted might be integers, doubles, characters, or objects. Section 7.11, Sorting Arrays, presented selection sort. The selection sort algorithm was extended to sort an array of objects in Section 19.5, Case Study: Sorting an Array of Objects. The Java API contains several overloaded sort methods for sorting primitive type values and objects in the **java.util.Arrays** and **java.util.Collections** classes. For simplicity, this chapter assumes:

1. data to be sorted are integers,
2. data are stored in an array, and
3. data are sorted in ascending order.

The programs can be easily modified to sort other types of data, to sort in descending order, or to sort data in an **ArrayList** or a **LinkedList**.

There are many algorithms for sorting. You have already learned selection sort. This chapter introduces insertion sort, bubble sort, merge sort, quick sort, bucket sort, radix sort, and external sort.

## 23.2 Insertion Sort



*The insertion-sort algorithm sorts a list of values by repeatedly inserting a new element into a sorted sublist until the whole list is sorted.*



insertion sort animation on Companion Website

Figure 23.1 shows how to sort the list {2, 9, 5, 4, 8, 1, 6} using insertion sort.

The algorithm can be described as follows:

```
for (int i = 1; i < list.length; i++) {
 insert list[i] into a sorted sublist list[0..i-1] so that
 list[0..i] is sorted.
}
```

To insert **list[i]** into **list[0..i-1]**, save **list[i]** into a temporary variable, say **currentElement**. Move **list[i-1]** to **list[i]** if **list[i-1] > currentElement**, move **list[i-2]** to **list[i-1]** if **list[i-2] > currentElement**, and so on, until **list[i-k] <= currentElement** or **k > i** (we pass the first element of the sorted list). Assign **currentElement** to **list[i-k+1]**. For example, to insert 4 into {2, 5, 9} in Step 4 in Figure 23.2, move **list[2]** (9) to **list[3]** since **9 > 4**, and move **list[1]** (5) to **list[2]** since **5 > 4**. Finally, move **currentElement** (4) to **list[1]**.

Step 1: Initially, the sorted sublist contains the first element in the list. Insert 9 into the sublist.



Step 2: The sorted sublist is {2, 9}. Insert 5 into the sublist.



Step 3: The sorted sublist is {2, 5, 9}. Insert 4 into the sublist.



Step 4: The sorted sublist is {2, 4, 5, 9}. Insert 8 into the sublist.



Step 5: The sorted sublist is {2, 4, 5, 8, 9}. Insert 1 into the sublist.



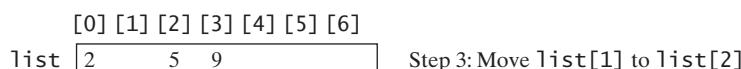
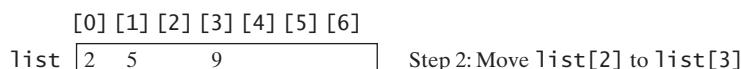
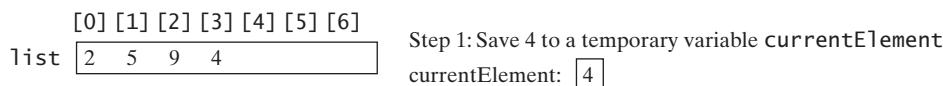
Step 6: The sorted sublist is {1, 2, 4, 5, 8, 9}. Insert 6 into the sublist.



Step 7: The entire list is now sorted.



**FIGURE 23.1** Insertion sort repeatedly inserts a new element into a sorted sublist.



**FIGURE 23.2** A new element is inserted into a sorted sublist.

The algorithm can be expanded and implemented as in Listing 23.1.

### LISTING 23.1 InsertionSort.java

```

1 public class InsertionSort {
2 /** The method for sorting the numbers */
3 public static void insertionSort(int[] list) {
4 for (int i = 1; i < list.length; i++) {
5 /** Insert list[i] into a sorted sublist list[0..i-1] so that
6 list[0..i] is sorted. */
7 int currentElement = list[i];
8 int k;
9 for (k = i - 1; k >= 0 && list[k] > currentElement; k--) { shift
10 list[k + 1] = list[k];
11 }
12 }
13 }
14
```

```

11 }
12
13 // Insert the current element into list[k + 1]
14 list[k + 1] = currentElement;
15 }
16 }
17 }
```

insert

The `insertionSort(int[] list)` method sorts any array of `int` elements. The method is implemented with a nested `for` loop. The outer loop (with the loop control variable `i`) (line 4) is iterated in order to obtain a sorted sublist, which ranges from `list[0]` to `list[i]`. The inner loop (with the loop control variable `k`) inserts `list[i]` into the sublist from `list[0]` to `list[i-1]`.

To better understand this method, trace it with the following statements:

```

int[] list = {1, 9, 4, 6, 5, -4};
InsertionSort.insertionSort(list);
```

insertion sort time complexity

The insertion sort algorithm presented here sorts a list of elements by repeatedly inserting a new element into a sorted partial array until the whole array is sorted. At the  $k$ th iteration, to insert an element into an array of size  $k$ , it may take  $k$  comparisons to find the insertion position, and  $k$  moves to insert the element. Let  $T(n)$  denote the complexity for insertion sort and  $c$  denote the total number of other operations such as assignments and additional comparisons in each iteration. Thus,

$$\begin{aligned}
T(n) &= (2 + c) + (2 \times 2 + c) + \cdots + (2 \times (n - 1) + c) \\
&= 2(1 + 2 + \cdots + n - 1) + c(n - 1) \\
&= 2 \frac{(n - 1)n}{2} + cn - c = n^2 - n + cn - c \\
&= O(n^2)
\end{aligned}$$

Therefore, the complexity of the insertion sort algorithm is  $O(n^2)$ . Hence, the selection sort and insertion sort are of the same time complexity.



**23.1** Describe how an insertion sort works. What is the time complexity for an insertion sort?

**23.2** Use Figure 23.1 as an example to show how to apply a bubble sort on {45, 11, 50, 59, 60, 2, 4, 7, 10}.

**23.3** If a list is already sorted, how many comparisons will the `insertionSort` method perform?

### 23.3 Bubble Sort



A bubble sort sorts the array in multiple phases. Each pass successively swaps the neighboring elements if the elements are not in order.

bubble sort

The bubble sort algorithm makes several passes through the array. On each pass, successive neighboring pairs are compared. If a pair is in decreasing order, its values are swapped; otherwise, the values remain unchanged. The technique is called a *bubble sort* or *sinking sort*, because the smaller values gradually “bubble” their way to the top and the larger values sink to the bottom. After the first pass, the last element becomes the largest in the array. After the second pass, the second-to-last element becomes the second largest in the array. This process is continued until all elements are sorted.

Figure 23.3a shows the first pass of a bubble sort on an array of six elements (2 9 5 4 8 1). Compare the elements in the first pair (2 and 9), and no swap is needed because they are already in order. Compare the elements in the second pair (9 and 5), and swap 9 with 5 because 9 is greater than 5. Compare the elements in the third pair (9 and 4), and swap 9 with 4. Compare the elements in the fourth pair (9 and 8), and swap 9 with 8. Compare the elements in the fifth pair (9 and 1), and swap 9 with 1. The pairs being compared are highlighted and the numbers already sorted are italicized in Figure 23.3.

bubble sort illustration



bubble sort on the  
Companion Website

|                                                                                                                                                                                                                                                                                                                                                                                     |              |              |              |              |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------|--------------|--------------|--------------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| <table border="1"><tr><td>2</td><td>9</td><td>5</td><td>4</td><td>8</td><td>1</td></tr><tr><td>2</td><td>5</td><td>9</td><td>4</td><td>8</td><td>1</td></tr><tr><td>2</td><td>5</td><td>4</td><td>9</td><td>8</td><td>1</td></tr><tr><td>2</td><td>5</td><td>4</td><td>8</td><td>9</td><td>1</td></tr><tr><td>2</td><td>5</td><td>4</td><td>8</td><td>1</td><td>9</td></tr></table> | 2            | 9            | 5            | 4            | 8 | 1 | 2 | 5 | 9 | 4 | 8 | 1 | 2 | 5 | 4 | 9 | 8 | 1 | 2 | 5 | 4 | 8 | 9 | 1 | 2 | 5 | 4 | 8 | 1 | 9 | <table border="1"><tr><td>2</td><td>5</td><td>4</td><td>8</td><td>1</td><td>9</td></tr><tr><td>2</td><td>4</td><td>5</td><td>8</td><td>1</td><td>9</td></tr><tr><td>2</td><td>4</td><td>5</td><td>8</td><td>1</td><td>9</td></tr><tr><td>2</td><td>4</td><td>5</td><td>1</td><td>8</td><td>9</td></tr><tr><td>2</td><td>4</td><td>5</td><td>1</td><td>8</td><td>9</td></tr></table> | 2 | 5 | 4 | 8 | 1 | 9 | 2 | 4 | 5 | 8 | 1 | 9 | 2 | 4 | 5 | 8 | 1 | 9 | 2 | 4 | 5 | 1 | 8 | 9 | 2 | 4 | 5 | 1 | 8 | 9 | <table border="1"><tr><td>2</td><td>4</td><td>5</td><td>1</td><td>8</td><td>9</td></tr><tr><td>2</td><td>4</td><td>5</td><td>1</td><td>8</td><td>9</td></tr><tr><td>2</td><td>4</td><td>5</td><td>1</td><td>8</td><td>9</td></tr><tr><td>2</td><td>4</td><td>5</td><td>1</td><td>8</td><td>9</td></tr><tr><td>2</td><td>4</td><td>5</td><td>1</td><td>8</td><td>9</td></tr></table> | 2 | 4 | 5 | 1 | 8 | 9 | 2 | 4 | 5 | 1 | 8 | 9 | 2 | 4 | 5 | 1 | 8 | 9 | 2 | 4 | 5 | 1 | 8 | 9 | 2 | 4 | 5 | 1 | 8 | 9 | <table border="1"><tr><td>2</td><td>4</td><td>1</td><td>5</td><td>8</td><td>9</td></tr><tr><td>2</td><td>1</td><td>4</td><td>5</td><td>8</td><td>9</td></tr><tr><td>2</td><td>1</td><td>4</td><td>5</td><td>8</td><td>9</td></tr><tr><td>2</td><td>1</td><td>4</td><td>5</td><td>8</td><td>9</td></tr><tr><td>2</td><td>1</td><td>4</td><td>5</td><td>8</td><td>9</td></tr></table> | 2 | 4 | 1 | 5 | 8 | 9 | 2 | 1 | 4 | 5 | 8 | 9 | 2 | 1 | 4 | 5 | 8 | 9 | 2 | 1 | 4 | 5 | 8 | 9 | 2 | 1 | 4 | 5 | 8 | 9 | <table border="1"><tr><td>1</td><td>2</td><td>4</td><td>5</td><td>8</td><td>9</td></tr><tr><td>1</td><td>2</td><td>4</td><td>5</td><td>8</td><td>9</td></tr><tr><td>1</td><td>2</td><td>4</td><td>5</td><td>8</td><td>9</td></tr><tr><td>1</td><td>2</td><td>4</td><td>5</td><td>8</td><td>9</td></tr><tr><td>1</td><td>2</td><td>4</td><td>5</td><td>8</td><td>9</td></tr></table> | 1 | 2 | 4 | 5 | 8 | 9 | 1 | 2 | 4 | 5 | 8 | 9 | 1 | 2 | 4 | 5 | 8 | 9 | 1 | 2 | 4 | 5 | 8 | 9 | 1 | 2 | 4 | 5 | 8 | 9 |
| 2                                                                                                                                                                                                                                                                                                                                                                                   | 9            | 5            | 4            | 8            | 1 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 2                                                                                                                                                                                                                                                                                                                                                                                   | 5            | 9            | 4            | 8            | 1 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 2                                                                                                                                                                                                                                                                                                                                                                                   | 5            | 4            | 9            | 8            | 1 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 2                                                                                                                                                                                                                                                                                                                                                                                   | 5            | 4            | 8            | 9            | 1 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 2                                                                                                                                                                                                                                                                                                                                                                                   | 5            | 4            | 8            | 1            | 9 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 2                                                                                                                                                                                                                                                                                                                                                                                   | 5            | 4            | 8            | 1            | 9 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 2                                                                                                                                                                                                                                                                                                                                                                                   | 4            | 5            | 8            | 1            | 9 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 2                                                                                                                                                                                                                                                                                                                                                                                   | 4            | 5            | 8            | 1            | 9 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 2                                                                                                                                                                                                                                                                                                                                                                                   | 4            | 5            | 1            | 8            | 9 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 2                                                                                                                                                                                                                                                                                                                                                                                   | 4            | 5            | 1            | 8            | 9 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 2                                                                                                                                                                                                                                                                                                                                                                                   | 4            | 5            | 1            | 8            | 9 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 2                                                                                                                                                                                                                                                                                                                                                                                   | 4            | 5            | 1            | 8            | 9 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 2                                                                                                                                                                                                                                                                                                                                                                                   | 4            | 5            | 1            | 8            | 9 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 2                                                                                                                                                                                                                                                                                                                                                                                   | 4            | 5            | 1            | 8            | 9 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 2                                                                                                                                                                                                                                                                                                                                                                                   | 4            | 5            | 1            | 8            | 9 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 2                                                                                                                                                                                                                                                                                                                                                                                   | 4            | 1            | 5            | 8            | 9 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 2                                                                                                                                                                                                                                                                                                                                                                                   | 1            | 4            | 5            | 8            | 9 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 2                                                                                                                                                                                                                                                                                                                                                                                   | 1            | 4            | 5            | 8            | 9 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 2                                                                                                                                                                                                                                                                                                                                                                                   | 1            | 4            | 5            | 8            | 9 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 2                                                                                                                                                                                                                                                                                                                                                                                   | 1            | 4            | 5            | 8            | 9 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 1                                                                                                                                                                                                                                                                                                                                                                                   | 2            | 4            | 5            | 8            | 9 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 1                                                                                                                                                                                                                                                                                                                                                                                   | 2            | 4            | 5            | 8            | 9 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 1                                                                                                                                                                                                                                                                                                                                                                                   | 2            | 4            | 5            | 8            | 9 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 1                                                                                                                                                                                                                                                                                                                                                                                   | 2            | 4            | 5            | 8            | 9 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 1                                                                                                                                                                                                                                                                                                                                                                                   | 2            | 4            | 5            | 8            | 9 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| (a) 1st pass                                                                                                                                                                                                                                                                                                                                                                        | (b) 2nd pass | (c) 3rd pass | (d) 4th pass | (e) 5th pass |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                                                                                                                                                                                                     |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |

**FIGURE 23.3** Each pass compares and orders the pairs of elements sequentially.

The first pass places the largest number (9) as the last in the array. In the second pass, as shown in Figure 23.3b, you compare and order pairs of elements sequentially. There is no need to consider the last pair, because the last element in the array is already the largest. In the third pass, as shown in Figure 23.3c, you compare and order pairs of elements sequentially except the last two elements, because they are already in order. So in the  $k$ th pass, you don't need to consider the last  $k - 1$  elements, because they are already ordered.

The algorithm for a bubble sort is described in Listing 23.2.

algorithm

### LISTING 23.2 Bubble Sort Algorithm

```

1 for (int k = 1; k < list.length; k++) {
2 // Perform the kth pass
3 for (int i = 0; i < list.length - k; i++) {
4 if (list[i] > list[i + 1])
5 swap list[i] with list[i + 1];
6 }
7 }
```

Note that if no swap takes place in a pass, there is no need to perform the next pass, because all the elements are already sorted. You can use this property to improve the algorithm in Listing 23.2 as in Listing 23.3.

### LISTING 23.3 Improved Bubble Sort Algorithm

```

1 boolean needNextPass = true;
2 for (int k = 1; k < list.length && needNextPass; k++) {
3 // Array may be sorted and next pass not needed
4 needNextPass = false;
5 // Perform the kth pass
6 for (int i = 0; i < list.length - k; i++) {
7 if (list[i] > list[i + 1]) {
8 swap list[i] with list[i + 1];
9 needNextPass = true; // Next pass still needed
10 }
11 }
12 }
```

The algorithm can be implemented in Listing 23.4.

### LISTING 23.4 BubbleSort.java

```

1 public class BubbleSort {
2 /* Bubble sort method */
3 public static void bubbleSort(int[] list) {
4 boolean needNextPass = true;
5
6 for (int k = 1; k < list.length && needNextPass; k++) {
7 // Array may be sorted and next pass not needed
8 needNextPass = false;
9 for (int i = 0; i < list.length - k; i++) {
10 if (list[i] > list[i + 1]) {
11 // Swap list[i] with list[i + 1]
12 int temp = list[i];
13 list[i] = list[i + 1];
14 list[i + 1] = temp;
15
16 needNextPass = true; // Next pass still needed
17 }
18 }
19 }
20 }
21
22 /* A test method */
23 public static void main(String[] args) {
24 int[] list = {2, 3, 2, 5, 6, 1, -2, 3, 14, 12};
25 bubbleSort(list);
26 for (int i = 0; i < list.length; i++)
27 System.out.print(list[i] + " ");
28 }
29 }

```

perform one pass



-2 1 2 2 3 3 5 6 12 14

bubble sort time complexity

In the best case, the bubble sort algorithm needs just the first pass to find that the array is already sorted—no next pass is needed. Since the number of comparisons is  $n - 1$  in the first pass, the best-case time for a bubble sort is  $O(n)$ .

In the worst case, the bubble sort algorithm requires  $n - 1$  passes. The first pass makes  $n - 1$  comparisons; the second pass makes  $n - 2$  comparisons; and so on; the last pass makes 1 comparison. Thus, the total number of comparisons is:

$$\begin{aligned}
 & (n - 1) + (n - 2) + \cdots + 2 + 1 \\
 &= \frac{(n - 1)n}{2} = \frac{n^2}{2} - \frac{n}{2} = O(n^2)
 \end{aligned}$$

Therefore, the worst-case time for a bubble sort is  $O(n^2)$ .



- 23.4** Describe how a bubble sort works. What is the time complexity for a bubble sort?
- 23.5** Use Figure 23.3 as an example to show how to apply a bubble sort on {45, 11, 50, 59, 60, 2, 4, 7, 10}.
- 23.6** If a list is already sorted, how many comparisons will the **bubbleSort** method perform?

## 23.4 Merge Sort

The merge sort algorithm can be described recursively as follows: The algorithm divides the array into two halves and applies a merge sort on each half recursively. After the two halves are sorted, merge them.



The algorithm for a merge sort is given in Listing 23.5.

### LISTING 23.5 Merge Sort Algorithm

```

1 public static void mergeSort(int[] list) {
2 if (list.length > 1) {
3 mergeSort(list[0 ... list.length / 2]);
4 mergeSort(list[list.length / 2 + 1 ... list.length]);
5 merge list[0 ... list.length / 2] with
6 list[list.length / 2 + 1 ... list.length];
7 }
8 }

```

base condition  
sort first half  
sort second half  
merge two halves

Figure 23.4 illustrates a merge sort of an array of eight elements (2 9 5 4 8 1 6 7). The original array is split into (2 9 5 4) and (8 1 6 7). Apply a merge sort on these two subarrays recursively to split (2 9 5 4) into (2 9) and (5 4) and (8 1 6 7) into (8 1) and (6 7). This process continues until the subarray contains only one element. For example, array (2 9) is split into the subarrays (2) and (9). Since array (2) contains a single element, it cannot be further split. Now merge (2) with (9) into a new sorted array (2 9); merge (5) with (4) into a new sorted array (4 5). Merge (2 9) with (4 5) into a new sorted array (2 4 5 9), and finally merge (2 4 5 9) with (1 6 7 8) into a new sorted array (1 2 4 5 6 7 8 9).

merge sort illustration

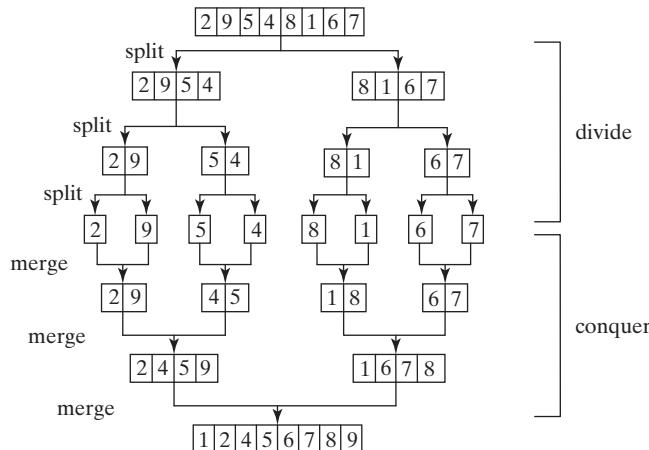


FIGURE 23.4 Merge sort employs a divide-and-conquer approach to sort the array.

The recursive call continues dividing the array into subarrays until each subarray contains only one element. The algorithm then merges these small subarrays into larger sorted subarrays until one sorted array results.

The merge sort algorithm is implemented in Listing 23.6.

### LISTING 23.6 MergeSort.java

```

1 public class MergeSort {
2 /** The method for sorting the numbers */
3 public static void mergeSort(int[] list) {
4 if (list.length > 1) {

```

base case

```

5 // Merge sort the first half
6 int[] firstHalf = new int[list.length / 2];
7 System.arraycopy(list, 0, firstHalf, 0, list.length / 2);
sort first half
8 mergeSort(firstHalf);
9
10 // Merge sort the second half
11 int secondHalfLength = list.length - list.length / 2;
12 int[] secondHalf = new int[secondHalfLength];
13 System.arraycopy(list, list.length / 2,
14 secondHalf, 0, secondHalfLength);
15 mergeSort(secondHalf);
16
17 // Merge firstHalf with secondHalf into list
18 merge(firstHalf, secondHalf, list);
19 }
20
21
22 /** Merge two sorted lists */
23 public static void merge(int[] list1, int[] list2, int[] temp) {
24 int current1 = 0; // Current index in list1
25 int current2 = 0; // Current index in list2
26 int current3 = 0; // Current index in temp
27
28 while (current1 < list1.length && current2 < list2.length) {
29 if (list1[current1] < list2[current2])
30 temp[current3++] = list1[current1++];
31 else
32 temp[current3++] = list2[current2++];
33 }
34
35 while (current1 < list1.length)
36 temp[current3++] = list1[current1++];
37
38 while (current2 < list2.length)
39 temp[current3++] = list2[current2++];
40 }
41
42 /** A test method */
43 public static void main(String[] args) {
44 int[] list = {2, 3, 2, 5, 6, 1, -2, 3, 14, 12};
45 mergeSort(list);
46 for (int i = 0; i < list.length; i++)
47 System.out.print(list[i] + " ");
48 }
49 }
```

The `mergeSort` method (lines 3–20) creates a new array `firstHalf`, which is a copy of the first half of `list` (line 7). The algorithm invokes `mergeSort` recursively on `firstHalf` (line 8). The length of the `firstHalf` is `list.length / 2` and the length of the `secondHalf` is `list.length - list.length / 2`. The new array `secondHalf` was created to contain the second part of the original array `list`. The algorithm invokes `mergeSort` recursively on `secondHalf` (line 15). After `firstHalf` and `secondHalf` are sorted, they are merged to `list` (line 18). Thus, array `list` is now sorted.

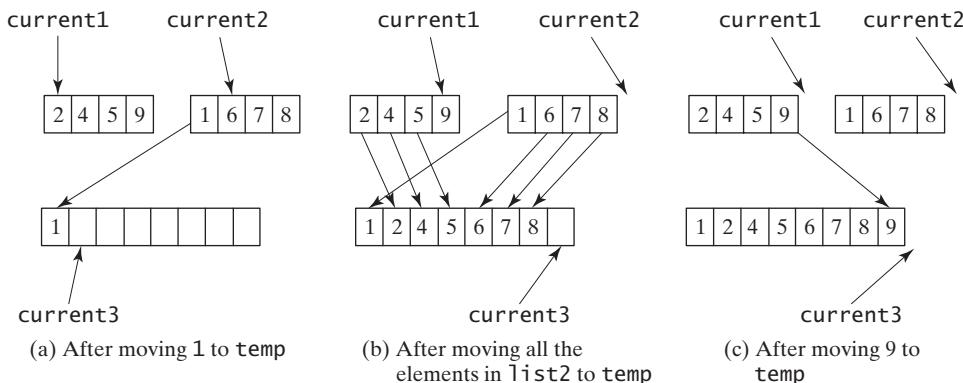
The `merge` method (lines 23–40) merges two sorted arrays `list1` and `list2` into array `temp`. `current1` and `current2` point to the current element to be considered in `list1` and `list2` (lines 24–26). The method repeatedly compares the current elements from `list1` and `list2` and moves the smaller one to `temp`. `current1` is increased by 1 (line 30) if the smaller one is in `list1` and `current2` is increased by 1 (line 32) if the smaller one is

in `list2`. Finally, all the elements in one of the lists are moved to `temp`. If there are still unmoved elements in `list1`, copy them to `temp` (lines 35–36). If there are still unmoved elements in `list2`, copy them to `temp` (lines 38–39).

Figure 23.5 illustrates how to merge the two arrays `list1` (2 4 5 9) and `list2` (1 6 7 8). Initially the current elements to be considered in the arrays are 2 and 1. Compare them and move the smaller element 1 to `temp`, as shown in Figure 23.5a. `current2` and `current3` are increased by 1. Continue to compare the current elements in the two arrays and move the smaller one to `temp` until one of the arrays is completely moved. As shown in Figure 23.5b, all the elements in `list2` are moved to `temp` and `current1` points to element 9 in `list1`. Copy 9 to `temp`, as shown in Figure 23.5c.

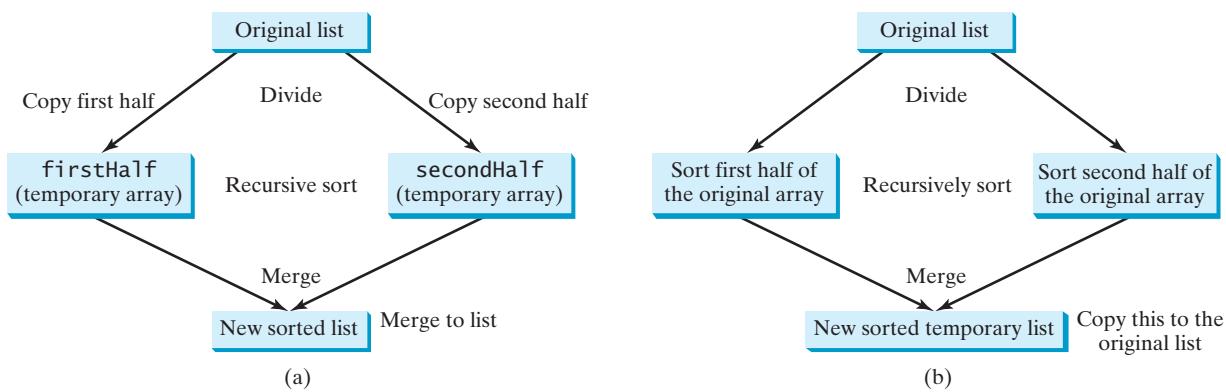


merge animation on  
Companion Website



**FIGURE 23.5** Two sorted arrays are merged into one sorted array.

The `mergeSort` method creates two temporary arrays (lines 6, 12) during the dividing process, copies the first half and the second half of the array into the temporary arrays (lines 7, 13), sorts the temporary arrays (lines 8, 15), and then merges them into the original array (line 18), as shown in Figure 23.6a. You can rewrite the code to recursively sort the first half of the array and the second half of the array without creating new temporary arrays, and then merge the two arrays into a temporary array and copy its contents to the original array, as shown in Figure 23.6b. This is left for you to do in Programming Exercise 23.20.



**FIGURE 23.6** Temporary arrays are created to support a merge sort.



### Note

A merge sort can be implemented efficiently using parallel processing. See Section 30.16, Parallel Programming, for a parallel implementation of a merge sort.

merge sort time complexity

Let  $T(n)$  denote the time required for sorting an array of  $n$  elements using a merge sort. Without loss of generality, assume  $n$  is a power of 2. The merge sort algorithm splits the array into two subarrays, sorts the subarrays using the same algorithm recursively, and then merges the subarrays. Therefore,

$$T(n) = T\left(\frac{n}{2}\right) + T\left(\frac{n}{2}\right) + \text{mergetime}$$

The first  $T\left(\frac{n}{2}\right)$  is the time for sorting the first half of the array, and the second  $T\left(\frac{n}{2}\right)$  is the time for sorting the second half. To merge two subarrays, it takes at most  $n - 1$  comparisons to compare the elements from the two subarrays and  $n$  moves to move elements to the temporary array. Thus, the total time is  $2n - 1$ . Therefore,

$$T(n) = T\left(\frac{n}{2}\right) + T\left(\frac{n}{2}\right) + 2n - 1 = O(n \log n)$$

 $O(n \log n)$  merge sort

The complexity of a merge sort is  $O(n \log n)$ . This algorithm is better than selection sort, insertion sort, and bubble sort, because the time complexity of these algorithms is  $O(n^2)$ . The `sort` method in the `java.util.Arrays` class is implemented using a variation of the merge sort algorithm.



- 23.7** Describe how a merge sort works. What is the time complexity for a merge sort?
- 23.8** Use Figure 23.4 as an example to show how to apply a merge sort on {45, 11, 50, 59, 60, 2, 4, 7, 10}.
- 23.9** What is wrong if lines 6–15 in Listing 23.6, MergeSort.java, are replaced by the following code?

```
// Merge sort the first half
int[] firstHalf = new int[list.length / 2 + 1];
System.arraycopy(list, 0, firstHalf, 0, list.length / 2 + 1);
mergeSort(firstHalf);

// Merge sort the second half
int secondHalfLength = list.length - list.length / 2 - 1;
int[] secondHalf = new int[secondHalfLength];
System.arraycopy(list, list.length / 2 + 1,
 secondHalf, 0, secondHalfLength);
mergeSort(secondHalf);
```

## 23.5 Quick Sort



quick sort

A quick sort works as follows: The algorithm selects an element, called the pivot, in the array. It divides the array into two parts, so that all the elements in the first part are less than or equal to the pivot and all the elements in the second part are greater than the pivot. The quick sort algorithm is then recursively applied to the first part and then the second part.

The quick sort algorithm, developed by C.A.R. Hoare in 1962, is described in Listing 23.7.

### LISTING 23.7 Quick Sort Algorithm

```
1 public static void quickSort(int[] list) {
2 if (list.length > 1) {
3 select a pivot;
4 partition list into list1 and list2 such that
```

base condition  
select the pivot  
partition the list

```

5 all elements in list1 <= pivot and
6 all elements in list2 > pivot; pivot
7 quickSort(list1);
8 quickSort(list2);
9 }
10 }
```



sort first part  
sort second part

how to partition

quick sort illustration

Each partition places the pivot in the right place. The selection of the pivot affects the performance of the algorithm. Ideally, the algorithm should choose the pivot that divides the two parts evenly. For simplicity, assume the first element in the array is chosen as the pivot. (Programming Exercise 23.4 proposes an alternative strategy for selecting the pivot.)

Figure 23.7 illustrates how to sort an array (5 2 9 3 8 4 0 1 6 7) using quick sort. Choose the first element, 5, as the pivot. The array is partitioned into two parts, as shown in Figure 23.7b. The highlighted pivot is placed in the right place in the array. Apply quick sort on two partial arrays (4 2 1 3 0) and then (8 9 6 7). The pivot 4 partitions (4 2 1 3 0) into just one partial array (0 2 1 3), as shown in Figure 23.7c. Apply quick sort on (0 2 1 3). The pivot 0 partitions it into just one partial array (2 1 3), as shown in Figure 23.7d. Apply quick sort on (2 1 3). The pivot 2 partitions it into (1) and (3), as shown in Figure 23.7e. Apply quick sort on (1). Since the array contains just one element, no further partition is needed.



**FIGURE 23.7** The quick sort algorithm is recursively applied to partial arrays.

The quick sort algorithm is implemented in Listing 23.8. There are two overloaded `quickSort` methods in the class. The first method (line 2) is used to sort an array. The second is a helper method (line 6) that sorts a partial array with a specified range.

### LISTING 23.8 QuickSort.java

```

1 public class QuickSort {
2 public static void quickSort(int[] list) {
3 quickSort(list, 0, list.length - 1); sort method
4 }
5
6 public static void quickSort(int[] list, int first, int last) { helper method
7 if (last > first) {
8 int pivotIndex = partition(list, first, last);
9 quickSort(list, first, pivotIndex - 1);
10 quickSort(list, pivotIndex + 1, last); recursive call
11 }
12 }
13 }
```

```

12 }
13
14 /** Partition the array list[first..last] */
15 public static int partition(int[] list, int first, int last) {
16 int pivot = list[first]; // Choose the first element as the pivot
17 int low = first + 1; // Index for forward search
18 int high = last; // Index for backward search
19
20 while (high > low) {
21 // Search forward from left
22 while (low <= high && list[low] <= pivot)
23 low++;
24
25 // Search backward from right
26 while (low <= high && list[high] > pivot)
27 high--;
28
29 // Swap two elements in the list
30 if (high > low) {
31 int temp = list[high];
32 list[high] = list[low];
33 list[low] = temp;
34 }
35 }
36
37 while (high > first && list[high] >= pivot)
38 high--;
39
40 // Swap pivot with list[high]
41 if (pivot > list[high]) {
42 list[first] = list[high];
43 list[high] = pivot;
44 return high;
45 }
46 else {
47 return first;
48 }
49 }
50
51 /** A test method */
52 public static void main(String[] args) {
53 int[] list = {2, 3, 2, 5, 6, 1, -2, 3, 14, 12};
54 quickSort(list);
55 for (int i = 0; i < list.length; i++)
56 System.out.print(list[i] + " ");
57 }
58 }
```



-2 1 2 2 3 3 5 6 12 14

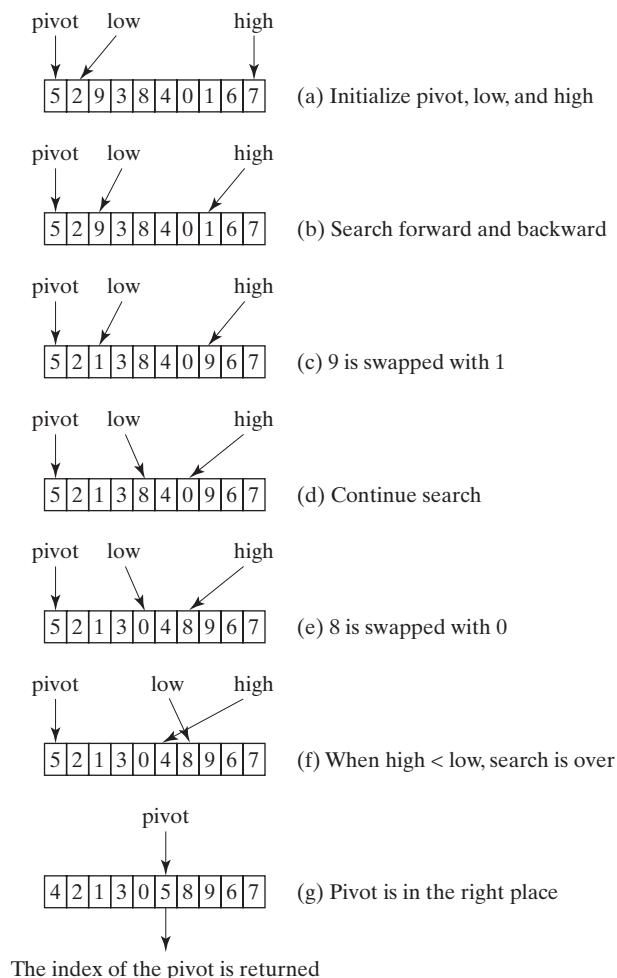
The `partition` method (lines 15–49) partitions the array `list[first..last]` using the pivot. The first element in the partial array is chosen as the pivot (line 16). Initially `low` points to the second element in the partial array (line 17) and `high` points to the last element in the partial array (line 18).

Starting from the left, the method searches forward in the array for the first element that is greater than the pivot (lines 22–23), then searches from the right backward for the first element in the array that is less than or equal to the pivot (lines 26–27). It then swaps these two

elements and repeats the same search and swap operations until all the elements are searched in a `while` loop (lines 20–35).

The method returns the new index for the pivot that divides the partial array into two parts if the pivot has been moved (line 44). Otherwise, it returns the original index for the pivot (line 47).

Figure 23.8 illustrates how to partition an array  $[5\ 2\ 9\ 3\ 8\ 4\ 0\ 1\ 6\ 7]$ . Choose the first element, 5, as the pivot. Initially `low` is the index that points to element 2 and `high` points to element 7, as shown in Figure 23.8a. Advance index `low` forward to search for the first element (9) that is greater than the pivot and move index `high` backward to search for the first element (1) that is less than or equal to the pivot, as shown in Figure 23.8b. Swap 9 with 1, as shown in Figure 23.8c. Continue the search and move `low` to point to element 8 and `high` to point to element 0, as shown in Figure 23.8d. Swap element 8 with 0, as shown in Figure 23.8e. Continue to move `low` until it passes `high`, as shown in Figure 23.8f. Now all the elements are examined. Swap the pivot with element 4 at index `high`. The final partition is shown in Figure 23.8g. The index of the pivot is returned when the method is finished.



**FIGURE 23.8** The `partition` method returns the index of the pivot after it is put in the correct place.

To partition an array of  $n$  elements, it takes  $n$  comparisons and  $n$  moves in the worst case. Thus, the time required for partition is  $O(n)$ .

In the worst case, the pivot divides the array each time into one big subarray with the other array empty. The size of the big subarray is one less than the one before divided. The algorithm requires  $(n - 1) + (n - 2) + \dots + 2 + 1 = O(n^2)$  time.

partition illustration



partition animation on  
Companion Website

$O(n)$  partition time

$O(n^2)$  worst-case time

*O(n log n)* best-case time

In the best case, the pivot divides the array each time into two parts of about the same size. Let  $T(n)$  denote the time required for sorting an array of  $n$  elements using quick sort. Thus,

$$\begin{array}{c} \text{recursive quick sort on} \\ \text{two subarrays} \end{array} \quad \begin{array}{c} T(n) = T\left(\frac{n}{2}\right) + T\left(\frac{n}{2}\right) + n. \\ \downarrow \qquad \downarrow \qquad \downarrow \\ \text{partition time} \end{array}$$

*O(n log n)* average-case time

quick sort vs. merge sort

Similar to the merge sort analysis,  $T(n) = O(n \log n)$ .

On the average, the pivot will not divide the array into two parts of the same size or one empty part each time. Statistically, the sizes of the two parts are very close. Therefore, the average time is  $O(n \log n)$ . The exact average-case analysis is beyond the scope of this book.

Both merge sort and quick sort employ the divide-and-conquer approach. For merge sort, the bulk of the work is to merge two sublists, which takes place *after* the sublists are sorted. For quick sort, the bulk of the work is to partition the list into two sublists, which takes place *before* the sublists are sorted. Merge sort is more efficient than quick sort in the worst case, but the two are equally efficient in the average case. Merge sort requires a temporary array for sorting two subarrays. Quick sort does not need additional array space. Thus, quick sort is more space efficient than merge sort.



**23.10** Describe how quick sort works. What is the time complexity for a quick sort?

**23.11** Why is quick sort more space efficient than merge sort?

**23.12** Use Figure 23.7 as an example to show how to apply a quick sort on {45, 11, 50, 59, 60, 2, 4, 7, 10}.



## 23.6 Heap Sort

A *heap sort* uses a binary heap. It first adds all the elements to a heap and then removes the largest elements successively to obtain a sorted list.

heap sort  
root  
left subtree  
right subtree  
length  
depth

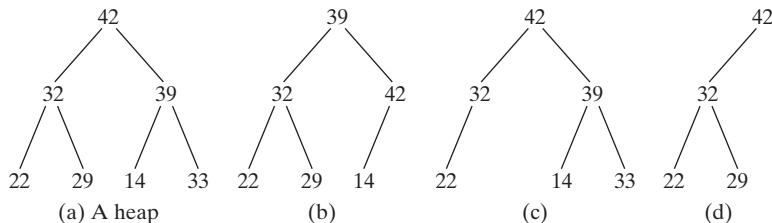
complete binary tree

*Heap sorts* use a binary heap, which is a complete binary tree. A binary tree is a hierarchical structure. It either is empty or it consists of an element, called the *root*, and two distinct binary trees, called the *left subtree* and *right subtree*. The *length* of a path is the number of the edges in the path. The *depth* of a node is the length of the path from the root to the node.

A *binary heap* is a binary tree with the following properties:

- **Shape property:** It is a complete binary tree.
- **Heap property:** Each node is greater than or equal to any of its children.

A binary tree is *complete* if each of its levels is full, except that the last level may not be full and all the leaves on the last level are placed leftmost. For example, in Figure 23.9, the binary trees in (a) and (b) are complete, but the binary trees in (c) and (d) are not complete. Further, the binary tree in (a) is a heap, but the binary tree in (b) is not a heap, because the root (39) is less than its right child (42).



**FIGURE 23.9** A binary heap is a special complete binary tree.

**Note**

*Heap* is a term with many meanings in computer science. In this chapter, heap means a binary heap.

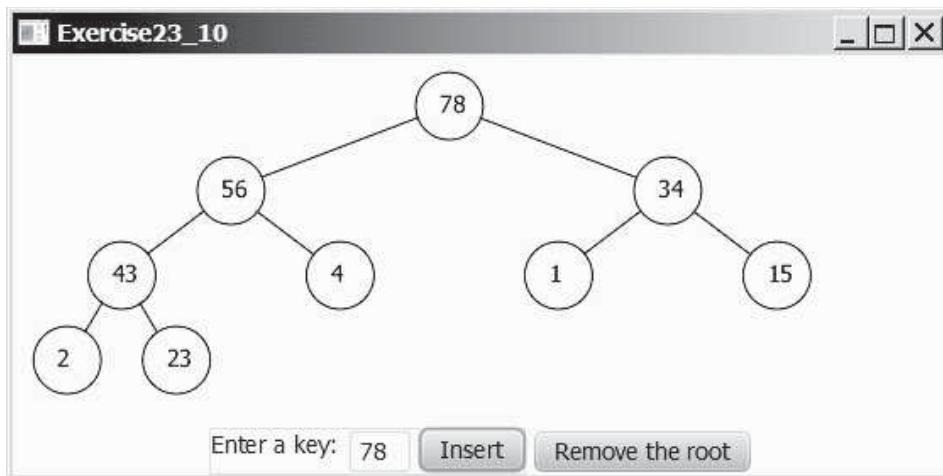
heap

**Pedagogical Note**

A heap can be implemented efficiently for inserting keys and for deleting the root. For an interactive demo on how a heap works, go to [www.cs.armstrong.edu/liang/animation/web/Heap.html](http://www.cs.armstrong.edu/liang/animation/web/Heap.html), as shown in Figure 23.10.



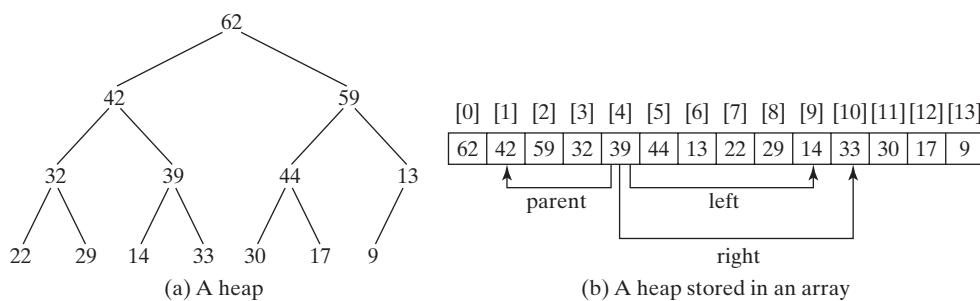
heap animation on  
Companion Website



**FIGURE 23.10** The heap animation tool enables you to insert a key and delete the root visually.

### 23.6.1 Storing a Heap

A heap can be stored in an [ArrayList](#) or an array if the heap size is known in advance. The heap in Figure 23.11a can be stored using the array in Figure 23.11b. The root is at position 0, and its two children are at positions 1 and 2. For a node at position  $i$ , its left child is at position  $2i + 1$ , its right child is at position  $2i + 2$ , and its parent is  $(i - 1)/2$ . For example, the node for element 39 is at position 4, so its left child (element 14) is at 9 ( $2 \times 4 + 1$ ), its right child (element 33) is at 10 ( $2 \times 4 + 2$ ), and its parent (element 42) is at 1 ( $((4 - 1)/2)$ ).



**FIGURE 23.11** A binary heap can be implemented using an array.

### 23.6.2 Adding a New Node

To add a new node to the heap, first add it to the end of the heap and then rebuild the tree as follows:

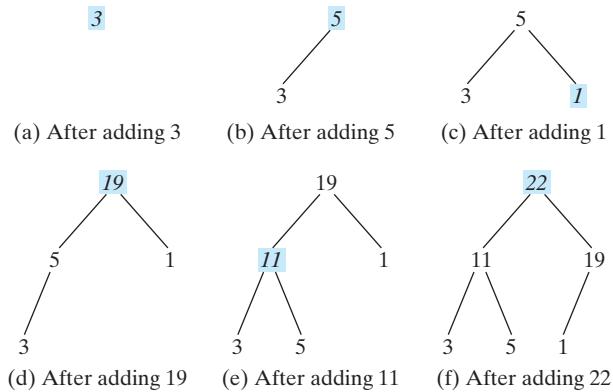
```
Let the last node be the current node;
while (the current node is greater than its parent) {
```

```

Swap the current node with its parent;
Now the current node is one level up;
}

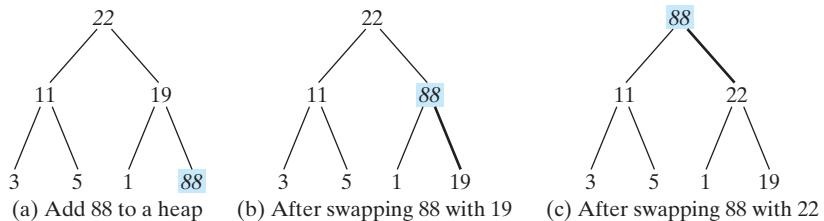
```

Suppose a heap is initially empty. That heap is shown in Figure 23.12, after adding numbers 3, 5, 1, 19, 11, and 22 in this order.



**FIGURE 23.12** Elements 3, 5, 1, 19, 11, and 22 are inserted into the heap.

Now consider adding 88 into the heap. Place the new node 88 at the end of the tree, as shown in Figure 23.13a. Swap 88 with 19, as shown in Figure 23.13b. Swap 88 with 22, as shown in Figure 23.13c.



**FIGURE 23.13** Rebuild the heap after adding a new node.

### 23.6.3 Removing the Root

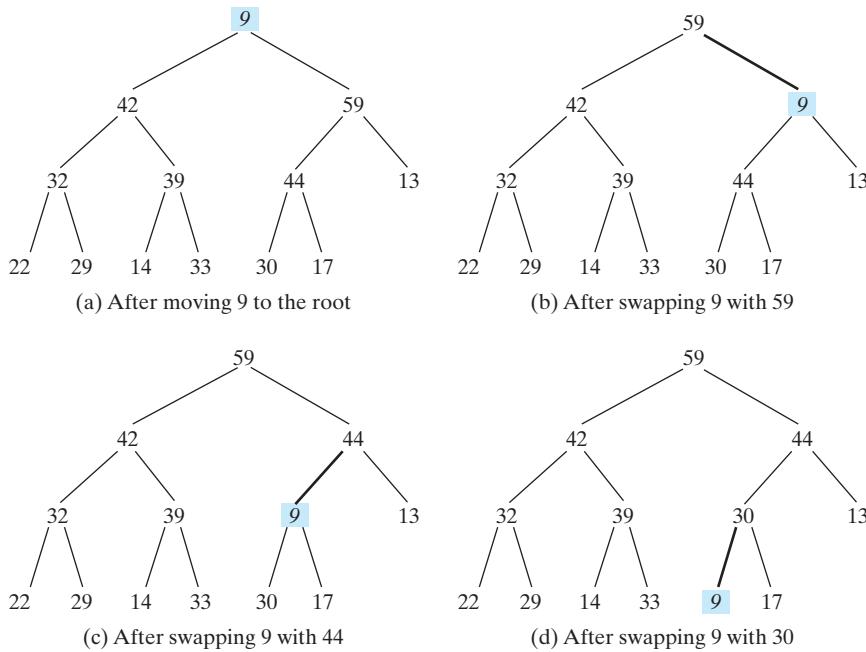
Often you need to remove the maximum element, which is the root in a heap. After the root is removed, the tree must be rebuilt to maintain the heap property. The algorithm for rebuilding the tree can be described as follows:

```

Move the last node to replace the root;
Let the root be the current node;
while (the current node has children and the current node is
 smaller than one of its children) {
 Swap the current node with the larger of its children;
 Now the current node is one level down;
}

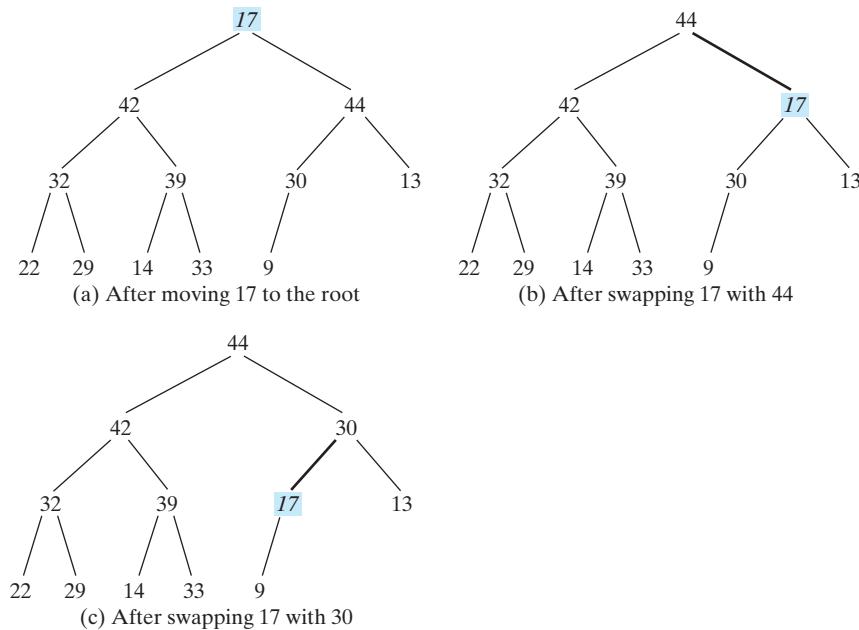
```

Figure 23.14 shows the process of rebuilding a heap after the root 62 is removed from Figure 23.11a. Move the last node, 9, to the root, as shown in Figure 23.14a. Swap 9 with 59, as shown in Figure 23.14b; swap 9 with 44, as shown in Figure 23.14c; and swap 9 with 30, as shown in Figure 23.14d.



**FIGURE 23.14** Rebuild the heap after the root 62 is removed.

Figure 23.15 shows the process of rebuilding a heap after the root, 59, is removed from Figure 23.14d. Move the last node, 17, to the root, as shown in Figure 23.15a. Swap 17 with 44, as shown in Figure 23.15b, and then swap 17 with 30, as shown in Figure 23.15c.



**FIGURE 23.15** Rebuild the heap after the root, 59, is removed.

#### 23.6.4 The Heap Class

Now you are ready to design and implement the **Heap** class. The class diagram is shown in Figure 23.16. Its implementation is given in Listing 23.9.

| Heap<E extends Comparable<E>> |                                                |
|-------------------------------|------------------------------------------------|
| -list: java.util.ArrayList<E> |                                                |
| +Heap()                       | Creates a default empty heap.                  |
| +Heap(objects: E[])           | Creates a heap with the specified objects.     |
| +add(newObject: E): void      | Adds a new object to the heap.                 |
| +remove(): E                  | Removes the root from the heap and returns it. |
| +getSize(): int               | Returns the size of the heap.                  |

FIGURE 23.16 The **Heap** class provides operations for manipulating a heap.**LISTING 23.9** **Heap.java**

```

internal heap representation
1 public class Heap<E extends Comparable<E>> {
2 private java.util.ArrayList<E> list = new java.util.ArrayList<>();
3
4 /** Create a default heap */
5 public Heap() {
6 }
7
8 /** Create a heap from an array of objects */
9 public Heap(E[] objects) {
10 for (int i = 0; i < objects.length; i++)
11 add(objects[i]);
12 }
13
14 /** Add a new object into the heap */
15 public void add(E newObject) {
16 list.add(newObject); // Append to the heap
17 int currentIndex = list.size() - 1; // The index of the last node
18
19 while (currentIndex > 0) {
20 int parentIndex = (currentIndex - 1) / 2;
21 // Swap if the current object is greater than its parent
22 if (list.get(currentIndex).compareTo(
23 list.get(parentIndex)) > 0) {
24 E temp = list.get(currentIndex);
25 list.set(currentIndex, list.get(parentIndex));
26 list.set(parentIndex, temp);
27 }
28 else
29 break; // The tree is a heap now
30 currentIndex = parentIndex;
31 }
32 }
33
34
35 /** Remove the root from the heap */
36 public E remove() {
37 if (list.size() == 0) return null;
38
39 E removedObject = list.get(0);
40 list.set(0, list.get(list.size() - 1));
41 list.remove(list.size() - 1);
42
43 int currentIndex = 0;
44 while (currentIndex < list.size()) {

```

no-arg constructor

constructor

add a new object  
append the object

swap with parent

heap now

remove the root  
empty heap

root  
new root  
remove the last

adjust the tree

```

45 int leftChildIndex = 2 * currentIndex + 1;
46 int rightChildIndex = 2 * currentIndex + 2;
47
48 // Find the maximum between two children
49 if (leftChildIndex >= list.size()) break; // The tree is a heap
50 int maxIndex = leftChildIndex;
51 if (rightChildIndex < list.size()) {
52 if (list.get(maxIndex).compareTo(
53 list.get(rightChildIndex)) < 0) {
54 maxIndex = rightChildIndex;
55 }
56 }
57
58 // Swap if the current node is less than the maximum
59 if (list.get(currentIndex).compareTo(
60 list.get(maxIndex)) < 0) {
61 E temp = list.get(maxIndex);
62 list.set(maxIndex, list.get(currentIndex));
63 list.set(currentIndex, temp);
64 currentIndex = maxIndex;
65 }
66 else
67 break; // The tree is a heap
68 }
69
70 return removedObject;
71 }
72
73 /** Get the number of nodes in the tree */
74 public int getSize() {
75 return list.size();
76 }
77 }
```

A heap is represented using an array list internally (line 2). You can change the array list to other data structures, but the `Heap` class contract will remain unchanged.

The `add(E newObject)` method (lines 15–33) appends the object to the tree and then swaps the object with its parent if the object is greater than its parent. This process continues until the new object becomes the root or is not greater than its parent.

The `remove()` method (lines 36–71) removes and returns the root. To maintain the heap property, the method moves the last object to the root position and swaps it with its larger child if it is less than the larger child. This process continues until the last object becomes a leaf or is not less than its children.

### 23.6.5 Sorting Using the `Heap` Class

To sort an array using a heap, first create an object using the `Heap` class, add all the elements to the heap using the `add` method, and remove all the elements from the heap using the `remove` method. The elements are removed in descending order. Listing 23.10 gives a program for sorting an array using a heap.

#### LISTING 23.10 `HeapSort.java`

```

1 public class HeapSort {
2 /** Heap sort method */
3 public static <E extends Comparable<E>> void heapSort(E[] list) {
4 // Create a Heap of integers
5 Heap<E> heap = new Heap<>();
6
7 int leftChildIndex = 2 * currentIndex + 1;
8 int rightChildIndex = 2 * currentIndex + 2;
9
10 // Find the maximum between two children
11 if (leftChildIndex >= list.size()) break; // The tree is a heap
12 int maxIndex = leftChildIndex;
13 if (rightChildIndex < list.size()) {
14 if (list.get(maxIndex).compareTo(
15 list.get(rightChildIndex)) < 0) {
16 maxIndex = rightChildIndex;
17 }
18 }
19
20 // Swap if the current node is less than the maximum
21 if (list.get(currentIndex).compareTo(
22 list.get(maxIndex)) < 0) {
23 E temp = list.get(maxIndex);
24 list.set(maxIndex, list.get(currentIndex));
25 list.set(currentIndex, temp);
26 currentIndex = maxIndex;
27 }
28 else
29 break; // The tree is a heap
30 }
31
32 return removedObject;
33 }
34
35 /** Get the number of nodes in the tree */
36 public int getSize() {
37 return list.size();
38 }
39 }
```

compare two children

swap with the larger child

create a Heap

```

7 // Add elements to the heap
8 for (int i = 0; i < list.length; i++)
9 heap.add(list[i]);
10
11 // Remove elements from the heap
12 for (int i = list.length - 1; i >= 0; i--)
13 list[i] = heap.remove();
14 }
15
16 /** A test method */
17 public static void main(String[] args) {
18 Integer[] list = {-44, -5, -3, 3, 3, 1, -4, 0, 1, 2, 4, 5, 53};
19 heapSort(list);
20 for (int i = 0; i < list.length; i++)
21 System.out.print(list[i] + " ");
22 }
23 }
```



-44 -5 -4 -3 0 1 1 2 3 3 4 5 53

invoke sort method

height of a heap

$O(n \log n)$  worst-case time

heap sort vs. merge sort

### 23.6.6 Heap Sort Time Complexity

Let us turn our attention to analyzing the time complexity for the heap sort. Let  $h$  denote the height for a heap of  $n$  elements. The height of a heap is the number of nodes in the longest path from the root to a leaf node. Since a heap is a complete binary tree, the first level has 1 node, the second level has 2 nodes, the  $k$ th level has  $2^{k-1}$  nodes, the  $(h-1)$ th level has  $2^{h-2}$  nodes, and the  $h$ th level has at least 1 and at most  $2^{h-1}$  nodes. Therefore,

$$1 + 2 + \dots + 2^{h-2} < n \leq 1 + 2 + \dots + 2^{h-2} + 2^{h-1}$$

That is,

$$\begin{aligned} 2^{h-1} - 1 &< n \leq 2^h - 1 \\ 2^{h-1} &< n + 1 \leq 2^h \\ h - 1 &< \log(n + 1) \leq h \end{aligned}$$

Thus,  $h < \log(n + 1) + 1$  and  $\log(n + 1) \leq h$ . Therefore,  $\log(n + 1) \leq h < \log(n + 1) + 1$ . Hence, the height of the heap is  $O(\log n)$ .

Since the `add` method traces a path from a leaf to a root, it takes at most  $h$  steps to add a new element to the heap. Thus, the total time for constructing an initial heap is  $O(n \log n)$  for an array of  $n$  elements. Since the `remove` method traces a path from a root to a leaf, it takes at most  $h$  steps to rebuild a heap after removing the root from the heap. Since the `remove` method is invoked  $n$  times, the total time for producing a sorted array from a heap is  $O(n \log n)$ .

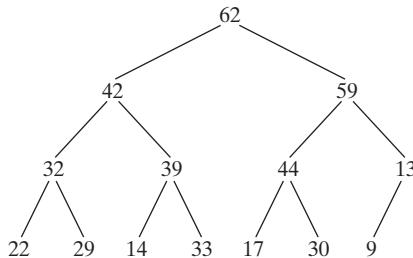
Both merge sorts and heap sorts require  $O(n \log n)$  time. A merge sort requires a temporary array for merging two subarrays; a heap sort does not need additional array space. Therefore, a heap sort is more space efficient than a merge sort.



- 23.13** What is a complete binary tree? What is a heap? Describe how to remove the root from a heap and how to add a new object to a heap.
- 23.14** What is the return value from invoking the `remove` method if the heap is empty?
- 23.15** Add the elements 4, 5, 1, 2, 9, and 3 into a heap in this order. Draw the diagrams to show the heap after each element is added.
- 23.16** Show the heap after the root in the heap in Figure 23.15c is removed.
- 23.17** What is the time complexity of inserting a new element into a heap and what is the time complexity of deleting an element from a heap?

**23.18** Show the steps of creating a heap using {45, 11, 50, 59, 60, 2, 4, 7, 10}.

**23.19** Given the following heap, show the steps of removing all nodes from the heap.



**23.20** Which of the following statements are wrong?

- 1 Heap<Object> heap1 = **new** Heap<>();
- 2 Heap<Number> heap2 = **new** Heap<>();
- 3 Heap<BigInteger> heap3 = **new** Heap<>();
- 4 Heap<Calendar> heap4 = **new** Heap<>();
- 5 Heap<String> heap5 = **new** Heap<>();

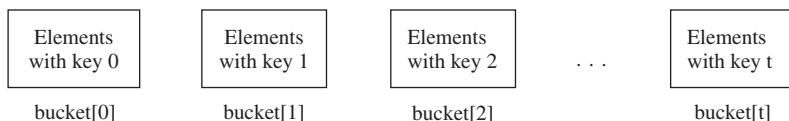
## 23.7 Bucket Sort and Radix Sort

*Bucket sorts and radix sorts are efficient for sorting integers.*



All sort algorithms discussed so far are general sorting algorithms that work for any types of keys (e.g., integers, strings, and any comparable objects). These algorithms sort the elements by comparing their keys. It has been proven that no sorting algorithms based on comparisons can perform better than  $O(n \log n)$ . However, if the keys are integers, you can use a bucket sort without having to compare the keys.

The bucket sort algorithm works as follows. Assume the keys are in the range from **0** to **t**. We need **t + 1** buckets labeled **0, 1, ..., t**. If an element's key is **i**, the element is put into the bucket **i**. Each bucket holds the elements with the same key value.



You can use an **ArrayList** to implement a bucket. The bucket sort algorithm for sorting a list of elements can be described as follows:

```

void bucketSort(E[] list) {
 E[] bucket = (E[])new java.util.ArrayList[t+1];

 // Distribute the elements from list to buckets
 for (int i = 0; i < list.length; i++) {
 int key = list[i].getKey(); // Assume element has the getKey() method

 if (bucket[key] == null)
 bucket[key] = new java.util.ArrayList<>();

 bucket[key].add(list[i]);
 }
}

```

```
// Now move the elements from the buckets back to list
int k = 0; // k is an index for list
for (int i = 0; i < bucket.length; i++) {
 if (bucket[i] != null) {
 for (int j = 0; j < bucket[i].size(); j++)
 list[k++] = bucket[i].get(j);
 }
}
```

Clearly, it takes  $O(n + t)$  time to sort the list and uses  $O(n + t)$  space, where  $n$  is the list size.

Note that if  $t$  is too large, using the bucket sort is not desirable. Instead, you can use a radix sort. The radix sort is based on the bucket sort, but a radix sort uses only ten buckets.

stable

radix sort



radix sort on Companion Website

queue

It is worthwhile to note that a bucket sort is *stable*, meaning that if two elements in the original list have the same key value, their order is not changed in the sorted list. That is, if element  $e_1$  and element  $e_2$  have the same key and  $e_1$  precedes  $e_2$  in the original list,  $e_1$  still precedes  $e_2$  in the sorted list.

Assume that the keys are positive integers. The idea for the *radix sort* is to divide the keys into subgroups based on their radix positions. It applies a bucket sort repeatedly for the key values on radix positions, starting from the least-significant position.

Consider sorting the elements with the following keys:

331, 454, 230, 34, 343, 45, 59, 453, 345, 231, 9

Apply the bucket sort on the last radix position, and the elements are put into the buckets as follows:

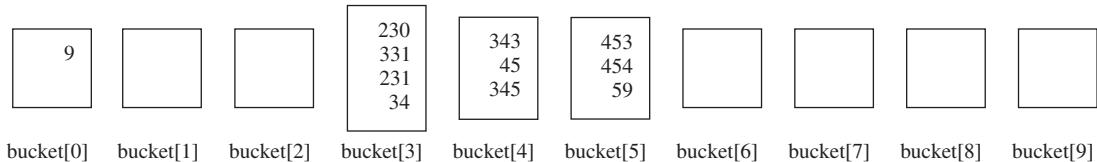


After being removed from the buckets, the elements are in the following order:

230, 331, 231, 343, 453, 454, 34, 45, 345, 59, 9

queue

Apply the bucket sort on the second-to-last radix position, and the elements are put into the buckets as follows:



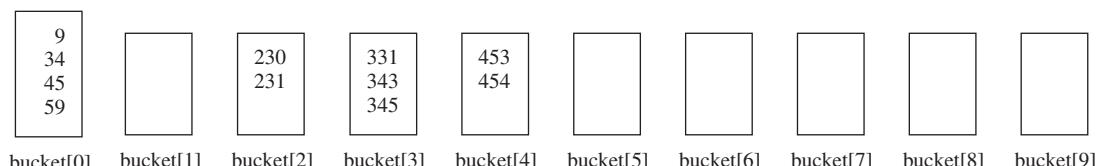
After being removed from the buckets, the elements are in the following order:

9, 230, 331, 231, 34, 343, 45, 345, 453, 454, 59

(Note that 9 is 009.)

queue

Apply the bucket sort on the third-to-last radix position, and the elements are put into the buckets as follows:



After being removed from the buckets, the elements are in the following order:

9, 34, 45, 59, 230, 231, 331, 343, 345, 453, 454

The elements are now sorted.

Radix sort takes  $O(dn)$  time to sort  $n$  elements with integer keys, where  $d$  is the maximum number of the radix positions among all keys.

**23.21** Can you sort a list of strings using a bucket sort?

**23.22** Show how the radix sort works using the numbers 454, 34, 23, 43, 74, 86, and 76.



## 23.8 External Sort

*You can sort a large amount data using an external sort.*

All the sort algorithms discussed in the preceding sections assume that all the data to be sorted are available at one time in internal memory, such as in an array. To sort data stored in an external file, you must first bring the data to the memory and then sort it internally. However, if the file is too large, all the data in the file cannot be brought to memory at one time. This section discusses how to sort data in a large external file. This is called an *external sort*.

For simplicity, assume that two million `int` values are stored in a binary file named `largedata.dat`. This file was created using the program in Listing 23.11.



### LISTING 23.11 CreateLargeFile.java

```

1 import java.io.*;
2
3 public class CreateLargeFile {
4 public static void main(String[] args) throws Exception {
5 DataOutputStream output = new DataOutputStream(
6 new BufferedOutputStream(
7 new FileOutputStream("largedata.dat")));
8
9 for (int i = 0; i < 800004; i++)
10 output.writeInt((int)(Math.random() * 1000000));
11
12 output.close();
13
14 // Display first 100 numbers
15 DataInputStream input = new DataInputStream(
16 new BufferedInputStream(new FileInputStream("largedata.dat")));
17 for (int i = 0; i < 100; i++)
18 System.out.print(input.readInt() + " ");
19
20 input.close();
21 }
22 }
```

a binary output stream

output an int value

close output file

read an int value

close input file

569193 131317 608695 776266 767910 624915 458599 5010 ... (omitted)



A variation of merge sort can be used to sort this file in two phases:

**Phase I:** Repeatedly bring data from the file to an array, sort the array using an internal sorting algorithm, and output the data from the array to a temporary file. This process is shown in Figure 23.17. Ideally, you want to create a large array, but its maximum size depends on how much memory is allocated to the JVM by the operating system. Assume that the maximum array size is 100,000 `int` values. In the temporary file, every 100,000

**int** values are sorted. They are denoted as  $S_1, S_2, \dots$ , and  $S_k$ , where the last segment,  $S_k$ , may contain less than 100000 values.



FIGURE 23.17 The original file is sorted in segments.

**Phase II:** Merge a pair of sorted segments (e.g.,  $S_1$  with  $S_2$ ,  $S_3$  with  $S_4$ ,  $\dots$ , and so on) into a larger sorted segment and save the new segment into a new temporary file. Continue the same process until only one sorted segment results. Figure 23.18 shows how to merge eight segments.

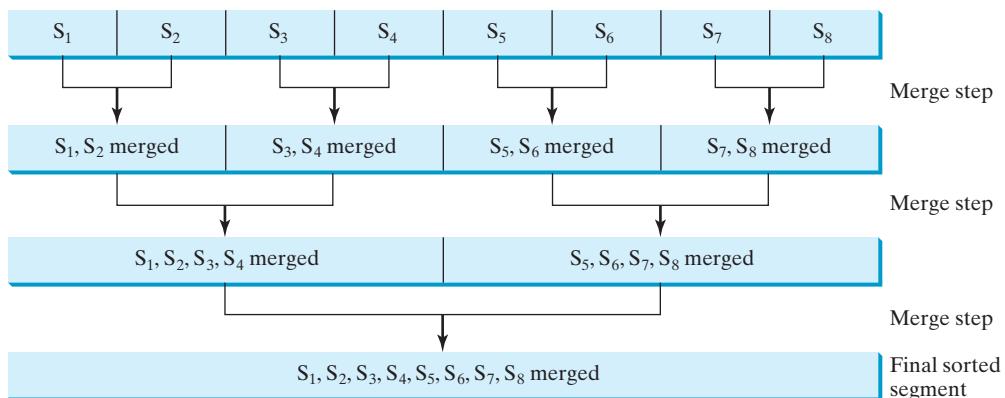


FIGURE 23.18 Sorted segments are merged iteratively.



### Note

It is not necessary to merge two successive segments. For example, you can merge  $S_1$  with  $S_5$ ,  $S_2$  with  $S_6$ ,  $S_3$  with  $S_7$  and  $S_4$  with  $S_8$ , in the first merge step. This observation is useful in implementing Phase II efficiently.

#### 23.8.1 Implementing Phase I

Listing 23.12 gives the method that reads each segment of data from a file, sorts the segment, and stores the sorted segments into a new file. The method returns the number of segments.

#### LISTING 23.12 Creating Initial Sorted Segments

```

1 /** Sort original file into sorted segments */
2 private static int initializeSegments
3 (int segmentSize, String originalFile, String f1)
4 throws Exception {
5 int[] list = new int[segmentSize];
6 DataInputStream input = new DataInputStream(

```

```

7 new BufferedInputStream(new FileInputStream(originalFile)));
8 DataOutputStream output = new DataOutputStream(
9 new BufferedOutputStream(new FileOutputStream(f1)));
10
11 int numberOfSegments = 0;
12 while (input.available() > 0) {
13 numberOfSegments++;
14 int i = 0;
15 for (; input.available() > 0 && i < segmentSize; i++) {
16 list[i] = input.readInt();
17 }
18
19 // Sort an array list[0..i-1]
20 java.util.Arrays.sort(list, 0, i);
21
22 // Write the array to f1.dat
23 for (int j = 0; j < i; j++) {
24 output.writeInt(list[j]);
25 }
26 }
27
28 input.close();
29 output.close();
30
31 return numberOfSegments;
32 }

```

original file  
file with sorted segments  
sort a segment  
output to file  
close file  
return # of segments

The method creates an array with the maximum size in line 5, a data input stream for the original file in line 6, and a data output stream for a temporary file in line 8. Buffered streams are used to improve performance.

Lines 14–17 read a segment of data from the file into the array. Line 20 sorts the array. Lines 23–25 write the data in the array to the temporary file.

The number of segments is returned in line 31. Note that every segment has **MAX\_ARRAY\_SIZE** number of elements except the last segment, which may have fewer elements.

### 23.8.2 Implementing Phase II

In each merge step, two sorted segments are merged to form a new segment. The size of the new segment is doubled. The number of segments is reduced by half after each merge step. A segment is too large to be brought to an array in memory. To implement a merge step, copy half the number of segments from the file **f1.dat** to a temporary file **f2.dat**. Then merge the first remaining segment in **f1.dat** with the first segment in **f2.dat** into a temporary file named **f3.dat**, as shown in Figure 23.19.

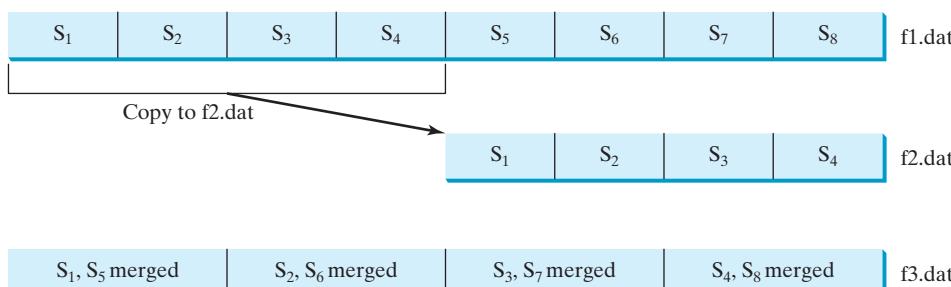


FIGURE 23.19 Sorted segments are merged iteratively.

**Note**

**f1.dat** may have one segment more than **f2.dat**. If so, move the last segment into **f3.dat** after the merge.

Listing 23.13 gives a method that copies the first half of the segments in f1.dat to f2.dat. Listing 23.14 gives a method that merges a pair of segments in f1.dat and f2.dat. Listing 23.15 gives a method that merges two segments.

### LISTING 23.13 Copying First Half Segments

input stream f1

output stream f2

segments copied

```

1 private static void copyHalfToF2(int numberofSegments,
2 int segmentSize, DataInputStream f1, DataOutputStream f2)
3 throws Exception {
4 for (int i = 0; i < (numberofSegments / 2) * segmentSize; i++) {
5 f2.writeInt(f1.readInt());
6 }
7 }
```

### LISTING 23.14 Merging All Segments

input stream f1 and f2

output stream f3

merge two segments

extra segment in f1?

```

1 private static void mergeSegments(int numberofSegments,
2 int segmentSize, DataInputStream f1, DataInputStream f2,
3 DataOutputStream f3) throws Exception {
4 for (int i = 0; i < numberofSegments; i++) {
5 mergeTwoSegments(segmentSize, f1, f2, f3);
6 }
7
8 // If f1 has one extra segment, copy it to f3
9 while (f1.available() > 0) {
10 f3.writeInt(f1.readInt());
11 }
12 }
```

### LISTING 23.15 Merging Two Segments

input stream f1 and f2

output stream f3

read from f1

read from f2

write to f3

segment in f1 finished

write to f3

segment in f2 finished

```

1 private static void mergeTwoSegments(int segmentSize,
2 DataInputStream f1, DataInputStream f2,
3 DataOutputStream f3) throws Exception {
4 int intFromF1 = f1.readInt();
5 int intFromF2 = f2.readInt();
6 int f1Count = 1;
7 int f2Count = 1;
8
9 while (true) {
10 if (intFromF1 < intFromF2) {
11 f3.writeInt(intFromF1);
12 if (f1.available() == 0 || f1Count++ >= segmentSize) {
13 f3.writeInt(intFromF2);
14 break;
15 }
16 else {
17 intFromF1 = f1.readInt();
18 }
19 }
20 else {
21 f3.writeInt(intFromF2);
22 if (f2.available() == 0 || f2Count++ >= segmentSize) {
23 f3.writeInt(intFromF1);
24 break;
25 }
26 }
27 }
28 }
```

```

26 else {
27 intFromF2 = f2.readInt();
28 }
29 }
30 }
31
32 while (f1.available() > 0 && f1Count++ < segmentSize) { remaining f1 segment
33 f3.writeInt(f1.readInt());
34 }
35
36 while (f2.available() > 0 && f2Count++ < segmentSize) { remaining f2 segment
37 f3.writeInt(f2.readInt());
38 }
39 }

```

### 23.8.3 Combining Two Phases

Listing 23.16 gives the complete program for sorting `int` values in `largedata.dat` and storing the sorted data in `sortedfile.dat`.

#### LISTING 23.16 SortLargeFile.java

```

1 import java.io.*;
2
3 public class SortLargeFile {
4 public static final int MAX_ARRAY_SIZE = 100000; max array size
5 public static final int BUFFER_SIZE = 100000; I/O stream buffer size
6
7 public static void main(String[] args) throws Exception {
8 // Sort largedata.dat to sortedfile.dat
9 sort("largedata.dat", "sortedfile.dat");
10
11 // Display the first 100 numbers in the sorted file
12 displayFile("sortedfile.dat");
13 }
14
15 /** Sort data in source file into target file */
16 public static void sort(String sourcefile, String targetfile)
17 throws Exception {
18 // Implement Phase 1: Create initial segments
19 int numberofSegments =
20 initializeSegments(MAX_ARRAY_SIZE, sourcefile, "f1.dat"); create initial segments
21
22 // Implement Phase 2: Merge segments recursively
23 merge(numberofSegments, MAX_ARRAY_SIZE,
24 "f1.dat", "f2.dat", "f3.dat", targetfile); merge recursively
25 }
26
27 /** Sort original file into sorted segments */
28 private static int initializeSegments
29 (int segmentSize, String originalFile, String f1)
30 throws Exception {
31 // Same as Listing 23.12, so omitted
32 }
33
34 private static void merge(int numberofSegments, int segmentSize,
35 String f1, String f2, String f3, String targetfile)
36 throws Exception {
37 if (numberofSegments > 1) {
38 mergeOneStep(numberofSegments, segmentSize, f1, f2, f3); merge one step

```

```

merge recursively 39 merge((numberOfSegments + 1) / 2, segmentSize * 2,
40 f3, f1, f2, targetfile);
41 }
42 else { // Rename f1 as the final sorted file
43 File sortedFile = new File(targetfile);
44 if (sortedFile.exists()) sortedFile.delete();
45 new File(f1).renameTo(sortedFile);
46 }
47 }

private static void mergeOneStep(int numberOfSegments,
50 int segmentSize, String f1, String f2, String f3)
51 throws Exception {
52 DataInputStream f1Input = new DataInputStream(
53 new BufferedInputStream(new FileInputStream(f1), BUFFER_SIZE));
54 DataOutputStream f2Output = new DataOutputStream(
55 new BufferedOutputStream(new FileOutputStream(f2), BUFFER_SIZE));
56
57 // Copy half number of segments from f1.dat to f2.dat
58 copyHalfToF2(numberOfSegments, segmentSize, f1Input, f2Output);
59 f2Output.close();
60
61 // Merge remaining segments in f1 with segments in f2 into f3
62 DataInputStream f2Input = new DataInputStream(
63 new BufferedInputStream(new FileInputStream(f2), BUFFER_SIZE));
64 DataOutputStream f3Output = new DataOutputStream(
65 new BufferedOutputStream(new FileOutputStream(f3), BUFFER_SIZE));
66
67 mergeSegments(numberOfSegments / 2,
68 segmentSize, f1Input, f2Input, f3Output);
69
70 f1Input.close();
71 f2Input.close();
72 f3Output.close();
73 }

74 /** Copy first half number of segments from f1.dat to f2.dat */
75 private static void copyHalfToF2(int numberOfSegments,
76 int segmentSize, DataInputStream f1, DataOutputStream f2)
77 throws Exception {
78 // Same as Listing 23.13, so omitted
79 }
80
81 /** Merge all segments */
82 private static void mergeSegments(int numberOfSegments,
83 int segmentSize, DataInputStream f1, DataInputStream f2,
84 DataOutputStream f3) throws Exception {
85 // Same as Listing 23.14, so omitted
86 }
87
88 /** Merges two segments */
89 private static void mergeTwoSegments(int segmentSize,
90 DataInputStream f1, DataInputStream f2,
91 DataOutputStream f3) throws Exception {
92 // Same as Listing 23.15, so omitted
93 }
94
95 /** Display the first 100 numbers in the specified file */
96 public static void displayFile(String filename) {
97 try {

```

```

99 DataInputStream input =
100 new DataInputStream(new FileInputStream(filename));
101 for (int i = 0; i < 100; i++)
102 System.out.print(input.readInt() + " ");
103 input.close();
104 }
105 catch (IOException ex) {
106 ex.printStackTrace();
107 }
108 }
109 }
```

0 1 1 1 2 2 2 3 3 4 5 6 8 8 9 9 9 10 10 11 . . . (omitted)



Before you run this program, first run Listing 23.11, CreateLargeFile.java, to create the file largedata.dat. Invoking `sort("largedata.dat", "sortedfile.dat")` (line 9) reads data from `largedata.dat` and writes sorted data to `sortedfile.dat`. Invoking `displayFile("sortedfile.dat")` (line 12) displays the first 100 numbers in the specified file. Note that the files are created using binary I/O. You cannot view them using a text editor such as Notepad.

The `sort` method first creates initial segments from the original array and stores the sorted segments in a new file, `f1.dat` (lines 19–20), then produces a sorted file in `targetfile` (lines 23–24).

The `merge` method

```
merge(int numberofSegments, int segmentSize,
 String f1, String f2, String f3, String targetfile)
```

merges the segments in `f1` into `f3` using `f2` to assist the merge. The `merge` method is invoked recursively with many merge steps. Each merge step reduces the `numberofSegments` by half and doubles the sorted segment size. After the completion of one merge step, the next merge step merges the new segments in `f3` to `f2` using `f1` to assist the merge. The statement to invoke the new merge method is

```
merge((numberofSegments + 1) / 2, segmentSize * 2,
 f3, f1, f2, targetfile);
```

The `numberofSegments` for the next merge step is `(numberofSegments + 1) / 2`. For example, if `numberofSegments` is 5, `numberofSegments` is 3 for the next merge step, because every two segments are merged but one is left unmerged.

The recursive `merge` method ends when `numberofSegments` is 1. In this case, `f1` contains sorted data. File `f1` is renamed to `targetfile` (line 45).

### 23.8.4 External Sort Complexity

In the external sort, the dominating cost is that of I/O. Assume  $n$  is the number of elements to be sorted in the file. In Phase I,  $n$  number of elements are read from the original file and output to a temporary file. Therefore, the I/O for Phase I is  $O(n)$ .

In Phase II, before the first merge step, the number of sorted segments is  $\frac{n}{c}$ , where  $c$  is `MAX_ARRAY_SIZE`. Each merge step reduces the number of segments by half. Thus, after the first merge step, the number of segments is  $\frac{n}{2c}$ . After the second merge step, the number of segments is  $\frac{n}{2^2 c}$ , and after the third merge step the number of segments is  $\frac{n}{2^3 c}$ . After  $\log\left(\frac{n}{c}\right)$

merge steps, the number of segments is reduced to 1. Therefore, the total number of merge steps is  $\log\left(\frac{n}{c}\right)$ .

In each merge step, half the number of segments are read from file **f1** and then written into a temporary file **f2**. The remaining segments in **f1** are merged with the segments in **f2**. The number of I/Os in each merge step is  $O(n)$ . Since the total number of merge steps is  $\log\left(\frac{n}{c}\right)$ , the total number of I/Os is

$$O(n) \times \log\left(\frac{n}{c}\right) = O(n \log n)$$

Therefore, the complexity of the external sort is  $O(n \log n)$ .



**23.23** Describe how external sort works. What is the complexity of the external sort algorithm?

**23.24** Ten numbers {2, 3, 4, 0, 5, 6, 7, 9, 8, 1} are stored in the external file **largedata.dat**. Trace the **SortLargeFile** program by hand with **MAX\_ARRAY\_SIZE** 2.

## KEY TERMS

bubble sort 864  
 bucket sort 881  
 complete binary tree 874  
 external sort 883  
 heap 875

heap sort 874  
 height of a heap 880  
 merge sort 867  
 quick sort 870  
 radix sort 882

## CHAPTER SUMMARY

1. The worst-case complexity for a selection sort, insertion sort, *bubble sort*, and *quick sort* is  $O(n^2)$ .
2. The average-case and worst-case complexity for a *merge sort* is  $O(n \log n)$ . The average time for a quick sort is also  $O(n \log n)$ .
3. *Heaps* are a useful data structure for designing efficient algorithms such as sorting. You learned how to define and implement a heap class, and how to insert and delete elements to/from a heap.
4. The time complexity for a *heap sort* is  $O(n \log n)$ .
5. *Bucket sorts* and *radix sorts* are specialized sorting algorithms for integer keys. These algorithms sort keys using buckets rather than by comparing keys. They are more efficient than general sorting algorithms.
6. A variation of the merge sort—called an *external sort*—can be applied to sort large amounts of data from external files.

## QUIZ

Answer the quiz for this chapter online at [www.cs.armstrong.edu/liang/intro10e/test.html](http://www.cs.armstrong.edu/liang/intro10e/test.html).

## PROGRAMMING EXERCISES

---

### Sections 23.3–23.5

- 23.1** (*Generic bubble sort*) Write the following two generic methods using bubble sort. The first method sorts the elements using the **Comparable** interface and the second uses the **Comparator** interface.

```
public static <E extends Comparable<E>>
 void bubbleSort(E[] list)
public static <E> void bubbleSort(E[] list,
 Comparator<? super E> comparator)
```

- 23.2** (*Generic merge sort*) Write the following two generic methods using merge sort. The first method sorts the elements using the **Comparable** interface and the second uses the **Comparator** interface.

```
public static <E extends Comparable<E>>
 void mergeSort(E[] list)
public static <E> void mergeSort(E[] list,
 Comparator<? super E> comparator)
```

- 23.3** (*Generic quick sort*) Write the following two generic methods using quick sort. The first method sorts the elements using the **Comparable** interface and the second uses the **Comparator** interface.

```
public static <E extends Comparable<E>>
 void quickSort(E[] list)
public static <E> void quickSort(E[] list,
 Comparator<? super E> comparator)
```

- 23.4** (*Improve quick sort*) The quick sort algorithm presented in the book selects the first element in the list as the pivot. Revise it by selecting the median among the first, middle, and last elements in the list.

- \*23.5** (*Generic heap sort*) Write the following two generic methods using heap sort. The first method sorts the elements using the **Comparable** interface and the second uses the **Comparator** interface.

```
public static <E extends Comparable<E>>
 void heapSort(E[] list)
public static <E> void heapSort(E[] list,
 Comparator<? super E> comparator)
```

- 23.6** (*Check order*) Write the following overloaded methods that check whether an array is ordered in ascending order or descending order. By default, the method checks ascending order. To check descending order, pass **false** to the ascending argument in the method.

```
public static boolean ordered(int[] list)
public static boolean ordered(int[] list, boolean ascending)
public static boolean ordered(double[] list)
public static boolean ordered
 (double[] list, boolean ascending)
public static <E extends Comparable<E>>
 boolean ordered(E[] list)
public static <E extends Comparable<E>> boolean ordered
 (E[] list, boolean ascending)
public static <E> boolean ordered(E[] list,
```

```
Comparator<? super E> comparator)
public static <E> boolean ordered(E[] list,
 Comparator<? super E> comparator, boolean ascending)
```

max-heap  
min-heap

### Section 23.6

- 23.7** (*Min-heap*) The heap presented in the text is also known as a *max-heap*, in which each node is greater than or equal to any of its children. A *min-heap* is a heap in which each node is less than or equal to any of its children. Min-heaps are often used to implement priority queues. Revise the **Heap** class in Listing 23.9 to implement a min-heap.

- \*23.8** (*Sort using a heap*) Implement the following **sort** method using a heap.

```
public static <E extends Comparable<E>> void sort(E[] list)
```

- \*23.9** (*Generic Heap using Comparator*) Revise **Heap** in Listing 23.9, using a generic parameter and a **Comparator** for comparing objects. Define a new constructor with a **Comparator** as its argument as follows:

```
Heap(Comparator<? super E> comparator)
```

- \*\*23.10** (*Heap visualization*) Write a program that displays a heap graphically, as shown in Figure 23.10. The program lets you insert and delete an element from the heap.

- 23.11** (*Heap clone and equals*) Implement the **clone** and **equals** method in the **Heap** class.

### Section 23.7

- \*23.12** (*Radix sort*) Write a program that randomly generates 1,000,000 integers and sorts them using radix sort.

- \*23.13** (*Execution time for sorting*) Write a program that obtains the execution time of selection sort, bubble sort, merge sort, quick sort, heap sort, and radix sort for input size 50,000, 100,000, 150,000, 200,000, 250,000, and 300,000. Your program should create data randomly and print a table like this:

| Array size | Selection Sort | Bubble Sort | Merge Sort | Quick Sort | Heap Sort | Radix Sort |
|------------|----------------|-------------|------------|------------|-----------|------------|
| 50,000     |                |             |            |            |           |            |
| 100,000    |                |             |            |            |           |            |
| 150,000    |                |             |            |            |           |            |
| 200,000    |                |             |            |            |           |            |
| 250,000    |                |             |            |            |           |            |
| 300,000    |                |             |            |            |           |            |

(Hint: You can use the following code template to obtain the execution time.)

```
long startTime = System.currentTimeMillis();
perform the task;
long endTime = System.currentTimeMillis();
long executionTime = endTime - startTime;
```

The text gives a recursive quick sort. Write a nonrecursive version in this exercise.

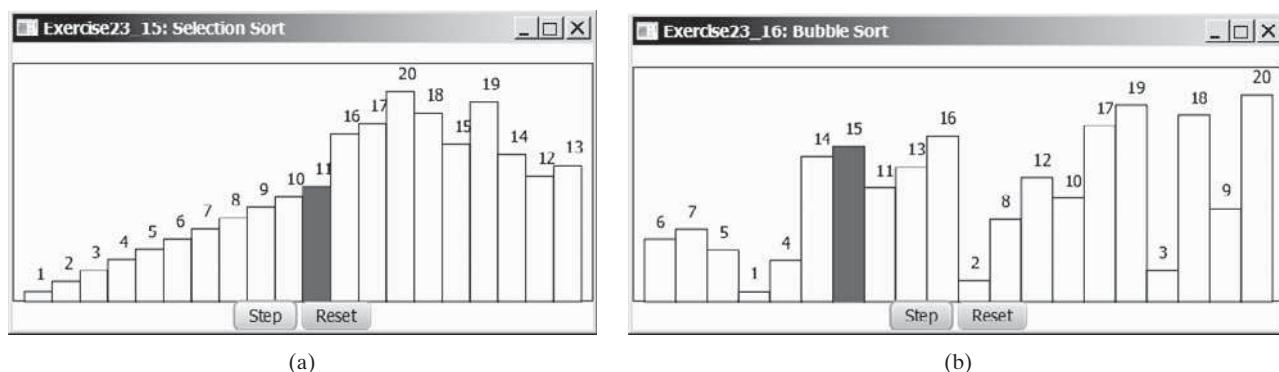
### Section 23.8

- \*23.14** (*Execution time for external sorting*) Write a program that obtains the execution time of external sorts for integers of size 5,000,000, 10,000,000, 15,000,000, 20,000,000, 25,000,000, and 30,000,000. Your program should print a table like this:

| File size | 5,000,000 | 10,000,000 | 15,000,000 | 20,000,000 | 25,000,000 | 30,000,000 |
|-----------|-----------|------------|------------|------------|------------|------------|
| Time      |           |            |            |            |            |            |

### Comprehensive

- \*23.15** (*Selection sort animation*) Write a program that animates the selection sort algorithm. Create an array that consists of 20 distinct numbers from 1 to 20 in a random order. The array elements are displayed in a histogram, as shown in Figure 23.20a. Clicking the *Step* button causes the program to perform an iteration of the outer loop in the algorithm and repaints the histogram for the new array. Color the last bar in the sorted subarray. When the algorithm is finished, display a message to inform the user. Clicking the *Reset* button creates a new random array for a new start. (You can easily modify the program to animate the insertion algorithm.)



**FIGURE 23.20** (a) The program animates selection sort. (b) The program animates bubble sort.

- \*23.16** (*Bubble sort animation*) Write a program that animates the bubble sort algorithm. Create an array that consists of 20 distinct numbers from 1 to 20 in a random order. The array elements are displayed in a histogram, as shown in Figure 23.20b. Clicking the *Step* button causes the program to perform one comparison in the algorithm and repaints the histogram for the new array. Color the bar that represents the number being considered in the swap. When the algorithm is finished, display a message to inform the user. Clicking the *Reset* button creates a new random array for a new start.

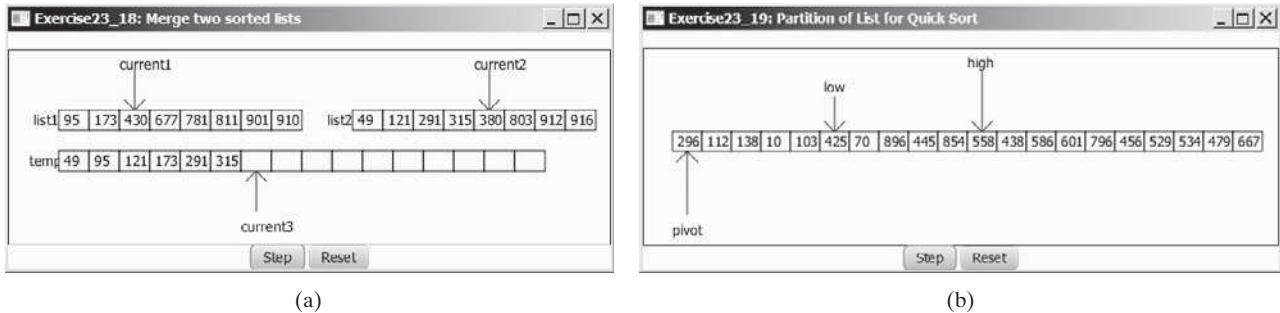
- \*23.17** (*Radix sort animation*) Write a program that animates the radix sort algorithm. Create an array that consists of 20 random numbers from 0 to 1,000. The array elements are displayed, as shown in Figure 23.21. Clicking the *Step* button causes the program to place a number in a bucket. The number that has just been placed is displayed in red. Once all the numbers are placed in the buckets, clicking the *Step* button collects all the numbers from the buckets and moves

them back to the array. When the algorithm is finished, clicking the *Step* button displays a message to inform the user. Clicking the *Reset* button creates a new random array for a new start.



**FIGURE 23.21** The program animates radix sort.

**\*23.18** (*Merge animation*) Write a program that animates the merge of two sorted lists. Create two arrays, **list1** and **list2**, each of which consists of 8 random numbers from 1 to 999. The array elements are displayed, as shown in Figure 23.22a. Clicking the *Step* button causes the program to move an element from **list1** or **list2** to **temp**. Clicking the *Reset* button creates two new random arrays for a new start. When the algorithm is finished, clicking the *Step* button displays a message to inform the user.



**FIGURE 23.22** The program animates a merge of two sorted lists. (b) The program animates a partition for quick sort.

**\*23.19** (*Quick sort partition animation*) Write a program that animates the partition for a quick sort. The program creates a list that consists of 20 random numbers from 1 to 999. The list is displayed, as shown in Figure 23.22b. Clicking the *Step* button causes the program to move **low** to the right or **high** to the left, or swap the elements at **low** and **high**. Clicking the *Reset* button creates a new list of random numbers for a new start. When the algorithm is finished, clicking the *Step* button displays a message to inform the user.

**\*23.20** (*Modify merge sort*) Rewrite the **mergeSort** method to recursively sort the first half of the array and the second half of the array without creating new temporary arrays, and then merge the two into a temporary array and copy its contents to the original array, as shown in Figure 23.6b.

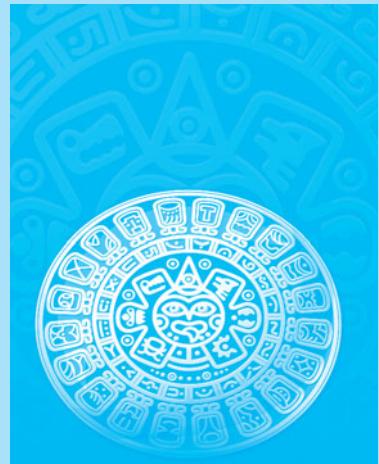
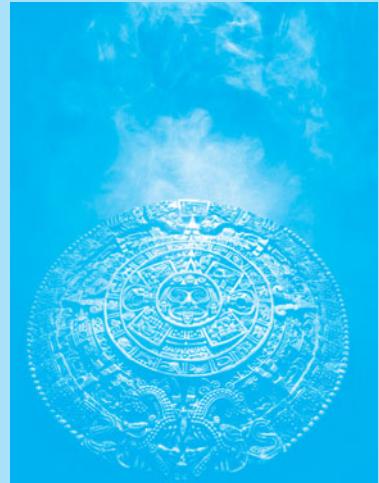
# CHAPTER

# 24

## IMPLEMENTING LISTS, STACKS, QUEUES, AND PRIORITY QUEUES

### Objectives

- To design common features of lists in an interface and provide skeleton implementation in a convenience abstract class (§24.2).
- To design and implement an array list using an array (§24.3).
- To design and implement a linked list using a linked structure (§24.4).
- To design and implement a stack class using an array list and a queue class using a linked list (§24.5).
- To design and implement a priority queue using a heap (§24.6).



## 24.1 Introduction



*This chapter focuses on implementing data structures.*

Lists, stacks, queues, and priority queues are classic data structures typically covered in a data structures course. They are supported in the Java API, and their uses were presented in Chapter 20, Lists, Stacks, Queues, and Priority Queues. This chapter will examine how these data structures are implemented under the hood. Implementation of sets and maps is covered in Chapter 27. Through these examples, you will learn how to design and implement custom data structures.

## 24.2 Common Features for Lists



*Common features of lists are defined in the `List` interface.*

A list is a popular data structure for storing data in sequential order—for example, a list of students, a list of available rooms, a list of cities, a list of books. You can perform the following operations on a list:

- Retrieve an element from the list.
- Insert a new element into the list.
- Delete an element from the list.
- Find out how many elements are in the list.
- Determine whether an element is in the list.
- Check whether the list is empty.

There are two ways to implement a list. One is to use an *array* to store the elements. Array size is fixed. If the capacity of the array is exceeded, you need to create a new, larger array and copy all the elements from the current array to the new array. The other approach is to use a *linked structure*. A linked structure consists of nodes. Each node is dynamically created to hold an element. All the nodes are linked together to form a list. Thus you can define two classes for lists. For convenience, let's name these two classes `MyArrayList` and `MyLinkedList`. These two classes have common operations but different implementations.



### Design Guide

The common operations can be generalized in an interface or an abstract class. A good strategy is to combine the virtues of interfaces and abstract classes by providing both an interface and a convenience abstract class in the design so that the user can use either of them, whichever is convenient. The abstract class provides a skeletal implementation of the interface, which minimizes the effort required to implement the interface.

convenience abstract class for interface



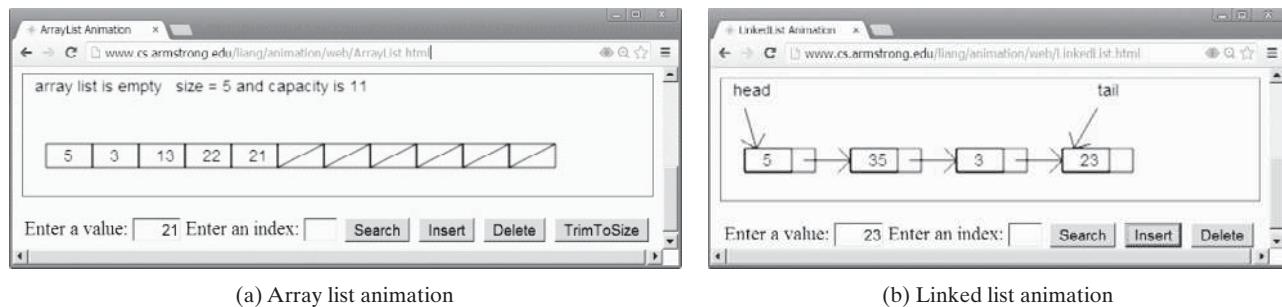
list animation on Companion Website



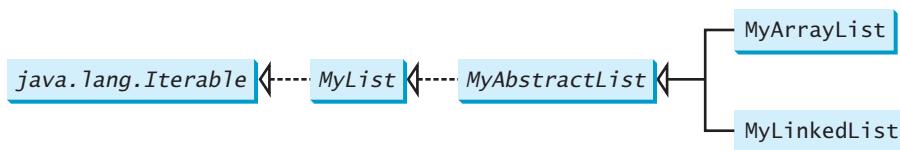
### Pedagogical Note

For an interactive demo on how array lists and linked lists work, go to [www.cs.armstrong.edu/liang/animation/web/ArrayList.html](http://www.cs.armstrong.edu/liang/animation/web/ArrayList.html) and [www.cs.armstrong.edu/liang/animation/web/LinkedList.html](http://www.cs.armstrong.edu/liang/animation/web/LinkedList.html), as shown in Figure 24.1.

Let us name the interface `MyList` and the convenience abstract class `MyAbstractList`. Figure 24.2 shows the relationship of `MyList`, `MyAbstractList`, `MyArrayList`, and `MyLinkedList`. The methods in `MyList` and the methods implemented in `MyAbstractList` are shown in Figure 24.3. Listing 24.1 gives the source code for `MyList`.



**FIGURE 24.1** The animation tool enables you to see how array lists and linked lists work.



**FIGURE 24.2** `MyList` defines a common interface for `MyAbstractList`, `MyArrayList`, and `MyLinkedList`.

### LISTING 24.1 `MyList.java`

```

1 public interface MyList<E> extends java.lang.Iterable<E> {
2 /** Add a new element at the end of this list */
3 public void add(E e);
4
5 /** Add a new element at the specified index in this list */
6 public void add(int index, E e);
7
8 /** Clear the list */
9 public void clear();
10
11 /** Return true if this list contains the element */
12 public boolean contains(E e);
13
14 /** Return the element from this list at the specified index */
15 public E get(int index);
16
17 /** Return the index of the first matching element in this list.
18 * Return -1 if no match. */
19 public int indexOf(E e);
20
21 /** Return true if this list doesn't contain any elements */
22 public boolean isEmpty();
23
24 /** Return the index of the last matching element in this list
25 * Return -1 if no match. */
26 public int lastIndexOf(E e);
27
28 /** Remove the first occurrence of the element e from this list.
29 * Shift any subsequent elements to the left.
30 * Return true if the element is removed. */

```

```

remove(e) 31 public boolean remove(E e);
32
33 /** Remove the element at the specified position in this list.
34 * Shift any subsequent elements to the left.
35 * Return the element that was removed from the list. */
36 public E remove(int index);
37
38 /** Replace the element at the specified position in this list
39 * with the specified element and return the old element. */
40 public Object set(int index, E e);
41
42 /** Return the number of elements in this list */
43 public int size();
44 }

```

**MyAbstractList** declares variable **size** to indicate the number of elements in the list. The methods **isEmpty()**, **size()**, **add(E)**, and **remove(E)** can be implemented in the class, as shown in Listing 24.2.



FIGURE 24.3 **MyList** defines the methods for manipulating a list. **MyAbstractList** provides a partial implementation of the **MyList** interface.

**LISTING 24.2** MyAbstractList.java

```

1 public abstract class MyAbstractList<E> implements MyList<E> {
2 protected int size = 0; // The size of the list
3
4 /** Create a default list */
5 protected MyAbstractList() {
6
7
8 /** Create a list from an array of objects */
9 protected MyAbstractList(E[] objects) {
10 for (int i = 0; i < objects.length; i++)
11 add(objects[i]);
12 }
13
14 @Override /** Add a new element at the end of this list */
15 public void add(E e) {
16 add(size, e);
17 }
18
19 @Override /** Return true if this list doesn't contain any elements */
20 public boolean isEmpty() {
21 return size == 0;
22 }
23
24 @Override /** Return the number of elements in this list */
25 public int size() {
26 return size;
27 }
28
29 @Override /** Remove the first occurrence of the element e
30 * from this list. Shift any subsequent elements to the left.
31 * Return true if the element is removed. */
32 public boolean remove(E e) {
33 if (indexOf(e) >= 0) {
34 remove(indexOf(e));
35 return true;
36 }
37 else
38 return false;
39 }
40 }

```

The following sections give the implementation for **MyArrayList** and **MyLinkedList**, respectively.

**Design Guide**

Protected data fields are rarely used. However, making **size** a protected data field in the **MyAbstractList** class is a good choice. The subclass of **MyAbstractList** can access **size**, but nonsubclasses of **MyAbstractList** in different packages cannot access it. As a general rule, you can declare protected data fields in abstract classes.

protected data field

- 24.1** Suppose **list** is an instance of **MyList**, can you get an iterator for **list** using **list.iterator()**?
- 24.2** Can you create a list using **new MyAbstractList()**?
- 24.3** What methods in **MyList** are overridden in **MyAbstractList**?
- 24.4** What are the benefits of defining both the **MyList** interface and the **MyAbstractList** class?



## 24.3 Array Lists



An array list is implemented using an array.

An array is a fixed-size data structure. Once an array is created, its size cannot be changed. Nevertheless, you can still use arrays to implement dynamic data structures. The trick is to create a larger new array to replace the current array, if the current array cannot hold new elements in the list.

Initially, an array, say `data` of `E[]` type, is created with a default size. When inserting a new element into the array, first make sure that there is enough room in the array. If not, create a new array twice as large as the current one. Copy the elements from the current array to the new array. The new array now becomes the current array. Before inserting a new element at a specified index, shift all the elements after the index to the right and increase the list size by 1, as shown in Figure 24.4.



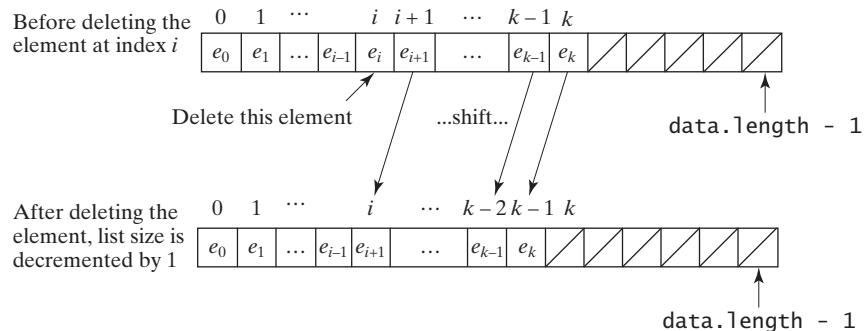
**FIGURE 24.4** Inserting a new element into the array requires that all the elements after the insertion point be shifted one position to the right, so that the new element can be inserted at the insertion point.



### Note

The data array is of type `E[]`. Each cell in the array actually stores the reference of an object.

To remove an element at a specified index, shift all the elements after the index to the left by one position and decrease the list size by 1, as shown in Figure 24.5.



**FIGURE 24.5** Deleting an element from the array requires that all the elements after the deletion point be shifted one position to the left.

`MyArrayList` uses an array to implement `MyAbstractList`, as shown in Figure 24.6. Its implementation is given in Listing 24.3.



FIGURE 24.6 `MyArrayList` implements a list using an array.

### LISTING 24.3 `MyArrayList.java`

```

1 public class MyArrayList<E> extends MyAbstractList<E> {
2 public static final int INITIAL_CAPACITY = 16;
3 private E[] data = (E[]) new Object[INITIAL_CAPACITY];
4
5 /** Create a default list */
6 public MyArrayList() {
7
8
9 /** Create a list from an array of objects */
10 public MyArrayList(E[] objects) {
11 for (int i = 0; i < objects.length; i++)
12 add(objects[i]); // Warning: don't use super(objects)!
13 }
14
15 @Override /** Add a new element at the specified index */
16 public void add(int index, E e) {
17 ensureCapacity();
18
19 // Move the elements to the right after the specified index
20 for (int i = size - 1; i >= index; i--)
21 data[i + 1] = data[i];
22
23 // Insert new element to data[index]
24 data[index] = e;
25
26 // Increase size by 1
27 size++;
28 }
29
30 /** Create a new larger array, double the current size + 1 */
31 private void ensureCapacity() {
32 if (size >= data.length) {
33 E[] newData = (E[])(new Object[size * 2 + 1]);
34 System.arraycopy(data, 0, newData, 0, size);
35 data = newData;
36 }
37 }
38 }

```

initial capacity  
create an array

no-arg constructor

constructor

add

ensureCapacity

double capacity + 1

```

39 @Override /** Clear the list */
40 public void clear() {
41 data = (E[])new Object[INITIAL_CAPACITY];
42 size = 0;
43 }
44
45 @Override /** Return true if this list contains the element */
46 public boolean contains(E e) {
47 for (int i = 0; i < size; i++)
48 if (e.equals(data[i])) return true;
49
50 return false;
51 }
52
53 @Override /** Return the element at the specified index */
54 public E get(int index) {
55 checkIndex(index);
56 return data[index];
57 }
58
59 private void checkIndex(int index) {
60 if (index < 0 || index >= size)
61 throw new IndexOutOfBoundsException
62 ("index " + index + " out of bounds");
63 }
64
65 @Override /** Return the index of the first matching element
66 * in this list. Return -1 if no match. */
67 public int indexOf(E e) {
68 for (int i = 0; i < size; i++)
69 if (e.equals(data[i])) return i;
70
71 return -1;
72 }
73
74 @Override /** Return the index of the last matching element
75 * in this list. Return -1 if no match. */
76 public int lastIndexOf(E e) {
77 for (int i = size - 1; i >= 0; i--)
78 if (e.equals(data[i])) return i;
79
80 return -1;
81 }
82
83 @Override /** Remove the element at the specified position
84 * in this list. Shift any subsequent elements to the left.
85 * Return the element that was removed from the list. */
86 public E remove(int index) {
87 checkIndex(index);
88
89 E e = data[index];
90
91 // Shift data to the left
92 for (int j = index; j < size - 1; j++)
93 data[j] = data[j + 1];
94
95 data[size - 1] = null; // This element is now null
96
97 // Decrement size
98 size--;

```

```

99
100 return e;
101 }
102
103 @Override /** Replace the element at the specified position
104 * in this list with the specified element. */
105 public E set(int index, E e) { set
106 checkIndex(index);
107 E old = data[index];
108 data[index] = e;
109 return old;
110 }
111
112 @Override
113 public String toString() { toString
114 StringBuilder result = new StringBuilder("[");
115
116 for (int i = 0; i < size; i++) {
117 result.append(data[i]);
118 if (i < size - 1) result.append(", ");
119 }
120
121 return result.toString() + "]";
122 }
123
124 /** Trims the capacity to current size */
125 public void trimToSize() { trimToSize
126 if (size != data.length) {
127 E[] newData = (E[])(new Object[size]);
128 System.arraycopy(data, 0, newData, 0, size);
129 data = newData;
130 } // If size == capacity, no need to trim
131 }
132
133 @Override /** Override iterator() defined in Iterable */
134 public java.util.Iterator<E> iterator() { iterator
135 return new ArrayListIterator();
136 }
137
138 private class ArrayListIterator implements java.util.Iterator<E> {
139 private int current = 0; // Current index
140
141 @Override
142 public boolean hasNext() {
143 return (current < size);
144 }
145
146 @Override
147 public E next() {
148 return data[current++];
149 }
150
151 @Override
152 public void remove() {
153 MyArrayList.this.remove(current);
154 }
155 }
156 }
157 }
```

The constant `INITIAL_CAPACITY` (line 2) is used to create an initial array `data` (line 3). Owing to generics type erasure, you cannot create a generic array using the syntax `new e[INITIAL_CAPACITY]`. To circumvent this limitation, an array of the `Object` type is created in line 3 and cast into `E[]`.

Note that the implementation of the second constructor in `MyArrayList` is the same as for `MyAbstractList`. Can you replace lines 11–12 with `super(objects)`? See Checkpoint Question 24.8 for answers.

add

The `add(int index, E e)` method (lines 16–28) inserts element `e` at the specified `index` in the array. This method first invokes `ensureCapacity()` (line 17), which ensures that there is a space in the array for the new element. It then shifts all the elements after the index one position to the right before inserting the element (lines 20–21). After the element is added, `size` is incremented by 1 (line 27). Note that the variable `size` is defined as `protected` in `MyAbstractList`, so it can be accessed in `MyArrayList`.

ensureCapacity

The `ensureCapacity()` method (lines 31–37) checks whether the array is full. If so, the program creates a new array that doubles the current array size + 1, copies the current array to the new array using the `System.arraycopy` method, and sets the new array as the current array.

clear

The `clear()` method (lines 40–43) creates a new array using the size as `INITIAL_CAPACITY` and resets the variable `size` to 0. The class will work if line 41 is deleted. However, the class will have a memory leak, because the elements are still in the array, although they are no longer needed. By creating a new array and assigning it to `data`, the old array and the elements stored in the old array become garbage, which will be automatically collected by the JVM.

contains

The `contains(E e)` method (lines 46–51) checks whether element `e` is contained in the array by comparing `e` with each element in the array using the `equals` method.

The `get(int index)` method (lines 54–57) checks if `index` is within the range and returns `data[index]` if `index` is in the range.

checkIndex

The `checkIndex(int index)` method (lines 59–63) checks if `index` is within the range. If not, the method throws an `IndexOutOfBoundsException` (line 61).

indexOf

The `indexOf(E e)` method (lines 67–72) compares element `e` with the elements in the array, starting from the first one. If a match is found, the index of the element is returned; otherwise, `-1` is returned.

lastIndexOf

The `lastIndexOf(E e)` method (lines 76–81) compares element `e` with the elements in the array, starting from the last one. If a match is found, the index of the element is returned; otherwise, `-1` is returned.

remove

The `remove(int index)` method (lines 86–101) shifts all the elements after the index one position to the left (lines 92–93) and decrements `size` by 1 (line 98). The last element is not used anymore and is set to `null` (line 95).

set

The `set(int index, E e)` method (lines 105–110) simply assigns `e` to `data[index]` to replace the element at the specified index with element `e`.

toString

The `toString()` method (lines 113–122) overrides the `toString` method in the `Object` class to return a string representing all the elements in the list.

trimToSize

The `trimToSize()` method (lines 125–131) creates a new array whose size matches the current array-list size (line 127), copies the current array to the new array using the `System.arraycopy` method (line 128), and sets the new array as the current array (line 129). Note that if `size == capacity`, there is no need to trim the size of the array.

iterator

The `iterator()` method defined in the `java.lang.Iterable` interface is implemented to return an instance on `java.util.Iterator` (lines 134–136). The `ArrayListIterator` class implements `Iterator` with concrete methods for `hasNext`, `next`, and `remove` (lines 143–155). It uses `current` to denote the current position of the element being traversed (line 140).

Listing 24.4 gives an example that creates a list using `MyArrayList`. It uses the `add` method to add strings to the list and the `remove` method to remove strings. Since

`MyArrayList` implements `Iterable`, the elements can be traversed using a for-each loop (lines 35–36).

#### LISTING 24.4 TestMyArrayList.java

```

1 public class TestMyArrayList {
2 public static void main(String[] args) {
3 // Create a list
4 MyList<String> list = new MyArrayList<String>(); create a list
5
6 // Add elements to the list
7 list.add("America"); // Add it to the list
8 System.out.println("(1) " + list); add to list
9
10 list.add(0, "Canada"); // Add it to the beginning of the list
11 System.out.println("(2) " + list);
12
13 list.add("Russia"); // Add it to the end of the list
14 System.out.println("(3) " + list);
15
16 list.add("France"); // Add it to the end of the list
17 System.out.println("(4) " + list);
18
19 list.add(2, "Germany"); // Add it to the list at index 2
20 System.out.println("(5) " + list);
21
22 list.add(5, "Norway"); // Add it to the list at index 5
23 System.out.println("(6) " + list);
24
25 // Remove elements from the list
26 list.remove("Canada"); // Same as list.remove(0) in this case
27 System.out.println("(7) " + list); remove from list
28
29 list.remove(2); // Remove the element at index 2
30 System.out.println("(8) " + list);
31
32 list.remove(list.size() - 1); // Remove the last element
33 System.out.print("(9) " + list + "\n(10) ");
34
35 for (String s: list) using iterator
36 System.out.print(s.toUpperCase() + " ");
37 }
38 }
```

- (1) [America]
- (2) [Canada, America]
- (3) [Canada, America, Russia]
- (4) [Canada, America, Russia, France]
- (5) [Canada, America, Germany, Russia, France]
- (6) [Canada, America, Germany, Russia, France, Norway]
- (7) [America, Germany, Russia, France, Norway]
- (8) [America, Germany, France, Norway]
- (9) [America, Germany, France]
- (10) AMERICA GERMANY FRANCE



**24.5** What are the limitations of the array data type?

**24.6** `MyArrayList` is implemented using an array, and an array is a fixed-size data structure. Why is `MyArrayList` considered a dynamic data structure?



- 24.7** Show the length of the array in `MyArrayList` after each of the following statements is executed.

```
1 MyArrayList<Double> list = new MyArrayList<>();
2 list.add(1.5);
3 list.trimToSize();
4 list.add(3.4);
5 list.add(7.4);
6 list.add(17.4);
```

- 24.8** What is wrong if lines 11–12 in Listing 24.3, `MyArrayList.java`,

```
for (int i = 0; i < objects.length; i++)
 add(objects[i]);
```

are replaced by

```
super(objects);
```

or

```
data = objects;
size = objects.length;
```

- 24.9** If you change the code in line 33 in Listing 24.3, `MyArrayList.java`, from

```
E[] newData = (E[])(new Object[size * 2 + 1]);
```

to

```
E[] newData = (E[])(new Object[size * 2]);
```

the program is incorrect. Can you find the reason?

- 24.10** Will the `MyArrayList` class have memory leak if the following code in line 41 is deleted?

```
data = (E[])new Object[INITIAL_CAPACITY];
```

- 24.11** The `get(index)` method invokes the `checkIndex(index)` method (lines 59–63 in Listing 24.3) to throw an `IndexOutOfBoundsException` if the index is out of bounds. Suppose the `add(index, e)` is implemented as follows:

```
public void add(int index, E e) {
 checkIndex(index);

 // Same as lines 17–27 in Listing 24.3 MyArrayList.java
}
```

What will happen if you run the following code?

```
MyArrayList<String> list = new MyArrayList<>();
list.add("New York");
```

## 24.4 Linked Lists



A linked list is implemented using a linked structure.

Since `MyArrayList` is implemented using an array, the methods `get(int index)` and `set(int index, E e)` for accessing and modifying an element through an index and the

`add(E e)` method for adding an element at the end of the list are efficient. However, the methods `add(int index, E e)` and `remove(int index)` are inefficient, because they require shifting a potentially large number of elements. You can use a linked structure to implement a list to improve efficiency for adding and removing an element at the beginning of a list.

#### 24.4.1 Nodes

In a linked list, each element is contained in an object, called the *node*. When a new element is added to the list, a node is created to contain it. Each node is linked to its next neighbor, as shown in Figure 24.7.

A node can be created from a class defined as follows:

```
class Node<E> {
 E element;
 Node<E> next;

 public Node(E e) {
 element = e;
 }
}
```



FIGURE 24.7 A linked list consists of any number of nodes chained together.

We use the variable `head` to refer to the first node in the list, and the variable `tail` to the last node. If the list is empty, both `head` and `tail` are `null`. Here is an example that creates a linked list to hold three nodes. Each node stores a string element.

Step 1: Declare `head` and `tail`.

```
Node<String> head = null; The list is empty now
Node<String> tail = null;
```

`head` and `tail` are both `null`. The list is empty.

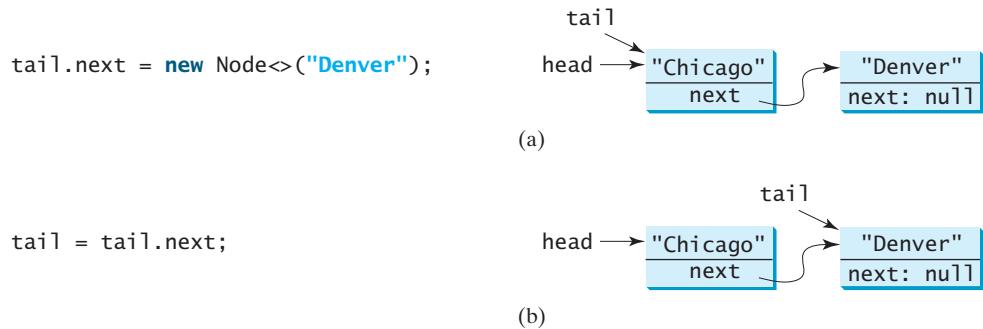
Step 2: Create the first node and append it to the list, as shown in Figure 24.8. After the first node is inserted in the list, `head` and `tail` point to this node.

```
head = new Node<>("Chicago");
tail = head; After the first node is inserted
```

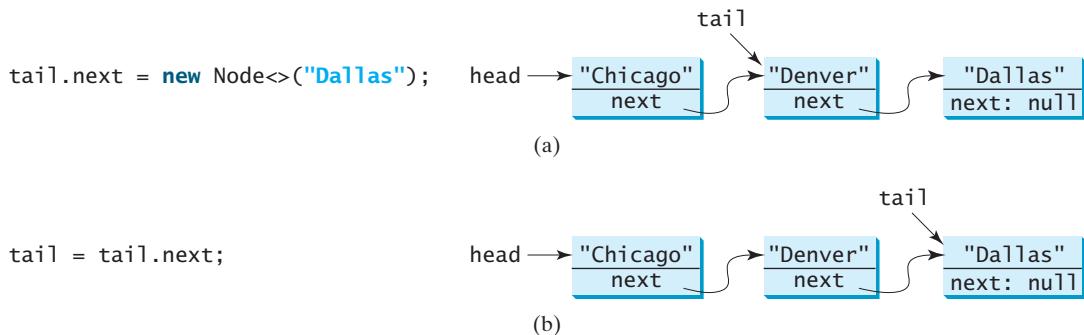
The diagram shows the state of the list after inserting the first node. It features a single node box labeled "Chicago". Above the box, an arrow labeled "head" points to the start of the box, and another arrow labeled "tail" also points to the start of the box. Below the box, the word "next: null" is written, indicating that this is the only node in the list.

FIGURE 24.8 Append the first node to the list. Both `head` and `tail` point to this node.

Step 3: Create the second node and append it into the list, as shown in Figure 24.9a. To append the second node to the list, link the first node with the new node. The new node is now the tail node, so you should move `tail` to point to this new node, as shown in Figure 24.9b.

**FIGURE 24.9** Append the second node to the list. Tail now points to this new node.

Step 4: Create the third node and append it to the list, as shown in Figure 24.10a. To append the new node to the list, link the last node in the list with the new node. The new node is now the tail node, so you should move `tail` to point to this new node, as shown in Figure 24.10b.

**FIGURE 24.10** Append the third node to the list.

Each node contains the element and a data field named `next` that points to the next element. If the node is the last in the list, its pointer data field `next` contains the value `null`. You can use this property to detect the last node. For example, you can write the following loop to traverse all the nodes in the list.

|                                                     |                                                                                                                                               |
|-----------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|
| current pointer<br>check last node<br><br>next node | <pre> 1  Node current = head; 2  while (current != null) { 3    System.out.println(current.element); 4    current = current.next; 5  } </pre> |
|-----------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|

The variable `current` points initially to the first node in the list (line 1). In the loop, the element of the current node is retrieved (line 3), and then `current` points to the next node (line 4). The loop continues until the current node is `null`.

#### 24.4.2 The `MyLinkedList` Class

The `MyLinkedList` class uses a linked structure to implement a dynamic list. It extends `MyAbstractList`. In addition, it provides the methods `addFirst`, `addLast`, `removeFirst`, `removeLast`, `getFirst`, and `getLast`, as shown in Figure 24.11.



FIGURE 24.11 MyLinkedList implements a list using a linked list of nodes.

Assuming that the class has been implemented, Listing 24.5 gives a test program that uses the class.

### LISTING 24.5 TestMyLinkedList.java

```

1 public class TestMyLinkedList {
2 /** Main method */
3 public static void main(String[] args) {
4 // Create a list for strings
5 MyLinkedList<String> list = new MyLinkedList<>(); create list
6
7 // Add elements to the list
8 list.add("America"); // Add it to the list append element
9 System.out.println("(1) " + list); print list
10
11 list.add(0, "Canada"); // Add it to the beginning of the list insert element
12 System.out.println("(2) " + list);
13
14 list.add("Russia"); // Add it to the end of the list append element
15 System.out.println("(3) " + list);
16
17 list.addLast("France"); // Add it to the end of the list append element
18 System.out.println("(4) " + list);
19
20 list.add(2, "Germany"); // Add it to the list at index 2 insert element
21 System.out.println("(5) " + list);
22
23 list.add(5, "Norway"); // Add it to the list at index 5 insert element
24 System.out.println("(6) " + list);
25
26 list.add(0, "Poland"); // Same as list.addFirst("Poland") insert element
27 System.out.println("(7) " + list);
28
29 // Remove elements from the list
30 list.remove(0); // Same as list.remove("Poland") in this case remove element
31 System.out.println("(8) " + list);

```

```

remove element 32
 33 list.remove(2); // Remove the element at index 2
 34 System.out.println("(9) " + list);
 35
remove element 36 list.remove(list.size() - 1); // Remove the last element
 37 System.out.print("(10) " + list + "\n(11) ");
 38
traverse using iterator 39 for (String s: list)
 40 System.out.print(s.toUpperCase() + " ");
 41 }
 42 }
```



```

(1) [America]
(2) [Canada, America]
(3) [Canada, America, Russia]
(4) [Canada, America, Russia, France]
(5) [Canada, America, Germany, Russia, France]
(6) [Canada, America, Germany, Russia, France, Norway]
(7) [Poland, Canada, America, Germany, Russia, France, Norway]
(8) [Canada, America, Germany, Russia, France, Norway]
(9) [Canada, America, Russia, France, Norway]
(10) [Canada, America, Russia, France]
(11) CANADA AMERICA RUSSIA FRANCE
```

### 24.4.3 Implementing MyLinkedList

Now let us turn our attention to implementing the `MyLinkedList` class. We will discuss how to implement the methods `addFirst`, `addLast`, `add(index, e)`, `removeFirst`, `removeLast`, and `remove(index)` and leave the other methods in the `MyLinkedList` class as exercises.

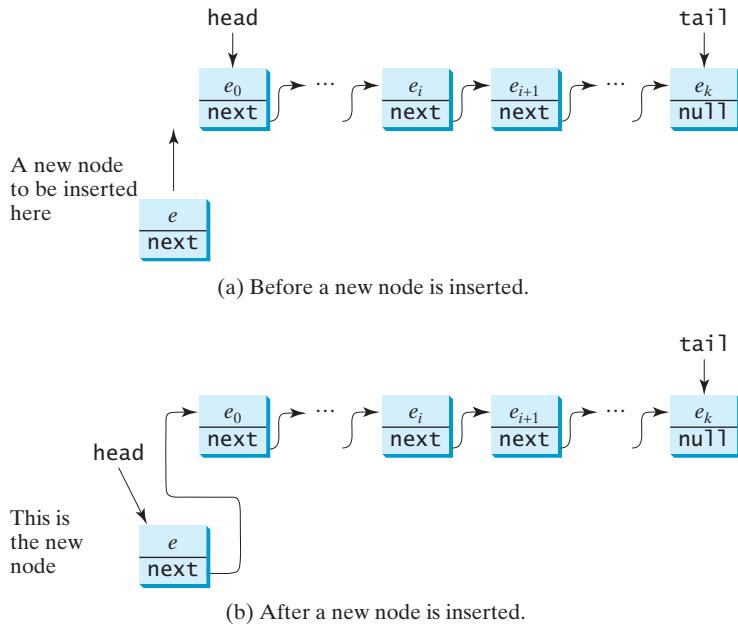
#### 24.4.3.1 Implementing addFirst(e)

The `addFirst(e)` method creates a new node for holding element `e`. The new node becomes the first node in the list. It can be implemented as follows:

```

create a node 1 public void addFirst(E e) {
link with head 2 Node<E> newNode = new Node<>(e); // Create a new node
head to new node 3 newNode.next = head; // link the new node with the head
increase size 4 head = newNode; // head points to the new node
 5 size++; // Increase list size
 6
was empty? 7 if (tail == null) // The new node is the only node in list
 8 tail = head;
 9 }
```

The `addFirst(e)` method creates a new node to store the element (line 2) and inserts the node at the beginning of the list (line 3), as shown in Figure 24.12a. After the insertion, `head` should point to this new element node (line 4), as shown in Figure 24.12b.



**FIGURE 24.12** A new element is added to the beginning of the list.

If the list is empty (line 7), both **head** and **tail** will point to this new node (line 8). After the node is created, **size** should be increased by **1** (line 5).

#### 24.4.3.2 Implementing addLast(e)

The **addLast(e)** method creates a node to hold the element and appends the node at the end of the list. It can be implemented as follows:

```

1 public void addLast(E e) {
2 Node<E> newNode = new Node<>(e); // Create a new node for e create a node
3
4 if (tail == null) {
5 head = tail = newNode; // The only node in list
6 }
7 else {
8 tail.next = newNode; // Link the new node with the last node
9 tail = tail.next; // tail now points to the last node
10 }
11
12 size++; // Increase size increase size
13 }
```

The **addLast(e)** method creates a new node to store the element (line 2) and appends it to the end of the list. Consider two cases:

1. If the list is empty (line 4), both **head** and **tail** will point to this new node (line 5);
2. Otherwise, link the node with the last node in the list (line 8). **tail** should now point to this new node (line 9). Figure 24.13a and Figure 24.13b show the new node for element **e** before and after the insertion.

In any case, after the node is created, the **size** should be increased by **1** (line 12).



FIGURE 24.13 A new element is added at the end of the list.

#### 24.4.3.3 Implementing add(index, e)

The `add(index, e)` method inserts an element into the list at the specified index. It can be implemented as follows:

```

1 public void add(int index, E e) {
2 if (index == 0) addFirst(e); // Insert first
3 else if (index >= size) addLast(e); // Insert last
4 else { // Insert in the middle
5 Node<E> current = head;
6 for (int i = 1; i < index; i++)
7 current = current.next;
8 Node<E> temp = current.next;
9 current.next = new Node<E>(e);
10 (current.next).next = temp;
11 size++;
12 }
13 }
```

insert first  
insert last  
  
create a node  
increase size

There are three cases when inserting an element into the list:

1. If `index` is 0, invoke `addFirst(e)` (line 2) to insert the element at the beginning of the list.
2. If `index` is greater than or equal to `size`, invoke `addLast(e)` (line 3) to insert the element at the end of the list.
3. Otherwise, create a new node to store the new element and locate where to insert it. As shown in Figure 24.14a, the new node is to be inserted between the nodes `current` and `temp`. The method assigns the new node to `current.next` and assigns `temp` to the new node's `next`, as shown in Figure 24.14b. The size is now increased by 1 (line 11).

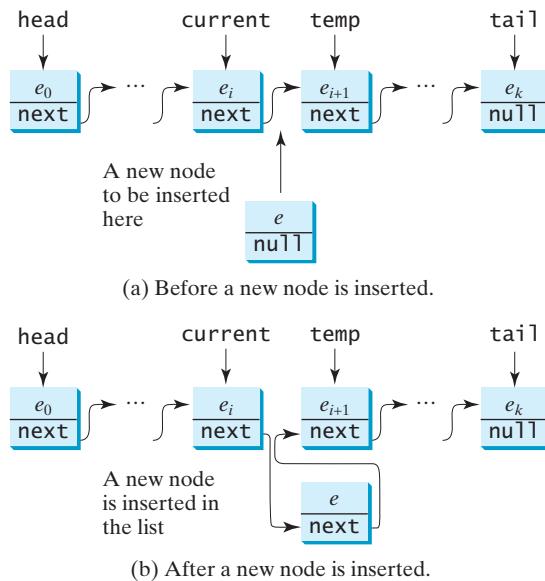
#### 24.4.3.4 Implementing removeFirst()

The `removeFirst()` method removes the first element from the list. It can be implemented as follows:

```

1 public E removeFirst() {
2 if (size == 0) return null; // Nothing to delete
3 else {
```

nothing to remove



**FIGURE 24.14** A new element is inserted in the middle of the list.

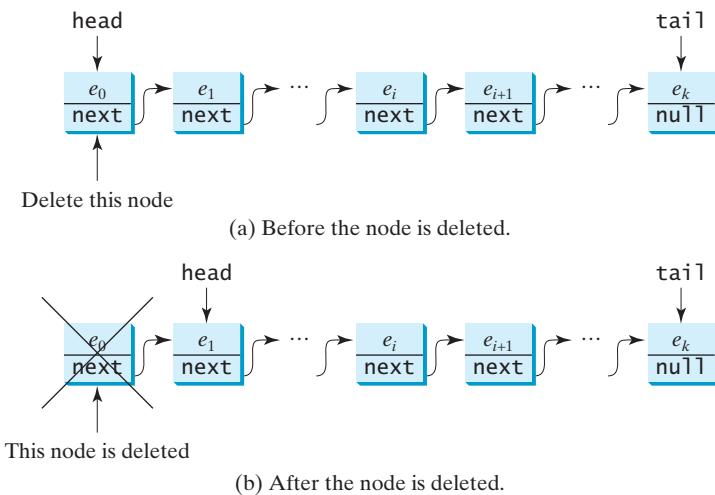
```

4 Node<E> temp = head; // Keep the first node temporarily
5 head = head.next; // Move head to point to next node
6 size--; // Reduce size by 1
7 if (head == null) tail = null; // List becomes empty
8 return temp.element(); // Return the deleted element
9 }
10 }
```

keep old head  
new head  
decrease size  
destroy the node

Consider two cases:

1. If the list is empty, there is nothing to delete, so return **null** (line 2).
2. Otherwise, remove the first node from the list by pointing **head** to the second node. Figure 24.15a and Figure 24.15b show the linked list before and after the deletion. The size is reduced by 1 after the deletion (line 6). If the list becomes empty, after removing the element, **tail** should be set to **null** (line 7).



**FIGURE 24.15** The first node is deleted from the list.

### 24.4.3.5 Implementing `removeLast()`

The `removeLast()` method removes the last element from the list. It can be implemented as follows:

```

empty?
size 1?

head and tail null
size is 0
return element

size > 1

move tail
reduce size
return element

1 public E removeLast() {
2 if (size == 0) return null; // Nothing to remove
3 else if (size == 1) { // Only one element in the list
4 Node<E> temp = head;
5 head = tail = null; // list becomes empty
6 size = 0;
7 return temp.element;
8 }
9 else {
10 Node<E> current = head;
11
12 for (int i = 0; i < size - 2; i++)
13 current = current.next;
14
15 Node<E> temp = tail;
16 tail = current;
17 tail.next = null;
18 size--;
19 return temp.element;
20 }
21 }
```

Consider three cases:

1. If the list is empty, return `null` (line 2).
2. If the list contains only one node, this node is destroyed; `head` and `tail` both become `null` (line 5). The size becomes `0` after the deletion (line 6) and the element value of the deleted node is returned (line 7).
3. Otherwise, the last node is destroyed (line 17) and the `tail` is repositioned to point to the second-to-last node. Figure 24.16a and Figure 24.16b show the last node before and after it is deleted. The size is reduced by `1` after the deletion (line 18) and the element value of the deleted node is returned (line 19).

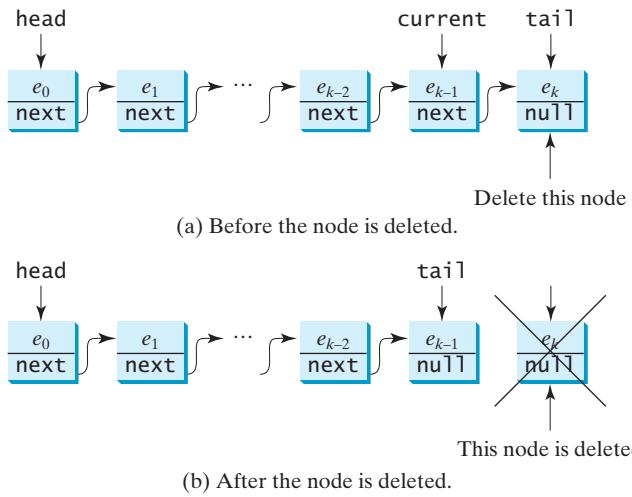


FIGURE 24.16 The last node is deleted from the list.

#### 24.4.3.6 Implementing `remove(index)`

The `remove(index)` method finds the node at the specified index and then removes it. It can be implemented as follows:

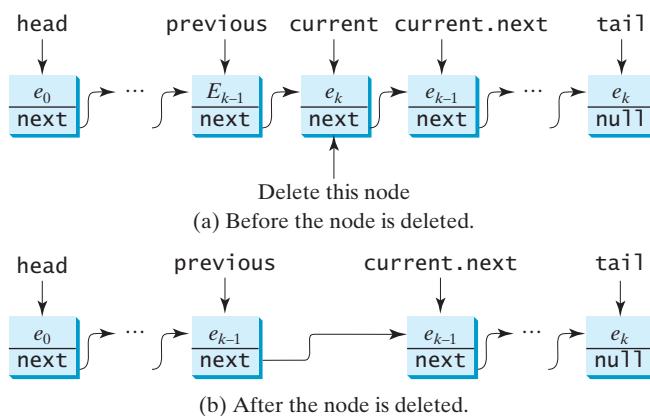
```

1 public E remove(int index) {
2 if (index < 0 || index >= size) return null; // Out of range
3 else if (index == 0) return removeFirst(); // Remove first
4 else if (index == size - 1) return removeLast(); // Remove last
5 else {
6 Node<E> previous = head;
7
8 for (int i = 1; i < index; i++) {
9 previous = previous.next;
10 }
11
12 Node<E> current = previous.next;
13 previous.next = current.next;
14 size--;
15 return current.element;
16 }
17 }
```

out of range  
remove first  
remove last  
  
locate previous  
  
locate current  
remove from list  
reduce size  
return element

Consider four cases:

1. If `index` is beyond the range of the list (i.e., `index < 0 || index >= size`), return `null` (line 2).
2. If `index` is `0`, invoke `removeFirst()` to remove the first node (line 3).
3. If `index` is `size - 1`, invoke `removeLast()` to remove the last node (line 4).
4. Otherwise, locate the node at the specified `index`. Let `current` denote this node and `previous` denote the node before this node, as shown in Figure 24.17a. Assign `current.next` to `previous.next` to eliminate the current node, as shown in Figure 24.17b.



**FIGURE 24.17** A node is deleted from the list.

Listing 24.6 gives the implementation of `MyLinkedList`. The implementation of `get(index)`, `indexOf(e)`, `lastIndexOf(e)`, `contains(e)`, and `set(index, e)` is omitted and left as an exercise. The `iterator()` method defined in the `java.lang.Iterable` interface is implemented to return an instance on `java.util.Iterator` (lines 126–128). The `LinkedListIterator` class implements `Iterator` with concrete methods for `hasNext`,

iterator

`next`, and `remove` (lines 134–149). This implementation uses `current` to point to the current position of the element being traversed (line 132). Initially, `current` points to the head of the list.

### LISTING 24.6 MyLinkedList.java

```

head, tail

no-arg constructor

constructor

getFirst

getLast

addFirst

addLast

add

removeFirst

1 public class MyLinkedList<E> extends MyAbstractList<E> {
2 private Node<E> head, tail;
3
4 /** Create a default list */
5 public MyLinkedList() {
6 }
7
8 /** Create a list from an array of objects */
9 public MyLinkedList(E[] objects) {
10 super(objects);
11 }
12
13 /** Return the head element in the list */
14 public E getFirst() {
15 if (size == 0) {
16 return null;
17 }
18 else {
19 return head.element;
20 }
21 }
22
23 /** Return the last element in the list */
24 public E getLast() {
25 if (size == 0) {
26 return null;
27 }
28 else {
29 return tail.element;
30 }
31 }
32
33 /** Add an element to the beginning of the list */
34 public void addFirst(E e) {
35 // Implemented in Section 24.4.3.1, so omitted here
36 }
37
38 /** Add an element to the end of the list */
39 public void addLast(E e) {
40 // Implemented in Section 24.4.3.2, so omitted here
41 }
42
43 @Override /** Add a new element at the specified index
44 * in this list. The index of the head element is 0 */
45 public void add(int index, E e) {
46 // Implemented in Section 24.4.3.3, so omitted here
47 }
48
49 /** Remove the head node and
50 * return the object that is contained in the removed node. */
51 public E removeFirst() {
52 // Implemented in Section 24.4.3.4, so omitted here
53 }
54

```

```

55 /** Remove the last node and
56 * return the object that is contained in the removed node. */
57 public E removeLast() { removeLast
58 // Implemented in Section 24.4.3.5, so omitted here
59 }
60
61 @Override /** Remove the element at the specified position in this
62 * list. Return the element that was removed from the list. */
63 public E remove(int index) { remove
64 // Implemented earlier in Section 24.4.3.6, so omitted here
65 }
66
67 @Override
68 public String toString() { toString
69 StringBuilder result = new StringBuilder("[");
70
71 Node<E> current = head;
72 for (int i = 0; i < size; i++) {
73 result.append(current.element);
74 current = current.next;
75 if (current != null) {
76 result.append(", ");
77 }
78 else {
79 result.append("]"); // Insert the closing] in the string
80 }
81 }
82
83 return result.toString();
84 }
85
86 @Override /** Clear the list */
87 public void clear() { clear
88 size = 0;
89 head = tail = null;
90 }
91
92 @Override /** Return true if this list contains the element e */
93 public boolean contains(E e) { contains
94 System.out.println("Implementation left as an exercise");
95 return true;
96 }
97
98 @Override /** Return the element at the specified index */
99 public E get(int index) { get
100 System.out.println("Implementation left as an exercise");
101 return null;
102 }
103
104 @Override /** Return the index of the head matching element
105 * in this list. Return -1 if no match. */
106 public int indexOf(E e) { indexOf
107 System.out.println("Implementation left as an exercise");
108 return 0;
109 }
110
111 @Override /** Return the index of the last matching element
112 * in this list. Return -1 if no match. */
113 public int lastIndexOf(E e) { lastIndexOf
114 System.out.println("Implementation left as an exercise");

```

```

115 return 0;
116 }
117
118 @Override /** Replace the element at the specified position
119 * in this list with the specified element. */
120 public E set(int index, E e) {
121 System.out.println("Implementation left as an exercise");
122 return null;
123 }
124
125 @Override /** Override iterator() defined in Iterable */
126 public java.util.Iterator<E> iterator() {
127 return new LinkedListIterator();
128 }
129
130 private class LinkedListIterator
131 implements java.util.Iterator<E> {
132 private Node<E> current = head; // Current index
133
134 @Override
135 public boolean hasNext() {
136 return (current != null);
137 }
138
139 @Override
140 public E next() {
141 E e = current.element;
142 current = current.next;
143 return e;
144 }
145
146 @Override
147 public void remove() {
148 System.out.println("Implementation left as an exercise");
149 }
150 }
151
152 // This class is only used in LinkedList, so it is private.
153 // This class does not need to access any
154 // instance members of LinkedList, so it is defined static.
155 private static class Node<E> {
156 E element;
157 Node<E> next;
158
159 public Node(E element) {
160 this.element = element;
161 }
162 }
163 }
```

#### 24.4.4 MyArrayList vs. MyLinkedList

Both **MyArrayList** and **MyLinkedList** can be used to store a list. **MyArrayList** is implemented using an array and **MyLinkedList** is implemented using a linked list. The overhead of **MyArrayList** is smaller than that of **MyLinkedList**. However, **MyLinkedList** is more efficient if you need to insert elements into and delete elements from the beginning of the list. Table 24.1 summarizes the complexity of the methods in **MyArrayList** and **MyLinkedList**. Note that **MyArrayList** is the same as **java.util.ArrayList** and **MyLinkedList** is the same as **java.util.LinkedList**.

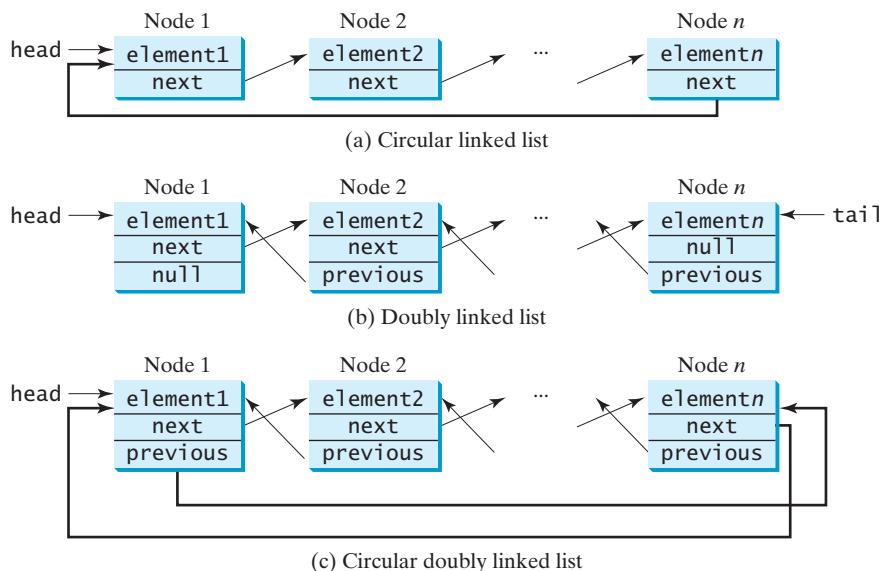
**TABLE 24.1** Time Complexities for Methods in `MyArrayList` and `MyLinkedList`

| Methods                            | <code>MyArrayList/ArrayList</code> | <code>MyLinkedList/LinkedList</code> |
|------------------------------------|------------------------------------|--------------------------------------|
| <code>add(e: E)</code>             | $O(1)$                             | $O(1)$                               |
| <code>add(index: int, e: E)</code> | $O(n)$                             | $O(n)$                               |
| <code>clear()</code>               | $O(1)$                             | $O(1)$                               |
| <code>contains(e: E)</code>        | $O(n)$                             | $O(n)$                               |
| <code>get(index: int)</code>       | $O(1)$                             | $O(n)$                               |
| <code>indexOf(e: E)</code>         | $O(n)$                             | $O(n)$                               |
| <code>isEmpty()</code>             | $O(1)$                             | $O(1)$                               |
| <code>lastIndexOf(e: E)</code>     | $O(n)$                             | $O(n)$                               |
| <code>remove(e: E)</code>          | $O(n)$                             | $O(n)$                               |
| <code>size()</code>                | $O(1)$                             | $O(1)$                               |
| <code>remove(index: int)</code>    | $O(n)$                             | $O(n)$                               |
| <code>set(index: int, e: E)</code> | $O(n)$                             | $O(n)$                               |
| <code>addFirst(e: E)</code>        | $O(n)$                             | $O(1)$                               |
| <code>removeFirst()</code>         | $O(n)$                             | $O(1)$                               |

## 24.4.5 Variations of Linked Lists

The linked list introduced in the preceding sections is known as a *singly linked list*. It contains a pointer to the list's first node, and each node contains a pointer to the next node sequentially. Several variations of the linked list are useful in certain applications.

A *circular, singly linked list* is like a singly linked list, except that the pointer of the last node points back to the first node, as shown in Figure 24.18a. Note that `tail` is not needed for circular linked lists. `head` points to the current node in the list. Insertion and deletion take place at the current node. A good application of a circular linked list is in the operating system that serves multiple users in a timesharing fashion. The system picks a user from a circular list and grants a small amount of CPU time, then moves on to the next user in the list.

**FIGURE 24.18** Linked lists may appear in various forms.

A *doubly linked list* contains nodes with two pointers. One points to the next node and the other to the previous node, as shown in Figure 24.18b. These two pointers are conveniently called a *forward pointer* and a *backward pointer*. Thus, a doubly linked list can be traversed forward and backward. The `java.util.LinkedList` class is implemented using a doubly linked list, and it supports traversing of the list forward and backward using the `ListIterator`.

A *circular, doubly linked list* is like a doubly linked list, except that the forward pointer of the last node points to the first node and the backward pointer of the first pointer points to the last node, as shown in Figure 24.18c.

The implementations of these linked lists are left as exercises.



**24.12** Both `MyArrayList` and `MyLinkedList` are used to store a list of objects. Why do we need both types of lists?

**24.13** Draw a diagram to show the linked list after each of the following statements is executed.

```
MyLinkedList<Double> list = new MyLinkedList<>();
list.add(1.5);
list.add(6.2);
list.add(3.4);
list.add(7.4);
list.remove(1.5);
list.remove(2);
```

**24.14** What is the time complexity of the `addFirst(e)` and `removeFirst()` methods in `MyLinkedList`?

**24.15** Suppose you need to store a list of elements. If the number of elements in the program is fixed, what data structure should you use? If the number of elements in the program changes, what data structure should you use?

**24.16** If you have to add or delete the elements at the beginning of a list, should you use `MyArrayList` or `MyLinkedList`? If most of the operations on a list involve retrieving an element at a given index, should you use `MyArrayList` or `MyLinkedList`?

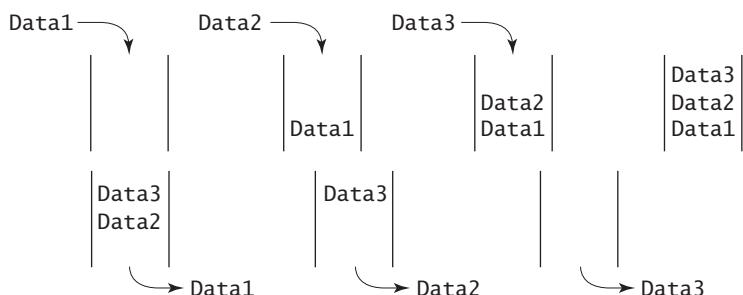
**24.17** Simplify the code in lines 75-80 in Listing 24.6 using a conditional expression.

## 24.5 Stacks and Queues



*Stacks can be implemented using array lists and queues can be implemented using linked lists.*

A stack can be viewed as a special type of list whose elements are accessed, inserted, and deleted only from the end (top), as shown in Figure 10.11. A queue represents a waiting list. It can be viewed as a special type of list whose elements are inserted into the end (tail) of the queue, and are accessed and deleted from the beginning (head), as shown in Figure 24.19.



**FIGURE 24.19** A queue holds objects in a first-in, first-out fashion.

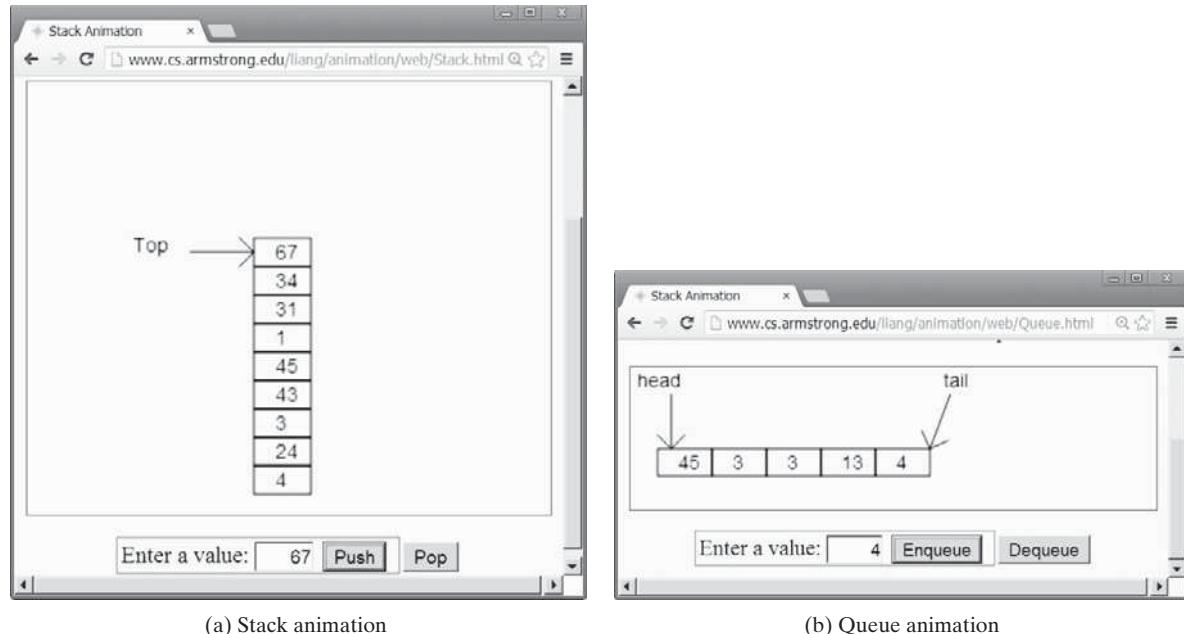


### Pedagogical Note

For an interactive demo on how stacks and queues work, go to [www.cs.armstrong.edu/liang/animation/web/Stack.html](http://www.cs.armstrong.edu/liang/animation/web/Stack.html), and [www.cs.armstrong.edu/liang/animation/web/Queue.html](http://www.cs.armstrong.edu/liang/animation/web/Queue.html), as shown in Figure 24.20.



stack and queue animation on Companion Website



**FIGURE 24.20** The animation tool enables you to see how stacks and queues work.

Since the insertion and deletion operations on a stack are made only at the end of the stack, it is more efficient to implement a stack with an array list than a linked list. Since deletions are made at the beginning of the list, it is more efficient to implement a queue using a linked list than an array list. This section implements a stack class using an array list and a queue class using a linked list.

There are two ways to design the stack and queue classes:

- Using inheritance: You can define a stack class by extending `ArrayList`, and a queue class by extending `LinkedList`, as shown in Figure 24.21a.
- Using composition: You can define an array list as a data field in the stack class, and a linked list as a data field in the queue class, as shown in Figure 24.21b.



(a) Using inheritance



(b) Using composition

**FIGURE 24.21** `GenericStack` and `GenericQueue` may be implemented using inheritance or composition.

Both designs are fine, but using composition is better because it enables you to define a completely new stack class and queue class without inheriting the unnecessary and inappropriate methods from the array list and linked list. The implementation of the stack class using the composition approach was given in Listing 19.1, `GenericStack.java`. Listing 24.7 implements the `GenericQueue` class using the composition approach. Figure 24.22 shows the UML of the class.

FIGURE 24.22 `GenericQueue` uses a linked list to provide a first-in, first-out data structure.**LISTING 24.7** `GenericQueue.java`

```

linked list
1 public class GenericQueue<E> {
2 private java.util.LinkedList<E> list
3 = new java.util.LinkedList<>();
4
enqueue
5 public void enqueue(E e) {
6 list.addLast(e);
7 }
8
dequeue
9 public E dequeue() {
10 return list.removeFirst();
11 }
12
getSize
13 public int getSize() {
14 return list.size();
15 }
16
toString
17 @Override
18 public String toString() {
19 return "Queue: " + list.toString();
20 }
21 }

```

A linked list is created to store the elements in a queue (lines 2–3). The `enqueue(e)` method (lines 5–7) adds element `e` into the tail of the queue. The `dequeue()` method (lines 9–11) removes an element from the head of the queue and returns the removed element. The `getSize()` method (lines 13–15) returns the number of elements in the queue.

Listing 24.8 gives an example that creates a stack using `GenericStack` and a queue using `GenericQueue`. It uses the `push(enqueue)` method to add strings to the stack (queue) and the `pop(dequeue)` method to remove strings from the stack (queue).

**LISTING 24.8** `TestStackQueue.java`

```

1 public class TestStackQueue {
2 public static void main(String[] args) {
3 // Create a stack
4 GenericStack<String> stack =
5 new GenericStack<>();
6
7 // Add elements to the stack
8 stack.push("Tom"); // Push it to the stack
9 System.out.println("(1) " + stack);
10
11 stack.push("Susan"); // Push it to the stack
12 System.out.println("(2) " + stack);
13
14 stack.push("Kim"); // Push it to the stack
15 stack.push("Michael"); // Push it to the stack
16 System.out.println("(3) " + stack);
17

```

```

18 // Remove elements from the stack
19 System.out.println("(4) " + stack.pop());
20 System.out.println("(5) " + stack.pop());
21 System.out.println("(6) " + stack);
22
23 // Create a queue
24 GenericQueue<String> queue = new GenericQueue<>();
25
26 // Add elements to the queue
27 queue.enqueue("Tom"); // Add it to the queue
28 System.out.println("(7) " + queue);
29
30 queue.enqueue("Susan"); // Add it to the queue
31 System.out.println("(8) " + queue);
32
33 queue.enqueue("Kim"); // Add it to the queue
34 queue.enqueue("Michael"); // Add it to the queue
35 System.out.println("(9) " + queue);
36
37 // Remove elements from the queue
38 System.out.println("(10) " + queue.dequeue());
39 System.out.println("(11) " + queue.dequeue());
40 System.out.println("(12) " + queue);
41 }
42 }
```

```

(1) stack: [Tom]
(2) stack: [Tom, Susan]
(3) stack: [Tom, Susan, Kim, Michael]
(4) Michael
(5) Kim
(6) stack: [Tom, Susan]
(7) Queue: [Tom]
(8) Queue: [Tom, Susan]
(9) Queue: [Tom, Susan, Kim, Michael]
(10) Tom
(11) Susan
(12) Queue: [Kim, Michael]
```



For a stack, the **push(e)** method adds an element to the top of the stack, and the **pop()** method removes the top element from the stack and returns the removed element. It is easy to see that the time complexity for the **push** and **pop** methods is  $O(1)$ .

stack time complexity

For a queue, the **enqueue(e)** method adds an element to the tail of the queue, and the **dequeue()** method removes the element from the head of the queue. It is easy to see that the time complexity for the **enqueue** and **dequeue** methods is  $O(1)$ .

queue time complexity

**24.18** You can use inheritance or composition to design the data structures for stacks and queues. Discuss the pros and cons of these two approaches.



**24.19** If **LinkedList** is replaced by **ArrayList** in lines 2–3 in Listing 24.7 **GenericQueue.java**, what will be the time complexity for the **enqueue** and **dequeue** methods?

**24.20** Which lines of the following code are wrong?

```

1 List<String> list = new ArrayList<>();
2 list.add("Tom");
3 list = new LinkedList<>();
4 list.add("Tom");
5 list = new GenericStack<>();
6 list.add("Tom");
```

## 24.6 Priority Queues



*Priority queues can be implemented using heaps.*

An ordinary queue is a first-in, first-out data structure. Elements are appended to the end of the queue and removed from the beginning. In a *priority queue*, elements are assigned with priorities. When accessing elements, the element with the highest priority is removed first. For example, the emergency room in a hospital assigns priority numbers to patients; the patient with the highest priority is treated first.

A priority queue can be implemented using a heap, in which the root is the object with the highest priority in the queue. Heaps were introduced in Section 23.6, Heap Sort. The class diagram for the priority queue is shown in Figure 24.23. Its implementation is given in Listing 24.9.



FIGURE 24.23 `MyPriorityQueue` uses a heap to provide a largest-in, first-out data structure.

### LISTING 24.9 `MyPriorityQueue.java`

|                         |                                                                                                                                                                                                                                                                                                                                                                                          |
|-------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| heap for priority queue | <pre> 1  public class MyPriorityQueue&lt;E extends Comparable&lt;E&gt;&gt; { 2      private Heap&lt;E&gt; heap = new Heap&lt;&gt;(); 3 4      public void enqueue(E newObject) { 5          heap.add(newObject); 6      } 7 8      public E dequeue() { 9          return heap.remove(); 10     } 11 12     public int getSize() { 13         return heap.getSize(); 14     } 15 }</pre> |
| enqueue                 |                                                                                                                                                                                                                                                                                                                                                                                          |
| dequeue                 |                                                                                                                                                                                                                                                                                                                                                                                          |
| getsize                 |                                                                                                                                                                                                                                                                                                                                                                                          |

Listing 24.10 gives an example of using a priority queue for patients. The `Patient` class is defined in lines 19–37. Four patients are created with associated priority values in lines 3–6. Line 8 creates a priority queue. The patients are enqueued in lines 10–13. Line 16 dequeues a patient from the queue.

### LISTING 24.10 `TestPriorityQueue.java`

|                         |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
|-------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| create a patient        | <pre> 1  public class TestPriorityQueue { 2      public static void main(String[] args) { 3          Patient patient1 = new Patient("John", 2); 4          Patient patient2 = new Patient("Jim", 1); 5          Patient patient3 = new Patient("Tim", 5); 6          Patient patient4 = new Patient("Cindy", 7); 7 8          MyPriorityQueue&lt;Patient&gt; priorityQueue 9              = new MyPriorityQueue&lt;&gt;(); 10         priorityQueue.enqueue(patient1); 11         priorityQueue.enqueue(patient2); 12 13         System.out.println("Priority Queue: " + 14             priorityQueue.toString()); 15 16         Patient patient = priorityQueue.dequeue(); 17         System.out.println("Dequeued patient: " + 18             patient.getName()); 19 20         priorityQueue.enqueue(patient); 21 22         System.out.println("Priority Queue: " + 23             priorityQueue.toString()); 24     } 25 }</pre> |
| create a priority queue |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
| add to queue            |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |

```

12 priorityQueue.enqueue(patient3);
13 priorityQueue.enqueue(patient4);
14
15 while (priorityQueue.getSize() > 0)
16 System.out.print(priorityQueue.dequeue() + " ");
17 } remove from queue
18
19 static class Patient implements Comparable<Patient> { inner class Patient
20 private String name;
21 private int priority;
22
23 public Patient(String name, int priority) {
24 this.name = name;
25 this.priority = priority;
26 }
27
28 @Override
29 public String toString() {
30 return name + "(priority:" + priority + ")";
31 }
32
33 @Override
34 public int compareTo(Patient patient) { compareTo
35 return this.priority - patient.priority;
36 }
37 }
38 }
```

Cindy(priority:7) Tim(priority:5) John(priority:2) Jim(priority:1)



**24.21** What is a priority queue?

**24.22** What are the time complexity of the `enqueue`, `dequeue`, and `getSize` methods in `MyPriorityQueue`?

**24.23** Which of the following statements are wrong?

- 1 MyPriorityQueue<Object> q1 = new MyPriorityQueue<>();
- 2 MyPriorityQueue<Number> q2 = new MyPriorityQueue<>();
- 3 MyPriorityQueue<Integer> q3 = new MyPriorityQueue<>();
- 4 MyPriorityQueue<Date> q4 = new MyPriorityQueue<>();
- 5 MyPriorityQueue<String> q5 = new MyPriorityQueue<>();

## CHAPTER SUMMARY

1. You learned how to implement array lists, linked lists, stacks, and queues.
2. To define a data structure is essentially to define a class. The class for a data structure should use data fields to store data and provide methods to support operations such as insertion and deletion.
3. To create a data structure is to create an instance from the class. You can then apply the methods on the instance to manipulate the data structure, such as inserting an element into the data structure or deleting an element from the data structure.
4. You learned how to implement a priority queue using a heap.

## Quiz

---

Answer the quiz for this chapter online at [www.cs.armstrong.edu/liang/intro10e/test.html](http://www.cs.armstrong.edu/liang/intro10e/test.html).

MyProgrammingLab™

## PROGRAMMING EXERCISES

---

- 24.1** (*Add set operations in `MyList`*) Define the following methods in `MyList` and implement them in `MyAbstractList`:

```
/** Adds the elements in otherList to this list.
 * Returns true if this list changed as a result of the call */
public boolean addAll(MyList<E> otherList);

/** Removes all the elements in otherList from this list
 * Returns true if this list changed as a result of the call */
public boolean removeAll(MyList<E> otherList);

/** Retains the elements in this list that are also in otherList
 * Returns true if this list changed as a result of the call */
public boolean retainAll(MyList<E> otherList);
```

Write a test program that creates two `MyArrayLists`, `list1` and `list2`, with the initial values `{"Tom", "George", "Peter", "Jean", "Jane"}` and `{"Tom", "George", "Michael", "Michelle", "Daniel"}`, then perform the following operations:

- Invokes `list1.addAll(list2)`, and displays `list1` and `list2`.
- Recreates `list1` and `list2` with the same initial values, invokes `list1.removeAll(list2)`, and displays `list1` and `list2`.
- Recreates `list1` and `list2` with the same initial values, invokes `list1.retainAll(list2)`, and displays `list1` and `list2`.

- \*24.2** (*Implement `MyLinkedList`*) The implementations of the methods `contains(E e)`, `get(int index)`, `indexOf(E e)`, `lastIndexOf(E e)`, and `set(int index, E e)` are omitted in the text. Implement these methods.

- \*24.3** (*Implement a doubly linked list*) The `MyLinkedList` class used in Listing 24.6 is a one-way directional linked list that enables one-way traversal of the list. Modify the `Node` class to add the new data field name `previous` to refer to the previous node in the list, as follows:

```
public class Node<E> {
 E element;
 Node<E> next;
 Node<E> previous;

 public Node(E e) {
 element = e;
 }
}
```

Implement a new class named `TwoWayLinkedList` that uses a doubly linked list to store elements. The `MyLinkedList` class in the text extends `MyAbstractList`. Define `TwoWayLinkedList` to extend the `java.util.AbstractSequentialList` class. You need to implement all the methods defined in `MyLinkedList` as well as the methods `listIterator()`

and `listIterator(int index)`. Both return an instance of `java.util.ListIterator<E>`. The former sets the cursor to the head of the list and the latter to the element at the specified index.

**24.4** (Use the `GenericStack` class) Write a program that displays the first 50 prime numbers in descending order. Use a stack to store the prime numbers.

**24.5** (Implement `GenericQueue` using inheritance) In Section 24.5, Stacks and Queues, `GenericQueue` is implemented using composition. Define a new queue class that extends `java.util.LinkedList`.

**\*24.6** (Generic `PriorityQueue` using `Comparator`) Revise `MyPriorityQueue` in Listing 24.9, using a generic parameter for comparing objects. Define a new constructor with a `Comparator` as its argument as follows:

```
PriorityQueue(Comparator<? super E> comparator)
```

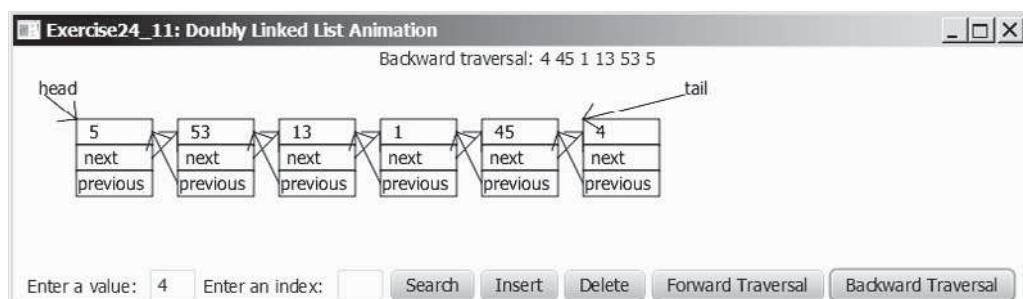
**\*\*24.7** (Animation: linked list) Write a program to animate search, insertion, and deletion in a linked list, as shown in Figure 24.1b. The *Search* button searches the specified value in the list. The *Delete* button deletes the specified value from the list. The *Insert* button appends the value into the list if the index is not specified; otherwise, it inserts the value into the specified index in the list.

**\*24.8** (Animation: array list) Write a program to animate search, insertion, and deletion in an array list, as shown in Figure 24.1a. The *Search* button searches the specified value in the list. The *Delete* button deletes the specified value from the list. The *Insert* button appends the value into the list if the index is not specified; otherwise, it inserts the value into the specified index in the list.

**\*24.9** (Animation: array list in slow motion) Improve the animation in the preceding programming exercise by showing the insertion and deletion operations in a slow motion, as shown at <http://www.cs.armstrong.edu/liang/animation/ArrayListAnimationInSlowMotion.html>.

**\*24.10** (Animation: stack) Write a program to animate push and pop in a stack, as shown in Figure 24.20a.

**\*24.11** (Animation: doubly linked list) Write a program to animate search, insertion, and deletion in a doubly linked list, as shown in Figure 24.24. The *Search* button searches the specified value in the list. The *Delete* button deletes the specified value from the list. The *Insert* button appends the value into the list if the index is not specified; otherwise, it inserts the value into the specified index in the list. Also add two buttons named *Forward Traversal* and *Backward Traversal* for displaying the elements in a forward and backward order, respectively, using iterators.



**FIGURE 24.24** The program animates the work of a doubly linked list.

- \*24.12** (*Animation: queue*) Write a program to animate the `enqueue` and `dequeue` operations on a queue, as shown in Figure 24.20b.
- \*24.13** (*Fibonacci number iterator*) Define an iterator class named `FibonacciIterator` for iterating Fibonacci numbers. The constructor takes an argument that specifies the limit of the maximum Fibonacci number. For example, new `FibonacciIterator(23302)` creates an iterator that iterates Fibonacci numbers less than or equal to `23302`. Write a test program that uses this iterator to display all Fibonacci numbers less than or equal to `100000`.
- \*24.14** (*Prime number iterator*) Define an iterator class named `PrimeIterator` for iterating prime numbers. The constructor takes an argument that specifies the limit of the maximum prime number. For example, new `PrimeIterator(23302)` creates an iterator that iterates prime numbers less than or equal to `23302`. Write a test program that uses this iterator to display all prime numbers less than or equal to `100000`.
- \*\*24.15** (*Test `MyArrayList`*) Design and write a complete test program to test if the `MyArrayList` class in Listing 24.3 meets all requirements.
- \*\*24.16** (*Test `MyLinkedList`*) Design and write a complete test program to test if the `MyLinkedList` class in Listing 24.6 meets all requirements.

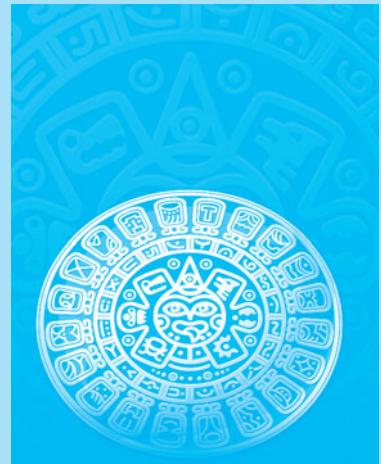
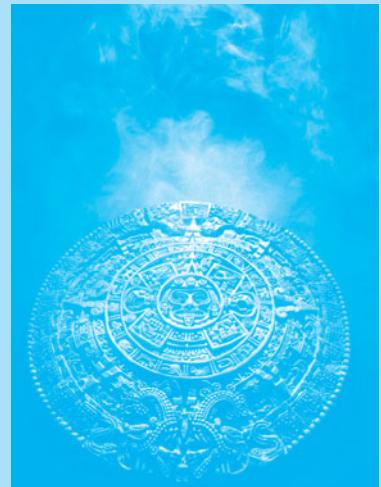
# CHAPTER

# 25

## BINARY SEARCH TREES

### Objectives

- To design and implement a binary search tree (§25.2).
- To represent binary trees using linked data structures (§25.2.1).
- To search an element in a binary search tree (§25.2.2).
- To insert an element into a binary search tree (§25.2.3).
- To traverse elements in a binary tree (§25.2.4).
- To design and implement the `Tree` interface, `AbstractTree` class, and the `BST` class (§25.2.5).
- To delete elements from a binary search tree (§25.3).
- To display a binary tree graphically (§25.4).
- To create iterators for traversing a binary tree (§25.5).
- To implement Huffman coding for compressing data using a binary tree (§25.6).



## 25.1 Introduction



*A tree is a classic data structure with many important applications.*

A *tree* provides a hierarchical organization in which data are stored in the nodes. This chapter introduces binary search trees. You will learn how to construct a binary search tree, how to search an element, insert an element, delete an element, and traverse elements in a binary search tree. You will also learn how to define and implement a custom data structure for a binary search tree.

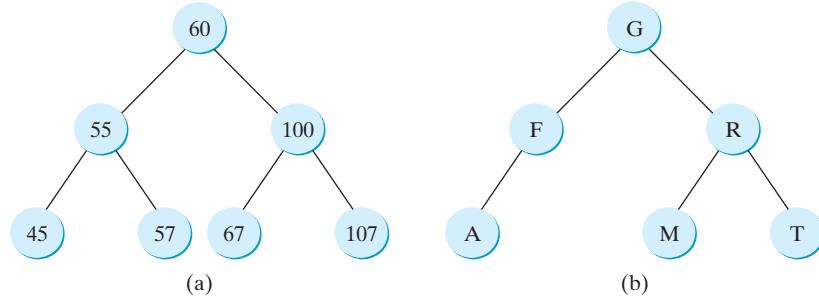
## 25.2 Binary Search Trees



*A binary search tree can be implemented using a linked structure.*

binary tree  
root  
left subtree  
right subtree

Recall that lists, stacks, and queues are linear structures that consist of a sequence of elements. A *binary tree* is a hierarchical structure. It either is empty or consists of an element, called the *root*, and two distinct binary trees, called the *left subtree* and *right subtree*, either or both of which may be empty. Examples of binary trees are shown in Figure 25.1.



**FIGURE 25.1** Each node in a binary tree has zero, one, or two subtrees.

length  
depth  
level  
sibling  
leaf  
height  
  
binary search tree

The *length* of a path is the number of the edges in the path. The *depth* of a node is the length of the path from the root to the node. The set of all nodes at a given depth is sometimes called a *level* of the tree. *Siblings* are nodes that share the same parent node. The root of a left (right) subtree of a node is called a *left (right) child* of the node. A node without children is called a *leaf*. The height of a nonempty tree is the length of the path from the root node to its furthest leaf. The *height* of a tree that contains a single node is 0. Conventionally, the height of an empty tree is -1. Consider the tree in Figure 25.1a. The length of the path from node 60 to 45 is 2. The depth of node 60 is 0, the depth of node 55 is 1, and the depth of node 45 is 2. The height of the tree is 2. Nodes 45 and 57 are siblings. Nodes 45, 57, 67, and 107 are at the same level.

A special type of binary tree called a *binary search tree* (BST) is often useful. A BST (with no duplicate elements) has the property that for every node in the tree, the value of any node in its left subtree is less than the value of the node, and the value of any node in its right subtree is greater than the value of the node. The binary trees in Figure 25.1 are all BSTs.

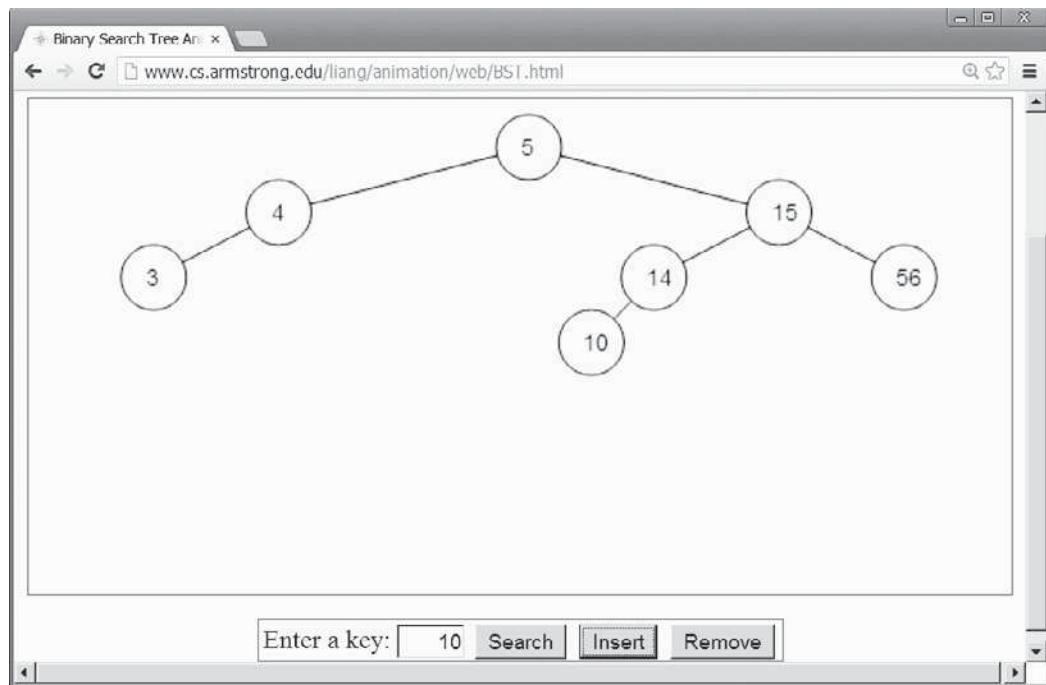


BST animation on Companion Website



### Pedagogical Note

For an interactive GUI demo to see how a BST works, go to [www.cs.armstrong.edu/liang/compsci/animations/web/BST.html](http://www.cs.armstrong.edu/liang/compsci/animations/web/BST.html), as shown in Figure 25.2.



**FIGURE 25.2** The animation tool enables you to insert, delete, and search elements.

### 25.2.1 Representing Binary Search Trees

A binary tree can be represented using a set of linked nodes. Each node contains a value and two links named *left* and *right* that reference the left child and right child, respectively, as shown in Figure 25.3.



**FIGURE 25.3** A binary tree can be represented using a set of linked nodes.

A node can be defined as a class, as follows:

```
class TreeNode<E> {
 protected E element;
 protected TreeNode<E> left;
 protected TreeNode<E> right;

 public TreeNode(E e) {
 element = e;
 }
}
```

The variable `root` refers to the root node of the tree. If the tree is empty, `root` is `null`. The following code creates the first three nodes of the tree in Figure 25.3.

```
// Create the root node
TreeNode<Integer> root = new TreeNode<>(60);

// Create the left child node
root.left = new TreeNode<>(55);

// Create the right child node
root.right = new TreeNode<>(100);
```

### 25.2.2 Searching for an Element

To search for an element in the BST, you start from the root and scan down from it until a match is found or you arrive at an empty subtree. The algorithm is described in Listing 25.1. Let `current` point to the root (line 2). Repeat the following steps until `current` is `null` (line 4) or the element matches `current.element` (line 12).

- If `element` is less than `current.element`, assign `current.left` to `current` (line 6).
- If `element` is greater than `current.element`, assign `current.right` to `current` (line 9).
- If `element` is equal to `current.element`, return `true` (line 12).

If `current` is `null`, the subtree is empty and the element is not in the tree (line 14).

### LISTING 25.1 Searching for an Element in a BST

|                 |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
|-----------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| start from root | <pre>1 public boolean search(E element) { 2     TreeNode&lt;E&gt; current = root; // Start from the root 3 4     while (current != null) 5         if (element &lt; current.element) { 6             current = current.left; // Go left 7         } 8         else if (element &gt; current.element) { 9             current = current.right; // Go right 10        } 11        else // Element matches current.element 12            return true; // Element is found 13 14    return false; // Element is not in the tree 15 }</pre> |
| left subtree    |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
| right subtree   |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
| found           |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
| not found       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |

### 25.2.3 Inserting an Element into a BST

To insert an element into a BST, you need to locate where to insert it in the tree. The key idea is to locate the parent for the new node. Listing 25.2 gives the algorithm.

### LISTING 25.2 Inserting an Element into a BST

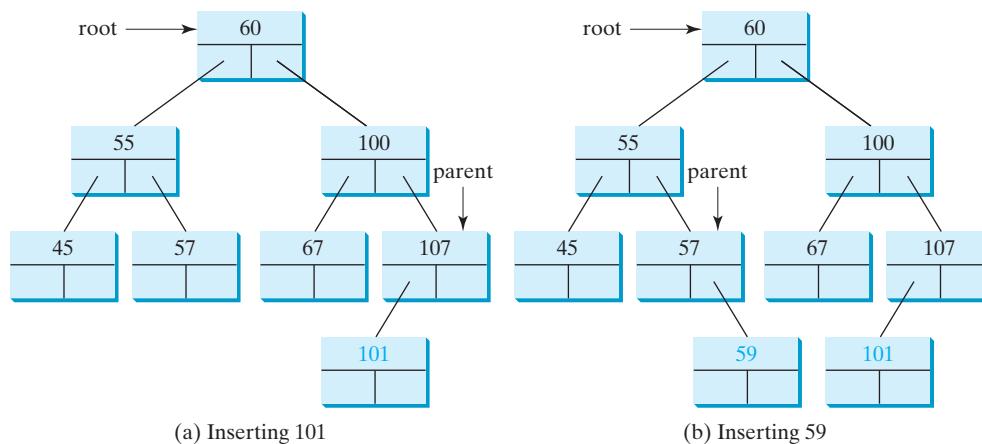
|                   |                                                                                                                                                                                                                                   |
|-------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| create a new node | <pre>1 boolean insert(E e) { 2     if (tree is empty) 3         // Create the node for e as the root; 4     else { 5         // Locate the parent node 6         parent = current = root; 7         while (current != null)</pre> |
| locate parent     |                                                                                                                                                                                                                                   |

```

8 if (e < the value in current.element) {
9 parent = current; // Keep the parent
10 current = current.left; // Go left
11 }
12 else if (e > the value in current.element) {
13 parent = current; // Keep the parent
14 current = current.right; // Go right
15 }
16 else
17 return false; // Duplicate node not inserted
18
19 // Create a new node for e and attach it to parent
20
21 return true; // Element inserted
22 }
23 }
```

If the tree is empty, create a root node with the new element (lines 2–3). Otherwise, locate the parent node for the new element node (lines 6–17). Create a new node for the element and link this node to its parent node. If the new element is less than the parent element, the node for the new element will be the left child of the parent. If the new element is greater than the parent element, the node for the new element will be the right child of the parent.

For example, to insert 101 into the tree in Figure 25.3, after the `while` loop finishes in the algorithm, `parent` points to the node for 107, as shown in Figure 25.4a. The new node for 101 becomes the left child of the parent. To insert 59 into the tree, after the `while` loop finishes in the algorithm, the parent points to the node for 57, as shown in Figure 25.4b. The new node for 59 becomes the right child of the parent.



**FIGURE 25.4** Two new elements are inserted into the tree.

#### 25.2.4 Tree Traversal

*Tree traversal* is the process of visiting each node in the tree exactly once. There are several ways to traverse a tree. This section presents *inorder*, *postorder*, *preorder*, *depth-first*, and *breadth-first* traversals.

With *inorder traversal*, the left subtree of the current node is visited first recursively, then the current node, and finally the right subtree of the current node recursively. The inorder traversal displays all the nodes in a BST in increasing order.

With *postorder traversal*, the left subtree of the current node is visited recursively first, then recursively the right subtree of the current node, and finally the current node itself. An application of postorder is to find the size of the directory in a file system. As shown in

tree traversal

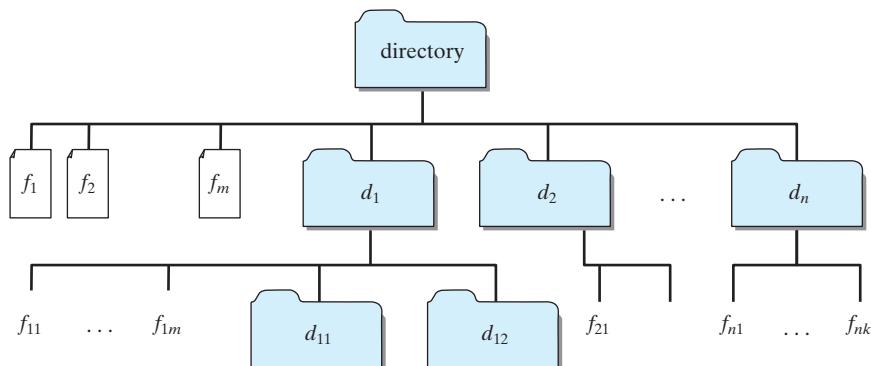
inorder traversal

postorder traversal

preorder traversal  
depth-first traversal

Figure 25.5, each directory is an internal node and a file is a leaf node. You can apply postorder to get the size of each file and subdirectory before finding the size of the root directory.

With *preorder traversal*, the current node is visited first, then recursively the left subtree of the current node, and finally the right subtree of the current node recursively. Depth-first traversal is the same as preorder traversal. An application of preorder is to print a structured document. As shown in Figure 25.6, you can print a book's table of contents using preorder traversal.



**FIGURE 25.5** A directory contains files and subdirectories.



**FIGURE 25.6** A tree can be used to represent a structured document such as a book and its chapters and sections.



### Note

You can reconstruct a binary search tree by inserting the elements in their preorder. The reconstructed tree preserves the parent and child relationship for the nodes in the original binary search tree.

breadth-first traversal

With breadth-first traversal, the nodes are visited level by level. First the root is visited, then all the children of the root from left to right, then the grandchildren of the root from left to right, and so on.

For example, in the tree in Figure 25.4b, the inorder is

45 55 57 59 60 67 100 101 107

The postorder is

45 59 57 55 67 101 107 100 60

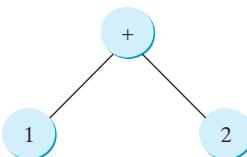
The preorder is

60 55 45 57 59 100 67 107 101

The breadth-first traversal is

60 55 100 45 57 67 107 59 101

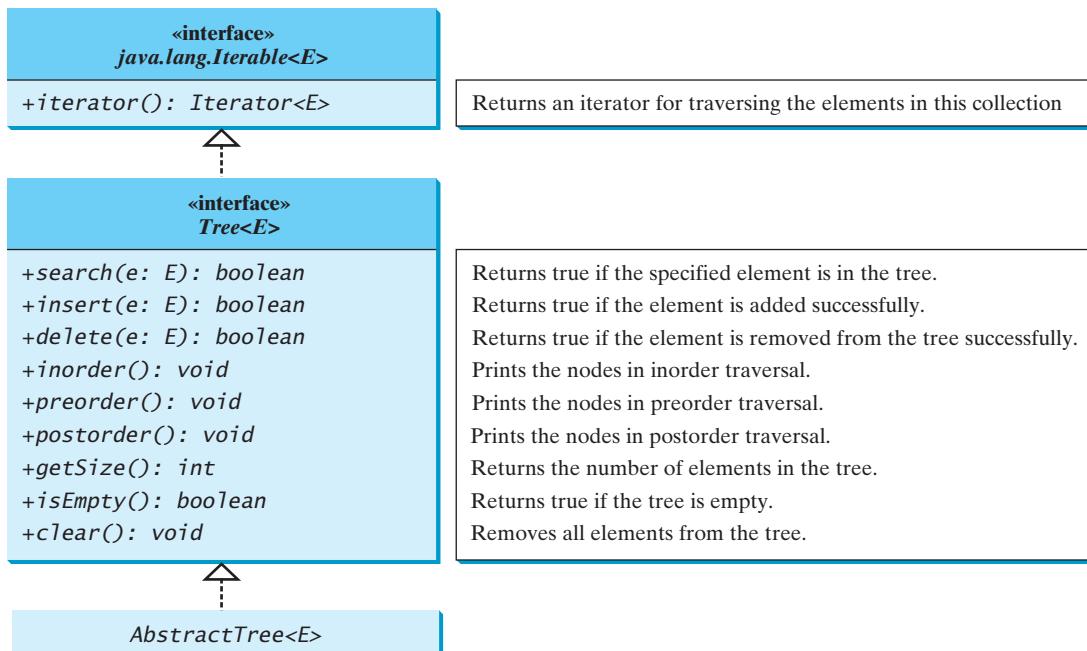
You can use the following tree to help remember inorder, postorder, and preorder.



The inorder is **1 + 2**, the postorder is **1 2 +**, and the preorder is **+ 1 2**.

### 25.2.5 The BST Class

Following the design pattern of the Java Collections Framework API, we use an interface named **Tree** to define all common operations for trees and provide an abstract class named **AbstractTree** that partially implements **Tree**, as shown in Figure 25.7. A concrete **BST** class can be defined to extend **AbstractTree**, as shown in Figure 25.8.



**FIGURE 25.7** The **Tree** interface defines common operations for trees, and the **AbstractTree** class partially implements **Tree**.

Listings 25.3, 25.4, and 25.5 give the implementations for **Tree**, **AbstractTree**, and **BST**.

### LISTING 25.3 Tree.java

```

1 public interface Tree<E> extends Iterable<E> {
2 /** Return true if the element is in the tree */
3 public boolean search(E e);
4
5 /** Insert element e into the binary search tree.
6 * Return true if the element is inserted successfully. */
7 public boolean insert(E e);
8

```

interface

search

insert

FIGURE 25.8 The **BST** class defines a concrete BST.

```

9 /** Delete the specified element from the tree.
10 * Return true if the element is deleted successfully. */
11 public boolean delete(E e);
12
13 /** Inorder traversal from the root*/
14 public void inorder();
15
16 /** Postorder traversal from the root */
17 public void postorder();
18
19 /** Preorder traversal from the root */
20 public void preorder();
21
22 /** Get the number of nodes in the tree */
23 public int getSize();
24
25 /** Return true if the tree is empty */
26 public boolean isEmpty();
27 }

```

**LISTING 25.4** *AbstractTree.java*

|                                  |                                                                 |
|----------------------------------|-----------------------------------------------------------------|
| abstract class                   | 1 <b>public abstract class</b> AbstractTree<E>                  |
| default inorder implementation   | 2 <b>implements</b> Tree<E> {                                   |
| default postorder implementation | 3     @Override <b>/** Inorder traversal from the root*/</b>    |
| default preorder implementation  | 4 <b>public void</b> inorder() {                                |
|                                  | 5     }                                                         |
|                                  | 6                                                               |
|                                  | 7     @Override <b>/** Postorder traversal from the root */</b> |
|                                  | 8 <b>public void</b> postorder() {                              |
|                                  | 9     }                                                         |
|                                  | 10    @Override <b>/** Preorder traversal from the root */</b>  |
|                                  | 11 <b>public void</b> preorder() {                              |
|                                  | 12    }                                                         |
|                                  | 13    @Override <b>/** Return true if the tree is empty */</b>  |
|                                  | 14 <b>public boolean</b> isEmpty() {                            |
|                                  | 15    }                                                         |

```

16 public boolean isEmpty() {
17 return getSize() == 0;
18 }
19 }
```

isEmpty implementation

### LISTING 25.5 BST.java

```

1 public class BST<E extends Comparable<E>>
2 extends AbstractTree<E> {
3 protected TreeNode<E> root;
4 protected int size = 0;
5
6 /** Create a default binary search tree */
7 public BST() {
8 }
9
10 /** Create a binary search tree from an array of objects */
11 public BST(E[] objects) {
12 for (int i = 0; i < objects.length; i++)
13 insert(objects[i]);
14 }
15
16 @Override /** Return true if the element is in the tree */
17 public boolean search(E e) {
18 TreeNode<E> current = root; // Start from the root
19
20 while (current != null) {
21 if (e.compareTo(current.element) < 0) {
22 current = current.left;
23 }
24 else if (e.compareTo(current.element) > 0) {
25 current = current.right;
26 }
27 else // element matches current.element
28 return true; // Element is found
29 }
30
31 return false;
32 }
33
34 @Override /** Insert element e into the binary search tree.
35 * Return true if the element is inserted successfully. */
36 public boolean insert(E e) {
37 if (root == null)
38 root = createNewNode(e); // Create a new root
39 else {
40 // Locate the parent node
41 TreeNode<E> parent = null;
42 TreeNode<E> current = root;
43 while (current != null)
44 if (e.compareTo(current.element) < 0) {
45 parent = current;
46 current = current.left;
47 }
48 else if (e.compareTo(current.element) > 0) {
49 parent = current;
50 current = current.right;
51 }
52 else
53 return false; // Duplicate node not inserted
54 }
55 }
56
57 protected void printInOrder() {
58 printInOrder(root);
59 }
60
61 private void printInOrder(TreeNode<E> current) {
62 if (current != null) {
63 printInOrder(current.left);
64 System.out.print(current.element + " ");
65 printInOrder(current.right);
66 }
67 }
68
69 public int getSize() {
70 return size;
71 }
72
73 public void setSize(int size) {
74 this.size = size;
75 }
76
77 public int getHeight() {
78 return height;
79 }
80
81 public void setHeight(int height) {
82 this.height = height;
83 }
84
85 public void printLevelOrder() {
86 printLevelOrder(root);
87 }
88
89 private void printLevelOrder(TreeNode<E> current) {
90 if (current != null) {
91 System.out.print(current.element + " ");
92 if (current.left != null)
93 printLevelOrder(current.left);
94 if (current.right != null)
95 printLevelOrder(current.right);
96 }
97 }
98
99 public void printPreOrder() {
100 printPreOrder(root);
101 }
102
103 private void printPreOrder(TreeNode<E> current) {
104 if (current != null) {
105 System.out.print(current.element + " ");
106 if (current.left != null)
107 printPreOrder(current.left);
108 if (current.right != null)
109 printPreOrder(current.right);
110 }
111 }
112
113 public void printPostOrder() {
114 printPostOrder(root);
115 }
116
117 private void printPostOrder(TreeNode<E> current) {
118 if (current != null) {
119 if (current.left != null)
120 printPostOrder(current.left);
121 if (current.right != null)
122 printPostOrder(current.right);
123 System.out.print(current.element + " ");
124 }
125 }
126
127 public void printLevelOrder() {
128 printLevelOrder(root);
129 }
130
131 private void printLevelOrder(TreeNode<E> current) {
132 if (current != null) {
133 System.out.print(current.element + " ");
134 if (current.left != null)
135 printLevelOrder(current.left);
136 if (current.right != null)
137 printLevelOrder(current.right);
138 }
139 }
140
141 public void printPreOrder() {
142 printPreOrder(root);
143 }
144
145 private void printPreOrder(TreeNode<E> current) {
146 if (current != null) {
147 System.out.print(current.element + " ");
148 if (current.left != null)
149 printPreOrder(current.left);
150 if (current.right != null)
151 printPreOrder(current.right);
152 }
153 }
154
155 public void printPostOrder() {
156 printPostOrder(root);
157 }
158
159 private void printPostOrder(TreeNode<E> current) {
160 if (current != null) {
161 if (current.left != null)
162 printPostOrder(current.left);
163 if (current.right != null)
164 printPostOrder(current.right);
165 System.out.print(current.element + " ");
166 }
167 }
168
169 public void printLevelOrder() {
170 printLevelOrder(root);
171 }
172
173 private void printLevelOrder(TreeNode<E> current) {
174 if (current != null) {
175 System.out.print(current.element + " ");
176 if (current.left != null)
177 printLevelOrder(current.left);
178 if (current.right != null)
179 printLevelOrder(current.right);
180 }
181 }
182
183 public void printPreOrder() {
184 printPreOrder(root);
185 }
186
187 private void printPreOrder(TreeNode<E> current) {
188 if (current != null) {
189 System.out.print(current.element + " ");
190 if (current.left != null)
191 printPreOrder(current.left);
192 if (current.right != null)
193 printPreOrder(current.right);
194 }
195 }
196
197 public void printPostOrder() {
198 printPostOrder(root);
199 }
200
201 private void printPostOrder(TreeNode<E> current) {
202 if (current != null) {
203 if (current.left != null)
204 printPostOrder(current.left);
205 if (current.right != null)
206 printPostOrder(current.right);
207 System.out.print(current.element + " ");
208 }
209 }
210
211 public void printLevelOrder() {
212 printLevelOrder(root);
213 }
214
215 private void printLevelOrder(TreeNode<E> current) {
216 if (current != null) {
217 System.out.print(current.element + " ");
218 if (current.left != null)
219 printLevelOrder(current.left);
220 if (current.right != null)
221 printLevelOrder(current.right);
222 }
223 }
224
225 public void printPreOrder() {
226 printPreOrder(root);
227 }
228
229 private void printPreOrder(TreeNode<E> current) {
230 if (current != null) {
231 System.out.print(current.element + " ");
232 if (current.left != null)
233 printPreOrder(current.left);
234 if (current.right != null)
235 printPreOrder(current.right);
236 }
237 }
238
239 public void printPostOrder() {
240 printPostOrder(root);
241 }
242
243 private void printPostOrder(TreeNode<E> current) {
244 if (current != null) {
245 if (current.left != null)
246 printPostOrder(current.left);
247 if (current.right != null)
248 printPostOrder(current.right);
249 System.out.print(current.element + " ");
250 }
251 }
252
253 public void printLevelOrder() {
254 printLevelOrder(root);
255 }
256
257 private void printLevelOrder(TreeNode<E> current) {
258 if (current != null) {
259 System.out.print(current.element + " ");
260 if (current.left != null)
261 printLevelOrder(current.left);
262 if (current.right != null)
263 printLevelOrder(current.right);
264 }
265 }
266
267 public void printPreOrder() {
268 printPreOrder(root);
269 }
270
271 private void printPreOrder(TreeNode<E> current) {
272 if (current != null) {
273 System.out.print(current.element + " ");
274 if (current.left != null)
275 printPreOrder(current.left);
276 if (current.right != null)
277 printPreOrder(current.right);
278 }
279 }
280
281 public void printPostOrder() {
282 printPostOrder(root);
283 }
284
285 private void printPostOrder(TreeNode<E> current) {
286 if (current != null) {
287 if (current.left != null)
288 printPostOrder(current.left);
289 if (current.right != null)
290 printPostOrder(current.right);
291 System.out.print(current.element + " ");
292 }
293 }
294
295 public void printLevelOrder() {
296 printLevelOrder(root);
297 }
298
299 private void printLevelOrder(TreeNode<E> current) {
300 if (current != null) {
301 System.out.print(current.element + " ");
302 if (current.left != null)
303 printLevelOrder(current.left);
304 if (current.right != null)
305 printLevelOrder(current.right);
306 }
307 }
308
309 public void printPreOrder() {
310 printPreOrder(root);
311 }
312
313 private void printPreOrder(TreeNode<E> current) {
314 if (current != null) {
315 System.out.print(current.element + " ");
316 if (current.left != null)
317 printPreOrder(current.left);
318 if (current.right != null)
319 printPreOrder(current.right);
320 }
321 }
322
323 public void printPostOrder() {
324 printPostOrder(root);
325 }
326
327 private void printPostOrder(TreeNode<E> current) {
328 if (current != null) {
329 if (current.left != null)
330 printPostOrder(current.left);
331 if (current.right != null)
332 printPostOrder(current.right);
333 System.out.print(current.element + " ");
334 }
335 }
336
337 public void printLevelOrder() {
338 printLevelOrder(root);
339 }
340
341 private void printLevelOrder(TreeNode<E> current) {
342 if (current != null) {
343 System.out.print(current.element + " ");
344 if (current.left != null)
345 printLevelOrder(current.left);
346 if (current.right != null)
347 printLevelOrder(current.right);
348 }
349 }
350
351 public void printPreOrder() {
352 printPreOrder(root);
353 }
354
355 private void printPreOrder(TreeNode<E> current) {
356 if (current != null) {
357 System.out.print(current.element + " ");
358 if (current.left != null)
359 printPreOrder(current.left);
360 if (current.right != null)
361 printPreOrder(current.right);
362 }
363 }
364
365 public void printPostOrder() {
366 printPostOrder(root);
367 }
368
369 private void printPostOrder(TreeNode<E> current) {
370 if (current != null) {
371 if (current.left != null)
372 printPostOrder(current.left);
373 if (current.right != null)
374 printPostOrder(current.right);
375 System.out.print(current.element + " ");
376 }
377 }
378
379 public void printLevelOrder() {
380 printLevelOrder(root);
381 }
382
383 private void printLevelOrder(TreeNode<E> current) {
384 if (current != null) {
385 System.out.print(current.element + " ");
386 if (current.left != null)
387 printLevelOrder(current.left);
388 if (current.right != null)
389 printLevelOrder(current.right);
390 }
391 }
392
393 public void printPreOrder() {
394 printPreOrder(root);
395 }
396
397 private void printPreOrder(TreeNode<E> current) {
398 if (current != null) {
399 System.out.print(current.element + " ");
400 if (current.left != null)
401 printPreOrder(current.left);
402 if (current.right != null)
403 printPreOrder(current.right);
404 }
405 }
406
407 public void printPostOrder() {
408 printPostOrder(root);
409 }
410
411 private void printPostOrder(TreeNode<E> current) {
412 if (current != null) {
413 if (current.left != null)
414 printPostOrder(current.left);
415 if (current.right != null)
416 printPostOrder(current.right);
417 System.out.print(current.element + " ");
418 }
419 }
420
421 public void printLevelOrder() {
422 printLevelOrder(root);
423 }
424
425 private void printLevelOrder(TreeNode<E> current) {
426 if (current != null) {
427 System.out.print(current.element + " ");
428 if (current.left != null)
429 printLevelOrder(current.left);
430 if (current.right != null)
431 printLevelOrder(current.right);
432 }
433 }
434
435 public void printPreOrder() {
436 printPreOrder(root);
437 }
438
439 private void printPreOrder(TreeNode<E> current) {
440 if (current != null) {
441 System.out.print(current.element + " ");
442 if (current.left != null)
443 printPreOrder(current.left);
444 if (current.right != null)
445 printPreOrder(current.right);
446 }
447 }
448
449 public void printPostOrder() {
450 printPostOrder(root);
451 }
452
453 private void printPostOrder(TreeNode<E> current) {
454 if (current != null) {
455 if (current.left != null)
456 printPostOrder(current.left);
457 if (current.right != null)
458 printPostOrder(current.right);
459 System.out.print(current.element + " ");
460 }
461 }
462
463 public void printLevelOrder() {
464 printLevelOrder(root);
465 }
466
467 private void printLevelOrder(TreeNode<E> current) {
468 if (current != null) {
469 System.out.print(current.element + " ");
470 if (current.left != null)
471 printLevelOrder(current.left);
472 if (current.right != null)
473 printLevelOrder(current.right);
474 }
475 }
476
477 public void printPreOrder() {
478 printPreOrder(root);
479 }
480
481 private void printPreOrder(TreeNode<E> current) {
482 if (current != null) {
483 System.out.print(current.element + " ");
484 if (current.left != null)
485 printPreOrder(current.left);
486 if (current.right != null)
487 printPreOrder(current.right);
488 }
489 }
490
491 public void printPostOrder() {
492 printPostOrder(root);
493 }
494
495 private void printPostOrder(TreeNode<E> current) {
496 if (current != null) {
497 if (current.left != null)
498 printPostOrder(current.left);
499 if (current.right != null)
500 printPostOrder(current.right);
501 System.out.print(current.element + " ");
502 }
503 }
504
505 public void printLevelOrder() {
506 printLevelOrder(root);
507 }
508
509 private void printLevelOrder(TreeNode<E> current) {
510 if (current != null) {
511 System.out.print(current.element + " ");
512 if (current.left != null)
513 printLevelOrder(current.left);
514 if (current.right != null)
515 printLevelOrder(current.right);
516 }
517 }
518
519 public void printPreOrder() {
520 printPreOrder(root);
521 }
522
523 private void printPreOrder(TreeNode<E> current) {
524 if (current != null) {
525 System.out.print(current.element + " ");
526 if (current.left != null)
527 printPreOrder(current.left);
528 if (current.right != null)
529 printPreOrder(current.right);
530 }
531 }
532
533 public void printPostOrder() {
534 printPostOrder(root);
535 }
536
537 private void printPostOrder(TreeNode<E> current) {
538 if (current != null) {
539 if (current.left != null)
540 printPostOrder(current.left);
541 if (current.right != null)
542 printPostOrder(current.right);
543 System.out.print(current.element + " ");
544 }
545 }
546
547 public void printLevelOrder() {
548 printLevelOrder(root);
549 }
550
551 private void printLevelOrder(TreeNode<E> current) {
552 if (current != null) {
553 System.out.print(current.element + " ");
554 if (current.left != null)
555 printLevelOrder(current.left);
556 if (current.right != null)
557 printLevelOrder(current.right);
558 }
559 }
560
561 public void printPreOrder() {
562 printPreOrder(root);
563 }
564
565 private void printPreOrder(TreeNode<E> current) {
566 if (current != null) {
567 System.out.print(current.element + " ");
568 if (current.left != null)
569 printPreOrder(current.left);
570 if (current.right != null)
571 printPreOrder(current.right);
572 }
573 }
574
575 public void printPostOrder() {
576 printPostOrder(root);
577 }
578
579 private void printPostOrder(TreeNode<E> current) {
580 if (current != null) {
581 if (current.left != null)
582 printPostOrder(current.left);
583 if (current.right != null)
584 printPostOrder(current.right);
585 System.out.print(current.element + " ");
586 }
587 }
588
589 public void printLevelOrder() {
590 printLevelOrder(root);
591 }
592
593 private void printLevelOrder(TreeNode<E> current) {
594 if (current != null) {
595 System.out.print(current.element + " ");
596 if (current.left != null)
597 printLevelOrder(current.left);
598 if (current.right != null)
599 printLevelOrder(current.right);
600 }
601 }
602
603 public void printPreOrder() {
604 printPreOrder(root);
605 }
606
607 private void printPreOrder(TreeNode<E> current) {
608 if (current != null) {
609 System.out.print(current.element + " ");
610 if (current.left != null)
611 printPreOrder(current.left);
612 if (current.right != null)
613 printPreOrder(current.right);
614 }
615 }
616
617 public void printPostOrder() {
618 printPostOrder(root);
619 }
620
621 private void printPostOrder(TreeNode<E> current) {
622 if (current != null) {
623 if (current.left != null)
624 printPostOrder(current.left);
625 if (current.right != null)
626 printPostOrder(current.right);
627 System.out.print(current.element + " ");
628 }
629 }
630
631 public void printLevelOrder() {
632 printLevelOrder(root);
633 }
634
635 private void printLevelOrder(TreeNode<E> current) {
636 if (current != null) {
637 System.out.print(current.element + " ");
638 if (current.left != null)
639 printLevelOrder(current.left);
640 if (current.right != null)
641 printLevelOrder(current.right);
642 }
643 }
644
645 public void printPreOrder() {
646 printPreOrder(root);
647 }
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649 private void printPreOrder(TreeNode<E> current) {
650 if (current != null) {
651 System.out.print(current.element + " ");
652 if (current.left != null)
653 printPreOrder(current.left);
654 if (current.right != null)
655 printPreOrder(current.right);
656 }
657 }
658
659 public void printPostOrder() {
660 printPostOrder(root);
661 }
662
663 private void printPostOrder(TreeNode<E> current) {
664 if (current != null) {
665 if (current.left != null)
666 printPostOrder(current.left);
667 if (current.right != null)
668 printPostOrder(current.right);
669 System.out.print(current.element + " ");
670 }
671 }
672
673 public void printLevelOrder() {
674 printLevelOrder(root);
675 }
676
677 private void printLevelOrder(TreeNode<E> current) {
678 if (current != null) {
679 System.out.print(current.element + " ");
680 if (current.left != null)
681 printLevelOrder(current.left);
682 if (current.right != null)
683 printLevelOrder(current.right);
684 }
685 }
686
687 public void printPreOrder() {
688 printPreOrder(root);
689 }
690
691 private void printPreOrder(TreeNode<E> current) {
692 if (current != null) {
693 System.out.print(current.element + " ");
694 if (current.left != null)
695 printPreOrder(current.left);
696 if (current.right != null)
697 printPreOrder(current.right);
698 }
699 }
699
700 public void printPostOrder() {
701 printPostOrder(root);
702 }
703
704 private void printPostOrder(TreeNode<E> current) {
705 if (current != null) {
706 if (current.left != null)
707 printPostOrder(current.left);
708 if (current.right != null)
709 printPostOrder(current.right);
710 System.out.print(current.element + " ");
711 }
712 }
712
713 public void printLevelOrder() {
714 printLevelOrder(root);
715 }
716
717 private void printLevelOrder(TreeNode<E> current) {
718 if (current != null) {
719 System.out.print(current.element + " ");
720 if (current.left != null)
721 printLevelOrder(current.left);
722 if (current.right != null)
723 printLevelOrder(current.right);
724 }
725 }
725
726 public void printPreOrder() {
727 printPreOrder(root);
728 }
729
729 private void printPreOrder(TreeNode<E> current) {
730 if (current != null) {
731 System.out.print(current.element + " ");
732 if (current.left != null)
733 printPreOrder(current.left);
734 if (current.right != null)
735 printPreOrder(current.right);
736 }
737 }
737
738 public void printPostOrder() {
739 printPostOrder(root);
740 }
741
742 private void printPostOrder(TreeNode<E> current) {
743 if (current != null) {
744 if (current.left != null)
745 printPostOrder(current.left);
746 if (current.right != null)
747 printPostOrder(current.right);
748 System.out.print(current.element + " ");
749 }
750 }
750
751 public void printLevelOrder() {
752 printLevelOrder(root);
753 }
754
755 private void printLevelOrder(TreeNode<E> current) {
756 if (current != null) {
757 System.out.print(current.element + " ");
758 if (current.left != null)
759 printLevelOrder(current.left);
760 if (current.right != null)
761 printLevelOrder(current.right);
762 }
763 }
763
764 public void printPreOrder() {
765 printPreOrder(root);
766 }
767
767 private void printPreOrder(TreeNode<E> current) {
768 if (current != null) {
769 System.out.print(current.element + " ");
770 if (current.left != null)
771 printPreOrder(current.left);
772 if (current.right != null)
773 printPreOrder(current.right);
774 }
775 }
775
776 public void printPostOrder() {
777 printPostOrder(root);
778 }
779
779 private void printPostOrder(TreeNode<E> current) {
780 if (current != null) {
781 if (current.left != null)
782 printPostOrder(current.left);
783 if (current.right != null)
784 printPostOrder(current.right);
785 System.out.print(current.element + " ");
786 }
787 }
787
788 public void printLevelOrder() {
789 printLevelOrder(root);
790 }
790
791 private void printLevelOrder(TreeNode<E> current) {
792 if (current != null) {
793 System.out.print(current.element + " ");
794 if (current.left != null)
795 printLevelOrder(current.left);
796 if (current.right != null)
797 printLevelOrder(current.right);
798 }
799 }
799
800 public void printPreOrder() {
801 printPreOrder(root);
802 }
803
803 private void printPreOrder(TreeNode<E> current) {
804 if (current != null) {
805 System.out.print(current.element + " ");
806 if (current.left != null)
807 printPreOrder(current.left);
808 if (current.right != null)
809 printPreOrder(current.right);
810 }
811 }
811
812 public void printPostOrder() {
813 printPostOrder(root);
814 }
815
815 private void printPostOrder(TreeNode<E> current) {
816 if (current != null) {
817 if (current.left != null)
818 printPostOrder(current.left);
819 if (current.right != null)
820 printPostOrder(current.right);
821 System.out.print(current.element + " ");
822 }
823 }
823
824 public void printLevelOrder() {
825 printLevelOrder(root);
826 }
827
827 private void printLevelOrder(TreeNode<E> current) {
828 if (current != null) {
829 System.out.print(current.element + " ");
830 if (current.left != null)
831 printLevelOrder(current.left);
832 if (current.right != null)
833 printLevelOrder(current.right);
834 }
835 }
835
836 public void printPreOrder() {
837 printPreOrder(root);
838 }
839
839 private void printPreOrder(TreeNode<E> current) {
840 if (current != null) {
841 System.out.print(current.element + " ");
842 if (current.left != null)
843 printPreOrder(current.left);
844 if (current.right != null)
845 printPreOrder(current.right);
846 }
847 }
847
848 public void printPostOrder() {
849 printPostOrder(root);
850 }
851
851 private void printPostOrder(TreeNode<E> current) {
852 if (current != null) {
853 if (current.left != null)
854 printPostOrder(current.left);
855 if (current.right != null)
856 printPostOrder(current.right);
857 System.out.print(current.element + " ");
858 }
859 }
859
860 public void printLevelOrder() {
861 printLevelOrder(root);
862 }
863
863 private void printLevelOrder(TreeNode<E> current) {
864 if (current != null) {
865 System.out.print(current.element + " ");
866 if (current.left != null)
867 printLevelOrder(current.left);
868 if (current.right != null)
869 printLevelOrder(current.right);
870 }
871 }
871
872 public void printPreOrder() {
873 printPreOrder(root);
874 }
875
875 private void printPreOrder(TreeNode<E> current) {
876 if (current != null) {
877 System.out.print(current.element + " ");
878 if (current.left != null)
879 printPreOrder(current.left);
880 if (current.right != null)
881 printPreOrder(current.right);
882 }
883 }
883
884 public void printPostOrder() {
885 printPostOrder(root);
886 }
887
887 private void printPostOrder(TreeNode<E> current) {
888 if (current != null) {
889 if (current.left != null)
890 printPostOrder(current.left);
891 if (current.right != null)
892 printPostOrder(current.right);
893 System.out.print(current.element + " ");
894 }
895 }
895
896 public void printLevelOrder() {
897 printLevelOrder(root);
898 }
899
900 private void printLevelOrder(TreeNode<E> current) {
901 if (current != null) {
902 System.out.print(current.element + " ");
903 if (current.left != null)
904 printLevelOrder(current.left);
905 if (current.right != null)
906 printLevelOrder(current.right);
907 }
908 }
908
909 public void printPreOrder() {
910 printPreOrder(root);
911 }
912
912 private void printPreOrder(TreeNode<E> current) {
913 if (current != null) {
914 System.out.print(current.element + " ");
915 if (current.left != null)
916 printPreOrder(current.left);
917 if (current.right != null)
918 printPreOrder(current.right);
919 }
920 }
920
921 public void printPostOrder() {
922 printPostOrder(root);
923 }
924
924 private void printPostOrder(TreeNode<E> current) {
925 if (current != null) {
926 if (current.left != null)
927 printPostOrder(current.left);
928 if (current.right != null)
929 printPostOrder(current.right);
930 System.out.print(current.element + " ");
931 }
932 }
932
933 public void printLevelOrder() {
934 printLevelOrder(root);
935 }
936
936 private void printLevelOrder(TreeNode<E> current) {
937 if (current != null) {
938 System.out.print(current.element + " ");
939 if (current.left != null)
940 printLevelOrder(current.left);
941 if (current.right != null)
942 printLevelOrder(current.right);
943 }
944 }
944
945 public void printPreOrder() {
946 printPreOrder(root);
947 }
948
948 private void printPreOrder(TreeNode<E> current) {
949 if (current != null) {
950 System.out.print(current.element + " ");
951 if (current.left != null)
952 printPreOrder(current.left);
953 if (current.right != null)
954 printPreOrder(current.right);
955 }
956 }
956
957 public void printPostOrder() {
958 printPostOrder(root);
959 }
960
960 private void printPostOrder(TreeNode<E> current) {
961 if (current != null) {
962 if (current.left != null)
963 printPostOrder(current.left);
964 if (current.right != null)
965 printPostOrder(current.right);
966 System.out.print(current.element + " ");
967 }
968 }
968
969 public void printLevelOrder() {
970 printLevelOrder(root);
971 }
972
972 private void printLevelOrder(TreeNode<E> current) {
973 if (current != null) {
974 System.out.print(current.element + " ");
975 if (current.left != null)
976 printLevelOrder(current.left);
977 if (current.right != null)
978 printLevelOrder(current.right);
979 }
980 }
980
981 public void printPreOrder() {
982 printPreOrder(root);
983 }
984
984 private void printPreOrder(TreeNode<E> current) {
985 if (current != null) {
986 System.out.print(current.element + " ");
987 if (current.left != null)
988 printPreOrder(current.left);
989 if (current.right != null)
990 printPreOrder(current.right);
991 }
992 }
992
993 public void printPostOrder() {
994 printPostOrder(root);
995 }
996
996 private void printPostOrder(TreeNode<E> current) {
997 if (current != null) {
998 if (current.left != null)
999 printPostOrder(current.left);
1000 printPostOrder(current.right);
1001 System.out.print(current.element + " ");
1002 }
1003 }
1003
1004 public void printLevelOrder() {
1005 printLevelOrder(root);
1006 }
1006
1006 private void printLevelOrder(TreeNode<E> current) {
1007 if (current != null) {
1008 System.out.print(current.element + " ");
1009 if (current.left != null)
1010 printLevelOrder(current.left);
1011 if (current.right != null)
1012 printLevelOrder(current.right);
1013 }
1014 }
1014
1015 public void printPreOrder() {
1016 printPreOrder(root);
1017 }
1017
1017 private void printPreOrder(TreeNode<E> current) {
1018 if (current != null) {
1019 System.out.print(current.element + " ");
1020 if (current.left != null)
1021 printPreOrder(current.left);
1022 if (current.right != null)
1023 printPreOrder(current.right);
1024 }
1025 }
1025
1026 public void printPostOrder() {
1027 printPostOrder(root);
1028 }
1028
1028 private void printPostOrder(TreeNode<E> current) {
1029 if (current != null) {
1030 if (current.left != null)
1031 printPostOrder(current.left);
1032 if (current.right != null)
1033 printPostOrder(current.right);
1034 System.out.print(current.element + " ");
1035 }
1036 }
1036
1037 public void printLevelOrder() {
1038 printLevelOrder(root);
1039 }
1039
1039 private void printLevelOrder(TreeNode<E> current) {
1040 if (current != null) {
1041 System.out.print(current.element + " ");
1042 if (current.left != null)
1043 printLevelOrder(current.left);
1044 if (current.right != null)
1045 printLevelOrder(current.right);
1046 }
1047 }
1047
1048 public void printPreOrder() {
1049 printPreOrder(root);
1050 }
1050
1050 private void printPreOrder(TreeNode<E> current) {
1051 if (current != null) {
1052 System.out.print(current.element + " ");
1053 if (current.left != null)
1054 printPreOrder(current.left);
1055 if (current.right != null)
1056 printPreOrder(current.right);
1057 }
1058 }
1058
1059 public void printPostOrder() {
1060 printPostOrder(root);
1061 }
1061
1061 private void printPostOrder(TreeNode<E> current) {
1062 if (current != null) {
1063 if (current.left != null)
1064 printPostOrder(current.left);
1065 if (current.right != null)
1066 printPostOrder(current.right);
1067 System.out.print(current.element + " ");
1068 }
1069 }
1069
1070 public void printLevelOrder() {
1071 printLevelOrder(root);
1072 }
1072
1072 private void printLevelOrder(TreeNode<E> current) {
1073 if (current != null) {
1074 System.out.print(current.element + " ");
1075 if (current.left != null)
1076 printLevelOrder(current.left);
1077 if (current.right != null)
1078 printLevelOrder(current.right);
1079 }
1080 }
1080
1081 public void printPreOrder() {
1082 printPreOrder(root);
1083 }
1083
1083 private void printPreOrder(TreeNode<E> current) {
1084 if (current != null) {
1085 System.out.print(current.element + " ");
1086 if (current.left != null)
1087 printPreOrder(current.left);
1088 if (current.right != null)
1089 printPreOrder(current.right);
1090 }
1091 }
1091
1092 public void printPostOrder() {
1093 printPostOrder(root);
1094 }
1094
1094 private void printPostOrder(TreeNode<E> current) {
1095 if (current != null) {
1096 if (current.left != null)
1097 printPostOrder(current.left);
1098 if (current.right != null)
1099 printPostOrder(current.right);
1100 System.out.print(current.element + " ");
1101 }
1102 }
1102
1103 public void printLevelOrder() {
1104 printLevelOrder(root);
1105 }
1105
1105 private void printLevelOrder(TreeNode<E> current) {
1106 if (current != null) {
1107 System.out.print(current.element + " ");
1108 if (current.left != null)
1109 printLevelOrder(current.left);
1110 if (current.right != null)
1111 printLevelOrder(current.right);
1112 }
1113 }
1113
1114 public void printPreOrder() {
1115 printPreOrder(root);
1116 }
1116
1116 private void printPreOrder(TreeNode<E> current) {
1117 if (current != null) {
1118 System.out.print(current.element + " ");
1119 if (current.left != null)
1120 printPreOrder(current.left);
1121 if (current.right != null)
1122 printPreOrder(current.right);
1123 }
1124 }
1124
1125 public void printPostOrder() {
1126 printPostOrder(root);
1127 }
1127
1127 private void printPostOrder(TreeNode<E> current) {
1128 if (current != null) {
1129 if (current.left != null)
1130 printPostOrder(current.left);
1131 if (current.right != null)
1132 printPostOrder(current.right);
1133 System.out.print(current.element + " ");
1134 }
1135 }
1135
1136 public void printLevelOrder() {
1137 printLevelOrder(root);
1138 }
1139
1139 private void printLevelOrder(TreeNode<E> current) {
1140 if (current != null) {
1141 System.out.print(current.element + " ");
1142 if (current.left != null)
1143 printLevelOrder(current.left);
1144 if (current.right != null)
1145 printLevelOrder(current.right);
1146 }
1147 }
1147
1148 public void printPreOrder() {
1149 printPreOrder(root);
1150 }
1150
1150 private void printPreOrder(TreeNode<E> current) {
1151 if (current != null) {
1152 System.out.print(current.element + " ");
1153 if (current.left != null)
1154 printPreOrder(current.left);
1155 if (current.right != null)
1156 printPreOrder(current.right);
1157 }
1158 }
1158
1159 public void printPostOrder() {
1160 printPostOrder(root);
1161 }
1161
1161 private void printPostOrder(TreeNode<E> current) {
1162 if (current != null) {
1163 if (current.left != null)
1164 printPostOrder(current.left);
1165 if (current.right != null)
1166 printPostOrder(current.right);
1167 System.out.print(current.element + " ");
1168 }
1169 }
1169
1170 public void printLevelOrder() {
1171 printLevelOrder(root);
1172 }
1173
1173 private void printLevelOrder(TreeNode<E> current) {
1174 if (current != null) {
1175 System.out.print(current.element + " ");
1176 if (current.left != null)
1177 printLevelOrder(current.left);
1178 if (current.right != null)
1179 printLevelOrder(current.right);
1180 }
1181 }
1181
1182 public void printPreOrder() {
1183 printPreOrder(root);
1184 }
1185
1185 private void printPreOrder(TreeNode<E> current) {
1186 if (current != null) {
1187 System.out.print(current.element + " ");
1188 if (current.left != null)
1189 printPreOrder(current.left);
1190 if (current.right !=
```

```

54
55 // Create the new node and attach it to the parent node
56 if (e.compareTo(parent.element) < 0)
57 parent.left = createTreeNode(e);
58 else
59 parent.right = createTreeNode(e);
60 }
61
62 size++;
63 return true; // Element inserted successfully
64 }

65 protected TreeNode<E> createTreeNode(E e) {
66 return new TreeNode<>(e);
67 }

68 @Override /** Inorder traversal from the root */
69 public void inorder() {
70 inorder(root);
71 }

72 /** Inorder traversal from a subtree */
73 protected void inorder(TreeNode<E> root) {
74 if (root == null) return;
75 inorder(root.left);
76 System.out.print(root.element + " ");
77 inorder(root.right);
78 }

79 @Override /** Postorder traversal from the root */
80 public void postorder() {
81 postorder(root);
82 }

83 /** Postorder traversal from a subtree */
84 protected void postorder(TreeNode<E> root) {
85 if (root == null) return;
86 postorder(root.left);
87 postorder(root.right);
88 System.out.print(root.element + " ");
89 }

90 @Override /** Preorder traversal from the root */
91 public void preorder() {
92 preorder(root);
93 }

94 /** Preorder traversal from a subtree */
95 protected void preorder(TreeNode<E> root) {
96 if (root == null) return;
97 System.out.print(root.element + " ");
98 preorder(root.left);
99 preorder(root.right);
100 }

101 /**
102 * This inner class is static, because it does not access
103 * any instance members defined in its outer class */
104 public static class TreeNode<E extends Comparable<E>> {
105 protected E element;
106 protected TreeNode<E> left;
107 }

```

```

114 protected TreeNode<E> right;
115
116 public TreeNode(E e) {
117 element = e;
118 }
119 }
120
121 @Override /** Get the number of nodes in the tree */
122 public int getSize() { getSize
123 return size;
124 }
125
126 /** Returns the root of the tree */
127 public TreeNode<E> getRoot() { getRoot
128 return root;
129 }
130
131 /** Returns a path from the root leading to the specified element */
132 public java.util.ArrayList<TreeNode<E>> path(E e) { path
133 java.util.ArrayList<TreeNode<E>> list =
134 new java.util.ArrayList<>();
135 TreeNode<E> current = root; // Start from the root
136
137 while (current != null) {
138 list.add(current); // Add the node to the list
139 if (e.compareTo(current.element) < 0) {
140 current = current.left;
141 }
142 else if (e.compareTo(current.element) > 0) {
143 current = current.right;
144 }
145 else
146 break;
147 }
148
149 return list; // Return an array list of nodes
150 }
151
152 @Override /** Delete an element from the binary search tree.
153 * Return true if the element is deleted successfully.
154 * Return false if the element is not in the tree. */
155 public boolean delete(E e) { delete
156 // Locate the node to be deleted and also locate its parent node
157 TreeNode<E> parent = null; locate parent
158 TreeNode<E> current = root; locate current
159 while (current != null) {
160 if (e.compareTo(current.element) < 0) {
161 parent = current;
162 current = current.left;
163 }
164 else if (e.compareTo(current.element) > 0) {
165 parent = current;
166 current = current.right;
167 }
168 else
169 break; // Element is in the tree pointed at by current
170 }
171
172 if (current == null) current found
173 return false; // Element is not in the tree
174
175 not found

```

```

174
175 // Case 1: current has no left child
176 if (current.left == null) {
177 // Connect the parent with the right child of the current node
178 if (parent == null) {
179 root = current.right;
180 }
181 else {
182 if (e.compareTo(parent.element) < 0)
183 parent.left = current.right;
184 else
185 parent.right = current.right;
186 }
187 }
188 else {
189 // Case 2: The current node has a left child.
190 // Locate the rightmost node in the left subtree of
191 // the current node and also its parent.
192 TreeNode<E> parentOfRightMost = current;
193 TreeNode<E> rightMost = current.left;
194
195 while (rightMost.right != null) {
196 parentOfRightMost = rightMost;
197 rightMost = rightMost.right; // Keep going to the right
198 }
199
200 // Replace the element in current by the element in rightMost
201 current.element = rightMost.element;
202
203 // Eliminate rightmost node
204 if (parentOfRightMost.right == rightMost)
205 parentOfRightMost.right = rightMost.left;
206 else
207 // Special case: parentOfRightMost == current
208 parentOfRightMost.left = rightMost.left;
209 }
210
211 size--;
212 return true; // Element deleted successfully
213 }
214
215 @Override /** Obtain an iterator. Use inorder. */
216 public java.util.Iterator<E> iterator() {
217 return new InorderIterator();
218 }
219
220 // Inner class InorderIterator
221 private class InorderIterator implements java.util.Iterator<E> {
222 // Store the elements in a list
223 private java.util.ArrayList<E> list =
224 new java.util.ArrayList<E>();
225 private int current = 0; // Point to the current element in list
226
227 public InorderIterator() {
228 inorder(); // Traverse binary tree and store elements in list
229 }
230
231 /** Inorder traversal from the root*/
232 private void inorder() {
233 inorder(root);

```

```

234 }
235
236 /** Inorder traversal from a subtree */
237 private void inorder(TreeNode<E> root) {
238 if (root == null) return;
239 inorder(root.left);
240 list.add(root.element);
241 inorder(root.right);
242 }
243
244 @Override /** More elements for traversing? */
245 public boolean hasNext() {
246 if (current < list.size())
247 return true;
248
249 return false;
250 }
251
252 @Override /** Get the current element and move to the next */
253 public E next() {
254 return list.get(current++);
255 }
256
257 @Override /** Remove the current element */
258 public void remove() {
259 delete(list.get(current)); // Delete the current element
260 list.clear(); // Clear the list
261 inorder(); // Rebuild the list
262 }
263
264
265 /** Remove all elements from the tree */
266 public void clear() {
267 root = null;
268 size = 0;
269 }
270 }
```

hasNext in iterator?  
get next element  
remove the current  
refresh list  
clear

The `insert(E e)` method (lines 36–64) creates a node for element `e` and inserts it into the tree. If the tree is empty, the node becomes the root. Otherwise, the method finds an appropriate parent for the node to maintain the order of the tree. If the element is already in the tree, the method returns `false`; otherwise it returns `true`.

The `inorder()` method (lines 71–81) invokes `inorder(root)` to traverse the entire tree. The method `inorder(TreeNode root)` traverses the tree with the specified root. This is a recursive method. It recursively traverses the left subtree, then the root, and finally the right subtree. The traversal ends when the tree is empty.

The `postorder()` method (lines 84–94) and the `preorder()` method (lines 97–107) are implemented similarly using recursion.

The `path(E e)` method (lines 132–150) returns a path of the nodes as an array list. The path starts from the root leading to the element. The element may not be in the tree. For example, in Figure 25.4a, `path(45)` contains the nodes for elements **60**, **55**, and **45**, and `path(58)` contains the nodes for elements **60**, **55**, and **57**.

The implementation of `delete()` and `iterator()` (lines 155–269) will be discussed in Sections 25.3 and 25.5.

Listing 25.6 gives an example that creates a binary search tree using `BST` (line 4). The program adds strings into the tree (lines 5–11), traverses the tree in inorder, postorder, and preorder (lines 14–20), searches for an element (line 24), and obtains a path from the node containing `Peter` to the root (lines 28–31).

create tree  
insert

inorder

postorder

preorder  
getSize

search

**LISTING 25.6** TestBST.java

```

1 public class TestBST {
2 public static void main(String[] args) {
3 // Create a BST
4 BST<String> tree = new BST<>();
5 tree.insert("George");
6 tree.insert("Michael");
7 tree.insert("Tom");
8 tree.insert("Adam");
9 tree.insert("Jones");
10 tree.insert("Peter");
11 tree.insert("Daniel");
12
13 // Traverse tree
14 System.out.print("Inorder (sorted): ");
15 tree.inorder();
16 System.out.print("\nPostorder: ");
17 tree.postorder();
18 System.out.print("\nPreorder: ");
19 tree.preorder();
20 System.out.print("\nThe number of nodes is " + tree.getSize());
21
22 // Search for an element
23 System.out.print("\nIs Peter in the tree? " +
24 tree.search("Peter"));
25
26 // Get a path from the root to Peter
27 System.out.print("\nA path from the root to Peter is: ");
28 java.util.ArrayList<BST.TreeNode<String>> path
29 = tree.path("Peter");
30 for (int i = 0; path != null && i < path.size(); i++)
31 System.out.print(path.get(i).element + " ");
32
33 Integer[] numbers = {2, 4, 3, 1, 8, 5, 6, 7};
34 BST<Integer> intTree = new BST<>(numbers);
35 System.out.print("\nInorder (sorted): ");
36 intTree.inorder();
37 }
38 }
```



```

Inorder (sorted): Adam Daniel George Jones Michael Peter Tom
Postorder: Daniel Adam Jones Peter Tom Michael George
Preorder: George Adam Daniel Michael Jones Tom Peter
The number of nodes is 7
Is Peter in the tree? true
A path from the root to Peter is: George Michael Tom Peter
Inorder (sorted): 1 2 3 4 5 6 7 8

```

The program checks `path != null` in line 30 to ensure that the path is not `null` before invoking `path.get(i)`. This is an example of defensive programming to avoid potential runtime errors.

The program creates another tree for storing `int` values (line 34). After all the elements are inserted in the trees, the trees should appear as shown in Figure 25.9.

If the elements are inserted in a different order (e.g., Daniel, Adam, Jones, Peter, Tom, Michael, George), the tree will look different. However, the inorder traversal prints elements in the same order as long as the set of elements is the same. The inorder traversal displays a sorted list.



**FIGURE 25.9** The BSTs in Listing 25.6 are pictured here after they are created.

- 25.1** Show the result of inserting [44](#) into Figure 25.4b.

**25.2** Show the inorder, preorder, and postorder of traversing the elements in the binary tree shown in Figure 25.1b.

**25.3** If a set of elements is inserted into a BST in two different orders, will the two corresponding BSTs look the same? Will the inorder traversal be the same? Will the postorder traversal be the same? Will the preorder traversal be the same?

**25.4** What is the time complexity of inserting an element into a BST?

**25.5** Implement the [search\(element\)](#) method using recursion.



## 25.3 Deleting Elements from a BST

*To delete an element from a BST, first locate it in the tree and then consider two cases—whether or not the node has a left child—before deleting the element and reconnecting the tree.*



The `insert(element)` method was presented in Section 25.2.3. Often you need to delete an element from a binary search tree. Doing so is far more complex than adding an element into a binary search tree.

To delete an element from a binary search tree, you need to first locate the node that contains the element and also its parent node. Let **current** point to the node that contains the element in the binary search tree and **parent** point to the parent of the **current** node. The **current** node may be a left child or a right child of the **parent** node. There are two cases to consider.

**Case 1:** The current node does not have a left child, as shown in Figure 25.10a. In this case, simply connect the parent with the right child of the current node, as shown in Figure 25.10b.

For example, to delete node **10** in Figure 25.11a, you would connect the parent of node **10** with the right child of node **10**, as shown in Figure 25.11b.



FIGURE 25.10 Case 1: The current node has no left child.

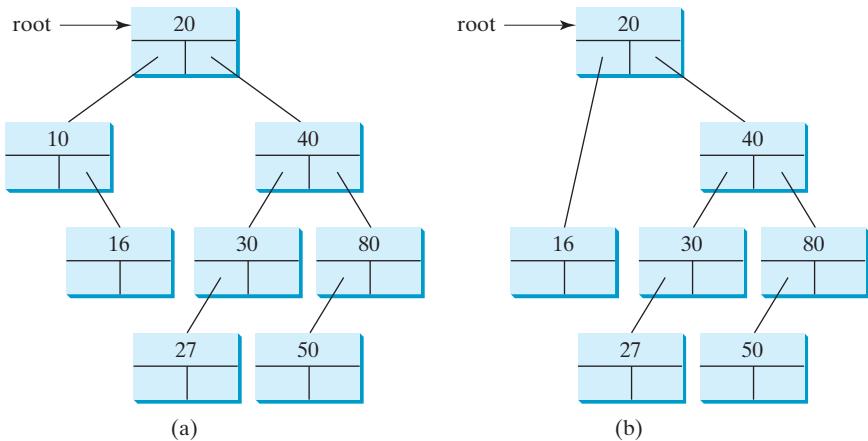


FIGURE 25.11 Case 1: Deleting node 10 from (a) results in (b).

delete a leaf

**Note**

If the current node is a leaf, it falls into Case 1. For example, to delete element 16 in Figure 25.11a, connect its right child (in this case, it is null) to the parent of node 16.

**Case 2:** The **current** node has a left child. Let **rightMost** point to the node that contains the largest element in the left subtree of the **current** node and **parentOfRightMost** point to the parent node of the **rightMost** node, as shown in Figure 25.12a. Note that the **rightMost** node cannot have a right child but may have a left child. Replace the element value in the **current** node with the one in the **rightMost** node, connect the **parentOfRightMost** node with the left child of the **rightMost** node, and delete the **rightMost** node, as shown in Figure 25.12b.

For example, consider deleting node 20 in Figure 25.13a. The **rightMost** node has the element value 16. Replace the element value 20 with 16 in the **current** node and make node 10 the parent for node 14, as shown in Figure 25.13b.

special case

**Note**

If the left child of **current** does not have a right child, **current.left** points to the large element in the left subtree of **current**. In this case, **rightMost** is **current**. **left** and **parentOfRightMost** is **current**. You have to take care of this special case to reconnect the right child of **rightMost** with **parentOfRightMost**.



**FIGURE 25.12** Case 2: The current node has a left child.



**FIGURE 25.13** Case 2: Deleting node 20 from (a) results in (b).

The algorithm for deleting an element from a binary search tree can be described in Listing 25.7.

**LISTING 25.7** Deleting an Element from a BST

```
1 boolean delete(E e) {
2 Locate element e in the tree;
3 if element e is not found
```

not in the tree

```

 4 return true;
 5
locate current 6 Let current be the node that contains e and parent be
locate parent 7 the parent of current;
 8
Case 1 9 if (current has no left child) // Case 1
10 Connect the right child of
11 current with parent; now current is not referenced, so
12 it is eliminated;
Case 2 13 else // Case 2
14 Locate the rightmost node in the left subtree of current.
15 Copy the element value in the rightmost node to current.
16 Connect the parent of the rightmost node to the left child
17 of rightmost node;
18
19 return true; // Element deleted
20 }

```

The complete implementation of the `delete` method is given in lines 155–213 in Listing 25.5. The method locates the node (named `current`) to be deleted and also locates its parent (named `parent`) in lines 157–170. If `current` is `null`, the element is not in the tree. Therefore, the method returns `false` (line 173). Please note that if `current` is `root`, `parent` is `null`. If the tree is empty, both `current` and `parent` are `null`.

Case 1 of the algorithm is covered in lines 176–187. In this case, the `current` node has no left child (i.e., `current.left == null`). If `parent` is `null`, assign `current.right` to `root` (lines 178–180). Otherwise, assign `current.right` to either `parent.left` or `parent.right`, depending on whether `current` is a left or right child of `parent` (182–185).

Case 2 of the algorithm is covered in lines 188–209. In this case, `current` has a left child. The algorithm locates the rightmost node (named `rightMost`) in the left subtree of the current node and also its parent (named `parentOfRightMost`) (lines 195–198). Replace the element in `current` by the element in `rightMost` (line 201); assign `rightMost.left` to either `parentOfRightMost.right` or `parentOfRightMost.left` (lines 204–208), depending on whether `rightMost` is a right or left child of `parentOfRightMost`.

Listing 25.8 gives a test program that deletes the elements from the binary search tree.

### LISTING 25.8 TestBSTDelete.java

```

1 public class TestBSTDelete {
2 public static void main(String[] args) {
3 BST<String> tree = new BST<>();
4 tree.insert("George");
5 tree.insert("Michael");
6 tree.insert("Tom");
7 tree.insert("Adam");
8 tree.insert("Jones");
9 tree.insert("Peter");
10 tree.insert("Daniel");
11 printTree(tree);
12
13 System.out.println("\nAfter delete George:");
14 tree.delete("George");
15 printTree(tree);
16
17 System.out.println("\nAfter delete Adam:");
18 tree.delete("Adam");
19 printTree(tree);
20
21 System.out.println("\nAfter delete Michael:");
22 tree.delete("Michael");

```

```

23 printTree(tree);
24 }
25
26 public static void printTree(BST tree) {
27 // Traverse tree
28 System.out.print("Inorder (sorted): ");
29 tree.inorder();
30 System.out.print("\nPostorder: ");
31 tree.postorder();
32 System.out.print("\nPreorder: ");
33 tree.preorder();
34 System.out.print("\nThe number of nodes is " + tree.getSize());
35 System.out.println();
36 }
37 }
```

Inorder (sorted): Adam Daniel George Jones Michael Peter Tom  
 Postorder: Daniel Adam Jones Peter Tom Michael George  
 Preorder: George Adam Daniel Michael Jones Tom Peter  
 The number of nodes is 7

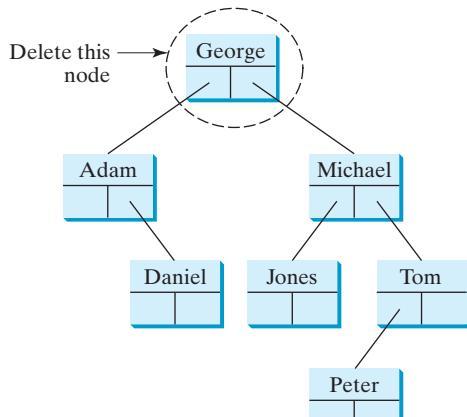


After delete George:  
 Inorder (sorted): Adam Daniel Jones Michael Peter Tom  
 Postorder: Adam Jones Peter Tom Michael Daniel  
 Preorder: Daniel Adam Michael Jones Tom Peter  
 The number of nodes is 6

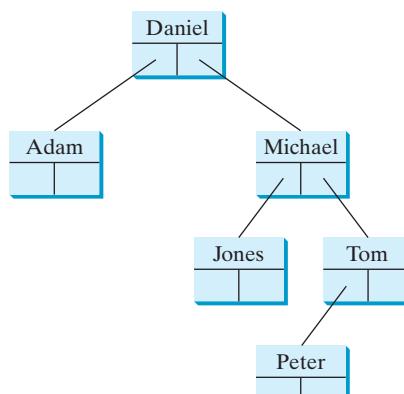
After delete Adam:  
 Inorder (sorted): Daniel Jones Michael Peter Tom  
 Postorder: Jones Peter Tom Michael Daniel  
 Preorder: Daniel Michael Jones Tom Peter  
 The number of nodes is 5

After delete Michael:  
 Inorder (sorted): Daniel Jones Peter Tom  
 Postorder: Peter Tom Jones Daniel  
 Preorder: Daniel Jones Tom Peter  
 The number of nodes is 4

Figures 25.14–25.16 show how the tree evolves as the elements are deleted from it.



(a) Deleting George



(b) After George is deleted

**FIGURE 25.14** Deleting George falls into Case 2.

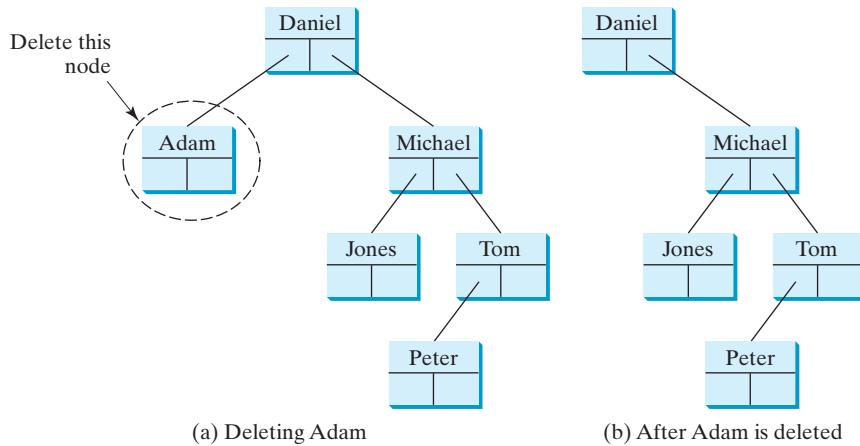


FIGURE 25.15 Deleting Adam falls into Case 1.

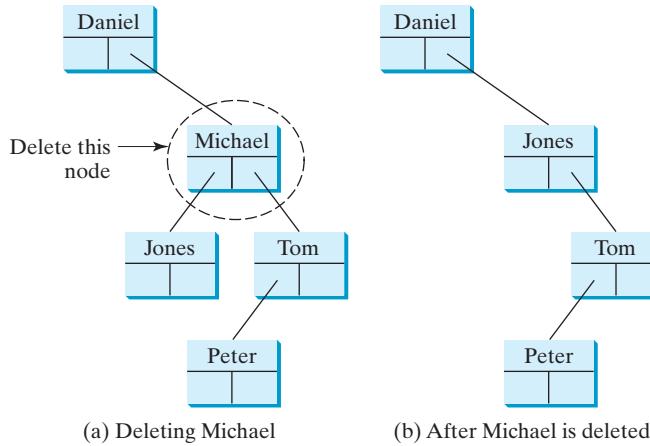


FIGURE 25.16 Deleting Michael falls into Case 2.

BST time complexity

**Note**

It is obvious that the time complexity for the inorder, preorder, and postorder is  $O(n)$ , since each node is traversed only once. The time complexity for search, insertion, and deletion is the height of the tree. In the worst case, the height of the tree is  $O(n)$ . If a tree is well-balanced, the height would be  $O(\log n)$ . We will introduce well-balanced binary trees in Chapter 26 and bonus Chapters 40 and 41.



- 25.6** Show the result of deleting 55 from the tree in Figure 25.4b.
- 25.7** Show the result of deleting 60 from the tree in Figure 25.4b.
- 25.8** What is the time complexity of deleting an element from a BST?
- 25.9** Is the algorithm correct if lines 204–208 in Listing 25.5 in Case 2 of the `delete()` method are replaced by the following code?

```
parentOfRightMost.right = rightMost.left;
```

## 25.4 Tree Visualization and MVC

You can use recursion to display a binary tree.



### Pedagogical Note

One challenge facing the data-structure course is to motivate students. Displaying a binary tree graphically will not only help you understand the working of a binary tree but perhaps also stimulate your interest in programming. This section introduces the techniques to visualize binary trees. You can also apply visualization techniques to other projects.

How do you display a binary tree? It is a recursive structure, so you can display a binary tree using recursion. You can simply display the root, then display the two subtrees recursively. The techniques for displaying the Sierpinski triangle (Listing 18.9, `SierpinskiTriangle.java`) can be applied to displaying a binary tree. For simplicity, we assume the keys are positive integers less than 100. Listings 25.9 and 25.10 give the program, and Figure 25.17 shows some sample runs of the program.

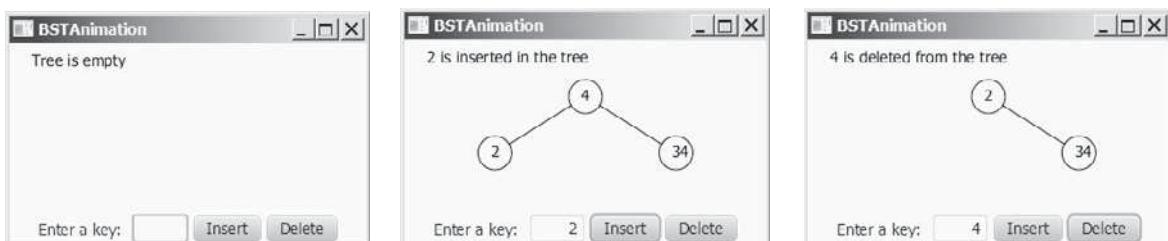


FIGURE 25.17 A binary tree is displayed graphically.

### LISTING 25.9 BSTAnimation.java

```

1 import javafx.application.Application;
2 import javafx.geometry.Pos;
3 import javafx.stage.Stage;
4 import javafx.scene.Scene;
5 import javafx.scene.control.Button;
6 import javafx.scene.control.Label;
7 import javafx.scene.control.TextField;
8 import javafx.scene.layout.BorderPane;
9 import javafx.scene.layout.HBox;
10
11 public class BSTAnimation extends Application {
12 @Override // Override the start method in the Application class
13 public void start(Stage primaryStage) {
14 BST<Integer> tree = new BST<>(); // Create a tree
15 create a tree
16 BorderPane pane = new BorderPane();
17 BTView view = new BTView(tree); // Create a BTView
18 pane.setCenter(view);
19 view for tree
20 TextField tfKey = new TextField();
21 tfKey.setPrefColumnCount(3);
22 tfKey.setAlignment(Pos.BASELINE_RIGHT);
23 Button btInsert = new Button("Insert");
24 Button btDelete = new Button("Delete");
25 HBox hBox = new HBox(5);
26 hBox.getChildren().addAll(new Label("Enter a key: "),

```

```

27 tfKey, btInsert, btDelete);
28 hBox.setAlignment(Pos.CENTER);
29 pane.setBottom(hBox);
30
place hBox
31 btInsert.setOnAction(e -> {
32 int key = Integer.parseInt(tfKey.getText());
33 if (tree.search(key)) { // key is in the tree already
34 view.displayTree();
35 view.setStatus(key + " is already in the tree");
36 } else {
37 tree.insert(key); // Insert a new key
38 view.displayTree();
39 view.setStatus(key + " is inserted in the tree");
40 }
41 });
42
handle insertion
43 btDelete.setOnAction(e -> {
44 int key = Integer.parseInt(tfKey.getText());
45 if (!tree.search(key)) { // key is not in the tree
46 view.displayTree();
47 view.setStatus(key + " is not in the tree");
48 } else {
49 tree.delete(key); // Delete a key
50 view.displayTree();
51 view.setStatus(key + " is deleted from the tree");
52 }
53 });
54
55 // Create a scene and place the pane in the stage
56 Scene scene = new Scene(pane, 450, 250);
57 primaryStage.setTitle("BSTAnimation"); // Set the stage title
58 primaryStage.setScene(scene); // Place the scene in the stage
59 primaryStage.show(); // Display the stage
60 }
61 }

```

**LISTING 25.10 BTView.java**

```

1 import javafx.scene.layout.Pane;
2 import javafx.scene.paint.Color;
3 import javafx.scene.shape.Circle;
4 import javafx.scene.shape.Line;
5 import javafx.scene.text.Text;
6
7 public class BTView extends Pane {
8 private BST<Integer> tree = new BST<>();
9 private double radius = 15; // Tree node radius
10 private double vGap = 50; // Gap between two levels in a tree
11
12 BTView(BST<Integer> tree) {
13 this.tree = tree;
14 setStatus("Tree is empty");
15 }
16
17 public void setStatus(String msg) {
18 getChildren().add(new Text(20, 20, msg));
19 }
20
tree to display
set a tree

```

```

21 public void displayTree() {
22 this.getChildren().clear(); // Clear the pane
23 if (tree.getRoot() != null) {
24 // Display tree recursively
25 displayTree(tree.getRoot(), getWidth() / 2, vGap,
26 getWidth() / 4);
27 }
28 }
29
30 /** Display a subtree rooted at position (x, y) */
31 private void displayTree(BST.TreeNode<Integer> root,
32 double x, double y, double hGap) {
33 if (root.left != null) {
34 // Draw a line to the left node
35 getChildren().add(new Line(x - hGap, y + vGap, x, y));
36 // Draw the left subtree recursively
37 displayTree(root.left, x - hGap, y + vGap, hGap / 2);
38 }
39
40 if (root.right != null) {
41 // Draw a line to the right node
42 getChildren().add(new Line(x + hGap, y + vGap, x, y));
43 // Draw the right subtree recursively
44 displayTree(root.right, x + hGap, y + vGap, hGap / 2);
45 }
46
47 // Display a node
48 Circle circle = new Circle(x, y, radius);
49 circle.setFill(Color.WHITE);
50 circle.setStroke(Color.BLACK);
51 getChildren().addAll(circle,
52 new Text(x - 4, y + 4, root.element + ""));
53 }
54 }
```

clear the display  
display tree recursively  
connect two nodes  
draw left subtree  
connect two nodes  
draw right subtree  
display a node

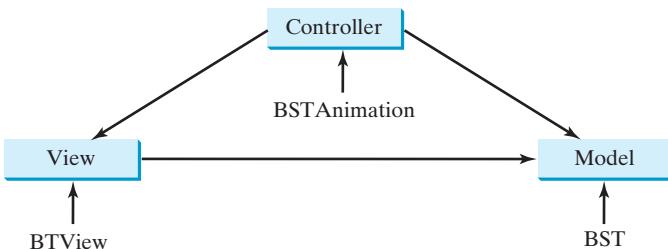
In Listing 25.9, BSTAnimation.java, a tree is created (line 14) and a tree view is placed in the pane (line 18). After a new key is inserted into the tree (line 37), the tree is repainted (line 38) to reflect the change. After a key is deleted (line 49), the tree is repainted (line 50) to reflect the change.

In Listing 25.10, BTView.java, the node is displayed as a circle with **radius 15** (line 48). The distance between two levels in the tree is defined in **vGap 50** (line 25). **hGap** (line 32) defines the distance between two nodes horizontally. This value is reduced by half (**hGap / 2**) in the next level when the **displayTree** method is called recursively (lines 44, 51). Note that **vGap** is not changed in the tree.

The method **displayTree** is recursively invoked to display a left subtree (lines 33–38) and a right subtree (lines 40–45) if a subtree is not empty. A line is added to the pane to connect two nodes (lines 35, 42). Note that the method first adds the lines to the pane and then adds the circle into the pane (line 52) so that the circles will be painted on top of the lines to achieve desired visual effects.

The program assumes that the keys are integers. You can easily modify the program with a generic type to display keys of characters or short strings.

Tree visualization is an example of the model-view-controller (MVC) software architecture. This is an important architecture for software development. The model is for storing and handling data. The view is for visually presenting the data. The controller handles the user interaction with the model and controls the view, as shown in Figure 25.18.



**FIGURE 25.18** The controller obtains data and stores it in a model. The view displays the data stored in the model.

The MVC architecture separates data storage and handling from the visual representation of the data. It has two major benefits:

- It makes multiple views possible so that data can be shared through the same model. For example, you can create a new view that displays the tree with the root on the left and tree grows horizontally to the right (see Programming Exercise 25.11).
- It simplifies the task of writing complex applications and makes the components scalable and easy to maintain. Changes can be made to the view without affecting the model, and vice versa.



- 25.10** How many times will the `displayTree` method be invoked if the tree is empty? How many times will the `displayTree` method be invoked if the tree has 100 nodes?
- 25.11** In what order are the nodes in the tree visited by the `displayTree` method: inorder, preorder, or postorder?
- 25.12** What would happen if the code in lines 47–52 in `BTView.java` is moved to line 33?
- 25.13** What is MVC? What are the benefits of the MVC?

## 25.5 Iterators

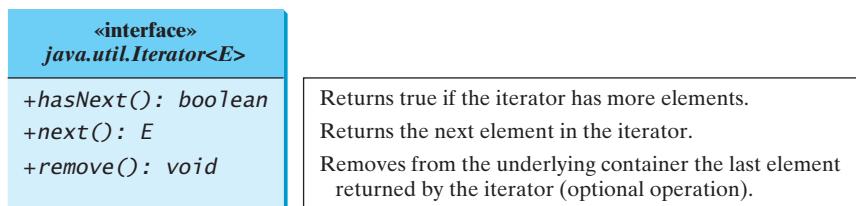


iterator

**BST** is iterable because it is defined as a subtype of the `java.lang.Iterable` interface.

The methods `inorder()`, `preorder()`, and `postorder()` display the elements in `inorder`, `preorder`, and `postorder` in a binary tree. These methods are limited to displaying the elements in a tree. If you wish to process the elements in a binary tree rather than display them, these methods cannot be used. Recall that an iterator is provided for traversing the elements in a set or list. You can apply the same approach in a binary tree to provide a uniform way of traversing the elements in a binary tree.

The `java.lang.Iterable` interface defines the `iterator` method, which returns an instance of the `java.util.Iterator` interface. The `java.util.Iterator` interface (see Figure 25.19) defines the common features of iterators.



**FIGURE 25.19** The `Iterator` interface defines a uniform way of traversing the elements in a container.

The `Tree` interface extends `java.lang.Iterable`. Since `BST` is a subclass of `AbstractTree` and `AbstractTree` implements `Tree`, `BST` is a subtype of `Iterable`. The `Iterable` interface contains the `iterator()` method that returns an instance of `java.util.Iterator`.

You can traverse a binary tree in inorder, preorder, or postorder. Since inorder is used frequently, we will use inorder for traversing the elements in a binary tree. We define an iterator class named `InorderIterator` to implement the `java.util.Iterator` interface in Listing 25.5 (lines 221–263). The `iterator` method simply returns an instance of `InorderIterator` (line 217).

The `InorderIterator` constructor invokes the `inorder` method (line 228). The `inorder(root)` method (lines 237–242) stores all the elements from the tree in `list`. The elements are traversed in `inorder`.

Once an `Iterator` object is created, its `current` value is initialized to `0` (line 225), which points to the first element in the list. Invoking the `next()` method returns the current element and moves `current` to point to the next element in the list (line 253).

The `hasNext()` method checks whether `current` is still in the range of `list` (line 246).

The `remove()` method removes the current element from the tree (line 259). Afterward, a new list is created (lines 260–261). Note that `current` does not need to be changed.

Listing 25.11 gives a test program that stores the strings in a BST and displays all strings in uppercase.

## LISTING 25.11 TestBSTWithIterator.java

```

1 public class TestBSTWithIterator {
2 public static void main(String[] args) {
3 BST<String> tree = new BST<>();
4 tree.insert("George");
5 tree.insert("Michael");
6 tree.insert("Tom");
7 tree.insert("Adam");
8 tree.insert("Jones");
9 tree.insert("Peter");
10 tree.insert("Daniel");
11
12 for (String s: tree)
13 System.out.print(s.toUpperCase() + " ");
14 }
15 }
```

ADAM DANIEL GEORGE JONES MICHAEL PETER TOM

how to create an iterator

use an iterator  
get uppercase letters



The foreach loop (lines 12–13) uses an iterator to traverse all elements in the tree.



### Design Guide

Iterator is an important software design pattern. It provides a uniform way of traversing the elements in a container, while hiding the container's structural details. By implementing the same interface `java.util.Iterator`, you can write a program that traverses the elements of all containers in the same way.

iterator pattern  
advantages of iterators



### Note

`java.util.Iterator` defines a forward iterator, which traverses the elements in the iterator in a forward direction, and each element can be traversed only once. The Java API also provides the `java.util.ListIterator`, which supports traversing in both forward and backward directions. If your data structure warrants flexible traversing, you may define iterator classes as a subtype of `java.util.ListIterator`.

variations of iterators

The implementation of the iterator is not efficient. Every time you remove an element through the iterator, the whole list is rebuilt (line 261 in Listing 25.5 BST.java). The client should always use the `delete` method in the `BinaryTree` class to remove an element. To prevent the user from using the `remove` method in the iterator, implement the iterator as follows:

```
public void remove() {
 throw new UnsupportedOperationException
 ("Removing an element from the iterator is not supported");
}
```

After making the `remove` method unsupported by the iterator class, you can implement the iterator more efficiently without having to maintain a list for the elements in the tree. You can use a stack to store the nodes, and the node on the top of the stack contains the element that is to be returned from the `next()` method. If the tree is well-balanced, the maximum stack size will be  $O(\log n)$ .



**25.14** What is an iterator?

**25.15** What method is defined in the `java.lang.Iterable<E>` interface?

**25.16** Suppose you delete `extends Iterable<E>` from line 1 in Listing 25.3, Tree.java. Will Listing 25.11 still compile?

**25.17** What is the benefit of being a subtype of `Iterable<E>`?



## 25.6 Case Study: Data Compression

*Huffman coding compresses data by using fewer bits to encode characters that occur more frequently. The codes for the characters are constructed based on the occurrence of the characters in the text using a binary tree, called the Huffman coding tree.*

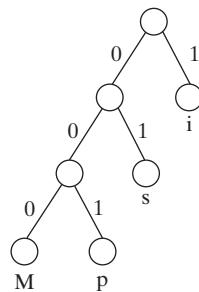
Huffman coding

Compressing data is a common task. There are many utilities available for compressing files. This section introduces Huffman coding, invented by David Huffman in 1952.

In ASCII, every character is encoded in 8 bits. If a text consists of 100 characters, it will take 800 bits to represent the text. The idea of Huffman coding is to use a fewer bits to encode frequently used characters in the text and more bits to encode less frequently used characters to reduce the overall size of the file. In Huffman coding, the characters' codes are constructed based on the characters' occurrence in the text using a binary tree, called the *Huffman coding tree*. Suppose the text is **Mississippi**. Its Huffman tree can be shown as in Figure 25.20a. The left and right edges of a node are assigned a value **0** and **1**, respectively. Each character is a leaf in the tree. The code for the character consists of the edge values in the path from the root to the leaf, as shown in Figure 25.20b. Since **i** and **s** appear more than **M** and **p** in the text, they are assigned shorter codes.

Based on the coding scheme in Figure 25.20,

| is encoded to      | is decoded to                |
|--------------------|------------------------------|
| Mississippi =====> | 000101011010110010011 =====> |
| Mississippi        | Mississippi                  |



(a) Huffman coding tree

| Character | Code | Frequency |
|-----------|------|-----------|
| M         | 000  | 1         |
| p         | 001  | 2         |
| s         | 01   | 4         |
| i         | 1    | 4         |

(b) Character code table

**FIGURE 25.20** The codes for characters are constructed based on the occurrence of characters in the text using a coding tree.

The coding tree is also used for decoding a sequence of bits into characters. To do so, start with the first bit in the sequence and determine whether to go to the left or right branch of the tree's root based on the bit value. Consider the next bit and continue to go down to the left or right branch based on the bit value. When you reach a leaf, you have found a character. The next bit in the stream is the first bit of the next character. For example, the stream **011001** is decoded to **sip**, with **01** matching **s**, **1** matching **i**, and **001** matching **p**.

To construct a *Huffman coding tree*, use an algorithm as follows:

decoding  
construct coding tree

1. Begin with a forest of trees. Each tree contains a node for a character. The weight of the node is the frequency of the character in the text.
2. Repeat the following action to combine trees until there is only one tree: Choose two trees with the smallest weight and create a new node as their parent. The weight of the new tree is the sum of the weight of the subtrees.
3. For each interior node, assign its left edge a value **0** and right edge a value **1**. All leaf nodes represent characters in the text.

Here is an example of building a coding tree for the text **Mississippi**. The frequency table for the characters is shown in Figure 25.20b. Initially the forest contains single-node trees, as shown in Figure 25.21a. The trees are repeatedly combined to form large trees until only one tree is left, as shown in Figure 25.21b–d.



**FIGURE 25.21** The coding tree is built by repeatedly combining the two smallest-weighted trees.

It is worth noting that no code is a prefix of another code. This property ensures that the streams can be decoded unambiguously.

prefix property

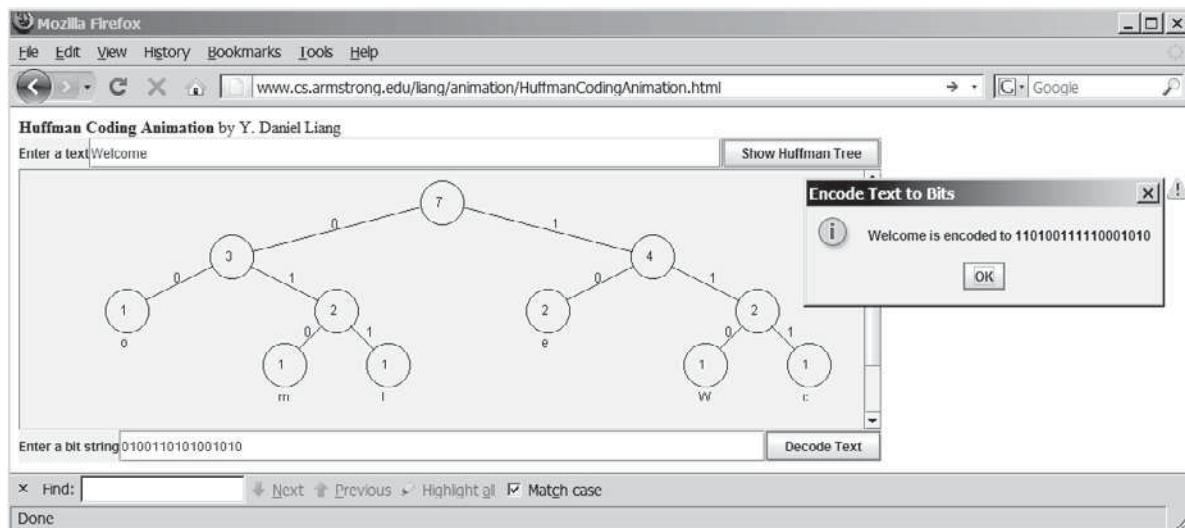


### Pedagogical Note

For an interactive GUI demo to see how Huffman coding works, go to [www.cs.armstrong.edu/liang/animation/HuffmanCodingAnimation.html](http://www.cs.armstrong.edu/liang/animation/HuffmanCodingAnimation.html), as shown in Figure 25.22.



Huffman coding animation on Companion Website



**FIGURE 25.22** The animation tool enables you to create and view a Huffman tree, and it performs encoding and decoding using the tree.

greedy algorithm

The algorithm used here is an example of a *greedy algorithm*. A greedy algorithm is often used in solving optimization problems. The algorithm makes the choice that is optimal locally in the hope that this choice will lead to a globally optimal solution. In this case, the algorithm always chooses two trees with the smallest weight and creates a new node as their parent. This intuitive optimal local solution indeed leads to a final optimal solution for constructing a Huffman tree. As another example, consider changing money into the fewest possible coins. A greedy algorithm would take the largest possible coin first. For example, for 98¢, you would use three quarters to make 75¢, additional two dimes to make 95¢, and additional three pennies to make the 98¢. The greedy algorithm finds an optimal solution for this problem. However, a greedy algorithm is not always going to find the optimal result; see the bin packing problem in Programming Exercise 25.22.

Listing 25.12 gives a program that prompts the user to enter a string, displays the frequency table of the characters in the string, and displays the Huffman code for each character.

### LISTING 25.12 HuffmanCode.java

count frequency

```

1 import java.util.Scanner;
2
3 public class HuffmanCode {
4 public static void main(String[] args) {
5 Scanner input = new Scanner(System.in);
6 System.out.print("Enter text: ");
7 String text = input.nextLine();
8
9 int[] counts = getCharacterFrequency(text); // Count frequency
10
11 System.out.printf("%-15s%-15s%-15s%-15s\n",
12 "ASCII Code", "Character", "Frequency", "Code");
13
14 Tree tree = getHuffmanTree(counts); // Create a Huffman tree
15 String[] codes = getCode(tree.root); // Get codes
16
17 for (int i = 0; i < codes.length; i++)
18 if (counts[i] != 0) // (char)i is not in text if counts[i] is 0
19 System.out.printf("%-15d%-15s%-15d%-15s\n",

```

get Huffman tree  
code for each character

```

20 i, (char)i + "", counts[i], codes[i]);
21 }
22
23 /** Get Huffman codes for the characters
24 * This method is called once after a Huffman tree is built
25 */
26 public static String[] getCode(Tree.Node root) { getCode
27 if (root == null) return null;
28 String[] codes = new String[2 * 128];
29 assignCode(root, codes);
30 return codes;
31 }
32
33 /* Recursively get codes to the leaf node */
34 private static void assignCode(Tree.Node root, String[] codes) { assignCode
35 if (root.left != null) {
36 root.left.code = root.code + "0";
37 assignCode(root.left, codes);
38
39 root.right.code = root.code + "1";
40 assignCode(root.right, codes);
41 }
42 else {
43 codes[(int)root.element] = root.code;
44 }
45 }
46
47 /** Get a Huffman tree from the codes */
48 public static Tree getHuffmanTree(int[] counts) { getHuffmanTree
49 // Create a heap to hold trees
50 Heap<Tree> heap = new Heap<>(); // Defined in Listing 23.9
51 for (int i = 0; i < counts.length; i++) {
52 if (counts[i] > 0)
53 heap.add(new Tree(counts[i], (char)i)); // A leaf node tree
54 }
55
56 while (heap.getSize() > 1) {
57 Tree t1 = heap.remove(); // Remove the smallest-weight tree
58 Tree t2 = heap.remove(); // Remove the next smallest
59 heap.add(new Tree(t1, t2)); // Combine two trees
60 }
61
62 return heap.remove(); // The final tree
63 }
64
65 /** Get the frequency of the characters */
66 public static int[] getCharacterFrequency(String text) { getCharacterFrequency
67 int[] counts = new int[256]; // 256 ASCII characters
68
69 for (int i = 0; i < text.length(); i++)
70 counts[(int)text.charAt(i)]++; // Count the characters in text
71
72 return counts;
73 }
74
75 /** Define a Huffman coding tree */
76 public static class Tree implements Comparable<Tree> { Huffman tree
77 Node root; // The root of the tree
78
79 /** Create a tree with two subtrees */

```

```

80 public Tree(Tree t1, Tree t2) {
81 root = new Node();
82 root.left = t1.root;
83 root.right = t2.root;
84 root.weight = t1.root.weight + t2.root.weight;
85 }
86
87 /** Create a tree containing a leaf node */
88 public Tree(int weight, char element) {
89 root = new Node(weight, element);
90 }
91
92 @Override /** Compare trees based on their weights */
93 public int compareTo(Tree t) {
94 if (root.weight < t.root.weight) // Purposely reverse the order
95 return 1;
96 else if (root.weight == t.root.weight)
97 return 0;
98 else
99 return -1;
100 }
101
102 public class Node {
103 char element; // Stores the character for a leaf node
104 int weight; // weight of the subtree rooted at this node
105 Node left; // Reference to the left subtree
106 Node right; // Reference to the right subtree
107 String code = ""; // The code of this node from the root
108
109 /** Create an empty node */
110 public Node() {
111 }
112
113 /** Create a node with the specified weight and character */
114 public Node(int weight, char element) {
115 this.weight = weight;
116 this.element = element;
117 }
118 }
119 }
120 }
```

tree node



| Enter text: Welcome | <input type="button" value="Enter"/> |           |      |
|---------------------|--------------------------------------|-----------|------|
| ASCII Code          | Character                            | Frequency | Code |
| 87                  | W                                    | 1         | 110  |
| 99                  | c                                    | 1         | 111  |
| 101                 | e                                    | 2         | 10   |
| 108                 | l                                    | 1         | 011  |
| 109                 | m                                    | 1         | 010  |
| 111                 | o                                    | 1         | 00   |

getCharacterFrequency

The program prompts the user to enter a text string (lines 5–7) and counts the frequency of the characters in the text (line 9). The **getCharacterFrequency** method (lines 66–73) creates an array **counts** to count the occurrences of each of the 256 ASCII characters in the text. If a character appears in the text, its corresponding count is increased by 1 (line 70).

The program obtains a Huffman coding tree based on `counts` (line 14). The tree consists of linked nodes. The `Node` class is defined in lines 102–118. Each node consists of properties `element` (storing character), `weight` (storing weight of the subtree under this node), `left` (linking to the left subtree), `right` (linking to the right subtree), and `code` (storing the Huffman code for the character). The `Tree` class (lines 76–119) contains the `root` property. From the root, you can access all the nodes in the tree. The `Tree` class implements `Comparable`. The trees are comparable based on their weights. The compare order is purposely reversed (lines 93–100) so that the smallest-weight tree is removed first from the heap of trees.

The `getHuffmanTree` method returns a Huffman coding tree. Initially, the single-node trees are created and added to the heap (lines 50–54). In each iteration of the `while` loop (lines 56–60), two smallest-weight trees are removed from the heap and are combined to form a big tree, and then the new tree is added to the heap. This process continues until the heap contains just one tree, which is our final Huffman tree for the text.

The `assignCode` method assigns the code for each node in the tree (lines 34–45). The `getCode` method gets the code for each character in the leaf node (lines 26–31). The element `codes[i]` contains the code for character `(char)i`, where `i` is from `0` to `255`. Note that `codes[i]` is `null` if `(char)i` is not in the text.

**25.18** Every internal node in a Huffman tree has two children. Is it true?

**25.19** What is a greedy algorithm? Give an example.

**25.20** If the `Heap` class in line 50 in Listing 25.10 is replaced by `java.util.PriorityQueue`, will the program still work?

Node class

Tree class

getHuffmanTree

assignCode  
getCode



## KEY TERMS

binary search tree 930

binary tree 930

breadth-first traversal 934

depth-first traversal 934

greedy algorithm 956

Huffman coding 954

inorder traversal 933

postorder traversal 933

preorder traversal 934

tree traversal 933

## CHAPTER SUMMARY

1. A *binary search tree* (BST) is a hierarchical data structure. You learned how to define and implement a BST class, how to insert and delete elements into/from a BST, and how to traverse a BST using *inorder*, *postorder*, *preorder*, depth-first, and breadth-first searches.
2. An iterator is an object that provides a uniform way of traversing the elements in a container, such as a set, a list, or a *binary tree*. You learned how to define and implement iterator classes for traversing the elements in a binary tree.
3. *Huffman coding* is a scheme for compressing data by using fewer bits to encode characters that occur more frequently. The codes for characters are constructed based on the occurrence of characters in the text using a binary tree, called the *Huffman coding tree*.

## QUIZ

Answer the quiz for this chapter online at [www.cs.armstrong.edu/liang/intro10e/quiz.html](http://www.cs.armstrong.edu/liang/intro10e/quiz.html).

**Sections 25.2–25.6**

- \*25.1** (*Add new methods in BST*) Add the following new methods in **BST**.

```
/** Displays the nodes in a breadth-first traversal */
public void breadthFirstTraversal()

/** Returns the height of this binary tree */
public int height()
```

- \*25.2** (*Test full binary tree*) A full binary tree is a binary tree with the leaves on the same level. Add a method in the **BST** class to return true if the tree is a full binary tree. (*Hint:* The number of nodes in a full binary tree is  $2^{\text{depth}} - 1$ .)

```
/** Returns true if the tree is a full binary tree */
boolean isFullBST()
```

- \*\*25.3** (*Implement inorder traversal without using recursion*) Implement the **inorder** method in **BST** using a stack instead of recursion. Write a test program that prompts the user to enter 10 integers, stores them in a BST, and invokes the **inorder** method to display the elements.

- \*\*25.4** (*Implement preorder traversal without using recursion*) Implement the **preorder** method in **BST** using a stack instead of recursion. Write a test program that prompts the user to enter 10 integers, stores them in a BST, and invokes the **preorder** method to display the elements.

- \*\*25.5** (*Implement postorder traversal without using recursion*) Implement the **postorder** method in **BST** using a stack instead of recursion. Write a test program that prompts the user to enter 10 integers, stores them in a BST, and invokes the **postorder** method to display the elements.

- \*\*25.6** (*Find the leaves*) Add a method in the **BST** class to return the number of the leaves as follows:

```
/** Returns the number of leaf nodes */
public int getNumberOfLeaves()
```

- \*\*25.7** (*Find the nonleaves*) Add a method in the **BST** class to return the number of the nonleaves as follows:

```
/** Returns the number of nonleaf nodes */
public int getNumberofNonLeaves()
```

- \*\*\*25.8** (*Implement bidirectional iterator*) The **java.util.Iterator** interface defines a forward iterator. The Java API also provides the **java.util.ListIterator** interface that defines a bidirectional iterator. Study **ListIterator** and define a bidirectional iterator for the **BST** class.

- \*\*25.9** (*Tree clone and equals*) Implement the **clone** and **equals** methods in the **BST** class. Two **BST** trees are equal if they contain the same elements. The **clone** method returns an identical copy of a **BST**.

- 25.10** (*Preorder iterator*) Add the following method in the **BST** class that returns an iterator for traversing the elements in a BST in preorder.

```
/** Returns an iterator for traversing the elements in preorder */
java.util.Iterator<E> preorderIterator()
```

- 25.11** (*Display tree*) Write a new view class that displays the tree horizontally with the root on the left as shown in Figure 25.23.



FIGURE 25.23 A binary tree is displayed horizontally.

- \*\*25.12** (*Test BST*) Design and write a complete test program to test if the **BST** class in Listing 25.5 meets all requirements.

- \*\*25.13** (*Add new buttons in BSTAnimation*) Modify Listing 25.9, **BSTAnimation.java**, to add three new buttons—*Show Inorder*, *Show Preorder*, and *Show Postorder*—to display the result in a label, as shown in Figure 25.24. You need also to modify **BST.java** to implement the **inorderList()**, **preorderList()**, and **postorderList()** methods so that each of these methods returns a **List** of the node elements in inorder, preorder, and postorder, as follows:

```
public java.util.List<E> inorderList();
public java.util.List<E> preorderList();
public java.util.List<E> postorderList();
```

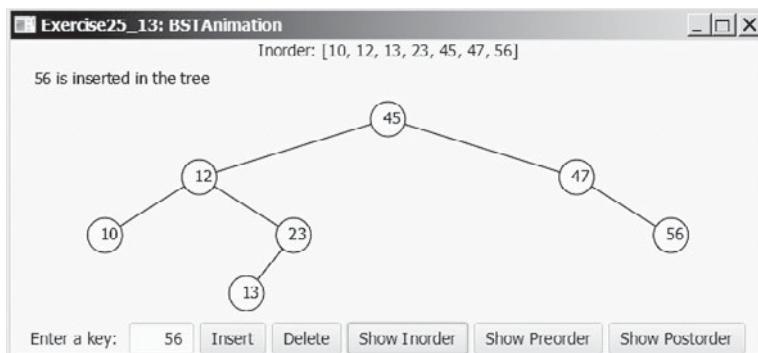


FIGURE 25.24 When you click the Show Inorder, Show Preorder, or Show Postorder button, the elements are displayed in an inorder, preorder, or postorder in a label.

- \*25.14** (*Generic BST using Comparator*) Revise **BST** in Listing 25.5, using a generic parameter and a **Comparator** for comparing objects. Define a new constructor with a **Comparator** as its argument as follows:

```
BST(Comparator<? super E> comparator)
```

- \*25.15** (*Parent reference for BST*) Redefine **TreeNode** by adding a reference to a node's parent, as shown below:



Reimplement the **insert** and **delete** methods in the **BST** class to update the parent for each node in the tree. Add the following new method in **BST**:

```

/** Returns the node for the specified element.
 * Returns null if the element is not in the tree. */
private TreeNode<E> getNode(E element)

/** Returns true if the node for the element is a leaf */
private boolean isLeaf(E element)

/** Returns the path of elements from the specified element
 * to the root in an array list. */
public ArrayList<E> getPath(E e)

```

Write a test program that prompts the user to enter 10 integers, adds them to the tree, deletes the first integer from the tree, and displays the paths for all leaf nodes. Here is a sample run:



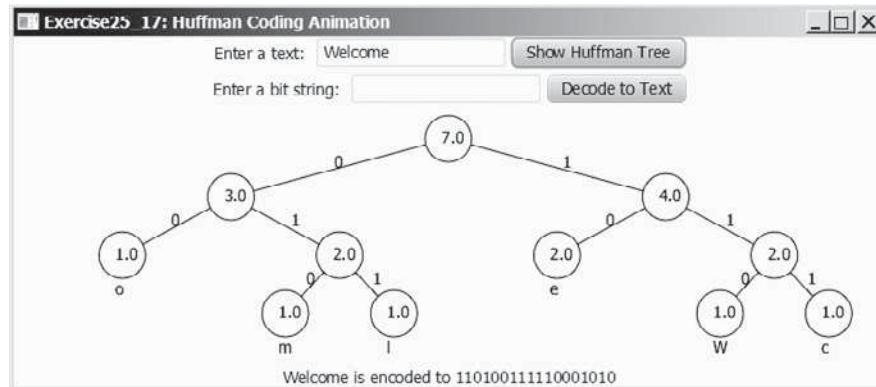
```

Enter 10 integers: 45 54 67 56 50 45 23 59 23 67 ↵Enter
[50, 54, 23]
[59, 56, 67, 54, 23]

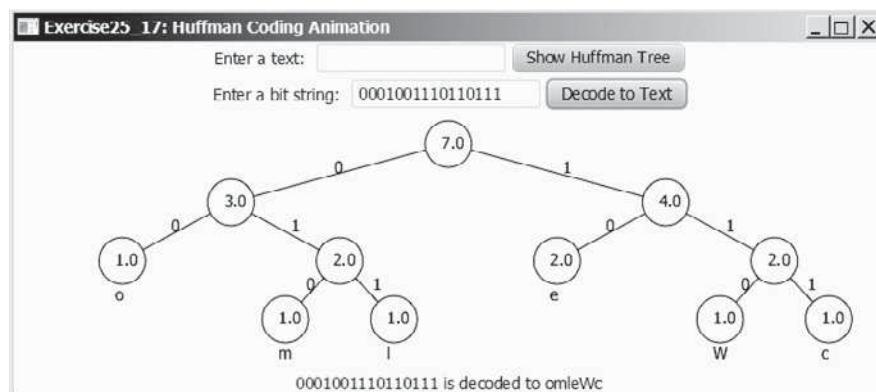
```

- \*\*\*25.16** (*Data compression: Huffman coding*) Write a program that prompts the user to enter a file name, then displays the frequency table of the characters in the file and displays the Huffman code for each character.

- \*\*\*25.17** (*Data compression: Huffman coding animation*) Write a program that enables the user to enter text and displays the Huffman coding tree based on the text, as shown in Figure 25.25a. Display the weight of the subtree inside the subtree's root circle. Display each leaf node's character. Display the encoded bits for the text in a label. When the user clicks the *Decode Text* button, a bit string is decoded into text displayed in the label, as shown in Figure 25.25b.



(a)



(b)

**FIGURE 25.25** (a) The animation shows the coding tree for a given text string and the encoded bits for the text are displayed in the label; (b) You can enter a bit string to display its text in the label.

**\*\*\*25.18** (*Compress a file*) Write a program that compresses a source file into a target file using the Huffman coding method. First use **ObjectOutputStream** to output the Huffman codes into the target file, and then use **BitOutputStream** in Programming Exercise 17.17 to output the encoded binary contents to the target file. Pass the files from the command line using the following command:

```
java Exercise25_18 sourcefile targetfile
```

**\*\*\*25.19** (*Decompress a file*) The preceding exercise compresses a file. The compressed file contains the Huffman codes and the compressed contents. Write a program that decompresses a source file into a target file using the following command:

```
java Exercise25_19 sourcefile targetfile
```

**25.20** (*Bin packing using first fit*) Write a program that packs the objects of various weights into containers. Each container can hold a maximum of 10 pounds. The program uses a greedy algorithm that places an object into the first bin in which it would fit. Your program should prompt the user to enter the total number of

objects and the weight of each object. The program displays the total number of containers needed to pack the objects and the contents of each container. Here is a sample run of the program:



```
Enter the number of objects: 6
Enter the weights of the objects: 7 5 2 3 5 8
Container 1 contains objects with weight 7 2
Container 2 contains objects with weight 5 3
Container 3 contains objects with weight 5
Container 4 contains objects with weight 8
```

Does this program produce an optimal solution, that is, finding the minimum number of containers to pack the objects?

**25.21**

(*Bin packing with smallest object first*) Rewrite the preceding program that uses a new greedy algorithm that places an object with the *smallest weight* into the first bin in which it would fit. Your program should prompt the user to enter the total number of objects and the weight of each object. The program displays the total number of containers needed to pack the objects and the contents of each container. Here is a sample run of the program:



```
Enter the number of objects: 6
Enter the weights of the objects: 7 5 2 3 5 8
Container 1 contains objects with weight 2 3 5
Container 2 contains objects with weight 5
Container 3 contains objects with weight 7
Container 4 contains objects with weight 8
```

Does this program produce an optimal solution, that is, finding the minimum number of containers to pack the objects?

**25.22**

(*Bin packing with largest object first*) Rewrite the preceding program that places an object with the *largest weight* into the first bin in which it would fit. Give an example to show that this program does not produce an optimal solution.

**25.23**

(*Optimal bin packing*) Rewrite the preceding program so that it finds an optimal solution that packs all objects using the smallest number of containers. Here is a sample run of the program:



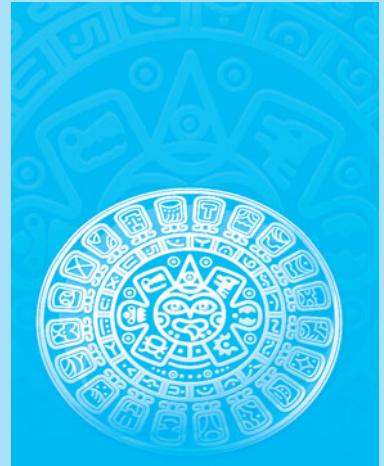
```
Enter the number of objects: 6 ↵ Enter
Enter the weights of the objects: 7 5 2 3 5 8 ↵ Enter
Container 1 contains objects with weight 7 3
Container 2 contains objects with weight 5 5
Container 3 contains objects with weight 2 8
The optimal number of bins is 3
```

What is the time complexity of your program?

# AVL TREES

## Objectives

- To know what an AVL tree is (§26.1).
- To understand how to rebalance a tree using the LL rotation, LR rotation, RR rotation, and RL rotation (§26.2).
- To design the `AVLTree` class by extending the `BST` class (§26.3).
- To insert elements into an AVL tree (§26.4).
- To implement tree rebalancing (§26.5).
- To delete elements from an AVL tree (§26.6).
- To implement the `AVLTree` class (§26.7).
- To test the `AVLTree` class (§26.8).
- To analyze the complexity of search, insertion, and deletion operations in AVL trees (§26.9).



## 26.1 Introduction



*AVL Tree is a balanced binary search tree.*

perfectly balanced tree

well-balanced tree

AVL tree

$O(\log n)$

balance factor

balanced

left-heavy

right-heavy



AVL tree animation on  
Companion Website

Chapter 25 introduced binary search trees. The search, insertion, and deletion times for a binary tree depend on the height of the tree. In the worst case, the height is  $O(n)$ . If a tree is *perfectly balanced*—i.e., a complete binary tree—its height is  $\log n$ . Can we maintain a perfectly balanced tree? Yes, but doing so will be costly. The compromise is to maintain a *well-balanced tree*—that is, the heights of every node’s two subtrees are about the same. This chapter introduces AVL trees. Web Chapters 40 and 41 introduce 2–4 trees and red–black trees.

AVL trees are well balanced. AVL trees were invented in 1962 by two Russian computer scientists, G. M. Adelson-Velsky and E. M. Landis (hence the name AVL). In an AVL tree, the difference between the heights of every node’s two subtrees is **0** or **1**. It can be shown that the maximum height of an AVL tree is  $O(\log n)$ .

The process for inserting or deleting an element in an AVL tree is the same as in a regular binary search tree, except that you may have to rebalance the tree after an insertion or deletion operation. The *balance factor* of a node is the height of its right subtree minus the height of its left subtree. A node is said to be *balanced* if its balance factor is **-1**, **0**, or **1**. A node is considered *left-heavy* if its balance factor is **-1**, and *right-heavy* if its balance factor is **+1**.

### Pedagogical Note

For an interactive GUI demo to see how an AVL tree works, go to [www.cs.armstrong.edu/liang/animation/web/AVLTree.html](http://www.cs.armstrong.edu/liang/animation/web/AVLTree.html), as shown in Figure 26.1.

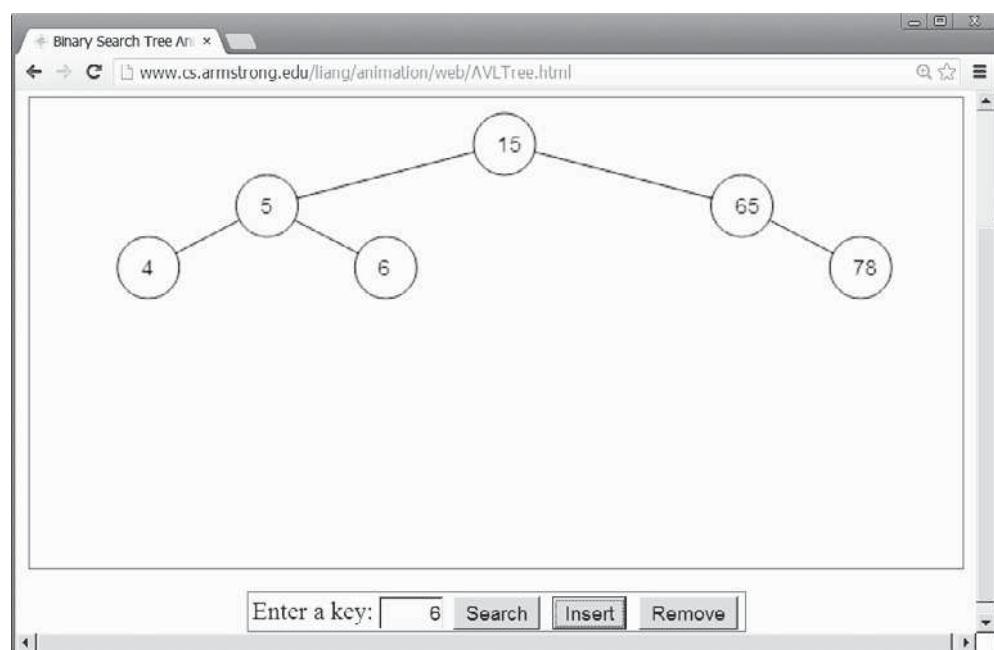


FIGURE 26.1 The animation tool enables you to insert, delete, and search elements.

## 26.2 Rebalancing Trees



*After inserting or deleting an element from an AVL tree, if the tree becomes unbalanced, perform a rotation operation to rebalance the tree.*

rotation

If a node is not balanced after an insertion or deletion operation, you need to rebalance it. The process of rebalancing a node is called *rotation*. There are four possible rotations: LL, RR, LR, and RL.

**LL rotation:** An *LL imbalance* occurs at a node **A**, such that **A** has a balance factor of **-2** and a left child **B** with a balance factor of **-1** or **0**, as shown in Figure 26.2a. This type of imbalance can be fixed by performing a single right rotation at **A**, as shown in Figure 26.2b.

**RR rotation:** An *RR imbalance* occurs at a node **A**, such that **A** has a balance factor of **+2** and a right child **B** with a balance factor of **+1** or **0**, as shown in Figure 26.3a. This type of imbalance can be fixed by performing a single left rotation at **A**, as shown in Figure 26.3b.

|             |              |
|-------------|--------------|
| LL rotation | LL imbalance |
| RR rotation | RR imbalance |

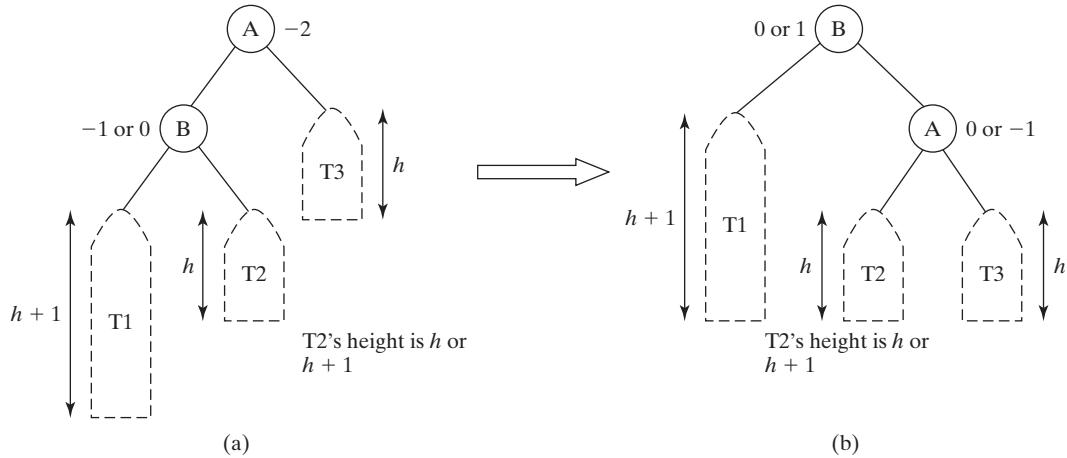


FIGURE 26.2 An LL rotation fixes an LL imbalance.

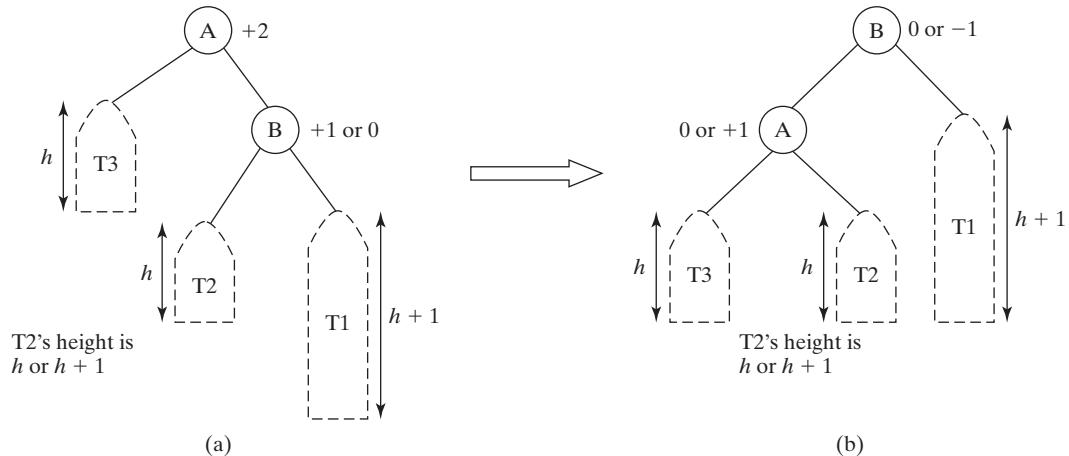


FIGURE 26.3 An RR rotation fixes an RR imbalance.

**LR rotation:** An *LR imbalance* occurs at a node **A**, such that **A** has a balance factor of **-2** and a left child **B** with a balance factor of **+1**, as shown in Figure 26.4a. Assume **B**'s right child is **C**. This type of imbalance can be fixed by performing a double rotation (first a single left rotation at **B** and then a single right rotation at **A**), as shown in Figure 26.4b.

|             |              |
|-------------|--------------|
| LR rotation | LR imbalance |
|-------------|--------------|

**RL rotation:** An *RL imbalance* occurs at a node **A**, such that **A** has a balance factor of **+2** and a right child **B** with a balance factor of **-1**, as shown in Figure 26.5a. Assume **B**'s left child is **C**. This type of imbalance can be fixed by performing a double rotation (first a single right rotation at **B** and then a single left rotation at **A**), as shown in Figure 26.5b.

|             |              |
|-------------|--------------|
| RL rotation | RL imbalance |
|-------------|--------------|

**26.1** What is an AVL tree? Describe the following terms: balance factor, left-heavy, and right-heavy.



**26.2** Show the balance factor of each node in the trees shown in Figure 26.6.

**26.3** Describe LL rotation, RR rotation, LR rotation, and RL rotation for an AVL tree.

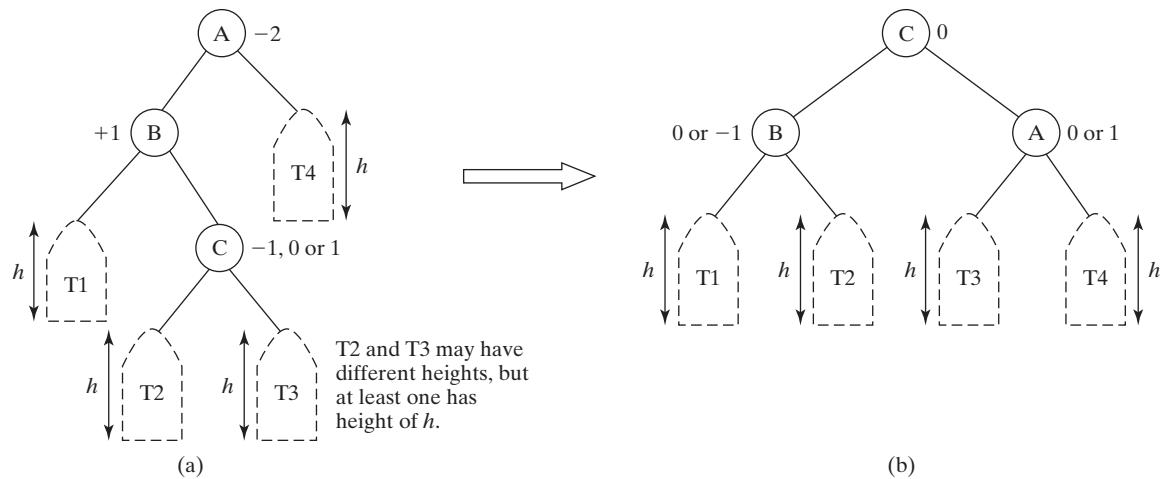


FIGURE 26.4 An LR rotation fixes an LR imbalance.

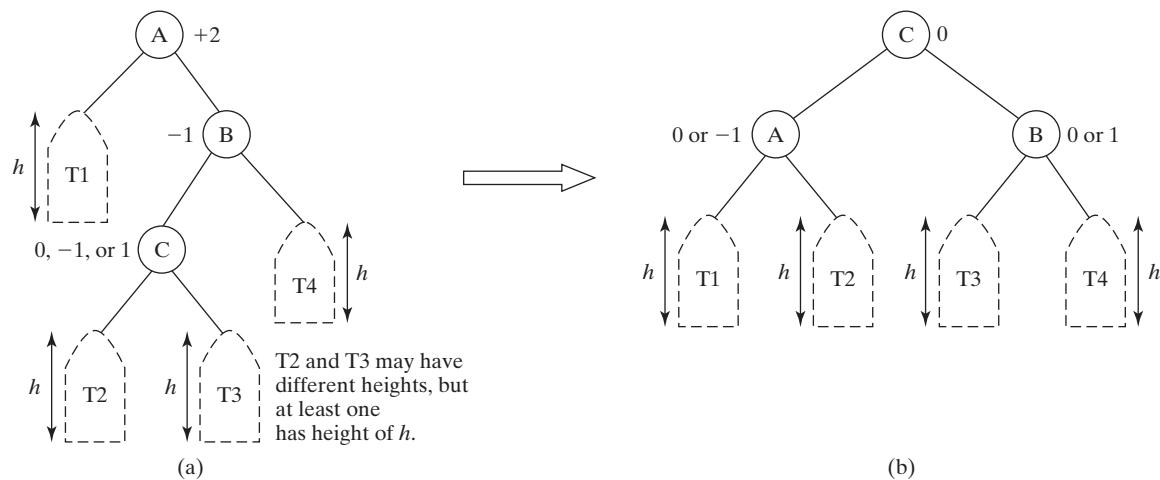


FIGURE 26.5 An RL rotation fixes an RL imbalance.

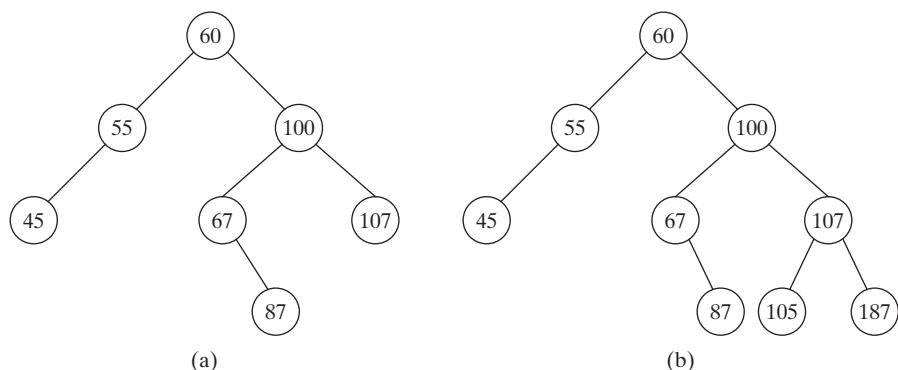


FIGURE 26.6 A balance factor determines whether a node is balanced.

## 26.3 Designing Classes for AVL Trees

Since an AVL tree is a binary search tree, `AVLTree` is designed as a subclass of `BST`.

An AVL tree is a binary tree, so you can define the `AVLTree` class to extend the `BST` class, as shown in Figure 26.7. The `BST` and `TreeNode` classes were defined in Section 25.2.5.

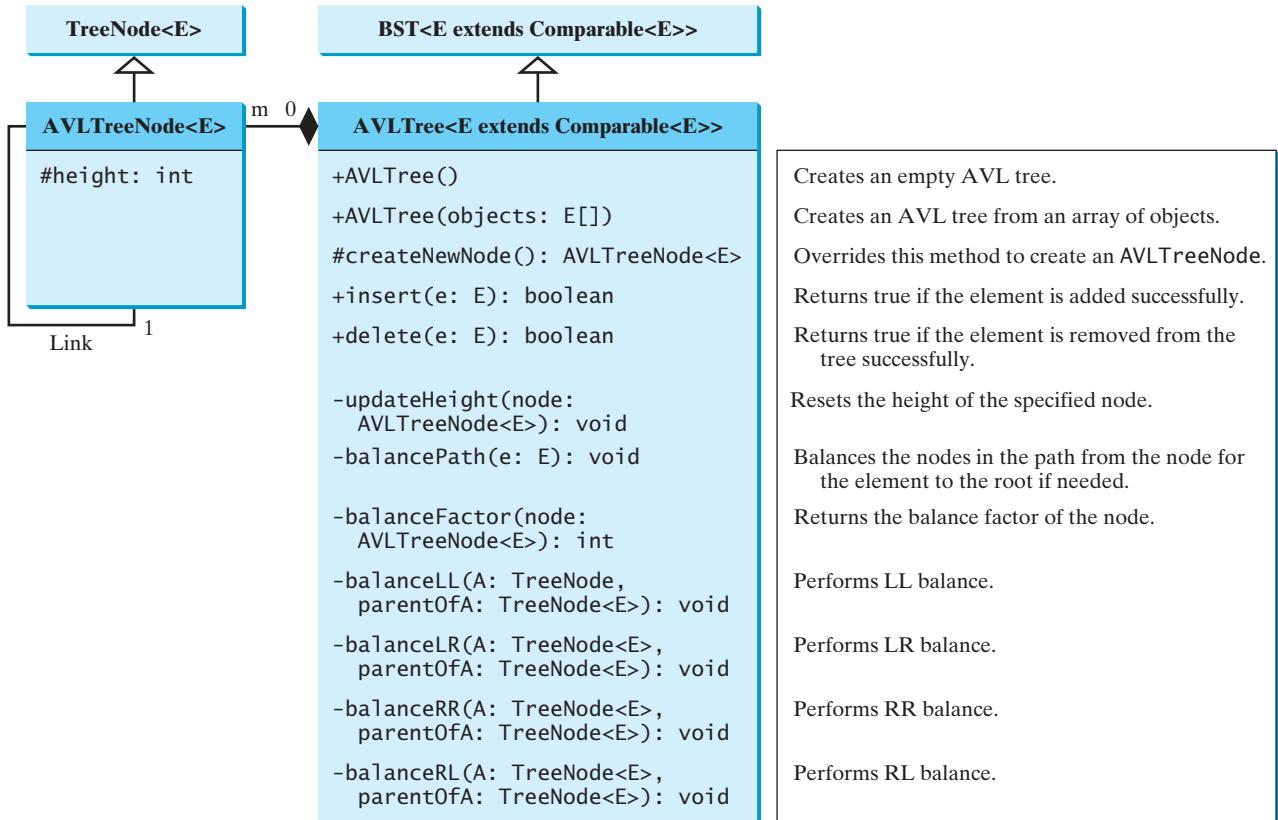


FIGURE 26.7 The `AVLTree` class extends `BST` with new implementations for the `insert` and `delete` methods.

In order to balance the tree, you need to know each node's height. For convenience, store the height of each node in `AVLTreeNode` and define `AVLTreeNode` to be a subclass of `BST(TreeNode)`. Note that `TreeNode` is defined as a static inner class in `BST`. `AVLTreeNode` will be defined as a static inner class in `AVLTree`. `AVLTreeNode` contains the data fields `element`, `left`, and `right`, which are inherited by `AVLTreeNode`. Thus, `AVLTreeNode` contains four data fields, as shown in Figure 26.8.



FIGURE 26.8 An `AVLTreeNode` contains the protected data fields `element`, `height`, `left`, and `right`.

createNewNode()

In the `BST` class, the `createNewNode()` method creates a `TreeNode` object. This method is overridden in the `AVLTree` class to create an `AVLTreeNode`. Note that the return type of the `createNewNode()` method in the `BST` class is `TreeNode`, but the return type of the `createNewNode()` method in the `AVLTree` class is `AVLTreeNode`. This is fine, since `AVLTreeNode` is a subclass of `TreeNode`.

Searching for an element in an `AVLTree` is the same as searching in a regular binary tree, so the `search` method defined in the `BST` class also works for `AVLTree`.

The `insert` and `delete` methods are overridden to insert and delete an element and perform rebalancing operations if necessary to ensure that the tree is balanced.



**26.4** What are the data fields in the `AVLTreeNode` class?

**26.5** True or false: `AVLTreeNode` is a subclass of `TreeNode`?

**26.6** True or false: `AVLTree` is a subclass of `BST`.



## 26.4 Overriding the `insert` Method

*Inserting an element into an AVL tree is the same as inserting it to a BST, except that the tree may need to be rebalanced.*

A new element is always inserted as a leaf node. As a result of adding a new node, the heights of the new leaf node's ancestors may increase. After inserting a new node, check the nodes along the path from the new leaf node up to the root. If an unbalanced node is found, perform an appropriate rotation using the algorithm in Listing 26.1.

### LISTING 26.1 Balancing Nodes on a Path

get the path

```

1 balancePath(E e) {
2 Get the path from the node that contains element e to the root,
3 as illustrated in Figure 26.9;
4 for each node A in the path leading to the root {
5 Update the height of A;
6 Let parentOfA denote the parent of A,
7 which is the next node in the path, or null if A is the root;
8
9 switch (balanceFactor(A)) {
10 case -2: if balanceFactor(A.left) == -1 or 0
11 Perform LL rotation; // See Figure 26.2
12 else
13 Perform LR rotation; // See Figure 26.4
14 break;
15 case +2: if balanceFactor(A.right) == +1 or 0
16 Perform RR rotation; // See Figure 26.3
17 else
18 Perform RL rotation; // See Figure 26.5
19 } // End of switch
20 } // End of for
21 } // End of method

```

update node height  
get parent node

is balanced?

LL rotation

LR rotation

RR rotation

RL rotation

The algorithm considers each node in the path from the new leaf node to the root. Update the height of the node on the path. If a node is balanced, no action is needed. If a node is not balanced, perform an appropriate rotation.



**26.7** For the AVL tree in Figure 26.6a, show the new AVL tree after adding element **40**. What rotation do you perform in order to rebalance the tree? Which node was unbalanced?



**FIGURE 26.9** The nodes along the path from the new leaf node may become unbalanced.

- 26.8** For the AVL tree in Figure 26.6a, show the new AVL tree after adding element **50**. What rotation do you perform in order to rebalance the tree? Which node was unbalanced?
- 26.9** For the AVL tree in Figure 26.6a, show the new AVL tree after adding element **80**. What rotation do you perform in order to rebalance the tree? Which node was unbalanced?
- 26.10** For the AVL tree in Figure 26.6a, show the new AVL tree after adding element **89**. What rotation do you perform in order to rebalance the tree? Which node was unbalanced?

## 26.5 Implementing Rotations

*An unbalanced tree becomes balanced by performing an appropriate rotation operation.*

Section 26.2, Rebalancing Trees, illustrated how to perform rotations at a node. Listing 26.2 gives the algorithm for the LL rotation, as illustrated in Figure 26.2.



### LISTING 26.2 LL Rotation Algorithm

```

1 balanceLL(TreeNode A, TreeNode parentOfA) {
2 Let B be the left child of A. left child of A
3
4 if (A is the root)
5 Let B be the new root reconnect B's parent
6 else {
7 if (A is a left child of parentOfA)
8 Let B be a left child of parentOfA;
9 else
10 Let B be a right child of parentOfA;
11 }
12
13 Make T2 the left subtree of A by assigning B.right to A.left; move subtrees
14 Make A the right child of B by assigning A to B.right; adjust height
15 Update the height of node A and node B;
16 } // End of method

```

Note that the height of nodes **A** and **B** can be changed, but the heights of other nodes in the tree are not changed. You can implement the RR, LR, and RL rotations in a similar manner.

## 26.6 Implementing the `delete` Method



*Deleting an element from an AVL tree is the same as deleting it from a BST, except that the tree may need to be rebalanced.*

As discussed in Section 25.3, Deleting Elements from a BST, to delete an element from a binary tree, the algorithm first locates the node that contains the element. Let `current` point to the node that contains the element in the binary tree and `parent` point to the parent of the `current` node. The `current` node may be a left child or a right child of the `parent` node. Two cases arise when deleting an element.

**Case 1:** The `current` node does not have a left child, as shown in Figure 25.10a. To delete the `current` node, simply connect the `parent` node with the right child of the `current` node, as shown in Figure 25.10b.

The height of the nodes along the path from the `parent` node up to the `root` may have decreased. To ensure that the tree is balanced, invoke

```
balancePath(parent.element); // Defined in Listing 26.1
```

**Case 2:** The `current` node has a left child. Let `rightMost` point to the node that contains the largest element in the left subtree of the `current` node and `parentOfRightMost` point to the parent node of the `rightMost` node, as shown in Figure 25.12a. The `rightMost` node cannot have a right child but it may have a left child. Replace the element value in the `current` node with the one in the `rightMost` node, connect the `parentOfRightMost` node with the left child of the `rightMost` node, and delete the `rightMost` node, as shown in Figure 25.12b.

The height of the nodes along the path from `parentOfRightMost` up to the root may have decreased. To ensure that the tree is balanced, invoke

```
balancePath(parentOfRightMost); // Defined in Listing 26.1
```



- 26.11** For the AVL tree in Figure 26.6a, show the new AVL tree after deleting element **107**. What rotation do you perform in order to rebalance the tree? Which node was unbalanced?
- 26.12** For the AVL tree in Figure 26.6a, show the new AVL tree after deleting element **60**. What rotation do you perform in order to rebalance the tree? Which node was unbalanced?
- 26.13** For the AVL tree in Figure 26.6a, show the new AVL tree after deleting element **55**. What rotation did you perform in order to rebalance the tree? Which node was unbalanced?
- 26.14** For the AVL tree in Figure 26.6b, show the new AVL tree after deleting elements **67** and **87**. What rotation did you perform in order to rebalance the tree? Which node was unbalanced?

## 26.7 The `AVLTree` Class



*The `AVLTree` class extends the `BST` class to override the `insert` and `delete` methods to rebalance the tree if necessary.*

Listing 26.3 gives the complete source code for the `AVLTree` class.

### LISTING 26.3 `AVLTree.java`

```
1 public class AVLTree<E extends Comparable<E>> extends BST<E> {
2 /** Create an empty AVL tree */
3 public AVLTree() {
```



```

63 if (balanceFactor((AVLTreeNode<E>)A.right) >= 0) {
64 balanceRR(A, parentOfA); // Perform RR rotation
65 }
66 else {
67 balanceRL(A, parentOfA); // Perform RL rotation
68 }
69 }
70 }
71 }
72
73 /** Return the balance factor of the node */
74 private int balanceFactor(AVLTreeNode<E> node) {
75 if (node.right == null) // node has no right subtree
76 return -node.height;
77 else if (node.left == null) // node has no left subtree
78 return +node.height;
79 else
80 return ((AVLTreeNode<E>)node.right).height -
81 ((AVLTreeNode<E>)node.left).height;
82 }
83
84 /** Balance LL (see Figure 26.2) */
85 private void balanceLL(TreeNode<E> A, TreeNode<E> parentOfA) {
86 TreeNode<E> B = A.left; // A is left-heavy and B is left-heavy
87
88 if (A == root) {
89 root = B;
90 }
91 else {
92 if (parentOfA.left == A) {
93 parentOfA.left = B;
94 }
95 else {
96 parentOfA.right = B;
97 }
98 }
99
100 A.left = B.right; // Make T2 the left subtree of A
101 B.right = A; // Make A the left child of B
102 updateHeight((AVLTreeNode<E>)A);
103 updateHeight((AVLTreeNode<E>)B);
104 }
105
106 /** Balance LR (see Figure 26.4) */
107 private void balanceLR(TreeNode<E> A, TreeNode<E> parentOfA) {
108 TreeNode<E> B = A.left; // A is left-heavy
109 TreeNode<E> C = B.right; // B is right-heavy
110
111 if (A == root) {
112 root = C;
113 }
114 else {
115 if (parentOfA.left == A) {
116 parentOfA.left = C;
117 }
118 else {
119 parentOfA.right = C;
120 }
121 }
122 }
123
124 /** Insert a new node into the AVL tree */
125 private void insert(TreeNode<E> A, E value) {
126 if (A == null)
127 A = new AVLTreeNode<E>(value);
128 else if (value < A.value)
129 insert(A.left, value);
130 else if (value > A.value)
131 insert(A.right, value);
132 else
133 return;
134
135 int balanceFactor = balanceFactor(A);
136
137 if (balanceFactor > 1) { // Left heavy
138 if (value < A.left.value)
139 A.left = rotateLeft(A.left, A.left.left);
140 A = rotateRight(A, A.left);
141 }
142 else if (balanceFactor < -1) { // Right heavy
143 if (value > A.right.value)
144 A.right = rotateRight(A.right, A.right.right);
145 A = rotateLeft(A, A.right);
146 }
147 else { // Balanced
148 A.height = 1;
149 }
150 }
151
152 /** Find the height of a node */
153 private int height(TreeNode<E> A) {
154 if (A == null)
155 return 0;
156 else
157 return A.height;
158 }
159
160 /** Find the maximum height of a subtree */
161 private int maxDepth(TreeNode<E> A) {
162 if (A == null)
163 return 0;
164 else
165 return Math.max(maxDepth(A.left), maxDepth(A.right)) + 1;
166 }
167
168 /** Update the height of a node */
169 private void updateHeight(TreeNode<E> A) {
170 A.height = maxDepth(A);
171 }
172
173 /** Rotate a tree to the left at node A */
174 private void rotateLeft(TreeNode<E> A, TreeNode<E> parentOfA) {
175 TreeNode<E> B = A.left;
176 A.left = B.right;
177 B.right = A;
178
179 A.height = maxDepth(A);
180 B.height = maxDepth(B);
181
182 parentOfA.left = B;
183 }
184
185 /** Rotate a tree to the right at node A */
186 private void rotateRight(TreeNode<E> A, TreeNode<E> parentOfA) {
187 TreeNode<E> B = A.right;
188 A.right = B.left;
189 B.left = A;
190
191 A.height = maxDepth(A);
192 B.height = maxDepth(B);
193
194 parentOfA.right = B;
195 }
196
197 /** Perform an RR double rotation at node A */
198 private void balanceRR(TreeNode<E> A, TreeNode<E> parentOfA) {
199 int balanceFactor = balanceFactor(A);
200
201 if (balanceFactor > 1) { // Left heavy
202 if (value < A.left.value)
203 A.left = rotateLeft(A.left, A.left.left);
204 A = rotateRight(A, A.left);
205 }
206 }
207
208 /** Perform an RL double rotation at node A */
209 private void balanceRL(TreeNode<E> A, TreeNode<E> parentOfA) {
210 int balanceFactor = balanceFactor(A);
211
212 if (balanceFactor < -1) { // Right heavy
213 if (value > A.right.value)
214 A.right = rotateRight(A.right, A.right.right);
215 A = rotateLeft(A, A.right);
216 }
217 }
218
219 /** Perform an LR double rotation at node A */
220 private void balanceLR(TreeNode<E> A, TreeNode<E> parentOfA) {
221 int balanceFactor = balanceFactor(A);
222
223 if (balanceFactor > 1) { // Left heavy
224 if (value < A.left.value)
225 A.left = rotateLeft(A.left, A.left.left);
226 A = rotateRight(A, A.left);
227 }
228 else if (balanceFactor < -1) { // Right heavy
229 if (value > A.right.value)
230 A.right = rotateRight(A.right, A.right.right);
231 A = rotateLeft(A, A.right);
232 }
233 }
234
235 /** Perform an RR double rotation at node A */
236 private void balanceRR(TreeNode<E> A, TreeNode<E> parentOfA) {
237 int balanceFactor = balanceFactor(A);
238
239 if (balanceFactor > 1) { // Left heavy
240 if (value < A.left.value)
241 A.left = rotateLeft(A.left, A.left.left);
242 A = rotateRight(A, A.left);
243 }
244 }
245
246 /** Perform an RL double rotation at node A */
247 private void balanceRL(TreeNode<E> A, TreeNode<E> parentOfA) {
248 int balanceFactor = balanceFactor(A);
249
250 if (balanceFactor < -1) { // Right heavy
251 if (value > A.right.value)
252 A.right = rotateRight(A.right, A.right.right);
253 A = rotateLeft(A, A.right);
254 }
255 }
256
257 /** Perform an LR double rotation at node A */
258 private void balanceLR(TreeNode<E> A, TreeNode<E> parentOfA) {
259 int balanceFactor = balanceFactor(A);
260
261 if (balanceFactor > 1) { // Left heavy
262 if (value < A.left.value)
263 A.left = rotateLeft(A.left, A.left.left);
264 A = rotateRight(A, A.left);
265 }
266 else if (balanceFactor < -1) { // Right heavy
267 if (value > A.right.value)
268 A.right = rotateRight(A.right, A.right.right);
269 A = rotateLeft(A, A.right);
270 }
271 }
272
273 /** Find the minimum value in a subtree */
274 private E minValue(TreeNode<E> A) {
275 if (A == null)
276 return null;
277 else if (A.left == null)
278 return A.value;
279 else
280 return minValue(A.left);
281 }
282
283 /** Find the maximum value in a subtree */
284 private E maxValue(TreeNode<E> A) {
285 if (A == null)
286 return null;
287 else if (A.right == null)
288 return A.value;
289 else
290 return maxValue(A.right);
291 }
292
293 /** Find the successor of a node */
294 private E successor(TreeNode<E> A) {
295 if (A == null)
296 return null;
297 else if (A.right != null)
298 return minValue(A.right);
299 else
300 return A.parent;
301 }
302
303 /** Find the predecessor of a node */
304 private E predecessor(TreeNode<E> A) {
305 if (A == null)
306 return null;
307 else if (A.left != null)
308 return maxValue(A.left);
309 else
310 return A.parent;
311 }
312
313 /** Find the in-order predecessor of a node */
314 private E inOrderPredecessor(TreeNode<E> A) {
315 if (A == null)
316 return null;
317 else if (A.left != null)
318 return A.left;
319 else
320 return A.parent;
321 }
322
323 /** Find the in-order successor of a node */
324 private E inOrderSuccessor(TreeNode<E> A) {
325 if (A == null)
326 return null;
327 else if (A.right != null)
328 return A.right;
329 else
330 return A.parent;
331 }
332
333 /** Find the minimum value in a subtree */
334 private E minValue(TreeNode<E> A) {
335 if (A == null)
336 return null;
337 else if (A.left == null)
338 return A.value;
339 else
340 return minValue(A.left);
341 }
342
343 /** Find the maximum value in a subtree */
344 private E maxValue(TreeNode<E> A) {
345 if (A == null)
346 return null;
347 else if (A.right == null)
348 return A.value;
349 else
350 return maxValue(A.right);
351 }
352
353 /** Find the in-order predecessor of a node */
354 private E inOrderPredecessor(TreeNode<E> A) {
355 if (A == null)
356 return null;
357 else if (A.left != null)
358 return A.left;
359 else
360 return A.parent;
361 }
362
363 /** Find the in-order successor of a node */
364 private E inOrderSuccessor(TreeNode<E> A) {
365 if (A == null)
366 return null;
367 else if (A.right != null)
368 return A.right;
369 else
370 return A.parent;
371 }
372
373 /** Find the minimum value in a subtree */
374 private E minValue(TreeNode<E> A) {
375 if (A == null)
376 return null;
377 else if (A.left == null)
378 return A.value;
379 else
380 return minValue(A.left);
381 }
382
383 /** Find the maximum value in a subtree */
384 private E maxValue(TreeNode<E> A) {
385 if (A == null)
386 return null;
387 else if (A.right == null)
388 return A.value;
389 else
390 return maxValue(A.right);
391 }
392
393 /** Find the in-order predecessor of a node */
394 private E inOrderPredecessor(TreeNode<E> A) {
395 if (A == null)
396 return null;
397 else if (A.left != null)
398 return A.left;
399 else
400 return A.parent;
401 }
402
403 /** Find the in-order successor of a node */
404 private E inOrderSuccessor(TreeNode<E> A) {
405 if (A == null)
406 return null;
407 else if (A.right != null)
408 return A.right;
409 else
410 return A.parent;
411 }
412
413 /** Find the minimum value in a subtree */
414 private E minValue(TreeNode<E> A) {
415 if (A == null)
416 return null;
417 else if (A.left == null)
418 return A.value;
419 else
420 return minValue(A.left);
421 }
422
423 /** Find the maximum value in a subtree */
424 private E maxValue(TreeNode<E> A) {
425 if (A == null)
426 return null;
427 else if (A.right == null)
428 return A.value;
429 else
430 return maxValue(A.right);
431 }
432
433 /** Find the in-order predecessor of a node */
434 private E inOrderPredecessor(TreeNode<E> A) {
435 if (A == null)
436 return null;
437 else if (A.left != null)
438 return A.left;
439 else
440 return A.parent;
441 }
442
443 /** Find the in-order successor of a node */
444 private E inOrderSuccessor(TreeNode<E> A) {
445 if (A == null)
446 return null;
447 else if (A.right != null)
448 return A.right;
449 else
450 return A.parent;
451 }
452
453 /** Find the minimum value in a subtree */
454 private E minValue(TreeNode<E> A) {
455 if (A == null)
456 return null;
457 else if (A.left == null)
458 return A.value;
459 else
460 return minValue(A.left);
461 }
462
463 /** Find the maximum value in a subtree */
464 private E maxValue(TreeNode<E> A) {
465 if (A == null)
466 return null;
467 else if (A.right == null)
468 return A.value;
469 else
470 return maxValue(A.right);
471 }
472
473 /** Find the in-order predecessor of a node */
474 private E inOrderPredecessor(TreeNode<E> A) {
475 if (A == null)
476 return null;
477 else if (A.left != null)
478 return A.left;
479 else
480 return A.parent;
481 }
482
483 /** Find the in-order successor of a node */
484 private E inOrderSuccessor(TreeNode<E> A) {
485 if (A == null)
486 return null;
487 else if (A.right != null)
488 return A.right;
489 else
490 return A.parent;
491 }
492
493 /** Find the minimum value in a subtree */
494 private E minValue(TreeNode<E> A) {
495 if (A == null)
496 return null;
497 else if (A.left == null)
498 return A.value;
499 else
500 return minValue(A.left);
501 }
502
503 /** Find the maximum value in a subtree */
504 private E maxValue(TreeNode<E> A) {
505 if (A == null)
506 return null;
507 else if (A.right == null)
508 return A.value;
509 else
510 return maxValue(A.right);
511 }
512
513 /** Find the in-order predecessor of a node */
514 private E inOrderPredecessor(TreeNode<E> A) {
515 if (A == null)
516 return null;
517 else if (A.left != null)
518 return A.left;
519 else
520 return A.parent;
521 }
522
523 /** Find the in-order successor of a node */
524 private E inOrderSuccessor(TreeNode<E> A) {
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526 return null;
527 else if (A.right != null)
528 return A.right;
529 else
530 return A.parent;
531 }
532
533 /** Find the minimum value in a subtree */
534 private E minValue(TreeNode<E> A) {
535 if (A == null)
536 return null;
537 else if (A.left == null)
538 return A.value;
539 else
540 return minValue(A.left);
541 }
542
543 /** Find the maximum value in a subtree */
544 private E maxValue(TreeNode<E> A) {
545 if (A == null)
546 return null;
547 else if (A.right == null)
548 return A.value;
549 else
550 return maxValue(A.right);
551 }
552
553 /** Find the in-order predecessor of a node */
554 private E inOrderPredecessor(TreeNode<E> A) {
555 if (A == null)
556 return null;
557 else if (A.left != null)
558 return A.left;
559 else
560 return A.parent;
561 }
562
563 /** Find the in-order successor of a node */
564 private E inOrderSuccessor(TreeNode<E> A) {
565 if (A == null)
566 return null;
567 else if (A.right != null)
568 return A.right;
569 else
570 return A.parent;
571 }
572
573 /** Find the minimum value in a subtree */
574 private E minValue(TreeNode<E> A) {
575 if (A == null)
576 return null;
577 else if (A.left == null)
578 return A.value;
579 else
580 return minValue(A.left);
581 }
582
583 /** Find the maximum value in a subtree */
584 private E maxValue(TreeNode<E> A) {
585 if (A == null)
586 return null;
587 else if (A.right == null)
588 return A.value;
589 else
590 return maxValue(A.right);
591 }
592
593 /** Find the in-order predecessor of a node */
594 private E inOrderPredecessor(TreeNode<E> A) {
595 if (A == null)
596 return null;
597 else if (A.left != null)
598 return A.left;
599 else
600 return A.parent;
601 }
602
603 /** Find the in-order successor of a node */
604 private E inOrderSuccessor(TreeNode<E> A) {
605 if (A == null)
606 return null;
607 else if (A.right != null)
608 return A.right;
609 else
610 return A.parent;
611 }
612
613 /** Find the minimum value in a subtree */
614 private E minValue(TreeNode<E> A) {
615 if (A == null)
616 return null;
617 else if (A.left == null)
618 return A.value;
619 else
620 return minValue(A.left);
621 }
622
623 /** Find the maximum value in a subtree */
624 private E maxValue(TreeNode<E> A) {
625 if (A == null)
626 return null;
627 else if (A.right == null)
628 return A.value;
629 else
630 return maxValue(A.right);
631 }
632
633 /** Find the in-order predecessor of a node */
634 private E inOrderPredecessor(TreeNode<E> A) {
635 if (A == null)
636 return null;
637 else if (A.left != null)
638 return A.left;
639 else
640 return A.parent;
641 }
642
643 /** Find the in-order successor of a node */
644 private E inOrderSuccessor(TreeNode<E> A) {
645 if (A == null)
646 return null;
647 else if (A.right != null)
648 return A.right;
649 else
650 return A.parent;
651 }
652
653 /** Find the minimum value in a subtree */
654 private E minValue(TreeNode<E> A) {
655 if (A == null)
656 return null;
657 else if (A.left == null)
658 return A.value;
659 else
660 return minValue(A.left);
661 }
662
663 /** Find the maximum value in a subtree */
664 private E maxValue(TreeNode<E> A) {
665 if (A == null)
666 return null;
667 else if (A.right == null)
668 return A.value;
669 else
670 return maxValue(A.right);
671 }
672
673 /** Find the in-order predecessor of a node */
674 private E inOrderPredecessor(TreeNode<E> A) {
675 if (A == null)
676 return null;
677 else if (A.left != null)
678 return A.left;
679 else
680 return A.parent;
681 }
682
683 /** Find the in-order successor of a node */
684 private E inOrderSuccessor(TreeNode<E> A) {
685 if (A == null)
686 return null;
687 else if (A.right != null)
688 return A.right;
689 else
690 return A.parent;
691 }
692
693 /** Find the minimum value in a subtree */
694 private E minValue(TreeNode<E> A) {
695 if (A == null)
696 return null;
697 else if (A.left == null)
698 return A.value;
699 else
700 return minValue(A.left);
701 }
702
703 /** Find the maximum value in a subtree */
704 private E maxValue(TreeNode<E> A) {
705 if (A == null)
706 return null;
707 else if (A.right == null)
708 return A.value;
709 else
710 return maxValue(A.right);
711 }
712
713 /** Find the in-order predecessor of a node */
714 private E inOrderPredecessor(TreeNode<E> A) {
715 if (A == null)
716 return null;
717 else if (A.left != null)
718 return A.left;
719 else
720 return A.parent;
721 }
722
723 /** Find the in-order successor of a node */
724 private E inOrderSuccessor(TreeNode<E> A) {
725 if (A == null)
726 return null;
727 else if (A.right != null)
728 return A.right;
729 else
730 return A.parent;
731 }
732
733 /** Find the minimum value in a subtree */
734 private E minValue(TreeNode<E> A) {
735 if (A == null)
736 return null;
737 else if (A.left == null)
738 return A.value;
739 else
740 return minValue(A.left);
741 }
742
743 /** Find the maximum value in a subtree */
744 private E maxValue(TreeNode<E> A) {
745 if (A == null)
746 return null;
747 else if (A.right == null)
748 return A.value;
749 else
750 return maxValue(A.right);
751 }
752
753 /** Find the in-order predecessor of a node */
754 private E inOrderPredecessor(TreeNode<E> A) {
755 if (A == null)
756 return null;
757 else if (A.left != null)
758 return A.left;
759 else
760 return A.parent;
761 }
762
763 /** Find the in-order successor of a node */
764 private E inOrderSuccessor(TreeNode<E> A) {
765 if (A == null)
766 return null;
767 else if (A.right != null)
768 return A.right;
769 else
770 return A.parent;
771 }
772
773 /** Find the minimum value in a subtree */
774 private E minValue(TreeNode<E> A) {
775 if (A == null)
776 return null;
777 else if (A.left == null)
778 return A.value;
779 else
780 return minValue(A.left);
781 }
782
783 /** Find the maximum value in a subtree */
784 private E maxValue(TreeNode<E> A) {
785 if (A == null)
786 return null;
787 else if (A.right == null)
788 return A.value;
789 else
790 return maxValue(A.right);
791 }
792
793 /** Find the in-order predecessor of a node */
794 private E inOrderPredecessor(TreeNode<E> A) {
795 if (A == null)
796 return null;
797 else if (A.left != null)
798 return A.left;
799 else
800 return A.parent;
801 }
802
803 /** Find the in-order successor of a node */
804 private E inOrderSuccessor(TreeNode<E> A) {
805 if (A == null)
806 return null;
807 else if (A.right != null)
808 return A.right;
809 else
810 return A.parent;
811 }
812
813 /** Find the minimum value in a subtree */
814 private E minValue(TreeNode<E> A) {
815 if (A == null)
816 return null;
817 else if (A.left == null)
818 return A.value;
819 else
820 return minValue(A.left);
821 }
822
823 /** Find the maximum value in a subtree */
824 private E maxValue(TreeNode<E> A) {
825 if (A == null)
826 return null;
827 else if (A.right == null)
828 return A.value;
829 else
830 return maxValue(A.right);
831 }
832
833 /** Find the in-order predecessor of a node */
834 private E inOrderPredecessor(TreeNode<E> A) {
835 if (A == null)
836 return null;
837 else if (A.left != null)
838 return A.left;
839 else
840 return A.parent;
841 }
842
843 /** Find the in-order successor of a node */
844 private E inOrderSuccessor(TreeNode<E> A) {
845 if (A == null)
846 return null;
847 else if (A.right != null)
848 return A.right;
849 else
850 return A.parent;
851 }
852
853 /** Find the minimum value in a subtree */
854 private E minValue(TreeNode<E> A) {
855 if (A == null)
856 return null;
857 else if (A.left == null)
858 return A.value;
859 else
860 return minValue(A.left);
861 }
862
863 /** Find the maximum value in a subtree */
864 private E maxValue(TreeNode<E> A) {
865 if (A == null)
866 return null;
867 else if (A.right == null)
868 return A.value;
869 else
870 return maxValue(A.right);
871 }
872
873 /** Find the in-order predecessor of a node */
874 private E inOrderPredecessor(TreeNode<E> A) {
875 if (A == null)
876 return null;
877 else if (A.left != null)
878 return A.left;
879 else
880 return A.parent;
881 }
882
883 /** Find the in-order successor of a node */
884 private E inOrderSuccessor(TreeNode<E> A) {
885 if (A == null)
886 return null;
887 else if (A.right != null)
888 return A.right;
889 else
890 return A.parent;
891 }
892
893 /** Find the minimum value in a subtree */
894 private E minValue(TreeNode<E> A) {
895 if (A == null)
896 return null;
897 else if (A.left == null)
898 return A.value;
899 else
900 return minValue(A.left);
901 }
902
903 /** Find the maximum value in a subtree */
904 private E maxValue(TreeNode<E> A) {
905 if (A == null)
906 return null;
907 else if (A.right == null)
908 return A.value;
909 else
910 return maxValue(A.right);
911 }
912
913 /** Find the in-order predecessor of a node */
914 private E inOrderPredecessor(TreeNode<E> A) {
915 if (A == null)
916 return null;
917 else if (A.left != null)
918 return A.left;
919 else
920 return A.parent;
921 }
922
923 /** Find the in-order successor of a node */
924 private E inOrderSuccessor(TreeNode<E> A) {
925 if (A == null)
926 return null;
927 else if (A.right != null)
928 return A.right;
929 else
930 return A.parent;
931 }
932
933 /** Find the minimum value in a subtree */
934 private E minValue(TreeNode<E> A) {
935 if (
```

```

121 }
122
123 A.left = C.right; // Make T3 the left subtree of A
124 B.right = C.left; // Make T2 the right subtree of B
125 C.left = B;
126 C.right = A;
127
128 // Adjust heights
129 updateHeight((AVLTreeNode<E>)A); update height
130 updateHeight((AVLTreeNode<E>)B);
131 updateHeight((AVLTreeNode<E>)C);
132 }
133
134 /** Balance RR (see Figure 26.3) */
135 private void balanceRR(TreeNode<E> A, TreeNode<E> parentOfA) { RR rotation
136 TreeNode<E> B = A.right; // A is right-heavy and B is right-heavy
137
138 if (A == root) {
139 root = B;
140 }
141 else {
142 if (parentOfA.left == A) {
143 parentOfA.left = B;
144 }
145 else {
146 parentOfA.right = B;
147 }
148 }
149
150 A.right = B.left; // Make T2 the right subtree of A
151 B.left = A;
152 updateHeight((AVLTreeNode<E>)A); update height
153 updateHeight((AVLTreeNode<E>)B);
154 }
155
156 /** Balance RL (see Figure 26.5) */
157 private void balanceRL(TreeNode<E> A, TreeNode<E> parentOfA) { RL rotation
158 TreeNode<E> B = A.right; // A is right-heavy
159 TreeNode<E> C = B.left; // B is left-heavy
160
161 if (A == root) {
162 root = C;
163 }
164 else {
165 if (parentOfA.left == A) {
166 parentOfA.left = C;
167 }
168 else {
169 parentOfA.right = C;
170 }
171 }
172
173 A.right = C.left; // Make T2 the right subtree of A
174 B.left = C.right; // Make T3 the left subtree of B
175 C.left = A;
176 C.right = B;
177
178 // Adjust heights

```

```

update height 179 updateHeight((AVLTreeNode<E>)A);
 180 updateHeight((AVLTreeNode<E>)B);
 181 updateHeight((AVLTreeNode<E>)C);
 182 }
 183
184 @Override /** Delete an element from the AVL tree.
185 * Return true if the element is deleted successfully
186 * Return false if the element is not in the tree */
187 public boolean delete(E element) {
188 if (root == null)
189 return false; // Element is not in the tree
190
191 // Locate the node to be deleted and also locate its parent node
192 TreeNode<E> parent = null;
193 TreeNode<E> current = root;
194 while (current != null) {
195 if (element.compareTo(current.element) < 0) {
196 parent = current;
197 current = current.left;
198 }
199 else if (element.compareTo(current.element) > 0) {
200 parent = current;
201 current = current.right;
202 }
203 else
204 break; // Element is in the tree pointed by current
205 }
206
207 if (current == null)
208 return false; // Element is not in the tree
209
210 // Case 1: current has no left children (See Figure 25.10)
211 if (current.left == null) {
212 // Connect the parent with the right child of the current node
213 if (parent == null) {
214 root = current.right;
215 }
216 else {
217 if (element.compareTo(parent.element) < 0)
218 parent.left = current.right;
219 else
220 parent.right = current.right;
221
222 // Balance the tree if necessary
223 balancePath(parent.element);
224 }
225 }
226 else {
227 // Case 2: The current node has a left child
228 // Locate the rightmost node in the left subtree of
229 // the current node and also its parent
230 TreeNode<E> parentOfRightMost = current;
231 TreeNode<E> rightMost = current.left;
232
233 while (rightMost.right != null) {
234 parentOfRightMost = rightMost;
235 rightMost = rightMost.right; // Keep going to the right
236 }
237
balance nodes

```

```

238 // Replace the element in current by the element in rightMost
239 current.element = rightMost.element;
240
241 // Eliminate rightmost node
242 if (parentOfRightMost.right == rightMost)
243 parentOfRightMost.right = rightMost.left;
244 else
245 // Special case: parentOfRightMost is current
246 parentOfRightMost.left = rightMost.left;
247
248 // Balance the tree if necessary
249 balancePath(parentOfRightMost.element); balance nodes
250 }
251
252 size--;
253 return true; // Element inserted
254 }
255
256 /** AVLTreeNode is TreeNode plus height */
257 protected static class AVLTreeNode<E extends Comparable<E>> extends BST.TreeNode<E> { inner AVLTreeNode class
258 protected int height = 0; // New data field
259
260 public AVLTreeNode(E e) {
261 super(e);
262 }
263 }
264 }
265 }
```

The `AVLTree` class extends `BST`. Like the `BST` class, the `AVLTree` class has a no-arg constructor that constructs an empty `AVLTree` (lines 3–4) and a constructor that creates an initial `AVLTree` from an array of elements (lines 7–9).

The `createNewNode()` method defined in the `BST` class creates a `TreeNode`. This method is overridden to return an `AVLTreeNode` (lines 12–14).

The `insert` method in `AVLTree` is overridden in lines 17–26. The method first invokes the `insert` method in `BST`, then invokes `balancePath(e)` (line 22) to ensure that the tree is balanced.

The `balancePath` method first gets the nodes on the path from the node that contains element `e` to the root (line 46). For each node in the path, update its height (line 49), check its balance factor (line 53), and perform appropriate rotations if necessary (lines 53–69).

Four methods for performing rotations are defined in lines 85–182. Each method is invoked with two `TreeNode` arguments—`A` and `parentOfA`—to perform an appropriate rotation at node `A`. How each rotation is performed is illustrated in Figures 26.2–26.5. After the rotation, the heights of nodes `A`, `B`, and `C` are updated (lines 102, 129, 152, 179).

The `delete` method in `AVLTree` is overridden in lines 187–264. The method is the same as the one implemented in the `BST` class, except that you have to rebalance the nodes after deletion in two cases (lines 224, 249).

**26.15** Why is the `createNewNode` method defined protected?

**26.16** When is the `updateHeight` method invoked? When is the `balanceFactor` method invoked? When is the `balancePath` method invoked?

**26.17** What are data fields in the `AVLTree` class?

**26.18** In the `insert` and `delete` methods, once you have performed a rotation to balance a node in the tree, is it possible that there are still unbalanced nodes?





## 26.8 Testing the AVLTree Class

*This section gives an example of using the `AVLTree` class.*

Listing 26.4 gives a test program. The program creates an `AVLTree` initialized with an array of the integers **25**, **20**, and **5** (lines 4–5), inserts elements in lines 9–18, and deletes elements in lines 22–28. Since `AVLTree` is a subclass of `BST` and the elements in a `BST` are iterable, the program uses a foreach loop to traverse all the elements in lines 33–35.

### LISTING 26.4 TestAVLTree.java

create an AVLTree

insert 34  
insert 50

insert 30

insert 10

delete 34  
delete 30  
delete 50

delete 5

for-each loop

```

1 public class TestAVLTree {
2 public static void main(String[] args) {
3 // Create an AVL tree
4 AVLTree<Integer> tree = new AVLTree<>(new Integer[]{25,
5 20, 5});
6 System.out.print("After inserting 25, 20, 5:");
7 printTree(tree);
8
9 tree.insert(34);
10 tree.insert(50);
11 System.out.print("\nAfter inserting 34, 50:");
12 printTree(tree);
13
14 tree.insert(30);
15 System.out.print("\nAfter inserting 30");
16 printTree(tree);
17
18 tree.insert(10);
19 System.out.print("\nAfter inserting 10");
20 printTree(tree);
21
22 tree.delete(34);
23 tree.delete(30);
24 tree.delete(50);
25 System.out.print("\nAfter removing 34, 30, 50:");
26 printTree(tree);
27
28 tree.delete(5);
29 System.out.print("\nAfter removing 5:");
30 printTree(tree);
31
32 System.out.print("\nTraverse the elements in the tree: ");
33 for (int e: tree) {
34 System.out.print(e + " ");
35 }
36 }
37
38 public static void printTree(BST tree) {
39 // Traverse tree
40 System.out.print("\nInorder (sorted): ");
41 tree.inorder();
42 System.out.print("\nPostorder: ");
43 tree.postorder();
44 System.out.print("\nPreorder: ");
45 tree.preorder();
46 System.out.print("\nThe number of nodes is " + tree.getSize());
}

```

```

47 System.out.println();
48 }
49 }
```

After inserting 25, 20, 5:  
 Inorder (sorted): 5 20 25  
 Postorder: 5 25 20  
 Preorder: 20 5 25  
 The number of nodes is 3

After inserting 34, 50:  
 Inorder (sorted): 5 20 25 34 50  
 Postorder: 5 25 50 34 20  
 Preorder: 20 5 34 25 50  
 The number of nodes is 5

After inserting 30  
 Inorder (sorted): 5 20 25 30 34 50  
 Postorder: 5 20 30 50 34 25  
 Preorder: 25 20 5 34 30 50  
 The number of nodes is 6

After inserting 10  
 Inorder (sorted): 5 10 20 25 30 34 50  
 Postorder: 5 20 10 30 50 34 25  
 Preorder: 25 10 5 20 34 30 50  
 The number of nodes is 7

After removing 34, 30, 50:  
 Inorder (sorted): 5 10 20 25  
 Postorder: 5 20 25 10  
 Preorder: 10 5 25 20  
 The number of nodes is 4

After removing 5:  
 Inorder (sorted): 10 20 25  
 Postorder: 10 25 20  
 Preorder: 20 10 25  
 The number of nodes is 3  
 Traverse the elements in the tree: 10 20 25



Figure 26.10 shows how the tree evolves as elements are added to the tree. After **25** and **20** are added, the tree is as shown in Figure 26.10a. **5** is inserted as a left child of **20**, as shown in Figure 26.10b. The tree is not balanced. It is left-heavy at node **25**. Perform an LL rotation to result in an AVL tree, as shown in Figure 26.10c.

After inserting **34**, the tree is shown in Figure 26.10d. After inserting **50**, the tree is as shown in Figure 26.10e. The tree is not balanced. It is right-heavy at node **25**. Perform an RR rotation to result in an AVL tree, as shown in Figure 26.10f.

After inserting **30**, the tree is as shown in Figure 26.10g. The tree is not balanced. Perform an RL rotation to result in an AVL tree, as shown in Figure 26.10h.

After inserting **10**, the tree is as shown in Figure 26.10i. The tree is not balanced. Perform an LR rotation to result in an AVL tree, as shown in Figure 26.10j.

**FIGURE 26.10** The tree evolves as new elements are inserted.

Figure 26.11 shows how the tree evolves as elements are deleted. After deleting **34**, **30**, and **50**, the tree is as shown in Figure 26.11b. The tree is not balanced. Perform an LL rotation to result in an AVL tree, as shown in Figure 26.11c.

After deleting **5**, the tree is as shown in Figure 26.11d. The tree is not balanced. Perform an RL rotation to result in an AVL tree, as shown in Figure 26.11e.



**26.19** Show the change of an AVL tree when inserting **1, 2, 3, 4, 10, 9, 7, 5, 8, 6** into the tree, in this order.

**26.20** For the tree built in the preceding question, show its change after **1, 2, 3, 4, 10, 9, 7, 5, 8, 6** are deleted from the tree in this order.

**26.21** Can you traverse the elements in an AVL tree using a foreach loop?



**FIGURE 26.11** The tree evolves as elements are deleted from the tree.

## 26.9 AVL Tree Time Complexity Analysis

Since the height of an AVL tree is  $O(\log n)$ , the time complexity of the **search**, **insert**, and **delete** methods in **AVLTree** is  $O(\log n)$ .

The time complexity of the **search**, **insert**, and **delete** methods in **AVLTree** depends on the height of the tree. We can prove that the height of the tree is  $O(\log n)$ .

Let  $G(h)$  denote the minimum number of nodes in an AVL tree with height  $h$ . Obviously,  $G(1)$  is 1 and  $G(2)$  is 2. The minimum number of nodes in an AVL tree with height  $h \geq 3$  must have two minimum subtrees: one with height  $h - 1$  and the other with height  $h - 2$ . Thus,

$$G(h) = G(h - 1) + G(h - 2) + 1$$

Recall that a Fibonacci number at index  $i$  can be described using the recurrence relation  $F(i) = F(i - 1) + F(i - 2)$ . Therefore, the function  $G(h)$  is essentially the same as  $F(i)$ . It can be proven that

$$h < 1.4405 \log(n + 2) - 1.3277$$

where  $n$  is the number of nodes in the tree. Hence, the height of an AVL tree is  $O(\log n)$ .

The **search**, **insert**, and **delete** methods involve only the nodes along a path in the tree. The **updateHeight** and **balanceFactor** methods are executed in a constant time for each node in the path. The **balancePath** method is executed in a constant time for a node in the path. Thus, the time complexity for the **search**, **insert**, and **delete** methods is  $O(\log n)$ .

**26.22** What is the maximum/minimum height for an AVL tree of 3 nodes, 5 nodes, and 7 nodes?

**26.23** If an AVL tree has a height of 3, what maximum number of nodes can the tree have? What minimum number of nodes can the tree have?

**26.24** If an AVL tree has a height of 4, what maximum number of nodes can the tree have? What minimum number of nodes can the tree have?



tree height



## KEY TERMS

---

|                             |     |                    |     |
|-----------------------------|-----|--------------------|-----|
| AVL tree                    | 966 | right-heavy        | 966 |
| balance factor              | 966 | RL rotation        | 967 |
| left-heavy                  | 966 | rotation           | 966 |
| LL rotation                 | 967 | RR rotation        | 967 |
| LR rotation                 | 967 | well-balanced tree | 966 |
| perfectly balanced tree 966 |     |                    |     |

## CHAPTER SUMMARY

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1. An *AVL tree* is a *well-balanced* binary tree. In an AVL tree, the difference between the heights of two subtrees for every node is **0** or **1**.
2. The process for inserting or deleting an element in an AVL tree is the same as in a regular binary search tree. The difference is that you may have to rebalance the tree after an insertion or deletion operation.
3. Imbalances in the tree caused by insertions and deletions are rebalanced through subtree rotations at the node of the imbalance.
4. The process of rebalancing a node is called a *rotation*. There are four possible rotations: *LL rotation*, *LR rotation*, *RR rotation*, and *RL rotation*.
5. The height of an AVL tree is  $O(\log n)$ . Therefore, the time complexities for the **search**, **insert**, and **delete** methods are  $O(\log n)$ .

## QUIZ

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Answer the quiz for this chapter online at [www.cs.armstrong.edu/liang/intro10e/quiz.html](http://www.cs.armstrong.edu/liang/intro10e/quiz.html).

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## PROGRAMMING EXERCISES

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- \*26.1** (*Display AVL tree graphically*) Write a program that displays an AVL tree along with its balance factor for each node.
- 26.2** (*Compare performance*) Write a test program that randomly generates 500,000 numbers and inserts them into a **BST**, reshuffles the 500,000 numbers and performs a search, and reshuffles the numbers again before deleting them from the tree. Write another test program that does the same thing for an **AVLTree**. Compare the execution times of these two programs.
- \*\*\*26.3** (*AVL tree animation*) Write a program that animates the AVL tree **insert**, **delete**, and **search** methods, as shown in Figure 26.1.
- \*\*26.4** (*Parent reference for BST*) Suppose that the **TreeNode** class defined in **BST** contains a reference to the node's parent, as shown in Programming Exercise 25.15. Implement the **AVLTree** class to support this change. Write a test program that adds numbers **1, 2, ..., 100** to the tree and displays the paths for all leaf nodes.
- \*\*26.5** (*The kth smallest element*) You can find the *k*th smallest element in a BST in  $O(n)$  time from an inorder iterator. For an AVL tree, you can find it in  $O(\log n)$  time. To achieve this, add a new data field named **size** in **AVLTreeNode** to store the number of nodes in the subtree rooted at this node. Note that the size of

a node  $v$  is one more than the sum of the sizes of its two children. Figure 26.12 shows an AVL tree and the `size` value for each node in the tree.



**FIGURE 26.12** The `size` data field in `AVLTreeNode` stores the number of nodes in the subtree rooted at the node.

In the `AVLTree` class, add the following method to return the  $k$ th smallest element in the tree.

```
public E find(int k)
```

The method returns `null` if  $k < 1$  or  $k > \text{the size of the tree}$ . This method can be implemented using the recursive method `find(k, root)`, which returns the  $k$ th smallest element in the tree with the specified root. Let **A** and **B** be the left and right children of the root, respectively. Assuming that the tree is not empty and  $k \leq \text{root.size}$ , `find(k, root)` can be recursively defined as follows:

$$\text{find}(k, \text{root}) = \begin{cases} \text{root.element, if } A \text{ is null and } k \text{ is 1;} \\ B.\text{element, if } A \text{ is null and } k \text{ is 2;} \\ \text{find}(k, A), \text{ if } k \leq A.\text{size;} \\ \text{root.element, if } k = A.\text{size} + 1; \\ \text{find}(k - A.\text{size} - 1, B), \text{ if } k > A.\text{size} + 1; \end{cases}$$

Modify the `insert` and `delete` methods in `AVLTree` to set the correct value for the `size` property in each node. The `insert` and `delete` methods will still be in  $O(\log n)$  time. The `find(k)` method can be implemented in  $O(\log n)$  time. Therefore, you can find the  $k$ th smallest element in an AVL tree in  $O(\log n)$  time.

Use the following main method to test your program:

```
import java.util.Scanner;

public class Exercise26_05 {
 public static void main(String[] args) {
 AVLTree<Double> tree = new AVLTree<>();
 Scanner input = new Scanner(System.in);
 System.out.print("Enter 15 numbers: ");
 for (int i = 0; i < 15; i++) {
 tree.insert(input.nextDouble());
 }

 System.out.print("Enter k: ");
 System.out.println("The " + k + "th smallest number is " +
 tree.find(k));
 }
}
```

- \*\*26.6** (*Test AVLTree*) Design and write a complete test program to test if the `AVLTree` class in Listing 26.4 meets all requirements.

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# HASHING

## Objectives

- To understand what hashing is and what hashing is used for (§27.2).
- To obtain the hash code for an object and design the hash function to map a key to an index (§27.3).
- To handle collisions using open addressing (§27.4).
- To know the differences among linear probing, quadratic probing, and double hashing (§27.4).
- To handle collisions using separate chaining (§27.5).
- To understand the load factor and the need for rehashing (§27.6).
- To implement [MyHashMap](#) using hashing (§27.7).
- To implement [MyHashSet](#) using hashing (§27.8).



## 27.1 Introduction



*Hashing is superefficient. It takes  $O(1)$  time to search, insert, and delete an element using hashing.*

why hashing?

The preceding chapter introduced binary search trees. An element can be found in  $O(\log n)$  time in a well-balanced search tree. Is there a more efficient way to search for an element in a container? This chapter introduces a technique called *hashing*. You can use hashing to implement a map or a set to search, insert, and delete an element in  $O(1)$  time.

## 27.2 What Is Hashing?



map  
key  
value

dictionary  
hash table  
associative array

hash table  
hash function  
hashing

*Hashing uses a hashing function to map a key to an index.*

Before introducing hashing, let us review map, which is a data structure that is implemented using hashing. Recall that a *map* (introduced in Section 21.5) is a container object that stores entries. Each entry contains two parts: a *key* and a *value*. The key, also called a *search key*, is used to search for the corresponding value. For example, a dictionary can be stored in a map, in which the words are the keys and the definitions of the words are the values.

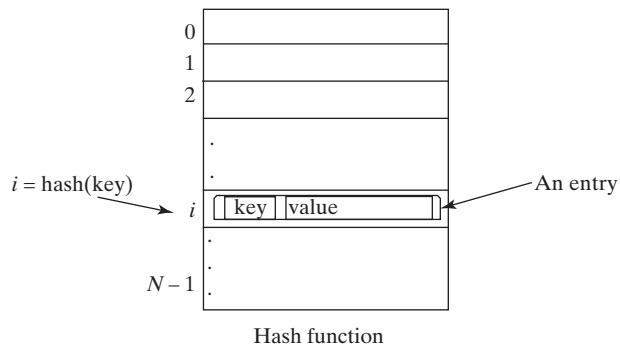


### Note

A map is also called a *dictionary*, a *hash table*, or an *associative array*.

The Java Collections Framework defines the `java.util.Map` interface for modeling maps. Three concrete implementations are `java.util.HashMap`, `java.util.LinkedHashMap`, and `java.util.TreeMap`. `java.util.HashMap` is implemented using hashing, `java.util.LinkedHashMap` using `LinkedList`, and `java.util.TreeMap` using red-black trees. (Bonus Chapter 41 introduces red-black trees.) You will learn the concept of hashing and use it to implement a hash map in this chapter.

If you know the index of an element in the array, you can retrieve the element using the index in  $O(1)$  time. So does that mean we can store the values in an array and use the key as the index to find the value? The answer is yes—if you can map a key to an index. The array that stores the values is called a *hash table*. The function that maps a key to an index in the hash table is called a *hash function*. As shown in Figure 27.1, a hash function obtains an index from a key and uses the index to retrieve the value for the key. *Hashing* is a technique that retrieves the value using the index obtained from the key without performing a search.



**FIGURE 27.1** A hash function maps a key to an index in the hash table.

perfect hash function

How do you design a hash function that produces an index from a key? Ideally, we would like to design a function that maps each search key to a different index in the hash table. Such a function is called a *perfect hash function*. However, it is difficult to find a perfect hash

function. When two or more keys are mapped to the same hash value, we say that a *collision* has occurred. Although there are ways to deal with collisions, which are discussed later in this chapter, it is better to avoid collisions in the first place. Thus, you should design a fast and easy-to-compute hash function that minimizes collisions.

collision

### 27.1 What is a hash function? What is a perfect hash function? What is a collision?



## 27.3 Hash Functions and Hash Codes

*A typical hash function first converts a search key to an integer value called a hash code, then compresses the hash code into an index to the hash table.*



Java's root class **Object** has the **hashCode** method, which returns an integer hash code. By default, the method returns the memory address for the object. The general contract for the **hashCode** method is as follows:

hash code  
hashCode()

1. You should override the **hashCode** method whenever the **equals** method is overridden to ensure that two equal objects return the same hash code.
2. During the execution of a program, invoking the **hashCode** method multiple times returns the same integer, provided that the object's data are not changed.
3. Two unequal objects may have the same hash code, but you should implement the **hashCode** method to avoid too many such cases.

### 27.3.1 Hash Codes for Primitive Types

For search keys of the type **byte**, **short**, **int**, and **char**, simply cast them to **int**. Therefore, two different search keys of any one of these types will have different hash codes.

byte, short, int, char

For a search key of the type **float**, use **Float.floatToIntBits(key)** as the hash code. Note that **floatToIntBits(float f)** returns an **int** value whose bit representation is the same as the bit representation for the floating number **f**. Thus, two different search keys of the **float** type will have different hash codes.

float

For a search key of the type **long**, simply casting it to **int** would not be a good choice, because all keys that differ in only the first 32 bits will have the same hash code. To take the first 32 bits into consideration, divide the 64 bits into two halves and perform the exclusive-or operation to combine the two halves. This process is called *folding*. The hash code for a **long** key is

long

folding

```
int hashCode = (int)(key ^ (key >> 32));
```

Note that **>>** is the right-shift operator that shifts the bits 32 positions to the right. For example, **1010110 >> 2** yields **0010101**. The **^** is the bitwise exclusive-or operator. It operates on two corresponding bits of the binary operands. For example, **1010110 ^ 0110111** yields **1100001**. For more on bitwise operations, see Appendix G, Bitwise Operations.

For a search key of the type **double**, first convert it to a **long** value using the **Double.doubleToLongBits** method, and then perform a folding as follows:

double  
folding

```
long bits = Double.doubleToLongBits(key);
int hashCode = (int)(bits ^ (bits >> 32));
```

### 27.3.2 Hash Codes for Strings

Search keys are often strings, so it is important to design a good hash function for strings. An intuitive approach is to sum the Unicode of all characters as the hash code for the string. This approach may work if two search keys in an application don't contain the same letters, but

polynomial hash code

it will produce a lot of collisions if the search keys contain the same letters, such as `tod` and `dot`.

A better approach is to generate a hash code that takes the position of characters into consideration. Specifically, let the hash code be

$$s_0 * b^{(n-1)} + s_1 * b^{(n-2)} + \dots + s_{n-1}$$

where  $s_i$  is `s.charAt(i)`. This expression is a polynomial for some positive  $b$ , so this is called a *polynomial hash code*. Using Horner's rule for polynomial evaluation (see Section 6.7), the hash code can be calculated efficiently as follows:

$$(\dots ((s_0 * b + s_1) * b + s_2) * b + \dots + s_{n-2}) * b + s_{n-1}$$

This computation can cause an overflow for long strings, but arithmetic overflow is ignored in Java. You should choose an appropriate value  $b$  to minimize collisions. Experiments show that good choices for  $b$  are 31, 33, 37, 39, and 41. In the `String` class, the `hashCode` is overridden using the polynomial hash code with  $b$  being 31.

### 27.3.3 Compressing Hash Codes

The hash code for a key can be a large integer that is out of the range for the hash-table index, so you need to scale it down to fit in the index's range. Assume the index for a hash table is between `0` and `N-1`. The most common way to scale an integer to between `0` and `N-1` is to use

$$h(hashCode) = hashCode \% N$$

To ensure that the indices are spread evenly, choose `N` to be a prime number greater than 2.

Ideally, you should choose a prime number for `N`. However, it is time consuming to find a large prime number. In the Java API implementation for `java.util.HashMap`, `N` is set to a value of the power of 2. There is a good reason for this choice. When `N` is a value of the power of 2,

$$h(hashCode) = hashCode \% N$$

is the same as

$$h(hashCode) = hashCode \& (N - 1)$$

The ampersand, `&`, is a bitwise AND operator (see Appendix G, Bitwise Operations). The AND of two corresponding bits yields a 1 if both bits are 1. For example, assume `N = 4` and `hashCode = 11, 11 \% 4 = 3`, which is the same as `01011 & 00011 = 11`. The `&` operator can be performed much faster than the `%` operator.

To ensure that the hashing is evenly distributed, a supplemental hash function is also used along with the primary hash function in the implementation of `java.util.HashMap`. This function is defined as:

```
private static int supplementalHash(int h) {
 h ^= (h >>> 20) ^ (h >>> 12);
 return h ^ (h >>> 7) ^ (h >>> 4);
}
```

`^` and `>>>` are bitwise exclusive-or and unsigned right-shift operations (also introduced in Appendix G). The bitwise operations are much faster than the multiplication, division, and remainder operations. You should replace these operations with the bitwise operations whenever possible.

The complete hash function is defined as:

$$h(hashCode) = supplementalHash(hashCode) \% N$$

This is the same as

```
h(hashCode) = supplementalHash(hashCode) & (N - 1)
```

since  $N$  is a value of the power of 2.

- 27.2** What is a hash code? What is the hash code for **Byte**, **Short**, **Integer**, and **Character**?
- 27.3** How is the hash code for a **Float** object computed?
- 27.4** How is the hash code for a **Long** object computed?
- 27.5** How is the hash code for a **Double** object computed?
- 27.6** How is the hash code for a **String** object computed?
- 27.7** How is a hash code compressed to an integer representing the index in a hash table?
- 27.8** If  $N$  is a value of the power of 2, is  $N / 2$  same as  $N \gg 1$ ?
- 27.9** If  $N$  is a value of the power of 2, is  $m \% N$  same as  $m \& (N - 1)$  for any integer  $m$ ?



## 27.4 Handling Collisions Using Open Addressing

A collision occurs when two keys are mapped to the same index in a hash table.

Generally, there are two ways for handling collisions: open addressing and separate chaining.



Open addressing is the process of finding an open location in the hash table in the event of a collision. Open addressing has several variations: *linear probing*, *quadratic probing*, and *double hashing*.

open addressing

### 27.4.1 Linear Probing

When a collision occurs during the insertion of an entry to a hash table, *linear probing* finds the next available location sequentially. For example, if a collision occurs at `hashTable[k % N]`, check whether `hashTable[(k+1) % N]` is available. If not, check `hashTable[(k+2) % N]` and so on, until an available cell is found, as shown in Figure 27.2.

add entry  
linear probing

circular hash table



#### Note

When probing reaches the end of the table, it goes back to the beginning of the table.  
Thus, the hash table is treated as if it were circular.

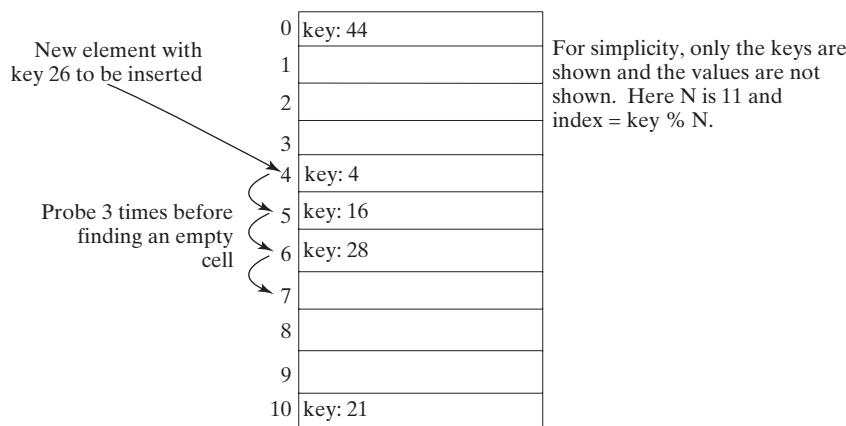


FIGURE 27.2 Linear probing finds the next available location sequentially.

search entry

To search for an entry in the hash table, obtain the index, say  $k$ , from the hash function for the key. Check whether  $\text{hashTable}[k \% N]$  contains the entry. If not, check whether  $\text{hashTable}[(k+1) \% N]$  contains the entry, and so on, until it is found, or an empty cell is reached.

remove entry

To remove an entry from the hash table, search the entry that matches the key. If the entry is found, place a special marker to denote that the entry is available. Each cell in the hash table has three possible states: occupied, marked, or empty. Note that a marked cell is also available for insertion.

cluster



linear probing animation on Companion Website



### Pedagogical Note

For an interactive GUI demo to see how linear probing works, go to [www.cs.armstrong.edu/liang/animation/HashingLinearProbingAnimation.html](http://www.cs.armstrong.edu/liang/animation/HashingLinearProbingAnimation.html), as shown in Figure 27.3.

#### 27.4.2 Quadratic Probing

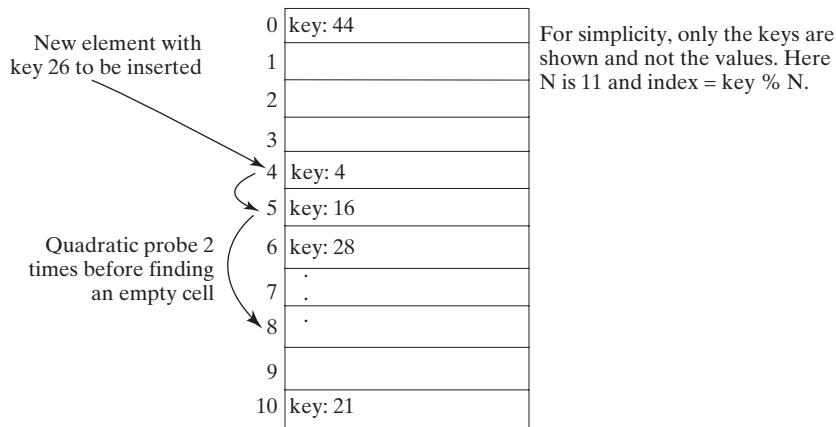
quadratic probing

*Quadratic probing* can avoid the clustering problem that can occur in linear probing. Linear probing looks at the consecutive cells beginning at index  $k$ . Quadratic probing, on the other hand, looks at the cells at indices  $(k + j^2) \% N$ , for  $j \geq 0$ , that is,  $k \% N, (k + 1)\% N, (k + 4)\% N, (k + 9)\% N$ , and so on, as shown in Figure 27.4.

|        |        |        |        |        |
|--------|--------|--------|--------|--------|
| [0][0] | [0][1] | [0][2] | [0][3] | [0][4] |
| [1][0] | [1][1] | [1][2] | [1][3] | [1][4] |
| [2][0] | [2][1] | [2][2] | [2][3] | [2][4] |
| [3][0] | [3][1] | [3][2] | [3][3] | [3][4] |
| [4][0] | [4][1] | [4][2] | [4][3] | [4][4] |

Enter Initial table size:  Enter a value:  Insert Delete Remove All Search a key:

FIGURE 27.3 The animation tool shows how linear probing works.



**FIGURE 27.4** Quadratic probing increases the next index in the sequence by  $j^2$  for  $j = 1, 2, 3, \dots$

Quadratic probing works in the same way as linear probing except for a change in the search sequence. Quadratic probing avoids linear probing's clustering problem, but it has its own clustering problem, called *secondary clustering*; that is, the entries that collide with an occupied entry use the same probe sequence.

Linear probing guarantees that an available cell can be found for insertion as long as the table is not full. However, there is no such guarantee for quadratic probing.



### Pedagogical NOTE

For an interactive GUI demo to see how quadratic probing works, go to [www.cs.armstrong.edu/liang/animation/HashingQuadraticProbingAnimation.html](http://www.cs.armstrong.edu/liang/animation/HashingQuadraticProbingAnimation.html), as shown in Figure 27.5.

secondary clustering



quadratic probing animation  
on Companion Website

double hashing

### 27.4.3 Double Hashing

Another open addressing scheme that avoids the clustering problem is known as *double hashing*. Starting from the initial index  $k$ , both linear probing and quadratic probing add an increment to  $k$  to define a search sequence. The increment is 1 for linear probing and  $j^2$  for quadratic probing. These increments are independent of the keys. Double hashing uses a secondary hash function  $h'(key)$  on the keys to determine the increments to avoid the clustering problem. Specifically, double hashing looks at the cells at indices  $(k + j * h'(key)) \% N$ , for  $j \geq 0$ , that is,  $k \% N, (k + h'(key)) \% N, (k + 2 * h'(key)) \% N, (k + 3 * h'(key)) \% N$ , and so on.

For example, let the primary hash function  $h$  and secondary hash function  $h'$  on a hash table of size 11 be defined as follows:

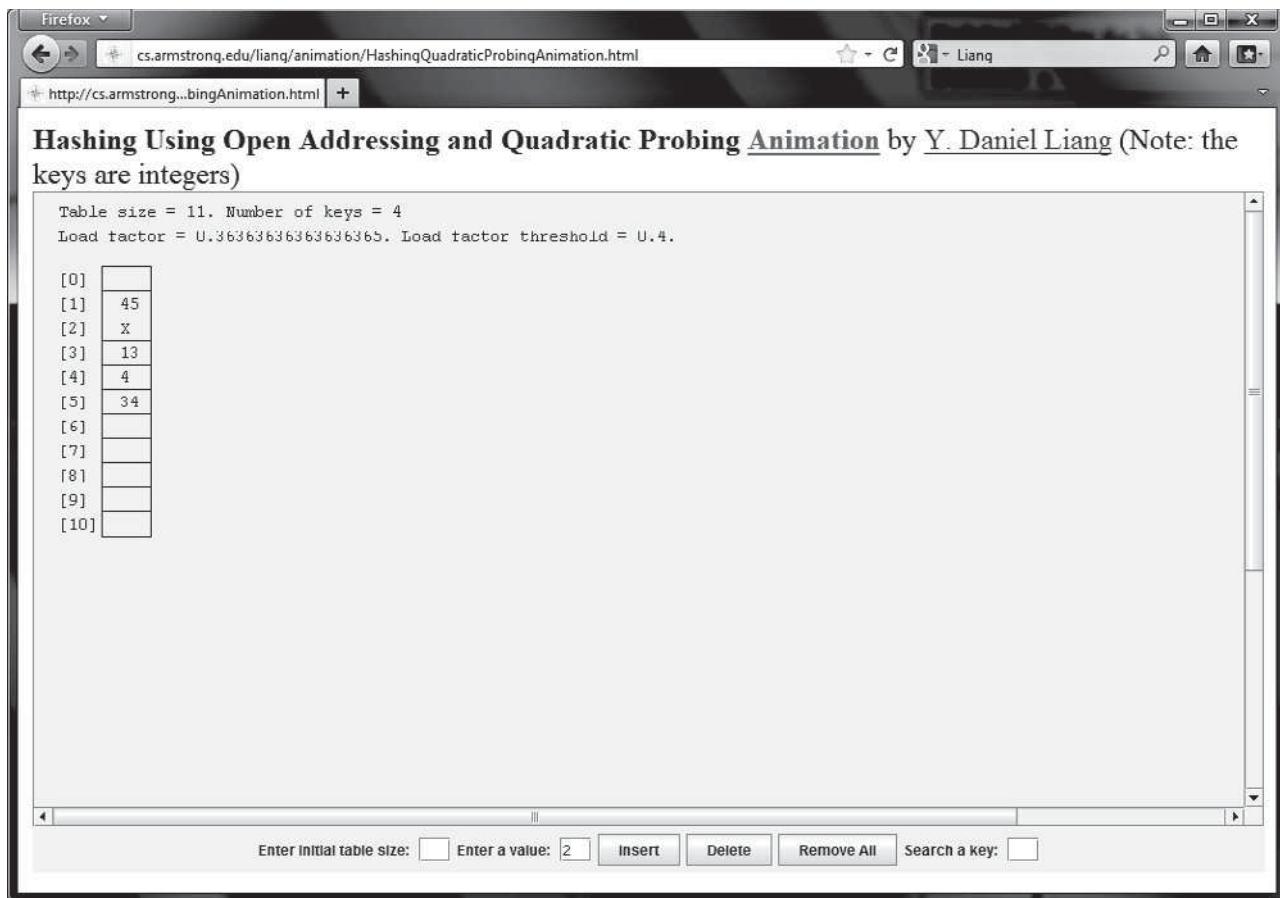
$$\begin{aligned} h(key) &= \text{key \% 11;} \\ h'(key) &= 7 - \text{key \% 7;} \end{aligned}$$

For a search key of 12, we have

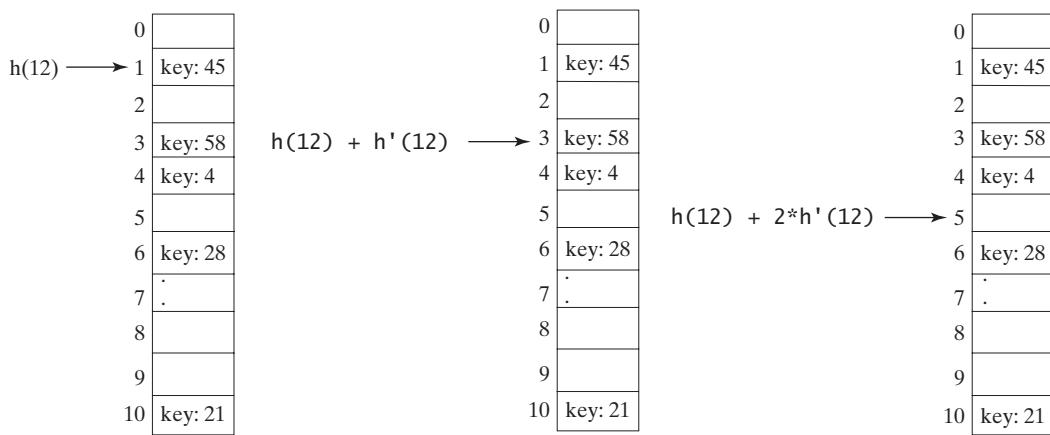
$$\begin{aligned} h(12) &= 12 \% 11 = 1; \\ h'(12) &= 7 - 12 \% 7 = 2; \end{aligned}$$

Suppose the elements with the keys 45, 58, 4, 28, and 21 are already placed in the hash table. We now insert the element with key 12. The probe sequence for key 12 starts at index 1. Since the cell at index 1 is already occupied, search the next cell at index 3 ( $1 + 1 * 2$ ). Since the cell at index 3 is already occupied, search the next cell at index 5 ( $1 + 2 * 2$ ). Since the cell at index 5 is empty, the element for key 12 is now inserted at this cell. The search process is illustrated in Figure 27.6.

The indices of the probe sequence are as follows: 1, 3, 5, 7, 9, 0, 2, 4, 6, 8, 10. This sequence reaches the entire table. You should design your functions to produce a probe sequence that



**FIGURE 27.5** The animation tool shows how quadratic probing works.



**FIGURE 27.6** The secondary hash function in a double hashing determines the increment of the next index in the probe sequence.

reaches the entire table. Note that the second function should never have a zero value, since zero is not an increment.



**27.10** What is open addressing? What is linear probing? What is quadratic probing? What is double hashing?

**27.11** Describe the clustering problem for linear probing.

- 27.12** What is secondary clustering?
- 27.13** Show the hash table of size 11 after inserting entries with keys 34, 29, 53, 44, 120, 39, 45, and 40, using linear probing.
- 27.14** Show the hash table of size 11 after inserting entries with keys 34, 29, 53, 44, 120, 39, 45, and 40, using quadratic probing.
- 27.15** Show the hash table of size 11 after inserting entries with keys 34, 29, 53, 44, 120, 39, 45, and 40, using double hashing with the following functions:

$$h(k) = k \% 11;$$

$$h'(k) = 7 - k \% 7;$$

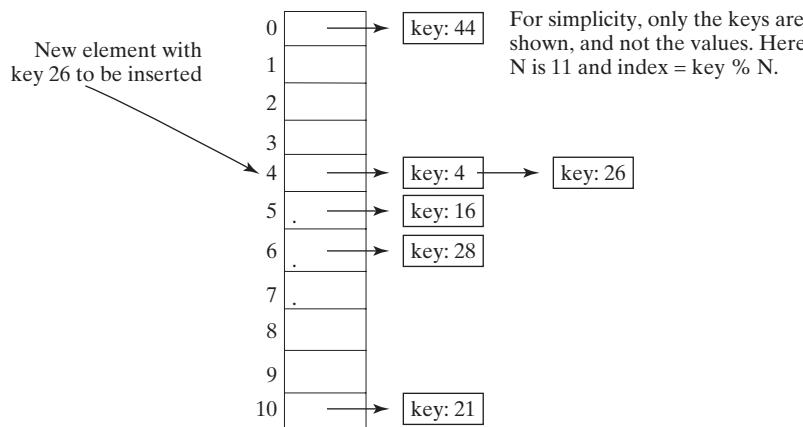
## 27.5 Handling Collisions Using Separate Chaining

The separate chaining scheme places all entries with the same hash index in the same location, rather than finding new locations. Each location in the separate chaining scheme uses a bucket to hold multiple entries.

You can implement a bucket using an array, `ArrayList`, or `LinkedList`. We will use `LinkedList` for demonstration. You can view each cell in the hash table as the reference to the head of a linked list, and elements in the linked list are chained starting from the head, as shown in Figure 27.7.



separate chaining  
implementing bucket



**FIGURE 27.7** Separate chaining scheme chains the entries with the same hash index in a bucket.

- 27.16** Show the hash table of size 11 after inserting entries with the keys 34, 29, 53, 44, 120, 39, 45, and 40, using separate chaining.



## 27.6 Load Factor and Rehashing

The load factor measures how full a hash table is. If the load factor is exceeded, increase the hash-table size and reload the entries into a new larger hash table. This is called rehashing.



rehashing

Load factor  $\lambda$  (lambda) measures how full a hash table is. It is the ratio of the number of elements to the size of the hash table, that is,  $\lambda = \frac{n}{N}$ , where  $n$  denotes the number of elements and  $N$  the number of locations in the hash table.

load factor

Note that  $\lambda$  is zero if the hash table is empty. For the open addressing scheme,  $\lambda$  is between 0 and 1;  $\lambda$  is 1 if the hash table is full. For the separate chaining scheme,  $\lambda$  can be any value.

As  $\lambda$  increases, the probability of a collision increases. Studies show that you should maintain the load factor under **0.5** for the open addressing scheme and under **0.9** for the separate chaining scheme.

threshold

Keeping the load factor under a certain threshold is important for the performance of hashing. In the implementation of the `java.util.HashMap` class in the Java API, the threshold **0.75** is used. Whenever the load factor exceeds the threshold, you need to increase the hash-table size and *rehash* all the entries in the map into a new larger hash table. Notice that you need to change the hash functions, since the hash-table size has been changed. To reduce the likelihood of rehashing, since it is costly, you should at least double the hash-table size. Even with periodic rehashing, hashing is an efficient implementation for map.

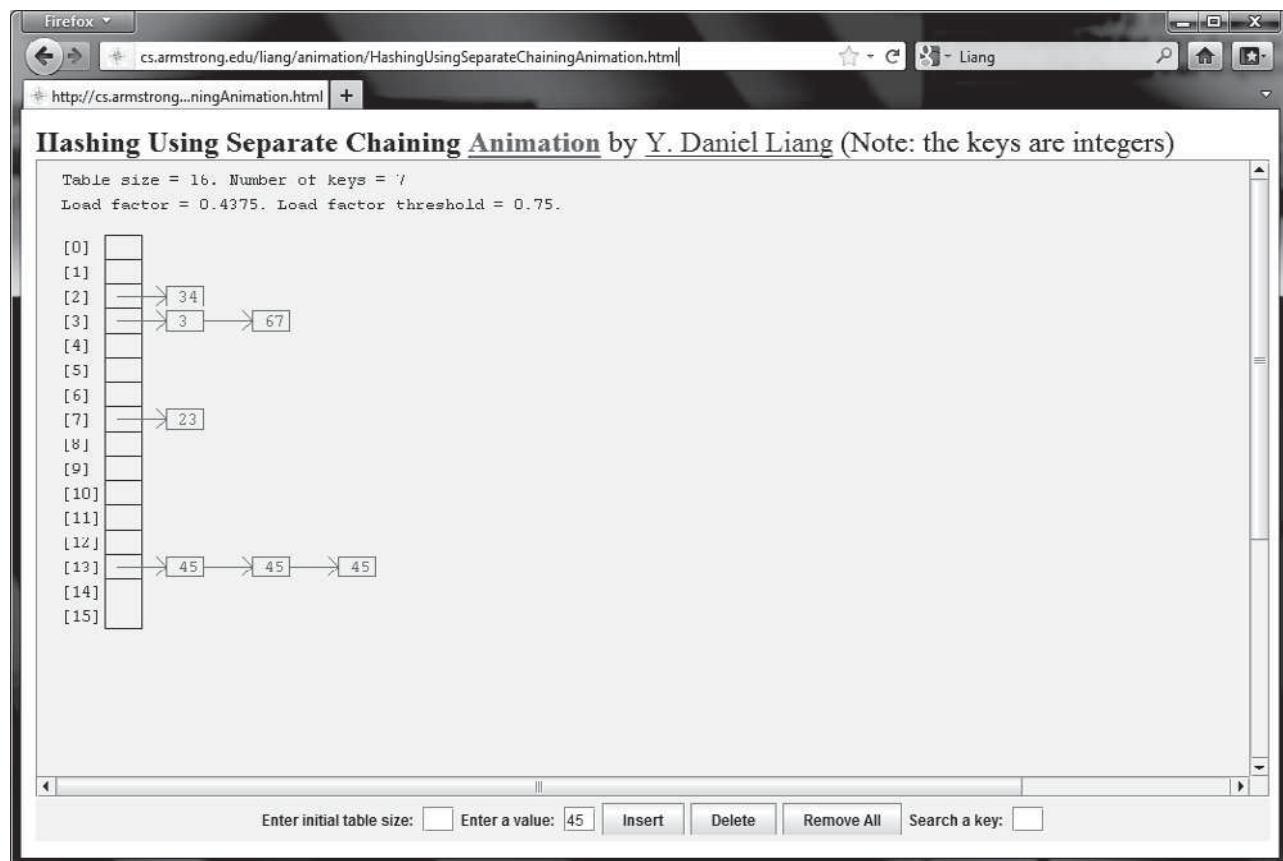


separate chaining animation  
on Companion Website



### Pedagogical Note

For an interactive GUI demo to see how separate chaining works, go to [www.cs.armstrong.edu/liang/animation/HashingUsingSeparateChainingAnimation.html](http://www.cs.armstrong.edu/liang/animation/HashingUsingSeparateChainingAnimation.html), as shown in Figure 27.8.



**FIGURE 27.8** The animation tool shows how separate chaining works.



**27.17** What is load factor? Assume the hash table has the initial size 4 and its load factor is 0.5; show the hash table after inserting entries with the keys 34, 29, 53, 44, 120, 39, 45, and 40, using linear probing.

**27.18** Assume the hash table has the initial size 4 and its load factor is 0.5; show the hash table after inserting entries with the keys 34, 29, 53, 44, 120, 39, 45, and 40, using quadratic probing.

- 27.19** Assume the hash table has the initial size 4 and its load factor is 0.5; show the hash table after inserting entries with the keys 34, 29, 53, 44, 120, 39, 45, and 40, using separate chaining.



## 27.7 Implementing a Map Using Hashing

A map can be implemented using hashing.

Now you understand the concept of hashing. You know how to design a good hash function to map a key to an index in a hash table, how to measure performance using the load factor, and how to increase the table size and rehash to maintain the performance. This section demonstrates how to implement a map using separate chaining.

We design our custom `Map` interface to mirror `java.util.Map` and name the interface `MyMap` and a concrete class `MyHashMap`, as shown in Figure 27.9.

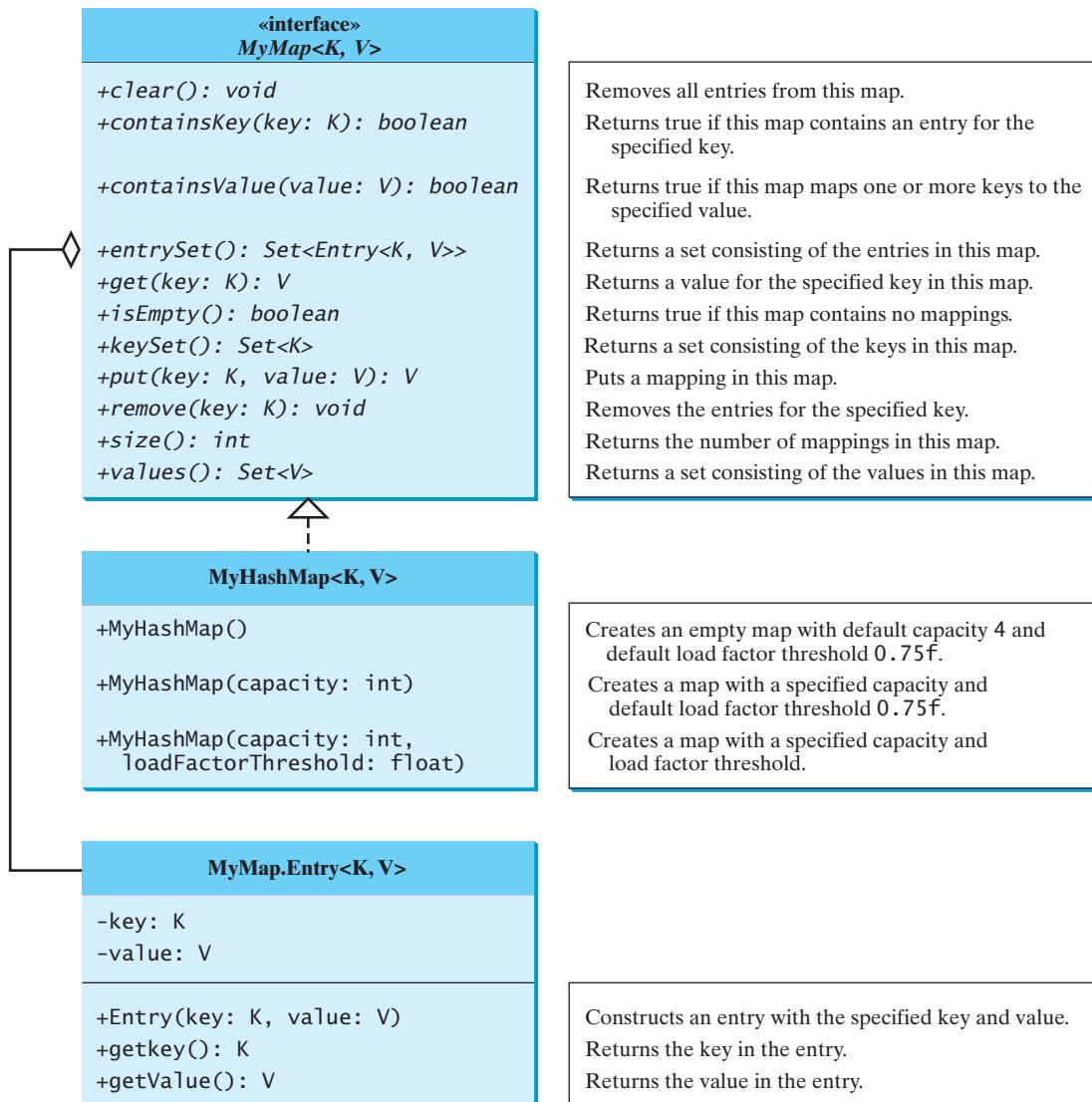


FIGURE 27.9 MyHashMap implements the MyMap interface.

How do you implement **MyHashMap**? If you use an **ArrayList** and store a new entry at the end of the list, the search time will be  $O(n)$ . If you implement **MyHashMap** using a binary tree, the search time will be  $O(\log n)$  if the tree is well balanced. Nevertheless, you can implement **MyHashMap** using hashing to obtain an  $O(1)$  time search algorithm. Listing 27.1 shows the **MyMap** interface and Listing 27.2 implements **MyHashMap** using separate chaining.

### LISTING 27.1 MyMap.java

```

interface MyMap
 clear
containsKey
containsValue
entrySet
get
isEmpty
keySet
put
remove
size
values
Entry inner class
1 public interface MyMap<K, V> {
2 /** Remove all of the entries from this map */
3 public void clear();
4
5 /** Return true if the specified key is in the map */
6 public boolean containsKey(K key);
7
8 /** Return true if this map contains the specified value */
9 public boolean containsValue(V value);
10
11 /** Return a set of entries in the map */
12 public java.util.Set<Entry<K, V>> entrySet();
13
14 /** Return the value that matches the specified key */
15 public V get(K key);
16
17 /** Return true if this map doesn't contain any entries */
18 public boolean isEmpty();
19
20 /** Return a set consisting of the keys in this map */
21 public java.util.Set<K> keySet();
22
23 /** Add an entry (key, value) into the map */
24 public V put(K key, V value);
25
26 /** Remove an entry for the specified key */
27 public void remove(K key);
28
29 /** Return the number of mappings in this map */
30 public int size();
31
32 /** Return a set consisting of the values in this map */
33 public java.util.Set<V> values();
34
35 /** Define an inner class for Entry */
36 public static class Entry<K, V> {
37 K key;
38 V value;
39
40 public Entry(K key, V value) {
41 this.key = key;
42 this.value = value;
43 }
44
45 public K getKey() {
46 return key;
47 }
48
49 public V getValue() {
50 return value;
51 }
52

```

```

53 @Override
54 public String toString() {
55 return "[" + key + ", " + value + "]";
56 }
57 }
58 }
```

**LISTING 27.2 MyHashMap.java**

```

1 import java.util.LinkedList;
2
3 public class MyHashMap<K, V> implements MyMap<K, V> {
4 // Define the default hash-table size. Must be a power of 2
5 private static int DEFAULT_INITIAL_CAPACITY = 4;
6
7 // Define the maximum hash-table size. 1 << 30 is same as 2^30
8 private static int MAXIMUM_CAPACITY = 1 << 30;
9
10 // Current hash-table capacity. Capacity is a power of 2
11 private int capacity;
12
13 // Define default load factor
14 private static float DEFAULT_MAX_LOAD_FACTOR = 0.75f;
15
16 // Specify a load factor used in the hash table
17 private float loadFactorThreshold;
18
19 // The number of entries in the map
20 private int size = 0;
21
22 // Hash table is an array with each cell being a linked list
23 LinkedList<MyMap.Entry<K,V>>[] table;
24
25 /** Construct a map with the default capacity and load factor */
26 public MyHashMap() {
27 this(DEFAULT_INITIAL_CAPACITY, DEFAULT_MAX_LOAD_FACTOR);
28 }
29
30 /** Construct a map with the specified initial capacity and
31 * default load factor */
32 public MyHashMap(int initialCapacity) {
33 this(initialCapacity, DEFAULT_MAX_LOAD_FACTOR);
34 }
35
36 /** Construct a map with the specified initial capacity
37 * and load factor */
38 public MyHashMap(int initialCapacity, float loadFactorThreshold) {
39 if (initialCapacity > MAXIMUM_CAPACITY)
40 this.capacity = MAXIMUM_CAPACITY;
41 else
42 this.capacity = trimToPowerOf2(initialCapacity);
43
44 this.loadFactorThreshold = loadFactorThreshold;
45 table = new LinkedList[capacity];
46 }
47
48 @Override /** Remove all of the entries from this map */
49 public void clear() {
50 size = 0;
51 removeEntries();
52 }
```

class MyHashMap  
default initial capacity  
maximum capacity  
current capacity  
default load factor  
load-factor threshold  
size  
hash table  
no-arg constructor  
constructor  
constructor  
clear

```

53
54 @Override /** Return true if the specified key is in the map */
55 public boolean containsKey(K key) {
56 if (get(key) != null)
57 return true;
58 else
59 return false;
60 }
61
62 @Override /** Return true if this map contains the value */
63 public boolean containsValue(V value) {
64 for (int i = 0; i < capacity; i++) {
65 if (table[i] != null) {
66 LinkedList<Entry<K, V>> bucket = table[i];
67 for (Entry<K, V> entry: bucket)
68 if (entry.getValue().equals(value))
69 return true;
70 }
71 }
72
73 return false;
74 }
75
76 @Override /** Return a set of entries in the map */
77 public java.util.Set<MyMap.Entry<K,V>> entrySet() {
78 java.util.Set<MyMap.Entry<K, V>> set =
79 new java.util.HashSet<>();
80
81 for (int i = 0; i < capacity; i++) {
82 if (table[i] != null) {
83 LinkedList<Entry<K, V>> bucket = table[i];
84 for (Entry<K, V> entry: bucket)
85 set.add(entry);
86 }
87 }
88
89 return set;
90 }
91
92 @Override /** Return the value that matches the specified key */
93 public V get(K key) {
94 int bucketIndex = hash(key.hashCode());
95 if (table[bucketIndex] != null) {
96 LinkedList<Entry<K, V>> bucket = table[bucketIndex];
97 for (Entry<K, V> entry: bucket)
98 if (entry.getKey().equals(key))
99 return entry.getValue();
100
101
102 return null;
103 }
104
105 @Override /** Return true if this map contains no entries */
106 public boolean isEmpty() {
107 return size == 0;
108 }
109
110 @Override /** Return a set consisting of the keys in this map */
111 public java.util.Set<K> keySet() {
112 java.util.Set<K> set = new java.util.HashSet<K>();

```

```

113
114 for (int i = 0; i < capacity; i++) {
115 if (table[i] != null) {
116 LinkedList<Entry<K, V>> bucket = table[i];
117 for (Entry<K, V> entry: bucket)
118 set.add(entry.getKey());
119 }
120 }
121
122 return set;
123 }
124
125 @Override /** Add an entry (key, value) into the map */
126 public V put(K key, V value) { put
127 if (get(key) != null) { // The key is already in the map
128 int bucketIndex = hash(key.hashCode());
129 LinkedList<Entry<K, V>> bucket = table[bucketIndex];
130 for (Entry<K, V> entry: bucket)
131 if (entry.getKey().equals(key)) {
132 V oldValue = entry.getValue();
133 // Replace old value with new value
134 entry.value = value;
135 // Return the old value for the key
136 return oldValue;
137 }
138 }
139
140 // Check load factor
141 if (size >= capacity * loadFactorThreshold) {
142 if (capacity == MAXIMUM_CAPACITY)
143 throw new RuntimeException("Exceeding maximum capacity");
144
145 rehash();
146 }
147
148 int bucketIndex = hash(key.hashCode());
149
150 // Create a linked list for the bucket if not already created
151 if (table[bucketIndex] == null) {
152 table[bucketIndex] = new LinkedList<Entry<K, V>>();
153 }
154
155 // Add a new entry (key, value) to hashTable[index]
156 table[bucketIndex].add(new MyMap.Entry<K, V>(key, value));
157
158 size++; // Increase size
159
160 return value;
161 }
162
163 @Override /** Remove the entries for the specified key */
164 public void remove(K key) { remove
165 int bucketIndex = hash(key.hashCode());
166
167 // Remove the first entry that matches the key from a bucket
168 if (table[bucketIndex] != null) {
169 LinkedList<Entry<K, V>> bucket = table[bucketIndex];
170 for (Entry<K, V> entry: bucket)
171 if (entry.getKey().equals(key)) {
172 bucket.remove(entry);

```

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```
173 size--; // Decrease size
174 break; // Remove just one entry that matches the key
175 }
176 }
177 }
178
179 @Override /** Return the number of entries in this map */
180 public int size() {
181 return size;
182 }
183
184 @Override /** Return a set consisting of the values in this map */
185 public java.util.Set<V> values() {
186 java.util.Set<V> set = new java.util.HashSet<>();
187
188 for (int i = 0; i < capacity; i++) {
189 if (table[i] != null) {
190 LinkedList<Entry<K, V>> bucket = table[i];
191 for (Entry<K, V> entry: bucket)
192 set.add(entry.getValue());
193 }
194 }
195
196 return set;
197 }
198
199 /** Hash function */
200 private int hashCode(int hashCode) {
201 return supplementalHash(hashCode) & (capacity - 1);
202 }
203
204 /** Ensure the hashing is evenly distributed */
205 private static int supplementalHash(int h) {
206 h ^= (h >>> 20) ^ (h >>> 12);
207 return h ^ (h >>> 7) ^ (h >>> 4);
208 }
209
210 /** Return a power of 2 for initialCapacity */
211 private int trimToPowerOf2(int initialCapacity) {
212 int capacity = 1;
213 while (capacity < initialCapacity) {
214 capacity <= 1; // Same as capacity *= 2. <= is more efficient
215 }
216
217 return capacity;
218 }
219
220 /** Remove all entries from each bucket */
221 private void removeEntries() {
222 for (int i = 0; i < capacity; i++) {
223 if (table[i] != null) {
224 table[i].clear();
225 }
226 }
227 }
228
229 /** Rehash the map */
230 private void rehash() {
231 java.util.Set<Entry<K, V>> set = entrySet(); // Get entries
232 capacity <= 1; // Same as capacity *= 2. <= is more efficient
```

## 27.7 Implementing a Map Using Hashing 1001

```

233 table = new LinkedList[capacity]; // Create a new hash table
234 size = 0; // Reset size to 0
235
236 for (Entry<K, V> entry: set) {
237 put(entry.getKey(), entry.getValue()); // Store to new table
238 }
239 }
240
241 @Override /** Return a string representation for this map */
242 public String toString() {toString
243 StringBuilder builder = new StringBuilder("[");
244
245 for (int i = 0; i < capacity; i++) {
246 if (table[i] != null && table[i].size() > 0)
247 for (Entry<K, V> entry: table[i])
248 builder.append(entry);
249 }
250
251 builder.append("]");
252 return builder.toString();
253 }
254 }
```

The `MyHashMap` class implements the `MyMap` interface using separate chaining. The parameters that determine the hash-table size and load factors are defined in the class. The default initial capacity is 4 (line 5) and the maximum capacity is  $2^{30}$  (line 8). The current hash-table capacity is designed as a value of the power of 2 (line 11). The default load-factor threshold is `0.75f` (line 14). You can specify a custom load-factor threshold when constructing a map. The custom load-factor threshold is stored in `loadFactorThreshold` (line 17). The data field `size` denotes the number of entries in the map (line 20). The hash table is an array. Each cell in the array is a linked list (line 23).

Three constructors are provided to construct a map. You can construct a default map with the default capacity and load-factor threshold using the no-arg constructor (lines 26–28), a map with the specified capacity and a default load-factor threshold (lines 32–34), and a map with the specified capacity and load-factor threshold (lines 38–46).

The `clear` method removes all entries from the map (lines 49–52). It invokes `removeEntries()`, which deletes all entries in the buckets (lines 221–227). The `removeEntries()` method takes  $O(capacity)$  time to clear all entries in the table.

The `containsKey(key)` method checks whether the specified key is in the map by invoking the `get` method (lines 55–60). Since the `get` method takes  $O(1)$  time, the `containsKey(key)` method takes  $O(1)$  time.

The `containsValue(value)` method checks whether the value is in the map (lines 63–74). This method takes  $O(capacity + size)$  time. It is actually  $O(capacity)$ , since  $capacity > size$ .

The `entrySet()` method returns a set that contains all entries in the map (lines 77–90). This method takes  $O(capacity)$  time.

The `get(key)` method returns the value of the first entry with the specified key (lines 93–103). This method takes  $O(1)$  time.

The `isEmpty()` method simply returns true if the map is empty (lines 106–108). This method takes  $O(1)$  time.

The `keySet()` method returns all keys in the map as a set. The method finds the keys from each bucket and adds them to a set (lines 111–123). This method takes  $O(capacity)$  time.

The `put(key, value)` method adds a new entry into the map. The method first tests if the key is already in the map (line 127), if so, it locates the entry and replaces the old value with the new value in the entry for the key (line 134) and the old value is returned (line 136). If

hash-table parameters

three constructors

`clear`

`containsKey`

`containsValue`

`entrySet`

`get`

`isEmpty`

`keySet`

`put`

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the key is new in the map, the new entry is created in the map (line 156). Before inserting the new entry, the method checks whether the size exceeds the load-factor threshold (line 141). If so, the program invokes `rehash()` (line 145) to increase the capacity and store entries into the new larger hash table.

rehash

The `rehash()` method first copies all entries in a set (line 231), doubles the capacity (line 232), creates a new hash table (line 233), and resets the size to 0 (line 234). The method then copies the entries into the new hash table (lines 236–238). The `rehash` method takes  $O(capacity)$  time. If no rehash is performed, the `put` method takes  $O(1)$  time to add a new entry.

remove

The `remove(key)` method removes the entry with the specified key in the map (lines 164–177). This method takes  $O(1)$  time.

size

The `size()` method simply returns the size of the map (lines 180–182). This method takes  $O(1)$  time.

values

The `values()` method returns all values in the map. The method examines each entry from all buckets and adds it to a set (lines 185–197). This method takes  $O(capacity)$  time.

hash

The `hash()` method invokes the `supplementalHash` to ensure that the hashing is evenly distributed to produce an index for the hash table (lines 200–208). This method takes  $O(1)$  time.

Table 27.1 summarizes the time complexities of the methods in `MyHashMap`.

**TABLE 27.1 Time Complexities for Methods in MyHashMap**

| Methods                              | Time          |
|--------------------------------------|---------------|
| <code>clear()</code>                 | $O(capacity)$ |
| <code>containsKey(key: Key)</code>   | $O(1)$        |
| <code>containsValue(value: V)</code> | $O(capacity)$ |
| <code>entrySet()</code>              | $O(capacity)$ |
| <code>get(key: K)</code>             | $O(1)$        |
| <code>isEmpty()</code>               | $O(1)$        |
| <code>keySet()</code>                | $O(capacity)$ |
| <code>put(key: K, value: V)</code>   | $O(1)$        |
| <code>remove(key: K)</code>          | $O(1)$        |
| <code>size()</code>                  | $O(1)$        |
| <code>values()</code>                | $O(capacity)$ |
| <code>rehash()</code>                | $O(capacity)$ |

Since rehashing does not happen very often, the time complexity for the `put` method is  $O(1)$ . Note that the complexities of the `clear`, `entrySet`, `keySet`, `values`, and `rehash` methods depend on `capacity`, so to avoid poor performance for these methods you should choose an initial capacity carefully.

Listing 27.3 gives a test program that uses `MyHashMap`.

### LISTING 27.3 TestMyHashMap.java

```
1 public class TestMyHashMap {
2 public static void main(String[] args) {
3 // Create a map
4 MyMap<String, Integer> map = new MyHashMap<>();
5 map.put("Smith", 30);
6 map.put("Anderson", 31);
7 map.put("Lewis", 29);
8 map.put("Cook", 29);
9 }
10 }
```

create a map  
put entries

```

9 map.put("Smith", 65);
10
11 System.out.println("Entries in map: " + map); display entries
12
13 System.out.println("The age for Lewis is " + get value
14 map.get("Lewis"));
15
16 System.out.println("Is Smith in the map? " + is key in map?
17 map.containsKey("Smith"));
18 System.out.println("Is age 33 in the map? " + is value in map?
19 map.containsValue(33));
20
21 map.remove("Smith");
22 System.out.println("Entries in map: " + map); remove entry
23
24 map.clear();
25 System.out.println("Entries in map: " + map);
26 }
27 }
```

```

Entries in map: [[Anderson, 31][Smith, 65][Lewis, 29][Cook, 29]]
The age for Lewis is 29
Is Smith in the map? true
Is age 33 in the map? false
Entries in map: [[Anderson, 31][Lewis, 29][Cook, 29]]
Entries in map: []
```



The program creates a map using `MyHashMap` (line 4) and adds five entries into the map (lines 5–9). Line 5 adds key `Smith` with value `30` and line 9 adds `Smith` with value `65`. The latter value replaces the former value. The map actually has only four entries. The program displays the entries in the map (line 11), gets a value for a key (line 14), checks whether the map contains the key (line 17) and a value (line 19), removes an entry with the key `Smith` (line 21), and redisplays the entries in the map (line 22). Finally, the program clears the map (line 24) and displays an empty map (line 25).

- 27.20** What is `1 << 30` in line 8 in Listing 27.2? What are the integers resulted from `1 << 1`, `1 << 2`, and `1 << 3`?
- 27.21** What are the integers resulted from `32 >> 1`, `32 >> 2`, `32 >> 3`, and `32 >> 4`?
- 27.22** In Listing 27.2, will the program work if `LinkedList` is replaced by `ArrayList`? In Listing 27.2, how do you replace the code in lines 55–59 using one line of code?
- 27.23** Describe how the `put(key, value)` method is implemented in the `MyHashMap` class.
- 27.24** In Listing 27.5, the `supplementalHash` method is declared static, can the `hash` method be declared static?
- 27.25** Show the output of the following code.



```

MyMap<String, String> map = new MyHashMap<>();
map.put("Texas", "Dallas");
map.put("Oklahoma", "Norman");
map.put("Texas", "Austin");
map.put("Oklahoma", "Tulsa");

System.out.println(map.get("Texas"));
System.out.println(map.size());
```

## 27.8 Implementing Set Using Hashing



hash set  
hash map  
set

MySet  
MyHashSet

*A hash set can be implemented using a hash map.*

A **set** (introduced in Chapter 21) is a data structure that stores distinct values. The Java Collections Framework defines the **java.util.Set** interface for modeling sets. Three concrete implementations are **java.util.HashSet**, **java.util.LinkedHashSet**, and **java.util.TreeSet**. **java.util.HashSet** is implemented using hashing, **java.util.LinkedHashSet** using **LinkedList**, and **java.util.TreeSet** using red-black trees.

You can implement **MyHashSet** using the same approach as for implementing **MyHashMap**. The only difference is that key/value pairs are stored in the map, while elements are stored in the set.

We design our custom **Set** interface to mirror **java.util.Set** and name the interface **MySet** and a concrete class **MyHashSet**, as shown in Figure 27.10.

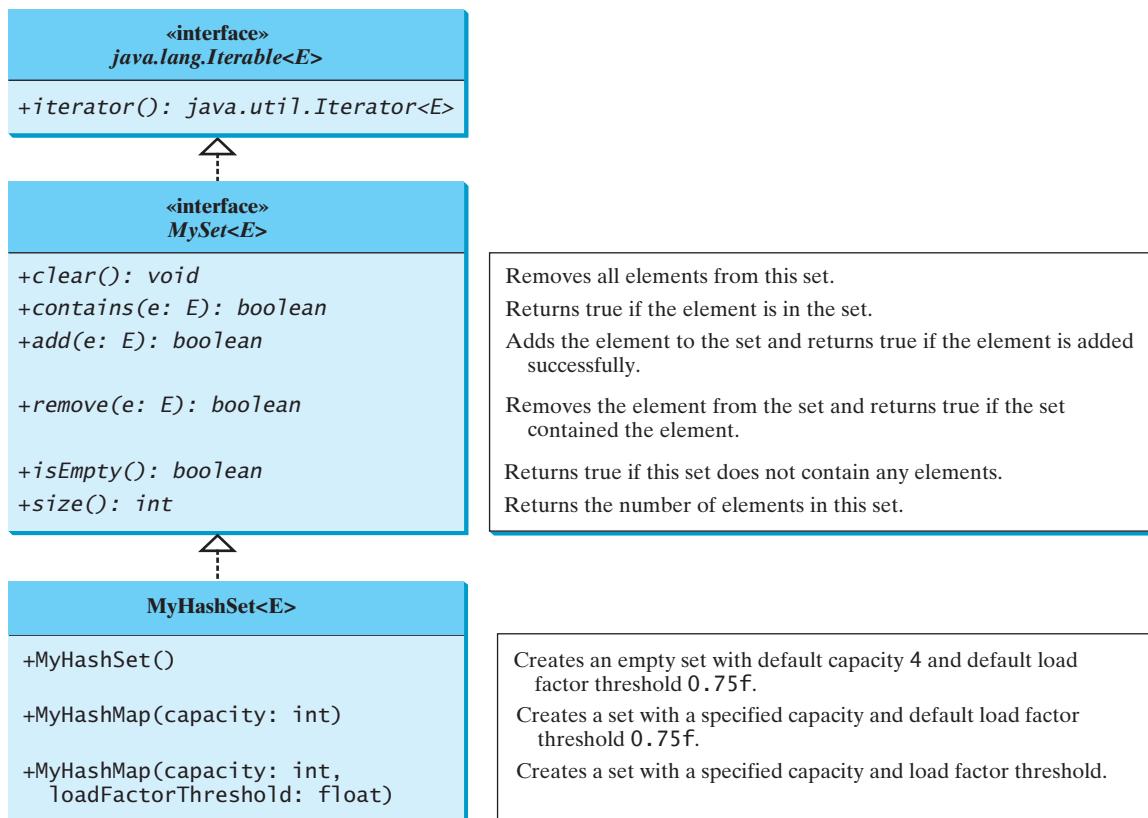


FIGURE 27.10 **MyHashSet** implements the **MySet** interface.

Listing 27.4 shows the **MySet** interface and Listing 27.5 implements **MyHashSet** using separate chaining.

### LISTING 27.4 MySet.java

```

1 public interface MySet<E> extends java.lang.Iterable<E> {
2 /** Remove all elements from this set */
3 public void clear();
4
5 /** Return true if the element is in the set */

```

clear

```

6 public boolean contains(E e); contains
7
8 /** Add an element to the set */
9 public boolean add(E e); add
10
11 /** Remove the element from the set */
12 public boolean remove(E e); remove
13
14 /** Return true if the set doesn't contain any elements */
15 public boolean isEmpty(); isEmpty
16
17 /** Return the number of elements in the set */
18 public int size(); size
19 }

```

**LISTING 27.5** MyHashSet.java

```

1 import java.util.LinkedList;
2
3 public class MyHashSet<E> implements MySet<E> {
4 // Define the default hash-table size. Must be a power of 2
5 private static int DEFAULT_INITIAL_CAPACITY = 4;
6
7 // Define the maximum hash-table size. 1 << 30 is same as 2^30
8 private static int MAXIMUM_CAPACITY = 1 << 30;
9
10 // Current hash-table capacity. Capacity is a power of 2
11 private int capacity;
12
13 // Define default load factor
14 private static float DEFAULT_MAX_LOAD_FACTOR = 0.75f;
15
16 // Specify a load-factor threshold used in the hash table
17 private float loadFactorThreshold;
18
19 // The number of elements in the set
20 private int size = 0;
21
22 // Hash table is an array with each cell being a linked list
23 private LinkedList<E>[] table;
24
25 /** Construct a set with the default capacity and load factor */
26 public MyHashSet() {
27 this(DEFAULT_INITIAL_CAPACITY, DEFAULT_MAX_LOAD_FACTOR);
28 }
29
30 /** Construct a set with the specified initial capacity and
31 * default load factor */
32 public MyHashSet(int initialCapacity) {
33 this(initialCapacity, DEFAULT_MAX_LOAD_FACTOR);
34 }
35
36 /** Construct a set with the specified initial capacity
37 * and load factor */
38 public MyHashSet(int initialCapacity, float loadFactorThreshold) {
39 if (initialCapacity > MAXIMUM_CAPACITY)
40 this.capacity = MAXIMUM_CAPACITY;
41 else
42 this.capacity = trimToPowerOf2(initialCapacity);

```

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```
43
44 this.loadFactorThreshold = loadFactorThreshold;
45 table = new LinkedList[capacity];
46 }
47
48 @Override /** Remove all elements from this set */
49 public void clear() {
50 size = 0;
51 removeElements();
52 }
53
54 @Override /** Return true if the element is in the set */
55 public boolean contains(E e) {
56 int bucketIndex = hash(e.hashCode());
57 if (table[bucketIndex] != null) {
58 LinkedList<E> bucket = table[bucketIndex];
59 for (E element: bucket)
60 if (element.equals(e))
61 return true;
62 }
63
64 return false;
65 }
66
67 @Override /** Add an element to the set */
68 public boolean add(E e) {
69 if (contains(e)) // Duplicate element not stored
70 return false;
71
72 if (size + 1 > capacity * loadFactorThreshold) {
73 if (capacity == MAXIMUM_CAPACITY)
74 throw new RuntimeException("Exceeding maximum capacity");
75
76 rehash();
77 }
78
79 int bucketIndex = hash(e.hashCode());
80
81 // Create a linked list for the bucket if not already created
82 if (table[bucketIndex] == null) {
83 table[bucketIndex] = new LinkedList<E>();
84 }
85
86 // Add e to hashTable[index]
87 table[bucketIndex].add(e);
88
89 size++; // Increase size
90
91 return true;
92 }
93
94 @Override /** Remove the element from the set */
95 public boolean remove(E e) {
96 if (!contains(e))
97 return false;
98
99 int bucketIndex = hash(e.hashCode());
100
101 // Create a linked list for the bucket if not already created
102 if (table[bucketIndex] != null) {
```

```

103 LinkedList<E> bucket = table[bucketIndex];
104 for (E element: bucket)
105 if (e.equals(element)) {
106 bucket.remove(element);
107 break;
108 }
109 }
110 size--; // Decrease size
111
112 return true;
113 }
114
115
116 @Override /** Return true if the set contain no elements */
117 public boolean isEmpty() { isEmpty
118 return size == 0;
119 }
120
121 @Override /** Return the number of elements in the set */
122 public int size() { size
123 return size;
124 }
125
126 @Override /** Return an iterator for the elements in this set */
127 public java.util.Iterator<E> iterator() { iterator
128 return new MyHashSetIterator(this);
129 }
130
131 /**
132 * Inner class for iterator */
133 private class MyHashSetIterator implements java.util.Iterator<E> { inner class
134 // Store the elements in a list
135 private java.util.ArrayList<E> list;
136 private int current = 0; // Point to the current element in list
137 private MyHashSet<E> set;
138
139 /**
140 * Create a list from the set */
141 public MyHashSetIterator(MyHashSet<E> set) {
142 this.set = set;
143 list = setToList();
144 }
145
146 /**
147 * Next element for traversing? */
148 public boolean hasNext() {
149 if (current < list.size())
150 return true;
151
152 return false;
153 }
154
155 /**
156 * Get current element and move cursor to the next */
157 public E next() {
158 return list.get(current++);
159 }
160
161 /**
162 * Remove the current element and refresh the list */
163 public void remove() {
164 // Delete the current element from the hash set
165 set.remove(list.get(current));
166 list.remove(current); // Remove current element from the list
167 }

```

## 1008 Chapter 27 Hashing

```
163 }
164
165 /** Hash function */
166 private int hashCode(int hashCode) {
167 return supplementalHash(hashCode) & (capacity - 1);
168 }
169
170 /** Ensure the hashing is evenly distributed */
171 private static int supplementalHash(int h) {
172 h ^= (h >>> 20) ^ (h >>> 12);
173 return h ^ (h >>> 7) ^ (h >>> 4);
174 }
175
176 /** Return a power of 2 for initialCapacity */
177 private int trimToPowerOf2(int initialCapacity) {
178 int capacity = 1;
179 while (capacity < initialCapacity) {
180 capacity <= 1; // Same as capacity *= 2. <= is more efficient
181 }
182
183 return capacity;
184 }
185
186 /** Remove all e from each bucket */
187 private void removeElements() {
188 for (int i = 0; i < capacity; i++) {
189 if (table[i] != null) {
190 table[i].clear();
191 }
192 }
193 }
194
195 /** Rehash the set */
196 private void rehash() {
197 java.util.ArrayList<E> list = setToList(); // Copy to a list
198 capacity <= 1; // Same as capacity *= 2. <= is more efficient
199 table = new LinkedList[capacity]; // Create a new hash table
200 size = 0;
201
202 for (E element: list) {
203 add(element); // Add from the old table to the new table
204 }
205 }
206
207 /** Copy elements in the hash set to an array list */
208 private java.util.ArrayList<E> setToList() {
209 java.util.ArrayList<E> list = new java.util.ArrayList<>();
210
211 for (int i = 0; i < capacity; i++) {
212 if (table[i] != null) {
213 for (E e: table[i]) {
214 list.add(e);
215 }
216 }
217 }
218
219 return list;
220 }
221
222 @Override /** Return a string representation for this set */

```

```

223 public String toString() { toString
224 java.util.ArrayList<E> list = setToList();
225 StringBuilder builder = new StringBuilder("[");
226
227 // Add the elements except the last one to the string builder
228 for (int i = 0; i < list.size() - 1; i++) {
229 builder.append(list.get(i) + ", ");
230 }
231
232 // Add the last element in the list to the string builder
233 if (list.size() == 0)
234 builder.append("]");
235 else
236 builder.append(list.get(list.size() - 1) + "]");
237
238 return builder.toString();
239 }
240 }
```

The **MyHashSet** class implements the **MySet** interface using separate chaining. Implementing **MyHashSet** is very similar to implementing **MyHashMap** except for the following differences:

1. The elements are stored in the hash table for **MyHashSet**, but the entries (key/value pairs) are stored in the hash table for **MyHashMap**.
2. **MySet** extends **java.lang.Iterable** and **MyHashSet** implements **MySet** and overrides **iterator()**. So the elements in **MyHashSet** are iterable.

Three constructors are provided to construct a set. You can construct a default set with the default capacity and load factor using the no-arg constructor (lines 26–28), a set with the specified capacity and a default load factor (lines 32–34), and a set with the specified capacity and load factor (lines 38–46).

The **clear** method removes all elements from the set (lines 49–52). It invokes **removeElements()**, which clears all table cells (line 190). Each table cell is a linked list that stores the elements with the same hash code. The **removeElements()** method takes  $O(capacity)$  time.

The **contains(element)** method checks whether the specified element is in the set by examining whether the designated bucket contains the element (lines 55–65). This method takes  $O(1)$  time.

The **add(element)** method adds a new element into the set. The method first checks if the element is already in the set (line 69). If so, the method returns false. The method then checks whether the size exceeds the load-factor threshold (line 72). If so, the program invokes **rehash()** (line 76) to increase the capacity and store elements into the new larger hash table.

The **rehash()** method first copies all elements in a list (line 197), doubles the capacity (line 198), creates a new hash table (line 199), and resets the size to 0 (line 200). The method then copies the elements into the new larger hash table (lines 202–204). The **rehash** method takes  $O(capacity)$  time. If no rehash is performed, the **add** method takes  $O(1)$  time to add a new element.

The **remove(element)** method removes the specified element in the set (lines 95–114). This method takes  $O(1)$  time.

The **size()** method simply returns the number of elements in the set (lines 122–124). This method takes  $O(1)$  time.

The **iterator()** method returns an instance of **java.util.Iterator**. The **MyHashSetIterator** class implements **java.util.Iterator** to create a forward iterator. When a **MyHashSetIterator** is constructed, it copies all the elements in the set to a list

MyHashSet vs. MyHashMap

three constructors

clear

contains

add

rehash

remove

size

iterator

## 1010 Chapter 27 Hashing

hash

(line 141). The variable `current` points to the element in the list. Initially, `current` is 0 (line 135), which points to the first element in the list. `MyHashSetIterator` implements the methods `hasNext()`, `next()`, and `remove()` in `java.util.Iterator`. Invoking `hasNext()` returns true if `current < list.size()`. Invoking `next()` returns the current element and moves `current` to point to the next element (line 153). Invoking `remove()` removes the current element in the iterator from the set.

The `hash()` method invokes the `supplementalHash` to ensure that the hashing is evenly distributed to produce an index for the hash table (lines 166–174). This method takes  $O(1)$  time.

Table 27.2 summarizes the time complexity of the methods in `MyHashSet`.

**TABLE 27.2 Time Complexities for Methods in MyHashSet**

| Methods                     | Time          |
|-----------------------------|---------------|
| <code>clear()</code>        | $O(capacity)$ |
| <code>contains(e: E)</code> | $O(1)$        |
| <code>add(e: E)</code>      | $O(1)$        |
| <code>remove(e: E)</code>   | $O(1)$        |
| <code>isEmpty()</code>      | $O(1)$        |
| <code>size()</code>         | $O(1)$        |
| <code>iterator()</code>     | $O(capacity)$ |
| <code>rehash()</code>       | $O(capacity)$ |

Listing 27.6 gives a test program that uses `MyHashSet`.

### LISTING 27.6 TestMyHashSet.java

create a set  
add elements

display elements  
set size

remove element

foreach loop

clear set

```
1 public class TestMyHashSet {
2 public static void main(String[] args) {
3 // Create a MyHashSet
4 MySet<String> set = new MyHashSet<>();
5 set.add("Smith");
6 set.add("Anderson");
7 set.add("Lewis");
8 set.add("Cook");
9 set.add("Smith");
10
11 System.out.println("Elements in set: " + set);
12 System.out.println("Number of elements in set: " + set.size());
13 System.out.println("Is Smith in set? " + set.contains("Smith"));
14
15 set.remove("Smith");
16 System.out.print("Names in set in uppercase are ");
17 for (String s: set)
18 System.out.print(s.toUpperCase() + " ");
19
20 set.clear();
21 System.out.println("\nElements in set: " + set);
22 }
23 }
```

```

Elements in set: [Cook, Anderson, Smith, Lewis]
Number of elements in set: 4
Is Smith in set? true
Names in set in uppercase are COOK ANDERSON LEWIS
Elements in set: []

```



The program creates a set using **MyHashSet** (line 4) and adds five elements to the set (lines 5–9). Line 5 adds **Smith** and line 9 adds **Smith** again. Since only nonduplicate elements are stored in the set, **Smith** appears in the set only once. The set actually has four elements. The program displays the elements (line 11), gets its size (line 12), checks whether the set contains a specified element (line 13), and removes an element (line 15). Since the elements in a set are iterable, a foreach loop is used to traverse all elements in the set (lines 17–18). Finally, the program clears the set (line 20) and displays an empty set (line 21).

**27.26** Why can you use a foreach loop to traverse the elements in a set?



**27.27** Describe how the **add(e)** method is implemented in the **MyHashSet** class.

**27.28** In Listing 27.5, the **remove** method in the iterator removes the current element from the set. It also removes the current element from the internal list (line 161):

```
list.remove(current); // Remove current element from the list
```

Is this necessary?

**27.29** Replace the code in lines 146–149 In Listing 27.5 using one statement.

## KEY TERMS

|                   |      |                       |     |
|-------------------|------|-----------------------|-----|
| associative array | 986  | linear probing        | 989 |
| cluster           | 990  | load factor           | 993 |
| dictionary        | 986  | open addressing       | 989 |
| double hashing    | 991  | perfect hash function | 986 |
| hash code         | 987  | polynomial hash code  | 988 |
| hash function     | 986  | quadratic probing     | 990 |
| hash map          | 1004 | rehashing             | 993 |
| hash set          | 1004 | secondary clustering  | 991 |
| hash table        | 986  | separate chaining     | 993 |

## CHAPTER SUMMARY

1. A *map* is a data structure that stores entries. Each entry contains two parts: a *key* and a *value*. The key is also called a *search key*, which is used to search for the corresponding value. You can implement a map to obtain  $O(1)$  time complexity on searching, retrieval, insertion, and deletion using the hashing technique.
2. A *set* is a data structure that stores elements. You can use the hashing technique to implement a set to achieve  $O(1)$  time complexity on searching, insertion, and deletion for a set.
3. *Hashing* is a technique that retrieves the value using the index obtained from a key without performing a search. A typical *hash function* first converts a search key to

an integer value called a *hash code*, then compresses the hash code into an index to the *hash table*.

4. A *collision* occurs when two keys are mapped to the same index in a hash table. Generally, there are two ways for handling collisions: *open addressing* and *separate chaining*.
5. Open addressing is the process of finding an open location in the hash table in the event of collision. Open addressing has several variations: *linear probing*, *quadratic probing*, and *double hashing*.
6. The *separate chaining* scheme places all entries with the same hash index into the same location, rather than finding new locations. Each location in the separate chaining scheme is called a *bucket*. A bucket is a container that holds multiple entries.

## Quiz

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Answer the quiz for this chapter online at [www.cs.armstrong.edu/liang/intro10e/quiz.html](http://www.cs.armstrong.edu/liang/intro10e/quiz.html).

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## PROGRAMMING EXERCISES

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- \*\*27.1** (*Implement MyMap using open addressing with linear probing*) Create a new concrete class that implements **MyMap** using open addressing with linear probing. For simplicity, use **f(key) = key % size** as the hash function, where **size** is the hash-table size. Initially, the hash-table size is **4**. The table size is doubled whenever the load factor exceeds the threshold (**0.5**).
- \*\*27.2** (*Implement MyMap using open addressing with quadratic probing*) Create a new concrete class that implements **MyMap** using open addressing with quadratic probing. For simplicity, use **f(key) = key % size** as the hash function, where **size** is the hash-table size. Initially, the hash-table size is **4**. The table size is doubled whenever the load factor exceeds the threshold (**0.5**).
- \*\*27.3** (*Implement MyMap using open addressing with double hashing*) Create a new concrete class that implements **MyMap** using open addressing with double hashing. For simplicity, use **f(key) = key % size** as the hash function, where **size** is the hash-table size. Initially, the hash-table size is **4**. The table size is doubled whenever the load factor exceeds the threshold (**0.5**).
- \*\*27.4** (*Modify MyHashMap with duplicate keys*) Modify **MyHashMap** to allow duplicate keys for entries. You need to modify the implementation for the **put(key, value)** method. Also add a new method named **getAll(key)** that returns a set of values that match the key in the map.
- \*\*27.5** (*Implement MyHashSet using MyHashMap*) Implement **MyHashSet** using **MyHashMap**. Note that you can create entries with **(key, key)**, rather than **(key, value)**.
- \*\*27.6** (*Animate linear probing*) Write a program that animates linear probing, as shown in Figure 27.3. You can change the initial size of the hash-table in the program. Assume the load-factor threshold is **0.75**.
- \*\*27.7** (*Animate separate chaining*) Write a program that animates **MyHashMap**, as shown in Figure 27.8. You can change the initial size of the table. Assume the load-factor threshold is **0.75**.

**\*\*27.8** (*Animate quadratic probing*) Write a program that animates quadratic probing, as shown in Figure 27.5. You can change the initial size of the hash-table in program. Assume the load-factor threshold is **0.75**.

**\*\*27.9** (*Implement hashCode for string*) Write a method that returns a hash code for string using the approach described in Section 27.3.2 with **b** value **31**. The function header is as follows:

```
public static int hashCodeForString(String s)
```

**\*\*27.10** (*Compare MyHashSet and MyArrayList*) **MyArrayList** is defined in Listing 24.3. Write a program that generates **1000000** random double values between **0** and **999999** and stores them in a **MyArrayList** and in a **MyHashSet**. Generate a list of **1000000** random double values between **0** and **1999999**. For each number in the list, test if it is in the array list and in the hash set. Run your program to display the total test time for the array list and for the hash set.

**\*\*27.11** (**setToList**) Write the following method that returns an **ArrayList** from a set.

```
public static <E> ArrayList<E> setToList(Set<E> s)
```

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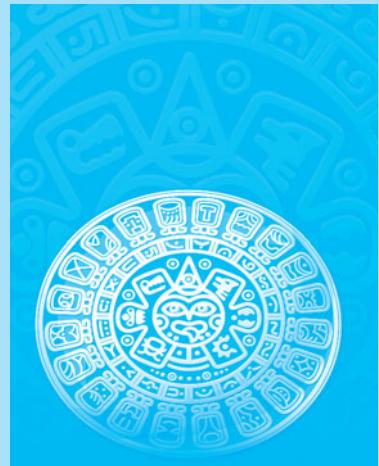
# CHAPTER

# 28

## GRAPHS AND APPLICATIONS

### Objectives

- To model real-world problems using graphs and explain the Seven Bridges of Königsberg problem (§28.1).
- To describe the graph terminologies: vertices, edges, simple graphs, weighted/unweighted graphs, and directed/undirected graphs (§28.2).
- To represent vertices and edges using lists, edge arrays, edge objects, adjacency matrices, and adjacency lists (§28.3).
- To model graphs using the `Graph` interface, the `AbstractGraph` class, and the `UnweightedGraph` class (§28.4).
- To display graphs visually (§28.5).
- To represent the traversal of a graph using the `AbstractGraph.Tree` class (§28.6).
- To design and implement depth-first search (§28.7).
- To solve the connected-circle problem using depth-first search (§28.8).
- To design and implement breadth-first search (§28.9).
- To solve the nine-tail problem using breadth-first search (§28.10).



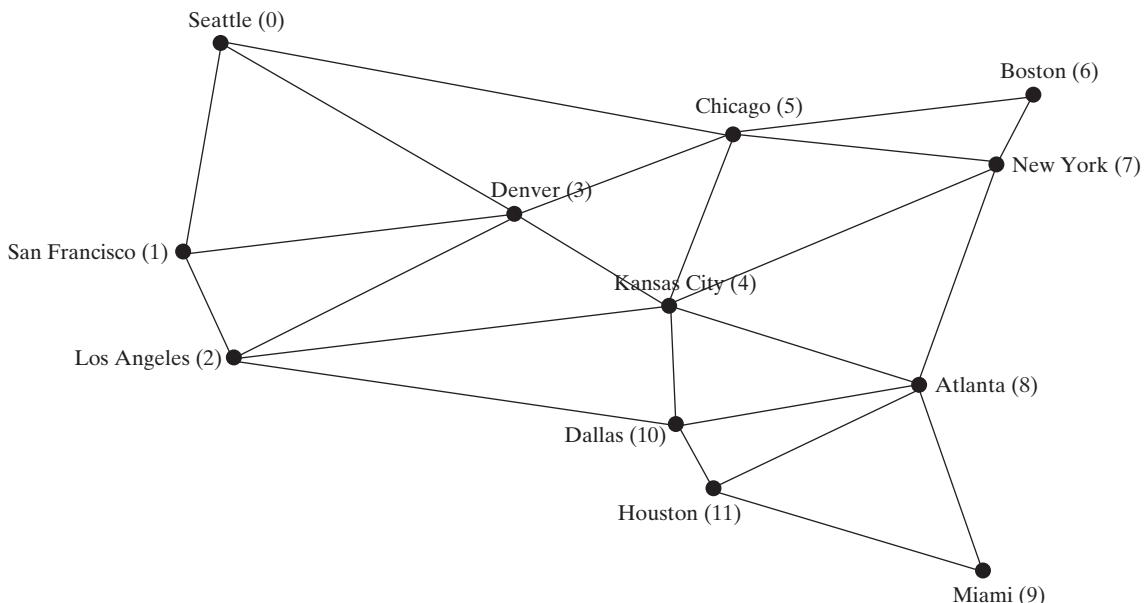
## 28.1 Introduction

problem



*Many real-world problems can be solved using graph algorithms.*

Graphs are useful in modeling and solving real-world problems. For example, the problem to find the least number of flights between two cities can be modeled using a graph, where the vertices represent cities and the edges represent the flights between two adjacent cities, as shown in Figure 28.1. The problem of finding the minimal number of connecting flights between two cities is reduced to finding a shortest path between two vertices in a graph.

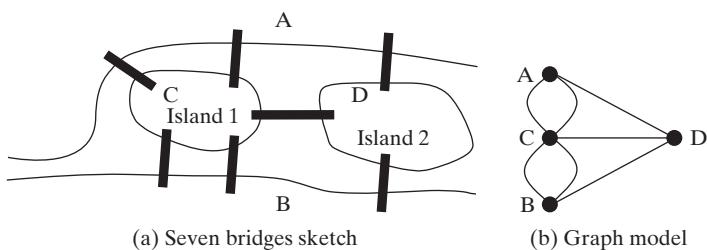


**FIGURE 28.1** A graph can be used to model the flights between the cities.

graph theory

Seven Bridges of Königsberg

The study of graph problems is known as *graph theory*. Graph theory was founded by Leonhard Euler in 1736, when he introduced graph terminology to solve the famous *Seven Bridges of Königsberg* problem. The city of Königsberg, Prussia (now Kaliningrad, Russia), was divided by the Pregel River. There were two islands on the river. The city and islands were connected by seven bridges, as shown in Figure 28.2a. The question is, can one take a walk, cross each bridge exactly once, and return to the starting point? Euler proved that it is not possible.



**FIGURE 28.2** Seven bridges connected islands and land.

To establish a proof, Euler first abstracted the Königsberg city map by eliminating all streets, producing the sketch shown in Figure 28.2a. Next, he replaced each land mass with

a dot, called a *vertex* or a *node*, and each bridge with a line, called an *edge*, as shown in Figure 28.2b. This structure with vertices and edges is called a *graph*.

Looking at the graph, we ask whether there is a path starting from any vertex, traversing all edges exactly once, and returning to the starting vertex. Euler proved that for such a path to exist, each vertex must have an even number of edges. Therefore, the Seven Bridges of Königsberg problem has no solution.

Graph problems are often solved using algorithms. Graph algorithms have many applications in various areas, such as in computer science, mathematics, biology, engineering, economics, genetics, and social sciences. This chapter presents the algorithms for depth-first search and breadth-first search, and their applications. The next chapter presents the algorithms for finding a minimum spanning tree and shortest paths in weighted graphs, and their applications.

## 28.2 Basic Graph Terminologies

*A graph consists of vertices, and edges that connect the vertices.*

This chapter does not assume that you have any prior knowledge of graph theory or discrete mathematics. We use plain and simple terms to define graphs.

What is a graph? A *graph* is a mathematical structure that represents relationships among entities in the real world. For example, the graph in Figure 28.1 represents the flights among cities, and the graph in Figure 28.2b represents the bridges among land masses.

A graph consists of a nonempty set of vertices (also known as *nodes* or *points*), and a set of edges that connect the vertices. For convenience, we define a graph as  $G = (V, E)$ , where  $V$  represents a set of vertices and  $E$  represents a set of edges. For example,  $V$  and  $E$  for the graph in Figure 28.1 are as follows:

```
V = {"Seattle", "San Francisco", "Los Angeles",
 "Denver", "Kansas City", "Chicago", "Boston", "New York",
 "Atlanta", "Miami", "Dallas", "Houston"};
E = {[{"Seattle", "San Francisco"}, {"Seattle", "Chicago"}, {"Seattle", "Denver"}, {"San Francisco", "Chicago"}, {"San Francisco", "Denver"}, {"Chicago", "Denver"}, {"Kansas City", "Chicago"}, {"Kansas City", "Denver"}, {"Kansas City", "Atlanta"}, {"Chicago", "Atlanta"}, {"Chicago", "Miami"}, {"Boston", "New York"}, {"Atlanta", "Miami"}, {"Miami", "Dallas"}, {"Dallas", "Houston"}];
...;
```

A graph may be directed or undirected. In a *directed graph*, each edge has a direction, which indicates that you can move from one vertex to the other through the edge. You can model parent/child relationships using a directed graph, where an edge from vertex A to B indicates that A is a parent of B. Figure 28.3a shows a directed graph.



what is a graph?

define a graph

directed vs. undirected graphs



FIGURE 28.3 Graphs may appear in many forms.

In an *undirected graph*, you can move in both directions between vertices. The graph in Figure 28.1 is undirected.

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weighted vs. unweighted graphs

adjacent vertices  
incident edges  
degree  
neighbor

loop  
parallel edge  
simple graph  
complete graph  
connected graph  
subgraph

cycle  
tree  
spanning tree



graph learning tool on Companion Website

Edges may be weighted or unweighted. For example, you can assign a weight for each edge in the graph in Figure 28.1 to indicate the flight time between the two cities.

Two vertices in a graph are said to be *adjacent* if they are connected by the same edge. Similarly, two edges are said to be *adjacent* if they are connected to the same vertex. An edge in a graph that joins two vertices is said to be *incident* to both vertices. The *degree* of a vertex is the number of edges incident to it.

Two vertices are called *neighbors* if they are adjacent. Similarly, two edges are called *neighbors* if they are adjacent.

A *loop* is an edge that links a vertex to itself. If two vertices are connected by two or more edges, these edges are called *parallel edges*. A *simple graph* is one that has doesn't have any loops or parallel edges. In a *complete graph*, every two pairs of vertices are connected, as shown in Figure 28.3b.

A graph is *connected* if there exists a path between any two vertices in the graph. A *subgraph* of a graph  $G$  is a graph whose vertex set is a subset of that of  $G$  and whose edge set is a subset of that of  $G$ . For example, the graph in Figure 28.3c is a subgraph of the graph in Figure 28.3b.

Assume that the graph is connected and undirected. A *cycle* is a closed path that starts from a vertex and ends at the same vertex. A connected graph is a *tree* if it does not have cycles. A *spanning tree* of a graph  $G$  is a connected subgraph of  $G$  and the subgraph is a tree that contains all vertices in  $G$ .

### Pedagogical Note

Before we introduce graph algorithms and applications, it is helpful to get acquainted with graphs using the interactive tool at [www.cs.armstrong.edu/liang/animation/GraphLearningTool.html](http://www.cs.armstrong.edu/liang/animation/GraphLearningTool.html), as shown in Figure 28.4. The tool allows you to add/remove/move vertices and draw edges using mouse gestures. You can also find depth-first search (DFS) trees and breadth-first search (BFS) trees, and a shortest path between two vertices.

The screenshot shows a Mozilla Firefox browser window with the title "Graph Learning Tool by Y. Daniel Liang". The address bar shows the URL <http://www.cs.armstrong.edu/liang/animation/GraphLearningTool.html>. The main content area is titled "Graph Learning Tool by Y. Daniel Liang". On the left, there is a "INSTRUCTIONS" box with the following mappings:  
Add: Left Click  
Move: Ctrl Drag  
Connect: Drag  
Remove: Right Click

The central part of the screen displays a graph with 10 nodes labeled 0 through 9. Node 0 is at the top left, node 1 is below it, node 2 is in the center, node 3 is above 0, node 4 is above 2, node 5 is to the right of 4, node 6 is below 5, node 7 is below 2, node 8 is to the right of 7, and node 9 is below 4. There are several edges: (0,1), (1,2), (2,3), (2,4), (2,5), (2,6), (2,7), (3,4), (4,5), (5,6), (6,8), (7,8), and (9,4). Some edges are solid black, while others are blue, indicating different types or selected edges.

At the bottom of the screen, there are two sets of buttons. The left set is for "Display DFS/BFS" and includes a "Starting vertex:" input field containing "0", a "DFS Tree" button, and a "BFS Tree" button. The right set is for "Find a shortest path" and includes a "Starting vertex:" input field containing "0", an "Ending vertex:" input field containing "6", and a "Shortest Path" button.

FIGURE 28.4 You can use the tool to create a graph with mouse gestures and show DFS/BFS trees and shortest paths.

- 28.1** What is the famous *Seven Bridges of Königsberg* problem?
- 28.2** What is a graph? Explain the following terms: undirected graph, directed graph, weighted graph, degree of a vertex, parallel edge, simple graph, complete graph, connected graph, cycle, subgraph, tree, and spanning tree.
- 28.3** How many edges are in a complete graph with 5 vertices? How many edges are in a tree of 5 vertices?
- 28.4** How many edges are in a complete graph with  $n$  vertices? How many edges are in a tree of  $n$  vertices?



## 28.3 Representing Graphs

*Representing a graph is to store its vertices and edges in a program. The data structure for storing a graph is arrays or lists.*

To write a program that processes and manipulates graphs, you have to store or represent data for the graphs in the computer.

### 28.3.1 Representing Vertices

The vertices can be stored in an array or a list. For example, you can store all the city names in the graph in Figure 28.1 using the following array:

```
String[] vertices = {"Seattle", "San Francisco", "Los Angeles",
 "Denver", "Kansas City", "Chicago", "Boston", "New York",
 "Atlanta", "Miami", "Dallas", "Houston"};
```



#### Note

The vertices can be objects of any type. For example, you can consider cities as objects that contain the information such as its name, population, and mayor. Thus, you may define vertices as follows:

vertex type

```
City city0 = new City("Seattle", 608660, "Mike McGinn");
...
City city11 = new City("Houston", 2099451, "Annise Parker");
City[] vertices = {city0, city1, ... , city11};

public class City {
 private String cityName;
 private int population;
 private String mayor;

 public City(String cityName, int population, String mayor) {
 this.cityName = cityName;
 this.population = population;
 this.mayor = mayor;
 }

 public String getCityName() {
 return cityName;
 }

 public int getPopulation() {
 return population;
 }
}
```

```

public String getMayor() {
 return mayor;
}

public void setMayor(String mayor) {
 this.mayor = mayor;
}

public void setPopulation(int population) {
 this.population = population;
}

```

The vertices can be conveniently labeled using natural numbers  $0, 1, 2, \dots, n - 1$ , for a graph for  $n$  vertices. Thus, `vertices[0]` represents "Seattle", `vertices[1]` represents "San Francisco", and so on, as shown in Figure 28.5.

|              |               |
|--------------|---------------|
| vertices[0]  | Seattle       |
| vertices[1]  | San Francisco |
| vertices[2]  | Los Angeles   |
| vertices[3]  | Denver        |
| vertices[4]  | Kansas City   |
| vertices[5]  | Chicago       |
| vertices[6]  | Boston        |
| vertices[7]  | New York      |
| vertices[8]  | Atlanta       |
| vertices[9]  | Miami         |
| vertices[10] | Dallas        |
| vertices[11] | Houston       |

FIGURE 28.5 An array stores the vertex names.

reference vertex



### Note

You can reference a vertex by its name or its index, whichever is more convenient. Obviously, it is easy to access a vertex via its index in a program.

#### 28.3.2 Representing Edges: Edge Array

The edges can be represented using a two-dimensional array. For example, you can store all the edges in the graph in Figure 28.1 using the following array:

```

int[][] edges = {
 {0, 1}, {0, 3}, {0, 5},
 {1, 0}, {1, 2}, {1, 3},
 {2, 1}, {2, 3}, {2, 4}, {2, 10},
 {3, 0}, {3, 1}, {3, 2}, {3, 4}, {3, 5},
 {4, 2}, {4, 3}, {4, 5}, {4, 7}, {4, 8}, {4, 10},
 {5, 0}, {5, 3}, {5, 4}, {5, 6}, {5, 7},
}

```

```

{6, 5}, {6, 7},
{7, 4}, {7, 5}, {7, 6}, {7, 8},
{8, 4}, {8, 7}, {8, 9}, {8, 10}, {8, 11},
{9, 8}, {9, 11},
{10, 2}, {10, 4}, {10, 8}, {10, 11},
{11, 8}, {11, 9}, {11, 10}
};

```

This representation is known as the *edge array*. The vertices and edges in Figure 28.3a can be represented as follows:

```

String[] names = {"Peter", "Jane", "Mark", "Cindy", "Wendy"};
int[][] edges = {{0, 2}, {1, 2}, {2, 4}, {3, 4}};

```

### 28.3.3 Representing Edges: Edge Objects

Another way to represent the edges is to define edges as objects and store the edges in a `java.util.ArrayList`. The `Edge` class can be defined as follows:

```

public class Edge {
 int u;
 int v;

 public Edge(int u, int v) {
 this.u = u;
 this.v = v;
 }

 public boolean equals(Object o) {
 return u == ((Edge)o).u && v == ((Edge)o).v;
 }
}

```

For example, you can store all the edges in the graph in Figure 28.1 using the following list:

```

java.util.ArrayList<Edge> list = new java.util.ArrayList<>();
list.add(new Edge(0, 1));
list.add(new Edge(0, 3));
list.add(new Edge(0, 5));
...

```

Storing `Edge` objects in an `ArrayList` is useful if you don't know the edges in advance.

While representing edges using an edge array or `Edge` objects in Section 28.3.2 and earlier in this section may be intuitive for input, it's not efficient for internal processing. The next two sections introduce the representation of graphs using *adjacency matrices* and *adjacency lists*. These two data structures are efficient for processing graphs.

### 28.3.4 Representing Edges: Adjacency Matrices

Assume that the graph has  $n$  vertices. You can use a two-dimensional  $n \times n$  matrix, say `adjacencyMatrix`, to represent the edges. Each element in the array is `0` or `1`. `adjacencyMatrix[i][j]` is `1` if there is an edge from vertex  $i$  to vertex  $j$ ; otherwise, `adjacencyMatrix[i][j]` is `0`. If the graph is undirected, the matrix is symmetric, because `adjacencyMatrix[i][j]` is the same as `adjacencyMatrix[j][i]`. For example, the edges in the graph in Figure 28.1 can be represented using an *adjacency matrix* as follows:

adjacency matrix

```

int[][] adjacencyMatrix = {
 {0, 1, 0, 1, 0, 1, 0, 0, 0, 0, 0}, // Seattle
 {1, 0, 1, 1, 0, 0, 0, 0, 0, 0, 0}, // San Francisco
}

```

```

{0, 1, 0, 1, 1, 1, 0, 0, 0, 0, 0}, // Los Angeles
{1, 1, 1, 0, 1, 1, 0, 0, 0, 0, 0}, // Denver
{0, 0, 1, 1, 0, 1, 0, 1, 1, 0, 0}, // Kansas City
{1, 0, 0, 1, 1, 0, 1, 1, 0, 0, 0}, // Chicago
{0, 0, 0, 0, 1, 0, 1, 0, 0, 0, 0}, // Boston
{0, 0, 0, 1, 1, 1, 0, 1, 0, 0, 0}, // New York
{0, 0, 0, 1, 1, 0, 0, 1, 0, 1, 1}, // Atlanta
{0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0}, // Miami
{0, 0, 1, 0, 1, 0, 0, 0, 1, 0, 0}, // Dallas
{0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 0} // Houston
};


```

**Note**

Since the matrix is symmetric for an undirected graph, to save storage you can use a ragged array.

ragged array

The adjacency matrix for the directed graph in Figure 28.3a can be represented as follows:

```

int[][] a = {{0, 0, 1, 0, 0}, // Peter
 {0, 0, 1, 0, 0}, // Jane
 {0, 0, 0, 1}, // Mark
 {0, 0, 0, 1}, // Cindy
 {0, 0, 0, 0}} // Wendy
};


```

### 28.3.5 Representing Edges: Adjacency Lists

adjacency vertex lists  
adjacency edge lists

You can represent edges using *adjacency vertex lists* or *adjacency edge lists*. An adjacency vertex list for a vertex  $i$  contains the vertices that are adjacent to  $i$  and an adjacency edge list for a vertex  $i$  contains the edges that are adjacent to  $i$ . You may define an array of lists. The array has  $n$  entries, and each entry is a list. The adjacency vertex list for vertex  $i$  contains all the vertices  $j$  such that there is an edge from vertex  $i$  to vertex  $j$ . For example, to represent the edges in the graph in Figure 28.1, you can create an array of lists as follows:

```
java.util.List<Integer>[] neighbors = new java.util.List[12];
```

**neighbors[0]** contains all vertices adjacent to vertex **0** (i.e., Seattle), **neighbors[1]** contains all vertices adjacent to vertex **1** (i.e., San Francisco), and so on, as shown in Figure 28.6.

To represent the adjacency edge lists for the graph in Figure 28.1, you can create an array of lists as follows:

```
java.util.List<Edge>[] neighbors = new java.util.List[12];
```

**neighbors[0]** contains all edges adjacent to vertex **0** (i.e., Seattle), **neighbors[1]** contains all edges adjacent to vertex **1** (i.e., San Francisco), and so on, as shown in Figure 28.7.

adjacency matrices vs.  
adjacency lists

**Note**

You can represent a graph using an adjacency matrix or adjacency lists. Which one is better? If the graph is dense (i.e., there are a lot of edges), using an adjacency matrix is preferred. If the graph is very sparse (i.e., very few edges), using adjacency lists is better, because using an adjacency matrix would waste a lot of space.

Both adjacency matrices and adjacency lists can be used in a program to make algorithms more efficient. For example, it takes  $O(1)$  constant time to check whether two vertices are connected using an adjacency matrix, and it takes linear time  $O(m)$  to print all edges in a graph using adjacency lists, where  $m$  is the number of edges.

|               |               |   |    |    |    |    |    |  |  |  |  |  |
|---------------|---------------|---|----|----|----|----|----|--|--|--|--|--|
| Seattle       | neighbors[0]  | 1 | 3  | 5  |    |    |    |  |  |  |  |  |
| San Francisco | neighbors[1]  | 0 | 2  | 3  |    |    |    |  |  |  |  |  |
| Los Angeles   | neighbors[2]  | 1 | 3  | 4  | 10 |    |    |  |  |  |  |  |
| Denver        | neighbors[3]  | 0 | 1  | 2  | 4  | 5  |    |  |  |  |  |  |
| Kansas City   | neighbors[4]  | 2 | 3  | 5  | 7  | 8  | 10 |  |  |  |  |  |
| Chicago       | neighbors[5]  | 0 | 3  | 4  | 6  | 7  |    |  |  |  |  |  |
| Boston        | neighbors[6]  | 5 | 7  |    |    |    |    |  |  |  |  |  |
| New York      | neighbors[7]  | 4 | 5  | 6  | 8  |    |    |  |  |  |  |  |
| Atlanta       | neighbors[8]  | 4 | 7  | 9  | 10 | 11 |    |  |  |  |  |  |
| Miami         | neighbors[9]  | 8 | 11 |    |    |    |    |  |  |  |  |  |
| Dallas        | neighbors[10] | 2 | 4  | 8  | 11 |    |    |  |  |  |  |  |
| Houston       | neighbors[11] | 8 | 9  | 10 |    |    |    |  |  |  |  |  |

**FIGURE 28.6** Edges in the graph in Figure 28.1 are represented using adjacency vertex lists.

|               |               |             |             |              |              |             |             |  |  |  |  |  |
|---------------|---------------|-------------|-------------|--------------|--------------|-------------|-------------|--|--|--|--|--|
| Seattle       | neighbors[0]  | Edge(0, 1)  | Edge(0, 3)  | Edge(0, 5)   |              |             |             |  |  |  |  |  |
| San Francisco | neighbors[1]  | Edge(1, 0)  | Edge(1, 2)  | Edge(1, 3)   |              |             |             |  |  |  |  |  |
| Los Angeles   | neighbors[2]  | Edge(2, 1)  | Edge(2, 3)  | Edge(2, 4)   | Edge(2, 10)  |             |             |  |  |  |  |  |
| Denver        | neighbors[3]  | Edge(3, 0)  | Edge(3, 1)  | Edge(3, 2)   | Edge(3, 4)   | Edge(3, 5)  |             |  |  |  |  |  |
| Kansas City   | neighbors[4]  | Edge(4, 2)  | Edge(4, 3)  | Edge(4, 5)   | Edge(4, 7)   | Edge(4, 8)  | Edge(4, 10) |  |  |  |  |  |
| Chicago       | neighbors[5]  | Edge(5, 0)  | Edge(5, 3)  | Edge(5, 4)   | Edge(5, 6)   | Edge(5, 7)  |             |  |  |  |  |  |
| Boston        | neighbors[6]  | Edge(6, 5)  | Edge(6, 7)  |              |              |             |             |  |  |  |  |  |
| New York      | neighbors[7]  | Edge(7, 4)  | Edge(7, 5)  | Edge(7, 6)   | Edge(7, 8)   |             |             |  |  |  |  |  |
| Atlanta       | neighbors[8]  | Edge(8, 4)  | Edge(8, 7)  | Edge(8, 9)   | Edge(8, 10)  | Edge(8, 11) |             |  |  |  |  |  |
| Miami         | neighbors[9]  | Edge(9, 8)  | Edge(9, 11) |              |              |             |             |  |  |  |  |  |
| Dallas        | neighbors[10] | Edge(10, 2) | Edge(10, 4) | Edge(10, 8)  | Edge(10, 11) |             |             |  |  |  |  |  |
| Houston       | neighbors[11] | Edge(11, 8) | Edge(11, 9) | Edge(11, 10) |              |             |             |  |  |  |  |  |

**FIGURE 28.7** Edges in the graph in Figure 28.1 are represented using adjacency edge lists.**Note**

Adjacency vertex list is simpler for representing unweighted graphs. However, adjacency edge lists are more flexible for a wide range of graph applications. It is easy to add additional constraints on edges using adjacency edge lists. For this reason, this book will use adjacency edge lists to represent graphs.

adjacency vertex list vs.  
adjacency edge lists

You can use arrays, array lists, or linked lists to store adjacency lists. We will use lists instead of arrays, because the lists are easily expandable to enable you to add new vertices. Further we will use array lists instead of linked lists, because our algorithms only require searching for adjacent vertices in the list. Using array lists is more efficient for our algorithms. Using array lists, the adjacency edge list in Figure 28.6 can be built as follows:

using ArrayList

```
List<ArrayList<Edge>> neighbors = new ArrayList<>();
neighbors.add(new ArrayList<Edge>());
neighbors.get(0).add(new Edge(0, 1));
```

```

neighbors.get(0).add(new Edge(0, 3));
neighbors.get(0).add(new Edge(0, 5));
neighbors.add(new ArrayList<Edge>());
neighbors.get(1).add(new Edge(1, 0));
neighbors.get(1).add(new Edge(1, 2));
neighbors.get(1).add(new Edge(1, 3));
...
...
neighbors.get(11).add(new Edge(11, 8));
neighbors.get(11).add(new Edge(11, 9));
neighbors.get(11).add(new Edge(11, 10));

```



- 28.5** How do you represent vertices in a graph? How do you represent edges using an edge array? How do you represent an edge using an edge object? How do you represent edges using an adjacency matrix? How do you represent edges using adjacency lists?
- 28.6** Represent the following graph using an edge array, a list of edge objects, an adjacency matrix, an adjacency vertex list, and an adjacency edge list, respectively.



## 28.4 Modeling Graphs



*The Graph interface defines the common operations for a graph.*

The Java Collections Framework serves as a good example for designing complex data structures. The common features of data structures are defined in the interfaces (e.g., **Collection**, **Set**, **List**, **Queue**), as shown in Figure 20.1. Abstract classes (e.g., **AbstractCollection**, **AbstractSet**, **AbstractList**) partially implement the interfaces. Concrete classes (e.g., **HashSet**, **LinkedHashSet**, **TreeSet**, **ArrayList**, **LinkedList**, **PriorityQueue**) provide concrete implementations. This design pattern is useful for modeling graphs. We will define an interface named **Graph** that contains all the common operations of graphs and an abstract class named **AbstractGraph** that partially implements the **Graph** interface. Many concrete graphs can be added to the design. For example, we will define such graphs named **UnweightedGraph** and **WeightedGraph**. The relationships of these interfaces and classes are illustrated in Figure 28.8.



**FIGURE 28.8** Graphs can be modeled using interfaces, abstract classes, and concrete classes.

What are the common operations for a graph? In general, you need to get the number of vertices in a graph, get all vertices in a graph, get the vertex object with a specified index, get the index of the vertex with a specified name, get the neighbors for a vertex, get the degree for a vertex, clear the graph, add a new vertex, add a new edge, perform a depth-first search, and

perform a breadth-first search. Depth-first search and breadth-first search will be introduced in the next section. Figure 28.9 illustrates these methods in the UML diagram.

**AbstractGraph** does not introduce any new methods. A list of vertices and an edge adjacency list are defined in the **AbstractGraph** class. With these data fields, it is sufficient to



FIGURE 28.9 The **Graph** interface defines the common operations for all types of graphs.

implement all the methods defined in the **Graph** interface. For convenience, we assume the graph is a simple graph, i.e., a vertex has no edge to itself and there are no parallel edges from vertex  $u$  to  $v$ .

**AbstractGraph** implements all the methods from **Graph**, and it does not introduce any new methods except a convenient **addEdge(edge)** method that adds an **Edge** object to the adjacency edge list. **UnweightedGraph** simply extends **AbstractGraph** with five constructors for creating the concrete **Graph** instances.

vertices and their indices



### Note

You can create a graph with any type of vertices. Each vertex is associated with an index, which is the same as the index of the vertex in the vertices list. If you create a graph without specifying the vertices, the vertices are the same as their indices.

why AbstractGraph?



### Note

The **AbstractGraph** class implements all the methods in the **Graph** interface. So why is it defined as abstract? In the future, you may need to add new methods to the **Graph** interface that cannot be implemented in **AbstractGraph**. To make the classes easy to maintain, it is desirable to define the **AbstractGraph** class as abstract.

Assume all these interfaces and classes are available. Listing 28.1 gives a test program that creates the graph in Figure 28.1 and another graph for the one in Figure 28.3a.

### LISTING 28.1 TestGraph.java

```

1 public class TestGraph {
2 public static void main(String[] args) {
3 String[] vertices = {"Seattle", "San Francisco", "Los Angeles",
4 "Denver", "Kansas City", "Chicago", "Boston", "New York",
5 "Atlanta", "Miami", "Dallas", "Houston"};
6
7 // Edge array for graph in Figure 28.1
8 int[][] edges = {
9 {0, 1}, {0, 3}, {0, 5},
10 {1, 0}, {1, 2}, {1, 3},
11 {2, 1}, {2, 3}, {2, 4}, {2, 10},
12 {3, 0}, {3, 1}, {3, 2}, {3, 4}, {3, 5},
13 {4, 2}, {4, 3}, {4, 5}, {4, 7}, {4, 8}, {4, 10},
14 {5, 0}, {5, 3}, {5, 4}, {5, 6}, {5, 7},
15 {6, 5}, {6, 7},
16 {7, 4}, {7, 5}, {7, 6}, {7, 8},
17 {8, 4}, {8, 7}, {8, 9}, {8, 10}, {8, 11},
18 {9, 8}, {9, 11},
19 {10, 2}, {10, 4}, {10, 8}, {10, 11},
20 {11, 8}, {11, 9}, {11, 10}
21 };
22
23 Graph<String> graph1 = new UnweightedGraph<>(vertices, edges);
24 System.out.println("The number of vertices in graph1: " +
25 + graph1.getSize());
26 System.out.println("The vertex with index 1 is " +
27 + graph1.getVertex(1));
28 System.out.println("The index for Miami is " +
29 graph1.getIndex("Miami"));
30 System.out.println("The edges for graph1:");
31 graph1.printEdges();
32
33 // List of Edge objects for graph in Figure 28.3a
34 String[] names = {"Peter", "Jane", "Mark", "Cindy", "Wendy"};

```

```

35 java.util.ArrayList<AbstractGraph.Edge> edgeList
36 = new java.util.ArrayList<>();
37 edgeList.add(new AbstractGraph.Edge(0, 2)); list of Edge objects
38 edgeList.add(new AbstractGraph.Edge(1, 2));
39 edgeList.add(new AbstractGraph.Edge(2, 4));
40 edgeList.add(new AbstractGraph.Edge(3, 4));
41 // Create a graph with 5 vertices
42 Graph<String> graph2 = new UnweightedGraph<>
43 (java.util.Arrays.asList(names), edgeList); create a graph
44 System.out.println("\nThe number of vertices in graph2: "
45 + graph2.getSize());
46 System.out.println("The edges for graph2:");
47 graph2.printEdges(); print edges
48 }
49 }
```

```

The number of vertices in graph1: 12
The vertex with index 1 is San Francisco
The index for Miami is 9
The edges for graph1:
Seattle (0): (0, 1) (0, 3) (0, 5)
San Francisco (1): (1, 0) (1, 2) (1, 3)
Los Angeles (2): (2, 1) (2, 3) (2, 4) (2, 10)
Denver (3): (3, 0) (3, 1) (3, 2) (3, 4) (3, 5)
Kansas City (4): (4, 2) (4, 3) (4, 5) (4, 7) (4, 8) (4, 10)
Chicago (5): (5, 0) (5, 3) (5, 4) (5, 6) (5, 7)
Boston (6): (6, 5) (6, 7)
New York (7): (7, 4) (7, 5) (7, 6) (7, 8)
Atlanta (8): (8, 4) (8, 7) (8, 9) (8, 10) (8, 11)
Miami (9): (9, 8) (9, 11)
Dallas (10): (10, 2) (10, 4) (10, 8) (10, 11)
Houston (11): (11, 8) (11, 9) (11, 10)
```

```
The number of vertices in graph2: 5
```

```
The edges for graph2:
Peter (0): (0, 2)
Jane (1): (1, 2)
Mark (2): (2, 4)
Cindy (3): (3, 4)
Wendy (4):
```



The program creates **graph1** for the graph in Figure 28.1 in lines 3–23. The vertices for **graph1** are defined in lines 3–5. The edges for **graph1** are defined in 8–21. The edges are represented using a two-dimensional array. For each row **i** in the array, **edges[i][0]** and **edges[i][1]** indicate that there is an edge from vertex **edges[i][0]** to vertex **edges[i][1]**. For example, the first row, **{0, 1}**, represents the edge from vertex **0** (**edges[0][0]**) to vertex **1** (**edges[0][1]**). The row **{0, 5}** represents the edge from vertex **0** (**edges[2][0]**) to vertex **5** (**edges[2][1]**). The graph is created in line 23. Line 31 invokes the **printEdges()** method on **graph1** to display all edges in **graph1**.

The program creates **graph2** for the graph in Figure 28.3a in lines 34–43. The edges for **graph2** are defined in lines 37–40. **graph2** is created using a list of **Edge** objects in line 43. Line 47 invokes the **printEdges()** method on **graph2** to display all edges in **graph2**.

Note that both **graph1** and **graph2** contain the vertices of strings. The vertices are associated with indices **0, 1, ..., n-1**. The index is the location of the vertex in **vertices**. For example, the index of vertex **Miami** is **9**.

Now we turn our attention to implementing the interface and classes. Listings 28.2, 28.3, and 28.4 give the `Graph` interface, the `AbstractGraph` class, and the `UnweightedGraph` class, respectively.

### LISTING 28.2 Graph.java

```

1 public interface Graph<V> {
2 /** Return the number of vertices in the graph */
3 public int getSize();
4
5 /** Return the vertices in the graph */
6 public java.util.List<V> getVertices();
7
8 /** Return the object for the specified vertex index */
9 public V getVertex(int index);
10
11 /** Return the index for the specified vertex object */
12 public int getIndex(V v);
13
14 /** Return the neighbors of vertex with the specified index */
15 public java.util.List<Integer> getNeighbors(int index);
16
17 /** Return the degree for a specified vertex */
18 public int getDegree(int v);
19
20 /** Print the edges */
21 public void printEdges();
22
23 /** Clear the graph */
24 public void clear();
25
26 /** Add a vertex to the graph */
27 public void addVertex(V vertex);
28
29 /** Add an edge to the graph */
30 public void addEdge(int u, int v);
31
32 /** Obtain a depth-first search tree starting from v */
33 public AbstractGraph<V>.Tree dfs(int v);
34
35 /** Obtain a breadth-first search tree starting from v */
36 public AbstractGraph<V>.Tree bfs(int v);
37 }
```

### LISTING 28.3 AbstractGraph.java

```

1 import java.util.*;
2
3 public abstract class AbstractGraph<V> implements Graph<V> {
4 protected List<V> vertices = new ArrayList<>(); // Store vertices
5 protected List<List<Edge>> neighbors
6 = new ArrayList<>(); // Adjacency lists
7
8 /** Construct an empty graph */
9 protected AbstractGraph() {
10 }
11
12 /** Construct a graph from vertices and edges stored in arrays */
13 protected AbstractGraph(V[] vertices, int[][] edges) {
```

```

14 for (int i = 0; i < vertices.length; i++)
15 addVertex(vertices[i]);
16
17 createAdjacencyLists(edges, vertices.length);
18 }
19
20 /** Construct a graph from vertices and edges stored in List */
21 protected AbstractGraph(List<V> vertices, List<Edge> edges) { constructor
22 for (int i = 0; i < vertices.size(); i++)
23 addVertex(vertices.get(i));
24
25 createAdjacencyLists(edges, vertices.size());
26 }
27
28 /** Construct a graph for integer vertices 0, 1, 2 and edge list */
29 protected AbstractGraph(List<Edge> edges, int numberOfVertices) { constructor
30 for (int i = 0; i < numberOfVertices; i++)
31 addVertex((V)(new Integer(i))); // vertices is {0, 1, ...}
32
33 createAdjacencyLists(edges, numberOfVertices);
34 }
35
36 /** Construct a graph from integer vertices 0, 1, and edge array */
37 protected AbstractGraph(int[][] edges, int numberOfVertices) { constructor
38 for (int i = 0; i < numberOfVertices; i++)
39 addVertex((V)(new Integer(i))); // vertices is {0, 1, ...}
40
41 createAdjacencyLists(edges, numberOfVertices);
42 }
43
44 /** Create adjacency lists for each vertex */
45 private void createAdjacencyLists(
46 int[][] edges, int numberOfVertices) {
47 for (int i = 0; i < edges.length; i++) {
48 addEdge(edges[i][0], edges[i][1]);
49 }
50 }
51
52 /** Create adjacency lists for each vertex */
53 private void createAdjacencyLists(
54 List<Edge> edges, int numberOfVertices) {
55 for (Edge edge: edges) {
56 addEdge(edge.u, edge.v);
57 }
58 }
59
60 @Override /** Return the number of vertices in the graph */
61 public int getSize() { getSize
62 return vertices.size();
63 }
64
65 @Override /** Return the vertices in the graph */
66 public List<V> getVertices() { getVertices
67 return vertices;
68 }
69
70 @Override /** Return the object for the specified vertex */
71 public V getVertex(int index) { getVertex
72 return vertices.get(index);
73 }

```

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```
74
75 @Override /** Return the index for the specified vertex object */
76 public int getIndex(V v) {
77 return vertices.indexOf(v);
78 }
79
80 @Override /** Return the neighbors of the specified vertex */
81 public List<Integer> getNeighbors(int index) {
82 List<Integer> result = new ArrayList<>();
83 for (Edge e: neighbors.get(index))
84 result.add(e.v);
85
86 return result;
87 }
88
89 @Override /** Return the degree for a specified vertex */
90 public int getDegree(int v) {
91 return neighbors.get(v).size();
92 }
93
94 @Override /** Print the edges */
95 public void printEdges() {
96 for (int u = 0; u < neighbors.size(); u++) {
97 System.out.print(getVertex(u) + " (" + u + "): ");
98 for (Edge e: neighbors.get(u)) {
99 System.out.print("(" + getVertex(e.u) + ", " +
100 getVertex(e.v) + ")");
101 }
102 System.out.println();
103 }
104 }
105
106 @Override /** Clear the graph */
107 public void clear() {
108 vertices.clear();
109 neighbors.clear();
110 }
111
112 @Override /** Add a vertex to the graph */
113 public boolean addVertex(V vertex) {
114 if (!vertices.contains(vertex)) {
115 vertices.add(vertex);
116 neighbors.add(new ArrayList<Edge>());
117 return true;
118 }
119 else {
120 return false;
121 }
122 }
123
124 /** Add an edge to the graph */
125 protected boolean addEdge(Edge e) {
126 if (e.u < 0 || e.u > getSize() - 1)
127 throw new IllegalArgumentException("No such index: " + e.u);
128
129 if (e.v < 0 || e.v > getSize() - 1)
130 throw new IllegalArgumentException("No such index: " + e.v);
131
132 if (!neighbors.get(e.u).contains(e)) {
133 neighbors.get(e.u).add(e);
134 }
135 }
136
137 /**
138 * Returns the number of edges connected to a vertex.
139 * @param v the vertex
140 * @return the degree of vertex v
141 */
142 public int getDegree(V v) {
143 return neighbors.get(v).size();
144 }
145
146 /**
147 * Prints all edges in the graph.
148 */
149 public void printEdges() {
150 for (int u = 0; u < neighbors.size(); u++) {
151 System.out.print(getVertex(u) + " (" + u + "): ");
152 for (Edge e: neighbors.get(u)) {
153 System.out.print("(" + getVertex(e.u) + ", " +
154 getVertex(e.v) + ")");
155 }
156 System.out.println();
157 }
158 }
159
160 /**
161 * Returns the number of vertices in the graph.
162 */
163 public int getSize() {
164 return vertices.size();
165 }
166
167 /**
168 * Returns the vertex at index i.
169 */
170 public V getVertex(int index) {
171 return vertices.get(index);
172 }
173
174 /**
175 * Returns the index of vertex v.
176 */
177 public int getIndex(V v) {
178 return vertices.indexOf(v);
179 }
180
181 /**
182 * Adds a vertex to the graph.
183 */
184 public void addVertex(V vertex) {
185 vertices.add(vertex);
186 neighbors.add(new ArrayList<Edge>());
187 }
188
189 /**
190 * Adds an edge to the graph.
191 */
192 protected void addEdge(Edge e) {
193 if (e.u < 0 || e.u > getSize() - 1)
194 throw new IllegalArgumentException("No such index: " + e.u);
195
196 if (e.v < 0 || e.v > getSize() - 1)
197 throw new IllegalArgumentException("No such index: " + e.v);
198
199 if (!neighbors.get(e.u).contains(e)) {
200 neighbors.get(e.u).add(e);
201 }
202 }
203
204 /**
205 * Returns the degree of vertex v.
206 */
207 public int getDegree(V v) {
208 return neighbors.get(v).size();
209 }
210
211 /**
212 * Prints all edges in the graph.
213 */
214 public void printEdges() {
215 for (int u = 0; u < neighbors.size(); u++) {
216 System.out.print(getVertex(u) + " (" + u + "): ");
217 for (Edge e: neighbors.get(u)) {
218 System.out.print("(" + getVertex(e.u) + ", " +
219 getVertex(e.v) + ")");
220 }
221 System.out.println();
222 }
223 }
224
225 /**
226 * Returns the number of vertices in the graph.
227 */
228 public int getSize() {
229 return vertices.size();
230 }
231
232 /**
233 * Returns the vertex at index i.
234 */
235 public V getVertex(int index) {
236 return vertices.get(index);
237 }
238
239 /**
240 * Returns the index of vertex v.
241 */
242 public int getIndex(V v) {
243 return vertices.indexOf(v);
244 }
245
246 /**
247 * Adds a vertex to the graph.
248 */
249 public void addVertex(V vertex) {
250 vertices.add(vertex);
251 neighbors.add(new ArrayList<Edge>());
252 }
253
254 /**
255 * Adds an edge to the graph.
256 */
257 protected void addEdge(Edge e) {
258 if (e.u < 0 || e.u > getSize() - 1)
259 throw new IllegalArgumentException("No such index: " + e.u);
260
261 if (e.v < 0 || e.v > getSize() - 1)
262 throw new IllegalArgumentException("No such index: " + e.v);
263
264 if (!neighbors.get(e.u).contains(e)) {
265 neighbors.get(e.u).add(e);
266 }
267 }
268
269 /**
270 * Returns the degree of vertex v.
271 */
272 public int getDegree(V v) {
273 return neighbors.get(v).size();
274 }
275
276 /**
277 * Prints all edges in the graph.
278 */
279 public void printEdges() {
280 for (int u = 0; u < neighbors.size(); u++) {
281 System.out.print(getVertex(u) + " (" + u + "): ");
282 for (Edge e: neighbors.get(u)) {
283 System.out.print("(" + getVertex(e.u) + ", " +
284 getVertex(e.v) + ")");
285 }
286 System.out.println();
287 }
288 }
289
290 /**
291 * Returns the number of vertices in the graph.
292 */
293 public int getSize() {
294 return vertices.size();
295 }
296
297 /**
298 * Returns the vertex at index i.
299 */
300 public V getVertex(int index) {
301 return vertices.get(index);
302 }
303
304 /**
305 * Returns the index of vertex v.
306 */
307 public int getIndex(V v) {
308 return vertices.indexOf(v);
309 }
310
311 /**
312 * Adds a vertex to the graph.
313 */
314 public void addVertex(V vertex) {
315 vertices.add(vertex);
316 neighbors.add(new ArrayList<Edge>());
317 }
318
319 /**
320 * Adds an edge to the graph.
321 */
322 protected void addEdge(Edge e) {
323 if (e.u < 0 || e.u > getSize() - 1)
324 throw new IllegalArgumentException("No such index: " + e.u);
325
326 if (e.v < 0 || e.v > getSize() - 1)
327 throw new IllegalArgumentException("No such index: " + e.v);
328
329 if (!neighbors.get(e.u).contains(e)) {
330 neighbors.get(e.u).add(e);
331 }
332 }
333
334 /**
335 * Returns the degree of vertex v.
336 */
337 public int getDegree(V v) {
338 return neighbors.get(v).size();
339 }
340
341 /**
342 * Prints all edges in the graph.
343 */
344 public void printEdges() {
345 for (int u = 0; u < neighbors.size(); u++) {
346 System.out.print(getVertex(u) + " (" + u + "): ");
347 for (Edge e: neighbors.get(u)) {
348 System.out.print("(" + getVertex(e.u) + ", " +
349 getVertex(e.v) + ")");
350 }
351 System.out.println();
352 }
353 }
354
355 /**
356 * Returns the number of vertices in the graph.
357 */
358 public int getSize() {
359 return vertices.size();
360 }
361
362 /**
363 * Returns the vertex at index i.
364 */
365 public V getVertex(int index) {
366 return vertices.get(index);
367 }
368
369 /**
370 * Returns the index of vertex v.
371 */
372 public int getIndex(V v) {
373 return vertices.indexOf(v);
374 }
375
376 /**
377 * Adds a vertex to the graph.
378 */
379 public void addVertex(V vertex) {
380 vertices.add(vertex);
381 neighbors.add(new ArrayList<Edge>());
382 }
383
384 /**
385 * Adds an edge to the graph.
386 */
387 protected void addEdge(Edge e) {
388 if (e.u < 0 || e.u > getSize() - 1)
389 throw new IllegalArgumentException("No such index: " + e.u);
390
391 if (e.v < 0 || e.v > getSize() - 1)
392 throw new IllegalArgumentException("No such index: " + e.v);
393
394 if (!neighbors.get(e.u).contains(e)) {
395 neighbors.get(e.u).add(e);
396 }
397 }
398
399 /**
400 * Returns the degree of vertex v.
401 */
402 public int getDegree(V v) {
403 return neighbors.get(v).size();
404 }
405
406 /**
407 * Prints all edges in the graph.
408 */
409 public void printEdges() {
410 for (int u = 0; u < neighbors.size(); u++) {
411 System.out.print(getVertex(u) + " (" + u + "): ");
412 for (Edge e: neighbors.get(u)) {
413 System.out.print("(" + getVertex(e.u) + ", " +
414 getVertex(e.v) + ")");
415 }
416 System.out.println();
417 }
418 }
419
420 /**
421 * Returns the number of vertices in the graph.
422 */
423 public int getSize() {
424 return vertices.size();
425 }
426
427 /**
428 * Returns the vertex at index i.
429 */
430 public V getVertex(int index) {
431 return vertices.get(index);
432 }
433
434 /**
435 * Returns the index of vertex v.
436 */
437 public int getIndex(V v) {
438 return vertices.indexOf(v);
439 }
440
441 /**
442 * Adds a vertex to the graph.
443 */
444 public void addVertex(V vertex) {
445 vertices.add(vertex);
446 neighbors.add(new ArrayList<Edge>());
447 }
448
449 /**
450 * Adds an edge to the graph.
451 */
452 protected void addEdge(Edge e) {
453 if (e.u < 0 || e.u > getSize() - 1)
454 throw new IllegalArgumentException("No such index: " + e.u);
455
456 if (e.v < 0 || e.v > getSize() - 1)
457 throw new IllegalArgumentException("No such index: " + e.v);
458
459 if (!neighbors.get(e.u).contains(e)) {
460 neighbors.get(e.u).add(e);
461 }
462 }
463
464 /**
465 * Returns the degree of vertex v.
466 */
467 public int getDegree(V v) {
468 return neighbors.get(v).size();
469 }
470
471 /**
472 * Prints all edges in the graph.
473 */
474 public void printEdges() {
475 for (int u = 0; u < neighbors.size(); u++) {
476 System.out.print(getVertex(u) + " (" + u + "): ");
477 for (Edge e: neighbors.get(u)) {
478 System.out.print("(" + getVertex(e.u) + ", " +
479 getVertex(e.v) + ")");
480 }
481 System.out.println();
482 }
483 }
484
485 /**
486 * Returns the number of vertices in the graph.
487 */
488 public int getSize() {
489 return vertices.size();
490 }
491
492 /**
493 * Returns the vertex at index i.
494 */
495 public V getVertex(int index) {
496 return vertices.get(index);
497 }
498
499 /**
500 * Returns the index of vertex v.
501 */
502 public int getIndex(V v) {
503 return vertices.indexOf(v);
504 }
505
506 /**
507 * Adds a vertex to the graph.
508 */
509 public void addVertex(V vertex) {
510 vertices.add(vertex);
511 neighbors.add(new ArrayList<Edge>());
512 }
513
514 /**
515 * Adds an edge to the graph.
516 */
517 protected void addEdge(Edge e) {
518 if (e.u < 0 || e.u > getSize() - 1)
519 throw new IllegalArgumentException("No such index: " + e.u);
520
521 if (e.v < 0 || e.v > getSize() - 1)
522 throw new IllegalArgumentException("No such index: " + e.v);
523
524 if (!neighbors.get(e.u).contains(e)) {
525 neighbors.get(e.u).add(e);
526 }
527 }
528
529 /**
530 * Returns the degree of vertex v.
531 */
532 public int getDegree(V v) {
533 return neighbors.get(v).size();
534 }
535
536 /**
537 * Prints all edges in the graph.
538 */
539 public void printEdges() {
540 for (int u = 0; u < neighbors.size(); u++) {
541 System.out.print(getVertex(u) + " (" + u + "): ");
542 for (Edge e: neighbors.get(u)) {
543 System.out.print("(" + getVertex(e.u) + ", " +
544 getVertex(e.v) + ")");
545 }
546 System.out.println();
547 }
548 }
549
550 /**
551 * Returns the number of vertices in the graph.
552 */
553 public int getSize() {
554 return vertices.size();
555 }
556
557 /**
558 * Returns the vertex at index i.
559 */
560 public V getVertex(int index) {
561 return vertices.get(index);
562 }
563
564 /**
565 * Returns the index of vertex v.
566 */
567 public int getIndex(V v) {
568 return vertices.indexOf(v);
569 }
570
571 /**
572 * Adds a vertex to the graph.
573 */
574 public void addVertex(V vertex) {
575 vertices.add(vertex);
576 neighbors.add(new ArrayList<Edge>());
577 }
578
579 /**
580 * Adds an edge to the graph.
581 */
582 protected void addEdge(Edge e) {
583 if (e.u < 0 || e.u > getSize() - 1)
584 throw new IllegalArgumentException("No such index: " + e.u);
585
586 if (e.v < 0 || e.v > getSize() - 1)
587 throw new IllegalArgumentException("No such index: " + e.v);
588
589 if (!neighbors.get(e.u).contains(e)) {
590 neighbors.get(e.u).add(e);
591 }
592 }
593
594 /**
595 * Returns the degree of vertex v.
596 */
597 public int getDegree(V v) {
598 return neighbors.get(v).size();
599 }
600
601 /**
602 * Prints all edges in the graph.
603 */
604 public void printEdges() {
605 for (int u = 0; u < neighbors.size(); u++) {
606 System.out.print(getVertex(u) + " (" + u + "): ");
607 for (Edge e: neighbors.get(u)) {
608 System.out.print("(" + getVertex(e.u) + ", " +
609 getVertex(e.v) + ")");
610 }
611 System.out.println();
612 }
613 }
614
615 /**
616 * Returns the number of vertices in the graph.
617 */
618 public int getSize() {
619 return vertices.size();
620 }
621
622 /**
623 * Returns the vertex at index i.
624 */
625 public V getVertex(int index) {
626 return vertices.get(index);
627 }
628
629 /**
630 * Returns the index of vertex v.
631 */
632 public int getIndex(V v) {
633 return vertices.indexOf(v);
634 }
635
636 /**
637 * Adds a vertex to the graph.
638 */
639 public void addVertex(V vertex) {
640 vertices.add(vertex);
641 neighbors.add(new ArrayList<Edge>());
642 }
643
644 /**
645 * Adds an edge to the graph.
646 */
647 protected void addEdge(Edge e) {
648 if (e.u < 0 || e.u > getSize() - 1)
649 throw new IllegalArgumentException("No such index: " + e.u);
650
651 if (e.v < 0 || e.v > getSize() - 1)
652 throw new IllegalArgumentException("No such index: " + e.v);
653
654 if (!neighbors.get(e.u).contains(e)) {
655 neighbors.get(e.u).add(e);
656 }
657 }
658
659 /**
660 * Returns the degree of vertex v.
661 */
662 public int getDegree(V v) {
663 return neighbors.get(v).size();
664 }
665
666 /**
667 * Prints all edges in the graph.
668 */
669 public void printEdges() {
670 for (int u = 0; u < neighbors.size(); u++) {
671 System.out.print(getVertex(u) + " (" + u + "): ");
672 for (Edge e: neighbors.get(u)) {
673 System.out.print("(" + getVertex(e.u) + ", " +
674 getVertex(e.v) + ")");
675 }
676 System.out.println();
677 }
678 }
679
680 /**
681 * Returns the number of vertices in the graph.
682 */
683 public int getSize() {
684 return vertices.size();
685 }
686
687 /**
688 * Returns the vertex at index i.
689 */
690 public V getVertex(int index) {
691 return vertices.get(index);
692 }
693
694 /**
695 * Returns the index of vertex v.
696 */
697 public int getIndex(V v) {
698 return vertices.indexOf(v);
699 }
700
701 /**
702 * Adds a vertex to the graph.
703 */
704 public void addVertex(V vertex) {
705 vertices.add(vertex);
706 neighbors.add(new ArrayList<Edge>());
707 }
708
709 /**
710 * Adds an edge to the graph.
711 */
712 protected void addEdge(Edge e) {
713 if (e.u < 0 || e.u > getSize() - 1)
714 throw new IllegalArgumentException("No such index: " + e.u);
715
716 if (e.v < 0 || e.v > getSize() - 1)
717 throw new IllegalArgumentException("No such index: " + e.v);
718
719 if (!neighbors.get(e.u).contains(e)) {
720 neighbors.get(e.u).add(e);
721 }
722 }
723
724 /**
725 * Returns the degree of vertex v.
726 */
727 public int getDegree(V v) {
728 return neighbors.get(v).size();
729 }
730
731 /**
732 * Prints all edges in the graph.
733 */
734 public void printEdges() {
735 for (int u = 0; u < neighbors.size(); u++) {
736 System.out.print(getVertex(u) + " (" + u + "): ");
737 for (Edge e: neighbors.get(u)) {
738 System.out.print("(" + getVertex(e.u) + ", " +
739 getVertex(e.v) + ")");
740 }
741 System.out.println();
742 }
743 }
744
745 /**
746 * Returns the number of vertices in the graph.
747 */
748 public int getSize() {
749 return vertices.size();
750 }
751
752 /**
753 * Returns the vertex at index i.
754 */
755 public V getVertex(int index) {
756 return vertices.get(index);
757 }
758
759 /**
760 * Returns the index of vertex v.
761 */
762 public int getIndex(V v) {
763 return vertices.indexOf(v);
764 }
765
766 /**
767 * Adds a vertex to the graph.
768 */
769 public void addVertex(V vertex) {
770 vertices.add(vertex);
771 neighbors.add(new ArrayList<Edge>());
772 }
773
774 /**
775 * Adds an edge to the graph.
776 */
777 protected void addEdge(Edge e) {
778 if (e.u < 0 || e.u > getSize() - 1)
779 throw new IllegalArgumentException("No such index: " + e.u);
780
781 if (e.v < 0 || e.v > getSize() - 1)
782 throw new IllegalArgumentException("No such index: " + e.v);
783
784 if (!neighbors.get(e.u).contains(e)) {
785 neighbors.get(e.u).add(e);
786 }
787 }
788
789 /**
790 * Returns the degree of vertex v.
791 */
792 public int getDegree(V v) {
793 return neighbors.get(v).size();
794 }
795
796 /**
797 * Prints all edges in the graph.
798 */
799 public void printEdges() {
800 for (int u = 0; u < neighbors.size(); u++) {
801 System.out.print(getVertex(u) + " (" + u + "): ");
802 for (Edge e: neighbors.get(u)) {
803 System.out.print("(" + getVertex(e.u) + ", " +
804 getVertex(e.v) + ")");
805 }
806 System.out.println();
807 }
808 }
809
810 /**
811 * Returns the number of vertices in the graph.
812 */
813 public int getSize() {
814 return vertices.size();
815 }
816
817 /**
818 * Returns the vertex at index i.
819 */
820 public V getVertex(int index) {
821 return vertices.get(index);
822 }
823
824 /**
825 * Returns the index of vertex v.
826 */
827 public int getIndex(V v) {
828 return vertices.indexOf(v);
829 }
830
831 /**
832 * Adds a vertex to the graph.
833 */
834 public void addVertex(V vertex) {
835 vertices.add(vertex);
836 neighbors.add(new ArrayList<Edge>());
837 }
838
839 /**
840 * Adds an edge to the graph.
841 */
842 protected void addEdge(Edge e) {
843 if (e.u < 0 || e.u > getSize() - 1)
844 throw new IllegalArgumentException("No such index: " + e.u);
845
846 if (e.v < 0 || e.v > getSize() - 1)
847 throw new IllegalArgumentException("No such index: " + e.v);
848
849 if (!neighbors.get(e.u).contains(e)) {
850 neighbors.get(e.u).add(e);
851 }
852 }
853
854 /**
855 * Returns the degree of vertex v.
856 */
857 public int getDegree(V v) {
858 return neighbors.get(v).size();
859 }
860
861 /**
862 * Prints all edges in the graph.
863 */
864 public void printEdges() {
865 for (int u = 0; u < neighbors.size(); u++) {
866 System.out.print(getVertex(u) + " (" + u + "): ");
867 for (Edge e: neighbors.get(u)) {
868 System.out.print("(" + getVertex(e.u) + ", " +
869 getVertex(e.v) + ")");
870 }
871 System.out.println();
872 }
873 }
874
875 /**
876 * Returns the number of vertices in the graph.
877 */
878 public int getSize() {
879 return vertices.size();
880 }
881
882 /**
883 * Returns the vertex at index i.
884 */
885 public V getVertex(int index) {
886 return vertices.get(index);
887 }
888
889 /**
890 * Returns the index of vertex v.
891 */
892 public int getIndex(V v) {
893 return vertices.indexOf(v);
894 }
895
896 /**
897 * Adds a vertex to the graph.
898 */
899 public void addVertex(V vertex) {
900 vertices.add(vertex);
901 neighbors.add(new ArrayList<Edge>());
902 }
903
904 /**
905 * Adds an edge to the graph.
906 */
907 protected void addEdge(Edge e) {
908 if (e.u < 0 || e.u > getSize() - 1)
909 throw new IllegalArgumentException("No such index: " + e.u);
910
911 if (e.v < 0 || e.v > getSize() - 1)
912 throw new IllegalArgumentException("No such index: " + e.v);
913
914 if (!neighbors.get(e.u).contains(e)) {
915 neighbors.get(e.u).add(e);
916 }
917 }
918
919 /**
920 * Returns the degree of vertex v.
921 */
922 public int getDegree(V v) {
923 return neighbors.get(v).size();
924 }
925
926 /**
927 * Prints all edges in the graph.
928 */
929 public void printEdges() {
930 for (int u = 0; u < neighbors.size(); u++) {
931 System.out.print(getVertex(u) + " (" + u + "): ");
932 for (Edge e: neighbors.get(u)) {
933 System.out.print("(" + getVertex(e.u) + ", " +
934 getVertex(e.v) + ")");
935 }
936 System.out.println();
937 }
938 }
939
940 /**
941 * Returns the number of vertices in the graph.
942 */
943 public int getSize() {
944 return vertices.size();
945 }
946
947 /**
948 * Returns the vertex at index i.
949 */
950 public V getVertex(int index) {
951 return vertices.get(index);
952 }
953
954 /**
955 * Returns the index of vertex v.
956 */
957 public int getIndex(V v) {
958 return vertices.indexOf(v);
959 }
960
961 /**
962 * Adds a vertex to the graph.
963 */
964 public void addVertex(V vertex) {
965 vertices.add(vertex);
966 neighbors.add(new ArrayList<Edge>());
967 }
968
969 /**
970 * Adds an edge to the graph.
971 */
972 protected void addEdge(Edge e) {
973 if (e.u < 0 || e.u > getSize() - 1)
974 throw new IllegalArgumentException("No such index: " + e.u);
975
976 if (e.v < 0 || e.v > getSize() - 1)
977 throw new IllegalArgumentException("No such index: " + e.v);
978
979 if (!neighbors.get(e.u).contains(e)) {
980 neighbors.get(e.u).add(e);
981 }
982 }
983
984 /**
985 * Returns the degree of vertex v.
986 */
987 public int getDegree(V v) {
988 return neighbors.get(v).size();
989 }
990
991 /**
992 * Prints all edges in the graph.
993 */
994 public void printEdges() {
995 for (int u = 0; u < neighbors.size(); u++) {
996 System.out.print(getVertex(u) + " (" + u + "): ");
997 for (Edge e: neighbors.get(u)) {
998 System.out.print("(" + getVertex(e.u) + ", " +
999 getVertex(e.v) + ")");
1000 }
1001 System.out.println();
1002 }
1003 }
```

```

134 return true;
135 }
136 else {
137 return false;
138 }
139 }
140
141 @Override /** Add an edge to the graph */
142 public boolean addEdge(int u, int v) {
143 return addEdge(new Edge(u, v));
144 }
145
146 /** Edge inner class inside the AbstractGraph class */
147 public static class Edge {
148 public int u; // Starting vertex of the edge
149 public int v; // Ending vertex of the edge
150
151 /** Construct an edge for (u, v) */
152 public Edge(int u, int v) {
153 this.u = u;
154 this.v = v;
155 }
156
157 public boolean equals(Object o) {
158 return u == ((Edge)o).u && v == ((Edge)o).v;
159 }
160 }
161
162 @Override /** Obtain a DFS tree starting from vertex v */
163 /** To be discussed in Section 28.7 */
164 public Tree dfs(int v) {
165 List<Integer> searchOrder = new ArrayList<>();
166 int[] parent = new int[vertices.size()];
167 for (int i = 0; i < parent.length; i++)
168 parent[i] = -1; // Initialize parent[i] to -1
169
170 // Mark visited vertices
171 boolean[] isVisited = new boolean[vertices.size()];
172
173 // Recursively search
174 dfs(v, parent, searchOrder, isVisited);
175
176 // Return a search tree
177 return new Tree(v, parent, searchOrder);
178 }
179
180 /** Recursive method for DFS search */
181 private void dfs(int u, int[] parent, List<Integer> searchOrder,
182 boolean[] isVisited) {
183 // Store the visited vertex
184 searchOrder.add(u);
185 isVisited[u] = true; // Vertex v visited
186
187 for (Edge e : neighbors.get(u)) {
188 if (!isVisited[e.v]) {
189 parent[e.v] = u; // The parent of vertex e.v is u
190 dfs(e.v, parent, searchOrder, isVisited); // Recursive search
191 }
192 }
193 }

```

addEdge overloaded

Edge inner class

dfs method

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```
194
195 @Override /** Starting bfs search from vertex v */
196 /** To be discussed in Section 28.9 */
197 public Tree bfs(int v) {
198 List<Integer> searchOrder = new ArrayList<>();
199 int[] parent = new int[vertices.size()];
200 for (int i = 0; i < parent.length; i++)
201 parent[i] = -1; // Initialize parent[i] to -1
202
203 java.util.LinkedList<Integer> queue =
204 new java.util.LinkedList<>(); // list used as a queue
205 boolean[] isVisited = new boolean[vertices.size()];
206 queue.offer(v); // Enqueue v
207 isVisited[v] = true; // Mark it visited
208
209 while (!queue.isEmpty()) {
210 int u = queue.poll(); // Dequeue to u
211 searchOrder.add(u); // u searched
212 for (Edge e: neighbors.get(u)) {
213 if (!isVisited[e.v]) {
214 queue.offer(e.v); // Enqueue w
215 parent[e.v] = u; // The parent of w is u
216 isVisited[e.v] = true; // Mark it visited
217 }
218 }
219 }
220
221 return new Tree(v, parent, searchOrder);
222 }
223
224 /** Tree inner class inside the AbstractGraph class */
225 /** To be discussed in Section 28.6 */
226 public class Tree {
227 private int root; // The root of the tree
228 private int[] parent; // Store the parent of each vertex
229 private List<Integer> searchOrder; // Store the search order
230
231 /** Construct a tree with root, parent, and searchOrder */
232 public Tree(int root, int[] parent, List<Integer> searchOrder) {
233 this.root = root;
234 this.parent = parent;
235 this.searchOrder = searchOrder;
236 }
237
238 /** Return the root of the tree */
239 public int getRoot() {
240 return root;
241 }
242
243 /** Return the parent of vertex v */
244 public int getParent(int v) {
245 return parent[v];
246 }
247
248 /** Return an array representing search order */
249 public List<Integer> getSearchOrder() {
250 return searchOrder;
251 }
252
253 /** Return number of vertices found */
254 public int getNumberOfVerticesFound() {
```

```

255 return searchOrder.size();
256 }
257
258 /** Return the path of vertices from a vertex to the root */
259 public List<V> getPath(int index) {
260 ArrayList<V> path = new ArrayList<>();
261
262 do {
263 path.add(vertices.get(index));
264 index = parent[index];
265 }
266 while (index != -1);
267
268 return path;
269 }
270
271 /** Print a path from the root to vertex v */
272 public void printPath(int index) {
273 List<V> path = getPath(index);
274 System.out.print("A path from " + vertices.get(root) + " to " +
275 vertices.get(index) + ": ");
276 for (int i = path.size() - 1; i >= 0; i--) {
277 System.out.print(path.get(i) + " ");
278 }
279 }
280
281 /** Print the whole tree */
282 public void printTree() {
283 System.out.println("Root is: " + vertices.get(root));
284 System.out.print("Edges: ");
285 for (int i = 0; i < parent.length; i++) {
286 if (parent[i] != -1) {
287 // Display an edge
288 System.out.print("(" + vertices.get(parent[i]) + ", " +
289 vertices.get(i) + ")");
290 }
291 }
292 System.out.println();
293 }
294 }
```

## LISTING 28.4 UnweightedGraph.java

```

1 import java.util.*;
2
3 public class UnweightedGraph<V> extends AbstractGraph<V> {
4 /** Construct an empty graph */
5 public UnweightedGraph() { no-arg constructor
6 }
7
8 /** Construct a graph from vertices and edges stored in arrays */
9 public UnweightedGraph(V[] vertices, int[][] edges) { constructor
10 super(vertices, edges);
11 }
12
13 /** Construct a graph from vertices and edges stored in List */
14 public UnweightedGraph(List<V> vertices, List<Edge> edges) { constructor
15 super(vertices, edges);
16 }
17
18 /** Construct a graph for integer vertices 0, 1, 2 and edge list */

```

```

constructor 19 public UnweightedGraph(List<Edge> edges, int numberOfVertices) {
20 super(edges, numberOfVertices);
21 }
22
constructor 23 /** Construct a graph from integer vertices 0, 1, and edge array */
24 public UnweightedGraph(int[][] edges, int numberOfVertices) {
25 super(edges, numberOfVertices);
26 }
27 }

```

The code in the `Graph` interface in Listing 28.2 and the `UnweightedGraph` class in Listing 28.4 are straightforward. Let us digest the code in the `AbstractGraph` class in Listing 28.3.

The `AbstractGraph` class defines the data field `vertices` (line 4) to store vertices and `neighbors` (line 5) to store edges in adjacency lists. `neighbors.get(i)` stores all edges adjacent to vertex `i`. Four overloaded constructors are defined in lines 9–42 to create a default graph, or a graph from arrays or lists of edges and vertices. The `createAdjacencyLists(int[][] edges, int numberOfVertices)` method creates adjacency lists from edges in an array (lines 45–50). The `createAdjacencyLists(List<Edge> edges, int numberOfVertices)` method creates adjacency lists from edges in a list (lines 53–58).

The `getNeighbors(u)` method (lines 81–87) returns a list of vertices adjacent to vertex `u`. The `clear()` method (lines 106–110) removes all vertices and edges from the graph. The `addVertex(u)` method (lines 112–122) adds a new vertex to `vertices` and returns true. It returns false if the vertex is already in the graph (line 120).

The `addEdge(e)` method (lines 124–139) adds a new edge the adjacency edge list and returns true. It returns false if the edge is already in the graph. This method may throw `IllegalArgumentException` if the edge is invalid (lines 126–130).

The `printEdges()` method (lines 95–104) displays all vertices and edges adjacent to each vertex.

The code in lines 164–293 gives the methods for finding a depth-first search tree and a breadth-first search tree, which will be introduced in Sections 28.7 and 28.9, respectively.



**28.7** Describe the relationships among `Graph`, `AbstractGraph`, and `UnweightedGraph`.

**28.8** For the code in Listing 28.1, `TestGraph.java`, what is `graph1.getIndex("Seattle")`? What is `graph1.getDegree(5)`? What is `graph1.getVertex(4)`?



## 28.5 Graph Visualization

*To display a graph visually, each vertex must be assigned a location.*

The preceding section introduced how to model a graph using the `Graph` interface, `AbstractGraph` class, and `UnweightedGraph` class. This section discusses how to display graphs graphically. In order to display a graph, you need to know where each vertex is displayed and the name of each vertex. To ensure a graph can be displayed, we define an interface named `Displayable` that has the methods for obtaining the `x-` and `y-`coordinates and their names, and make vertices instances of `Displayable`, in Listing 28.5.

### LISTING 28.5 Displayable.java

Displayable interface

```

1 public interface Displayable {
2 public int getX(); // Get x-coordinate of the vertex
3 public int getY(); // Get y-coordinate of the vertex
4 public String getName(); // Get display name of the vertex
5 }

```

A graph with `Displayable` vertices can now be displayed on a pane named `GraphView`, as shown in Listing 28.6.

**LISTING 28.6** GraphView.java

```

1 import javafx.scene.layout.Pane;
2 import javafx.scene.shape.Circle;
3 import javafx.scene.shape.Line;
4 import javafx.scene.text.Text;
5
6 public class GraphView extends Pane {
7 private Graph<? extends Displayable> graph;
8
9 public GraphView(Graph<? extends Displayable> graph) {
10 this.graph = graph;
11
12 // Draw vertices
13 java.util.List<? extends Displayable> vertices
14 = graph.getVertices();
15 for (int i = 0; i < graph.getSize(); i++) {
16 int x = vertices.get(i).getX();
17 int y = vertices.get(i).getY();
18 String name = vertices.get(i).getName();
19
20 getChildren().add(new Circle(x, y, 16)); // Display a vertex
21 getChildren().add(new Text(x - 8, y - 18, name));
22 }
23
24 // Draw edges for pairs of vertices
25 for (int i = 0; i < graph.getSize(); i++) {
26 java.util.List<Integer> neighbors = graph.getNeighbors(i);
27 int x1 = graph.getVertex(i).getX();
28 int y1 = graph.getVertex(i).getY();
29 for (int v: neighbors) {
30 int x2 = graph.getVertex(v).getX();
31 int y2 = graph.getVertex(v).getY();
32
33 // Draw an edge for (i, v)
34 getChildren().add(new Line(x1, y1, x2, y2));
35 }
36 }
37 }
38 }
```

extends Pane  
Displayable vertices

display a vertex  
display a text

draw an edge

To display a graph on a pane, simply create an instance of `GraphView` by passing the graph as an argument in the constructor (line 9). The class for the graph's vertex must implement the `Displayable` interface in order to display the vertices (lines 13–22). For each vertex index `i`, invoking `graph.getNeighbors(i)` returns its adjacency list (line 26). From this list, you can find all vertices that are adjacent to `i` and draw a line to connect `i` with its adjacent vertex (lines 27–34).

Listing 28.7 gives an example of displaying the graph in Figure 28.1, as shown in Figure 28.10.

**LISTING 28.7** DisplayUSMap.java

```

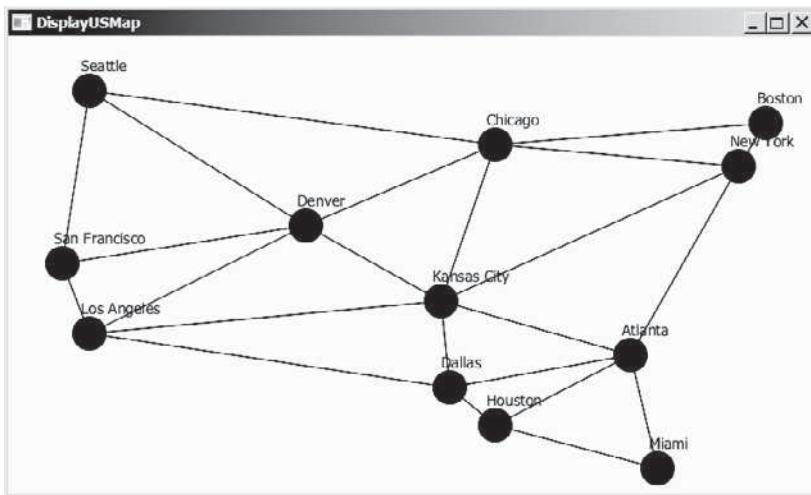
1 import javafx.application.Application;
2 import javafx.scene.Scene;
3 import javafx.stage.Stage;
4
5 public class DisplayUSMap extends Application {
6 @Override // Override the start method in the Application class
7 public void start(Stage primaryStage) {
8 City[] vertices = {new City("Seattle", 75, 50),
9
10 }
```

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```
9 new City("San Francisco", 50, 210),
10 new City("Los Angeles", 75, 275), new City("Denver", 275, 175),
11 new City("Kansas City", 400, 245),
12 new City("Chicago", 450, 100), new City("Boston", 700, 80),
13 new City("New York", 675, 120), new City("Atlanta", 575, 295),
14 new City("Miami", 600, 400), new City("Dallas", 408, 325),
15 new City("Houston", 450, 360) };
16
17 // Edge array for graph in Figure 28.1
18 int[][] edges = {
19 {0, 1}, {0, 3}, {0, 5}, {1, 0}, {1, 2}, {1, 3},
20 {2, 1}, {2, 3}, {2, 4}, {2, 10},
21 {3, 0}, {3, 1}, {3, 2}, {3, 4}, {3, 5},
22 {4, 2}, {4, 3}, {4, 5}, {4, 7}, {4, 8}, {4, 10},
23 {5, 0}, {5, 3}, {5, 4}, {5, 6}, {5, 7},
24 {6, 5}, {6, 7}, {7, 4}, {7, 5}, {7, 6}, {7, 8},
25 {8, 4}, {8, 7}, {8, 9}, {8, 10}, {8, 11},
26 {9, 8}, {9, 11}, {10, 2}, {10, 4}, {10, 8}, {10, 11},
27 {11, 8}, {11, 9}, {11, 10}
28 };
29
30 Graph<City> graph = new UnweightedGraph<>(vertices, edges);
31
32 // Create a scene and place it in the stage
33 Scene scene = new Scene(new GraphView(graph), 750, 450);
34 primaryStage.setTitle("DisplayUSMap"); // Set the stage title
35 primaryStage.setScene(scene); // Place the scene in the stage
36 primaryStage.show(); // Display the stage
37 }
38
39 static class City implements Displayable {
40 private int x, y;
41 private String name;
42
43 City(String name, int x, int y) {
44 this.name = name;
45 this.x = x;
46 this.y = y;
47 }
48
49 @Override
50 public int getX() {
51 return x;
52 }
53
54 @Override
55 public int getY() {
56 return y;
57 }
58
59 @Override
60 public String getName() {
61 return name;
62 }
63 }
64 }
```

The class `City` is defined to model the vertices with their coordinates and names (lines 39–63). The program creates a graph with the vertices of the `City` type (line 30). Since `City` implements `Displayable`, a `GraphView` object created for the graph displays the graph in the pane (line 33).

As an exercise to get acquainted with the graph classes and interfaces, add a city (e.g., Savannah) with appropriate edges into the graph.



**FIGURE 28.10** The graph is displayed in the pane.

- 28.9** Will Listing 28.7 `DisplayUSMap.java` work, if the code in lines 30–34 in Listing 28.6 `GraphView.java` is replaced by the following code?

```
if (i < v) {
 int x2 = graph.getVertex(v).getX();
 int y2 = graph.getVertex(v).getY();

 // Draw an edge for (i, v)
 getChildren().add(new Line(x1, y1, x2, y2));
}
```



- 28.10** For the `graph1` object created in Listing 28.1, `TestGraph.java`, can you create a `GraphView` object as follows?

```
GraphView view = new GraphView(graph1);
```



## 28.6 Graph Traversals

*Depth-first and breadth-first are two common ways to traverse a graph.*



*Graph traversal* is the process of visiting each vertex in the graph exactly once. There are two popular ways to traverse a graph: *depth-first traversal* (or *depth-first search*) and *breadth-first traversal* (or *breadth-first search*). Both traversals result in a spanning tree, which can be modeled using a class, as shown in Figure 28.11. Note that `Tree` is an inner class defined in the `AbstractGraph` class. `AbstractGraph<V>.Tree` is different from the `Tree` interface defined in Section 25.2.5. `AbstractGraph.Tree` is a specialized class designed for describing the parent–child relationship of the nodes, whereas the `Tree` interface defines common operations such as searching, inserting, and deleting in a tree. Since there is no need to perform these operations for a spanning tree, `AbstractGraph<V>.Tree` is not defined as a subtype of `Tree`.

depth-first search

The `Tree` class is defined as an inner class in the `AbstractGraph` class in lines 226–293 in Listing 28.3. The constructor creates a tree with the root, edges, and a search order.

breadth-first search

The `Tree` class defines seven methods. The `getRoot()` method returns the root of the tree. You can get the order of the vertices searched by invoking the `getSearchOrder()` method. You can invoke `getParent(v)` to find the parent of vertex `v` in the search. Invoking `getNumberOfVerticesFound()` returns the number of vertices searched. The method `getPath(index)` returns a list of vertices from the specified vertex index to the root. Invoking `printPath(v)` displays a path from the root to `v`. You can display all edges in the tree using the `printTree()` method.

| <b>AbstractGraph&lt;V&gt;.Tree</b>                          |                                                                         |
|-------------------------------------------------------------|-------------------------------------------------------------------------|
| -root: int                                                  | The root of the tree.                                                   |
| -parent: int[]                                              | The parents of the vertices.                                            |
| -searchOrder: List<Integer>                                 | The orders for traversing the vertices.                                 |
| +Tree(root: int, parent: int[], searchOrder: List<Integer>) | Constructs a tree with the specified root, parent, and searchOrder.     |
| +getRoot(): int                                             | Returns the root of the tree.                                           |
| +getSearchOrder(): List<Integer>                            | Returns the order of vertices searched.                                 |
| +getParent(index: int): int                                 | Returns the parent for the specified vertex index.                      |
| +getNumberOfVerticesFound(): int                            | Returns the number of vertices searched.                                |
| +getPath(index: int): List<V>                               | Returns a list of vertices from the specified vertex index to the root. |
| +printPath(index: int): void                                | Displays a path from the root to the specified vertex.                  |
| +printTree(): void                                          | Displays tree with the root and all edges.                              |

FIGURE 28.11 The **Tree** class describes the nodes with parent–child relationships.

Sections 28.7 and 28.9 will introduce depth-first search and breadth-first search, respectively. Both searches will result in an instance of the **Tree** class.



**28.11** Does **AbstractGraph<V>.Tree** implement the **Tree** interface defined in Listing 25.3 Tree.java?



**28.12** What method do you use to find the parent of a vertex in the tree?

## 28.7 Depth-First Search (DFS)

*The depth-first search of a graph starts from a vertex in the graph and visits all vertices in the graph as far as possible before backtracking.*

The depth-first search of a graph is like the depth-first search of a tree discussed in Section 25.2.4, Tree Traversal. In the case of a tree, the search starts from the root. In a graph, the search can start from any vertex.

A depth-first search of a tree first visits the root, then recursively visits the subtrees of the root. Similarly, the depth-first search of a graph first visits a vertex, then it recursively visits all the vertices adjacent to that vertex. The difference is that the graph may contain cycles, which could lead to an infinite recursion. To avoid this problem, you need to track the vertices that have already been visited.

The search is called *depth-first* because it searches “deeper” in the graph as much as possible. The search starts from some vertex  $v$ . After visiting  $v$ , it visits an unvisited neighbor of  $v$ . If  $v$  has no unvisited neighbor, the search backtracks to the vertex from which it reached  $v$ . We assume that the graph is connected and the search starting from any vertex can reach all the vertices. If this is not the case, see Programming Exercise 28.4 for finding connected components in a graph.

### 28.7.1 Depth-First Search Algorithm

The algorithm for the depth-first search is described in Listing 28.8.

#### LISTING 28.8 Depth-First Search Algorithm

Input:  $G = (V, E)$  and a starting vertex  $v$   
Output: a DFS tree rooted at  $v$

```
1 Tree dfs(vertex v) {
2 visit v;
```

```

3 for each neighbor w of v
4 if (w has not been visited) {
5 set v as the parent for w in the tree;
6 dfs(w);
7 }
8 }
```

check a neighbor  
recursive search

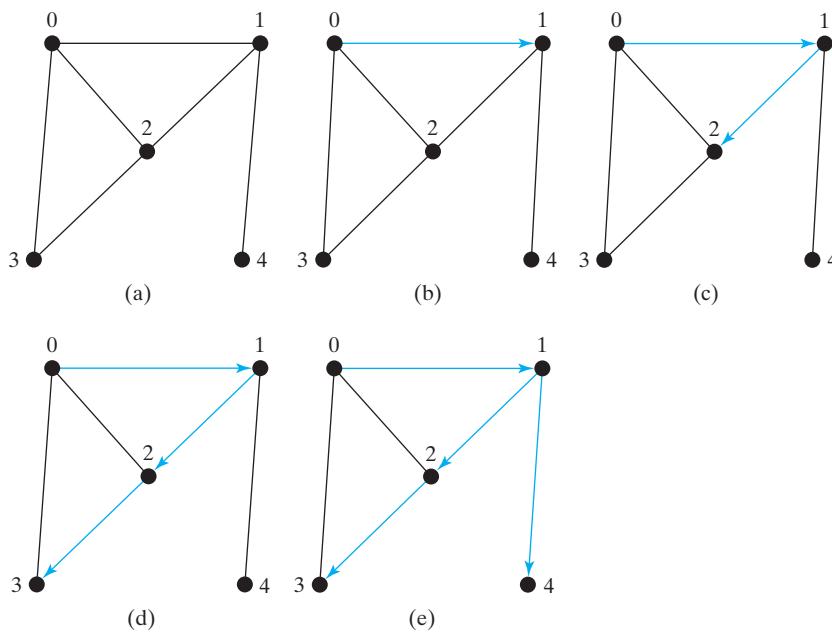
You can use an array named `isVisited` to denote whether a vertex has been visited. Initially, `isVisited[i]` is `false` for each vertex  $i$ . Once a vertex, say  $v$ , is visited, `isVisited[v]` is set to `true`.

Consider the graph in Figure 28.12a. Suppose we start the depth-first search from vertex 0. First visit 0, then any of its neighbors, say 1. Now 1 is visited, as shown in Figure 28.12b. Vertex 1 has three neighbors—0, 2, and 4. Since 0 has already been visited, you will visit either 2 or 4. Let us pick 2. Now 2 is visited, as shown in Figure 28.12c. Vertex 2 has three neighbors: 0, 1, and 3. Since 0 and 1 have already been visited, pick 3. 3 is now visited, as shown in Figure 28.12d. At this point, the vertices have been visited in this order:

**0, 1, 2, 3**

Since all the neighbors of 3 have been visited, backtrack to 2. Since all the vertices of 2 have been visited, backtrack to 1. 4 is adjacent to 1, but 4 has not been visited. Therefore, visit 4, as shown in Figure 28.12e. Since all the neighbors of 4 have been visited, backtrack to 1. Since all the neighbors of 1 have been visited, backtrack to 0. Since all the neighbors of 0 have been visited, the search ends.

Since each edge and each vertex is visited only once, the time complexity of the `dfs` method is  $O(|E| + |V|)$ , where  $|E|$  denotes the number of edges and  $|V|$  the number of vertices.



**FIGURE 28.12** Depth-first search visits a node and its neighbors recursively.

## 28.7.2 Implementation of Depth-First Search

The algorithm for DFS in Listing 28.8 uses recursion. It is natural to use recursion to implement it. Alternatively, you can use a stack (see Programming Exercise 28.3).

The `dfs(int v)` method is implemented in lines 164–193 in Listing 28.3. It returns an instance of the `Tree` class with vertex `v` as the root. The method stores the vertices searched in the list `searchOrder` (line 165), the parent of each vertex in the array `parent` (line 166), and uses the `isVisited` array to indicate whether a vertex has been visited (line 171). It invokes the helper method `dfs(v, parent, searchOrder, isVisited)` to perform a depth-first search (line 174).

In the recursive helper method, the search starts from vertex `u`. `u` is added to `searchOrder` in line 184 and is marked as visited (line 185). For each unvisited neighbor of `u`, the method is recursively invoked to perform a depth-first search. When a vertex `e.v` is visited, the parent of `e.v` is stored in `parent[e.v]` (line 189). The method returns when all vertices are visited for a connected graph, or in a connected component.

Listing 28.9 gives a test program that displays a DFS for the graph in Figure 28.1 starting from Chicago. The graphical illustration of the DFS starting from Chicago is shown in Figure 28.13. For an interactive GUI demo of DFS, go to [www.cs.armstrong.edu/liang/animation/USMapSearch.html](http://www.cs.armstrong.edu/liang/animation/USMapSearch.html).



U.S. Map Search

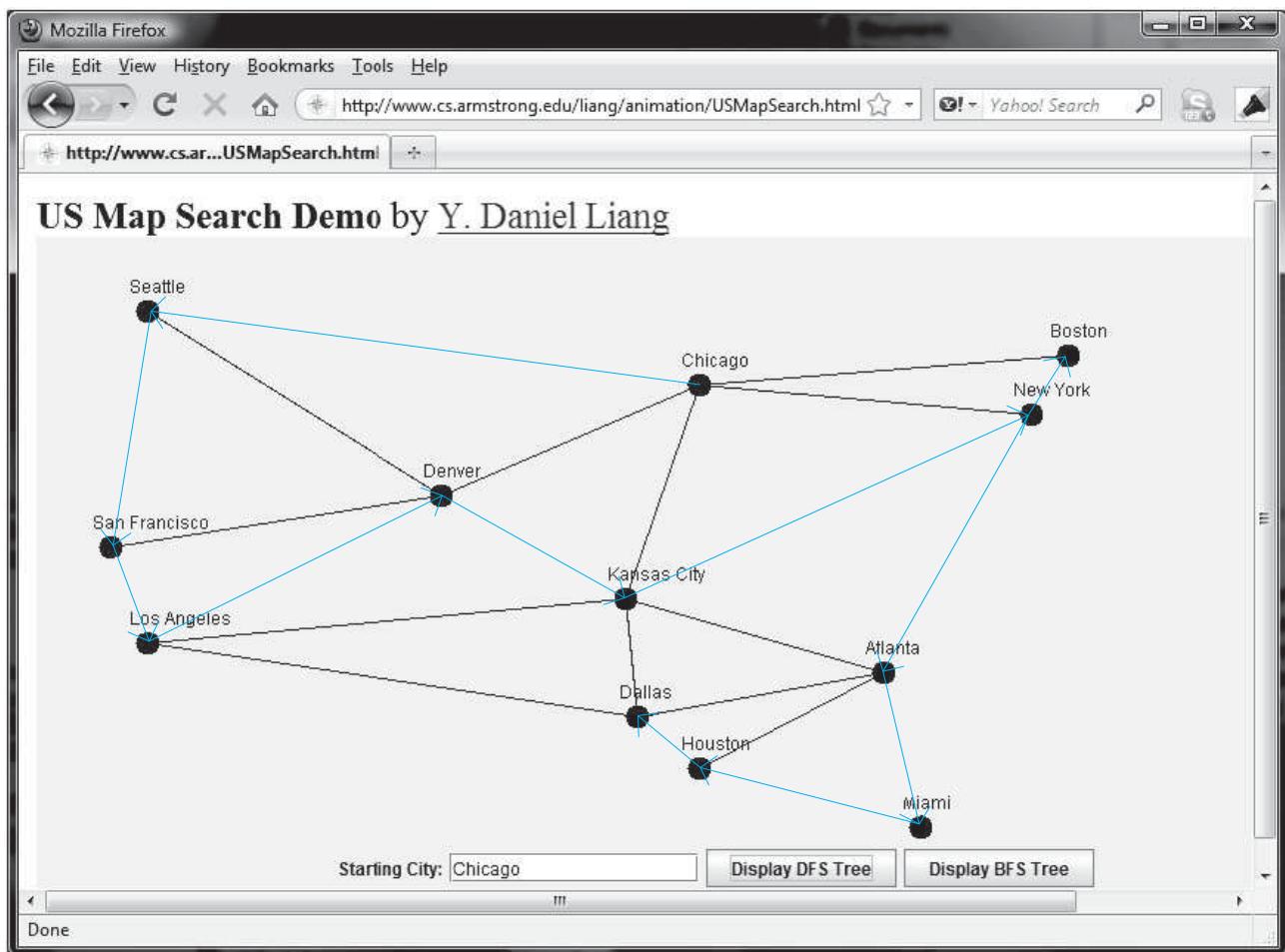
### LISTING 28.9 TestDFS.java

```

vertices
1 public class TestDFS {
2 public static void main(String[] args) {
3 String[] vertices = {"Seattle", "San Francisco", "Los Angeles",
4 "Denver", "Kansas City", "Chicago", "Boston", "New York",
5 "Atlanta", "Miami", "Dallas", "Houston"};
6
edges
7 int[][] edges = {
8 {0, 1}, {0, 3}, {0, 5},
9 {1, 0}, {1, 2}, {1, 3},
10 {2, 1}, {2, 3}, {2, 4}, {2, 10},
11 {3, 0}, {3, 1}, {3, 2}, {3, 4}, {3, 5},
12 {4, 2}, {4, 3}, {4, 5}, {4, 7}, {4, 8}, {4, 10},
13 {5, 0}, {5, 3}, {5, 4}, {5, 6}, {5, 7},
14 {6, 5}, {6, 7},
15 {7, 4}, {7, 5}, {7, 6}, {7, 8},
16 {8, 4}, {8, 7}, {8, 9}, {8, 10}, {8, 11},
17 {9, 8}, {9, 11},
18 {10, 2}, {10, 4}, {10, 8}, {10, 11},
19 {11, 8}, {11, 9}, {11, 10}
20 };
21
create a graph
22 Graph<String> graph = new UnweightedGraph<>(vertices, edges);
23 AbstractGraph<String>.Tree dfs =
24 graph.dfs(graph.getIndex("Chicago"));
25
get DFS
26 java.util.List<Integer> searchOrders = dfs.getSearchOrder();
27 System.out.println(dfs.getNumberVerticesFound() +
28 " vertices are searched in this DFS order:");
29 for (int i = 0; i < searchOrders.size(); i++)
30 System.out.print(graph.getVertex(searchOrders.get(i)) + " ");
31 System.out.println();
32
get search order
33 for (int i = 0; i < searchOrders.size(); i++)
34 if (dfs.getParent(i) != -1)
35 System.out.println("parent of " + graph.getVertex(i) +
36 " is " + graph.getVertex(dfs.getParent(i)));
37 }
38 }
```



```
12 vertices are searched in this DFS order:
Chicago Seattle San Francisco Los Angeles Denver
Kansas City New York Boston Atlanta Miami Houston Dallas
parent of Seattle is Chicago
parent of San Francisco is Seattle
parent of Los Angeles is San Francisco
parent of Denver is Los Angeles
parent of Kansas City is Denver
parent of Boston is New York
parent of New York is Kansas City
parent of Atlanta is New York
parent of Miami is Atlanta
parent of Dallas is Houston
parent of Houston is Miami
```



**FIGURE 28.13** A DFS search starts from Chicago.

### 28.7.3 Applications of the DFS

The depth-first search can be used to solve many problems, such as the following:

- Detecting whether a graph is connected. Search the graph starting from any vertex. If the number of vertices searched is the same as the number of vertices in the graph,

the graph is connected. Otherwise, the graph is not connected. (See Programming Exercise 28.1.)

- Detecting whether there is a path between two vertices (see Programming Exercise 28.5).
- Finding a path between two vertices (see Programming Exercise 28.5).
- Finding all connected components. A connected component is a maximal connected subgraph in which every pair of vertices are connected by a path (see Programming Exercise 28.4).
- Detecting whether there is a cycle in the graph (see Programming Exercise 28.6).
- Finding a cycle in the graph (see Programming Exercise 28.7).
- Finding a Hamiltonian path/cycle. A *Hamiltonian path* in a graph is a path that visits each vertex in the graph exactly once. A *Hamiltonian cycle* visits each vertex in the graph exactly once and returns to the starting vertex (see Programming Exercise 28.17).

The first six problems can be easily solved using the `dfs` method in Listing 28.3. To find a Hamiltonian path/cycle, you have to explore all possible DFSs to find the one that leads to the longest path. The Hamiltonian path/cycle has many applications, including for solving the well-known Knight's Tour problem, which is presented in Supplement VI.E on the Companion Website.



### 28.13 What is depth-first search?

**28.14** Draw a DFS tree for the graph in Figure 28.3b starting from node **A**.

**28.15** Draw a DFS tree for the graph in Figure 28.1 starting from vertex **Atlanta**.

**28.16** What is the return type from invoking `dfs(v)`?

**28.17** The depth-first search algorithm described in Listing 28.8 uses recursion. Alternatively, you can use a stack to implement it, as shown below. Point out the error in this algorithm and give a correct algorithm.

```
// Wrong version
Tree dfs(vertex v) {
 push v into the stack;
 mark v visited;

 while (the stack is not empty) {
 pop a vertex, say u, from the stack
 visit u;
 for each neighbor w of u
 if (w has not been visited)
 push w into the stack;
 }
}
```

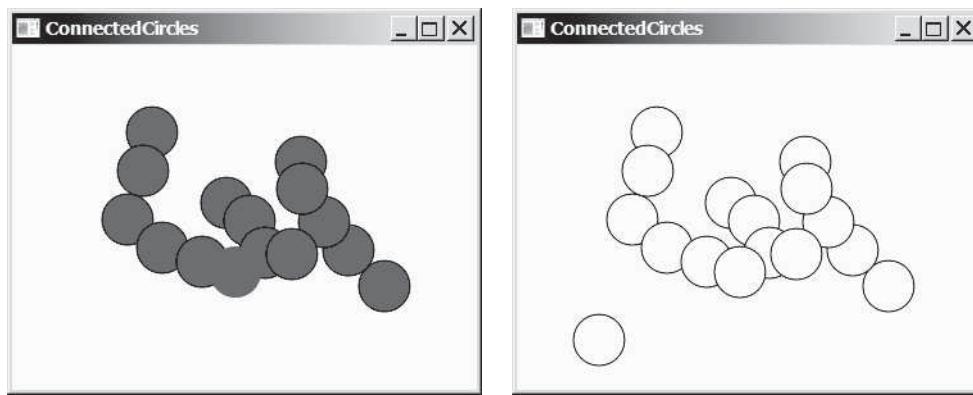
## 28.8 Case Study: The Connected Circles Problem



*The connected circles problem is to determine whether all circles in a two-dimensional plane are connected. This problem can be solved using a depth-first traversal.*

The DFS algorithm has many applications. This section applies the DFS algorithm to solve the connected circles problem.

In the connected circles problem, you determine whether all the circles in a two-dimensional plane are connected. If all the circles are connected, they are painted as filled circles, as shown in Figure 28.14a. Otherwise, they are not filled, as shown in Figure 28.14b.



(a) Circles are connected

(b) Circles are not connected

**FIGURE 28.14** You can apply DFS to determine whether the circles are connected.

We will write a program that lets the user create a circle by clicking a mouse in a blank area that is not currently covered by a circle. As the circles are added, the circles are repainted filled if they are connected or unfilled otherwise.

We will create a graph to model the problem. Each circle is a vertex in the graph. Two circles are connected if they overlap. We apply the DFS in the graph, and if all vertices are found in the depth-first search, the graph is connected.

The program is given in Listing 28.10.

### LISTING 28.10 ConnectedCircles.java

```

1 import javafx.application.Application;
2 import javafx.geometry.Point2D;
3 import javafx.scene.Node;
4 import javafx.scene.Scene;
5 import javafx.scene.layout.Pane;
6 import javafx.scene.paint.Color;
7 import javafx.scene.shape.Circle;
8 import javafx.stage.Stage;
9
10 public class ConnectedCircles extends Application {
11 @Override // Override the start method in the Application class
12 public void start(Stage primaryStage) {
13 // Create a scene and place it in the stage
14 Scene scene = new Scene(new CirclePane(), 450, 350);
15 primaryStage.setTitle("ConnectedCircles"); // Set the stage title
16 primaryStage.setScene(scene); // Place the scene in the stage
17 primaryStage.show(); // Display the stage
18 }
19
20 /** Pane for displaying circles */
21 class CirclePane extends Pane {
22 public CirclePane() {
23 this.setOnMouseClicked(e -> {
24 if (!isInsideACircle(new Point2D(e.getX(), e.getY()))) {
25 // Add a new circle
26 getChildren().add(new Circle(e.getX(), e.getY(), 20));
27 colorIfConnected();
28 }
29 });
30 }
31 }
32 }
```

create a circle pane

pane for showing circles

handle mouse clicked  
is it inside another circle?

add a new circle  
color if all connected

```

31
32 /** Returns true if the point is inside an existing circle */
33 private boolean isInsideACircle(Point2D p) {
34 for (Node circle: this.getChildren())
35 if (circle.contains(p))
36 return true;
37
38 return false;
39 }
40
41 /** Color all circles if they are connected */
42 private void colorIfConnected() {
43 if (getChildren().size() == 0)
44 return; // No circles in the pane
45
46 // Build the edges
47 java.util.List<AbstractGraph.Edge> edges
48 = new java.util.ArrayList<>();
49 for (int i = 0; i < getChildren().size(); i++)
50 for (int j = i + 1; j < getChildren().size(); j++)
51 if (overlaps((Circle)(getChildren().get(i)),
52 ((Circle)(getChildren().get(j))))) {
53 edges.add(new AbstractGraph.Edge(i, j));
54 edges.add(new AbstractGraph.Edge(j, i));
55 }
56
57 // Create a graph with circles as vertices
58 Graph<Node> graph = new UnweightedGraph<>
59 ((java.util.List<Node>)getChildren(), edges);
60 AbstractGraph<Node>.Tree tree = graph.dfs(0); // a DFS tree
61 boolean isAllCirclesConnected = getChildren().size() == tree
62 .getNumberOfVerticesFound();
63
64 for (Node circle: getChildren()) {
65 if (isAllCirclesConnected) { // All circles are connected
66 ((Circle)circle).setFill(Color.RED);
67 }
68 else {
69 ((Circle)circle).setStroke(Color.BLACK);
70 ((Circle)circle).setFill(Color.WHITE);
71 }
72 }
73 }
74
75
76 public static boolean overlaps(Circle circle1, Circle circle2) {
77 return new Point2D(circle1.getCenterX(), circle1.getCenterY()).
78 distance(circle2.getCenterX(), circle2.getCenterY())
79 <= circle1.getRadius() + circle2.getRadius();
80 }
81 }

```

The JavaFX **Circle** class contains the data fields **x**, **y**, and **radius**, which specify the circle's center location and radius. It also defines the **contains** for testing if a point is in the circle. The **overlaps** method (lines 76–80) checks whether two circles overlap.

When the user clicks the mouse outside of any existing circle, a new circle is created centered at the mouse point and the circle is added to the pane (line 26).

To detect whether the circles are connected, the program constructs a graph (lines 46–59). The circles are the vertices of the graph. The edges are constructed in lines 49–55. Two circle

vertices are connected if they overlap (line 51). The DFS of the graph results in a tree (line 60). The tree's `getNumberOfVerticesFound()` returns the number of vertices searched. If it is equal to the number of circles, all circles are connected (lines 61–62).

**28.18** How is a graph created for the connected circles problem?

**28.19** When you click the mouse inside a circle, does the program create a new circle?

**28.20** How does the program know if all circles are connected?



## 28.9 Breadth-First Search (BFS)

*The breadth-first search of a graph visits the vertices level by level. The first level consists of the starting vertex. Each next level consists of the vertices adjacent to the vertices in the preceding level.*



The breadth-first traversal of a graph is like the breadth-first traversal of a tree discussed in Section 25.2.4, Tree Traversal. With breadth-first traversal of a tree, the nodes are visited level by level. First the root is visited, then all the children of the root, then the grandchildren of the root, and so on. Similarly, the breadth-first search of a graph first visits a vertex, then all its adjacent vertices, then all the vertices adjacent to those vertices, and so on. To ensure that each vertex is visited only once, it skips a vertex if it has already been visited.

### 28.9.1 Breadth-First Search Algorithm

The algorithm for the breadth-first search starting from vertex  $v$  in a graph is described in Listing 28.11.

#### LISTING 28.11 Breadth-First Search Algorithm

Input:  $G = (V, E)$  and a starting vertex  $v$   
Output: a BFS tree rooted at  $v$

```

1 Tree bfs(vertex v) {
2 create an empty queue for storing vertices to be visited;
3 add v into the queue;
4 mark v visited;
5
6 while (the queue is not empty) {
7 dequeue a vertex, say u, from the queue;
8 add u into a list of traversed vertices;
9 for each neighbor w of u
10 if w has not been visited {
11 add w into the queue;
12 set u as the parent for w in the tree;
13 mark w visited;
14 }
15 }
16 }

```

create a queue  
enqueue  $v$

dequeue into  $u$   
 $u$  traversed  
check a neighbor  $w$   
 $w$  visited?  
enqueue  $w$

Consider the graph in Figure 28.15a. Suppose you start the breadth-first search from vertex 0. First visit 0, then visit all its neighbors, 1, 2, and 3, as shown in Figure 28.15b. Vertex 1 has three neighbors: 0, 2, and 4. Since 0 and 2 have already been visited, you will now visit just 4, as shown in Figure 28.15c. Vertex 2 has three neighbors, 0, 1, and 3, which have all been visited. Vertex 3 has three neighbors, 0, 2, and 4, which have all been visited. Vertex 4 has two neighbors, 1 and 3, which have all been visited. Hence, the search ends.

Since each edge and each vertex is visited only once, the time complexity of the `bfs` method is  $O(|E| + |V|)$ , where  $|E|$  denotes the number of edges and  $|V|$  the number of vertices.

BFS time complexity



**FIGURE 28.15** Breadth-first search visits a node, then its neighbors, then its neighbors's neighbors, and so on.

### 28.9.2 Implementation of Breadth-First Search

The `bfs(int v)` method is defined in the `Graph` interface and implemented in the `AbstractGraph` class in Listing 28.3 (lines 197–222). It returns an instance of the `Tree` class with vertex `v` as the root. The method stores the vertices searched in the list `searchOrder` (line 198), the parent of each vertex in the array `parent` (line 199), uses a linked list for a queue (lines 203–204), and uses the `isVisited` array to indicate whether a vertex has been visited (line 207). The search starts from vertex `v`. `v` is added to the queue in line 206 and is marked as visited (line 207). The method now examines each vertex `u` in the queue (line 210) and adds it to `searchOrder` (line 211). The method adds each unvisited neighbor `e.v` of `u` to the queue (line 214), sets its parent to `u` (line 215), and marks it as visited (line 216).

Listing 28.12 gives a test program that displays a BFS for the graph in Figure 28.1 starting from Chicago. The graphical illustration of the BFS starting from Chicago is shown in Figure 28.16. For an interactive GUI demo of BFS, go to [www.cs.armstrong.edu/liang/animation/USMapSearch.html](http://www.cs.armstrong.edu/liang/animation/USMapSearch.html).

#### LISTING 28.12 TestBFS.java

```

vertices
1 public class TestBFS {
2 public static void main(String[] args) {
3 String[] vertices = {"Seattle", "San Francisco", "Los Angeles",
4 "Denver", "Kansas City", "Chicago", "Boston", "New York",
5 "Atlanta", "Miami", "Dallas", "Houston"};
6
edges
7 int[][] edges = {
8 {0, 1}, {0, 3}, {0, 5},
9 {1, 0}, {1, 2}, {1, 3},
10 {2, 1}, {2, 3}, {2, 4}, {2, 10},
11 {3, 0}, {3, 1}, {3, 2}, {3, 4}, {3, 5},
12 {4, 2}, {4, 3}, {4, 5}, {4, 7}, {4, 8}, {4, 10},
13 {5, 0}, {5, 3}, {5, 4}, {5, 6}, {5, 7},
14 {6, 5}, {6, 7},
15 {7, 4}, {7, 5}, {7, 6}, {7, 8},
16 {8, 4}, {8, 7}, {8, 9}, {8, 10}, {8, 11},
17 {9, 8}, {9, 11},
18 {10, 2}, {10, 4}, {10, 8}, {10, 11},
19 {11, 8}, {11, 9}, {11, 10}
20 };
21
create a graph
22 Graph<String> graph = new UnweightedGraph<>(vertices, edges);
23 AbstractGraph<String>.Tree bfs =
24 graph.bfs(graph.getIndex("Chicago"));
25
create a BFS tree
26 java.util.List<Integer> searchOrders = bfs.getSearchOrder();
get search order

```

```

27 System.out.println(bfs.getNumberOfVerticesFound() +
28 " vertices are searched in this order:");
29 for (int i = 0; i < searchOrders.size(); i++)
30 System.out.println(graph.getVertex(searchOrders.get(i)));
31
32 for (int i = 0; i < searchOrders.size(); i++)
33 if (bfs.getParent(i) != -1)
34 System.out.println("parent of " + graph.getVertex(i) +
35 " is " + graph.getVertex(bfs.getParent(i)));
36 }
37 }
```

```

12 vertices are searched in this order:
Chicago Seattle Denver Kansas City Boston New York
San Francisco Los Angeles Atlanta Dallas Miami Houston
parent of Seattle is Chicago
parent of San Francisco is Seattle
parent of Los Angeles is Denver
parent of Denver is Chicago
parent of Kansas City is Chicago
parent of Boston is Chicago
parent of New York is Chicago
parent of Atlanta is Kansas City
parent of Miami is Atlanta
parent of Dallas is Kansas City
parent of Houston is Atlanta
```



### 28.9.3 Applications of the BFS

Many of the problems solved by the DFS can also be solved using the BFS. Specifically, the BFS can be used to solve the following problems:

- Detecting whether a graph is connected. A graph is connected if there is a path between any two vertices in the graph.
- Detecting whether there is a path between two vertices.
- Finding a shortest path between two vertices. You can prove that the path between the root and any node in the BFS tree is a shortest path between the root and the node. (See Check Point Question 28.25.)
- Finding all connected components. A connected component is a maximal connected subgraph in which every pair of vertices are connected by a path.
- Detecting whether there is a cycle in the graph (see Programming Exercise 28.6).
- Finding a cycle in the graph (see Programming Exercise 28.7).
- Testing whether a graph is bipartite. (A graph is bipartite if the vertices of the graph can be divided into two disjoint sets such that no edges exist between vertices in the same set.) (See Programming Exercise 28.8.)

**28.21** What is the return type from invoking `bfs(v)`?

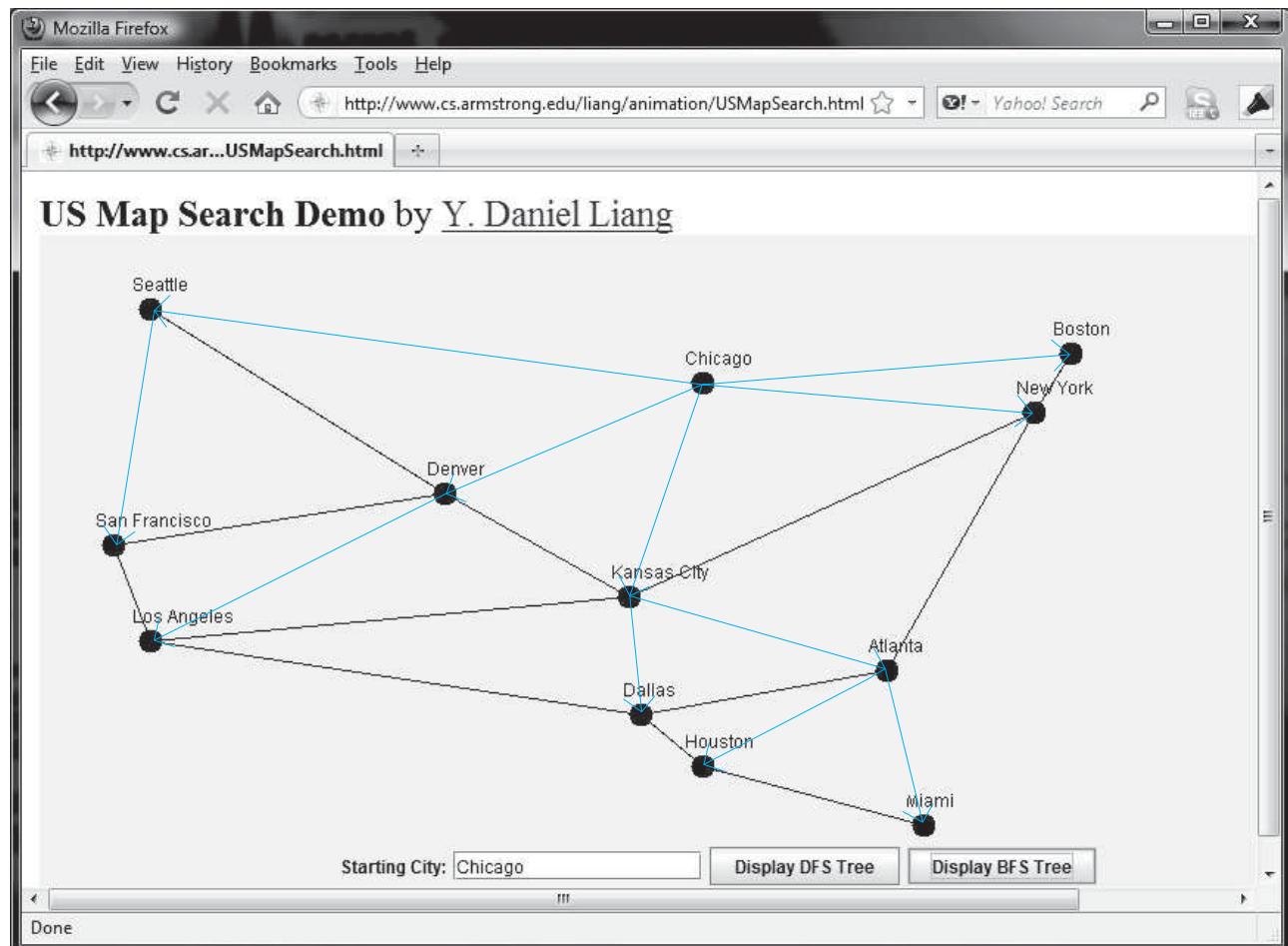
**28.22** What is breadth-first search?

**28.23** Draw a BFS tree for the graph in Figure 28.3b starting from node **A**.

**28.24** Draw a BFS tree for the graph in Figure 28.1 starting from vertex **Atlanta**.

**28.25** Prove that the path between the root and any node in the BFS tree is a shortest path between the root and the node.





**FIGURE 28.16** BFS search starts from Chicago.

## 28.10 Case Study: The Nine Tails Problem



*The nine tails problem can be reduced to the shortest path problem.*

The nine tails problem is as follows. Nine coins are placed in a three-by-three matrix with some face up and some face down. A legal move is to take a coin that is face up and reverse it, together with the coins adjacent to it (this does not include coins that are diagonally adjacent). Your task is to find the minimum number of moves that lead to all coins being face down. For example, start with the nine coins as shown in Figure 28.17a. After you flip the second coin in the last row, the nine coins are now as shown in Figure 28.17b. After you flip the second coin in the first row, the nine coins are all face down, as shown in Figure 28.17c.

|                                                                                                                                                                                                    |     |     |   |   |   |   |   |   |   |                                                                                                                                                                                                    |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                    |   |   |   |   |   |   |   |   |   |
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| T                                                                                                                                                                                                  | T   | T   |   |   |   |   |   |   |   |                                                                                                                                                                                                    |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                    |   |   |   |   |   |   |   |   |   |
| H                                                                                                                                                                                                  | H   | H   |   |   |   |   |   |   |   |                                                                                                                                                                                                    |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                    |   |   |   |   |   |   |   |   |   |
| H                                                                                                                                                                                                  | H   | H   |   |   |   |   |   |   |   |                                                                                                                                                                                                    |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                    |   |   |   |   |   |   |   |   |   |
| T                                                                                                                                                                                                  | H   | T   |   |   |   |   |   |   |   |                                                                                                                                                                                                    |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                    |   |   |   |   |   |   |   |   |   |
| T                                                                                                                                                                                                  | T   | T   |   |   |   |   |   |   |   |                                                                                                                                                                                                    |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                    |   |   |   |   |   |   |   |   |   |
| T                                                                                                                                                                                                  | T   | T   |   |   |   |   |   |   |   |                                                                                                                                                                                                    |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                    |   |   |   |   |   |   |   |   |   |
| T                                                                                                                                                                                                  | T   | T   |   |   |   |   |   |   |   |                                                                                                                                                                                                    |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                    |   |   |   |   |   |   |   |   |   |
| T                                                                                                                                                                                                  | T   | T   |   |   |   |   |   |   |   |                                                                                                                                                                                                    |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                    |   |   |   |   |   |   |   |   |   |
| (a)                                                                                                                                                                                                | (b) | (c) |   |   |   |   |   |   |   |                                                                                                                                                                                                    |   |   |   |   |   |   |   |   |   |                                                                                                                                                                                                    |   |   |   |   |   |   |   |   |   |

**FIGURE 28.17** The problem is solved when all coins are face down.

We will write a program that prompts the user to enter an initial state of the nine coins and displays the solution, as shown in the following sample run.



Enter the initial nine coins Hs and Ts: HHHHTTHHH

The steps to flip the coins are

HHH

TTT

HHH

HHH

THT

TTT

TTT

TTT

TTT

Each state of the nine coins represents a node in the graph. For example, the three states in Figure 28.17 correspond to three nodes in the graph. For convenience, we use a  $3 \times 3$  matrix to represent all nodes and use **0** for heads and **1** for tails. Since there are nine cells and each cell is either **0** or **1**, there are a total of  $2^9$  (512) nodes, labeled **0, 1, ..., 511**, as shown in Figure 28.18.

|                                                                                                                                                 |   |   |   |   |     |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |       |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |
|-------------------------------------------------------------------------------------------------------------------------------------------------|---|---|---|---|-----|---|---|---|---|-------------------------------------------------------------------------------------------------------------------------------------------------|---|---|---|---|---|---|---|---|---|-------------------------------------------------------------------------------------------------------------------------------------------------|---|---|---|---|---|---|---|---|---|-------------------------------------------------------------------------------------------------------------------------------------------------|---|---|---|---|---|---|---|---|---|-------|-------------------------------------------------------------------------------------------------------------------------------------------------|---|---|---|---|---|---|---|---|---|
| <table border="1"><tr><td>0</td><td>0</td><td>0</td></tr><tr><td>0</td><td>0</td><td>0</td></tr><tr><td>0</td><td>0</td><td>0</td></tr></table> | 0 | 0 | 0 | 0 | 0   | 0 | 0 | 0 | 0 | <table border="1"><tr><td>0</td><td>0</td><td>0</td></tr><tr><td>0</td><td>0</td><td>0</td></tr><tr><td>0</td><td>0</td><td>1</td></tr></table> | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | <table border="1"><tr><td>0</td><td>0</td><td>0</td></tr><tr><td>0</td><td>0</td><td>0</td></tr><tr><td>0</td><td>1</td><td>0</td></tr></table> | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | <table border="1"><tr><td>0</td><td>0</td><td>0</td></tr><tr><td>0</td><td>0</td><td>0</td></tr><tr><td>0</td><td>1</td><td>1</td></tr></table> | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | ..... | <table border="1"><tr><td>1</td><td>1</td><td>1</td></tr><tr><td>1</td><td>1</td><td>1</td></tr><tr><td>1</td><td>1</td><td>1</td></tr></table> | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 0                                                                                                                                               | 0 | 0 |   |   |     |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |       |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |
| 0                                                                                                                                               | 0 | 0 |   |   |     |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |       |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |
| 0                                                                                                                                               | 0 | 0 |   |   |     |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |       |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |
| 0                                                                                                                                               | 0 | 0 |   |   |     |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |       |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |
| 0                                                                                                                                               | 0 | 0 |   |   |     |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |       |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |
| 0                                                                                                                                               | 0 | 1 |   |   |     |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |       |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |
| 0                                                                                                                                               | 0 | 0 |   |   |     |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |       |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |
| 0                                                                                                                                               | 0 | 0 |   |   |     |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |       |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |
| 0                                                                                                                                               | 1 | 0 |   |   |     |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |       |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |
| 0                                                                                                                                               | 0 | 0 |   |   |     |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |       |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |
| 0                                                                                                                                               | 0 | 0 |   |   |     |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |       |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |
| 0                                                                                                                                               | 1 | 1 |   |   |     |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |       |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |
| 1                                                                                                                                               | 1 | 1 |   |   |     |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |       |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |
| 1                                                                                                                                               | 1 | 1 |   |   |     |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |       |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |
| 1                                                                                                                                               | 1 | 1 |   |   |     |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |       |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |
| 0                                                                                                                                               | 1 | 2 | 3 |   | 511 |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |       |                                                                                                                                                 |   |   |   |   |   |   |   |   |   |

**FIGURE 28.18** There are total of 512 nodes labeled in this order: **0, 1, 2, ..., 511**.

We assign an edge from node **v** to **u** if there is a legal move from **u** to **v**. Figure 28.19 shows a partial graph. Note there is an edge from **511** to **47**, since you can flip a cell in node **47** to become node **511**.

The last node in Figure 28.18 represents the state of nine face-down coins. For convenience, we call this last node the *target node*. Thus, the target node is labeled **511**. Suppose the initial state of the nine tails problem corresponds to the node **s**. The problem is reduced to finding a shortest path from node **s** to the target node, which is equivalent to finding a shortest path from node **s** to the target node in a BFS tree rooted at the target node.

Now the task is to build a graph that consists of 512 nodes labeled **0, 1, 2, ..., 511**, and edges among the nodes. Once the graph is created, obtain a BFS tree rooted at node **511**. From the BFS tree, you can find a shortest path from the root to any vertex. We will create a class named **NineTailModel**, which contains the method to get a shortest path from the target node to any other node. The class UML diagram is shown in Figure 28.20.

Visually, a node is represented in a  $3 \times 3$  matrix with the letters **H** and **T**. In our program, we use a single-dimensional array of nine characters to represent a node. For example, the node for vertex **1** in Figure 28.18 is represented as `{'H', 'H', 'H', 'H', 'H', 'H', 'H', 'H', 'T'}` in the array.

The **getEdges()** method returns a list of **Edge** objects.

The **getNode(index)** method returns the node for the specified index. For example, **getNode(0)** returns the node that contains nine **Hs**. **getNode(511)** returns the node that contains nine **Ts**. The **getIndex(node)** method returns the index of the node.

Note that the data field **tree** is defined as protected so that it can be accessed from the **WeightedNineTail** subclass in the next chapter.

The **getFlippedNode(char[] node, int position)** method flips the node at the specified position and its adjacent positions. This method returns the index of the new node.

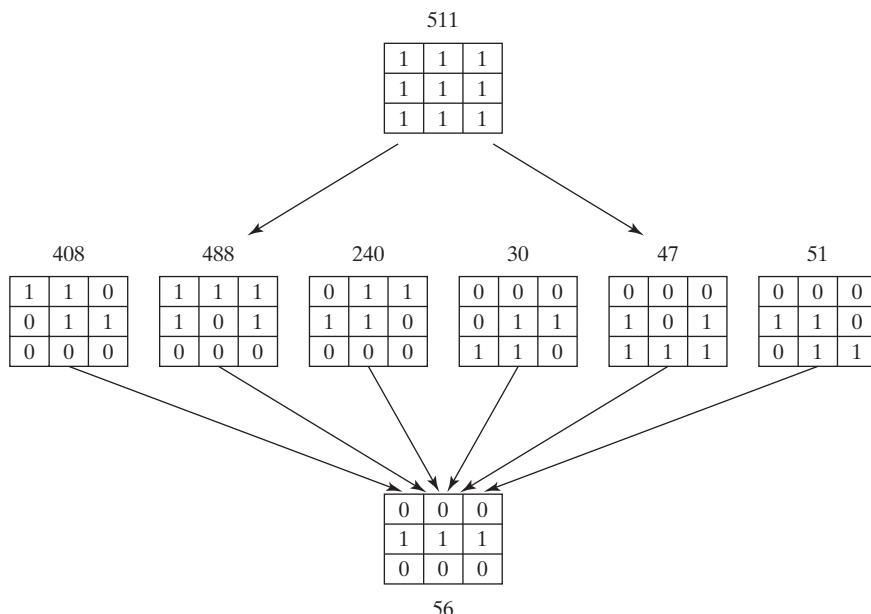
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The position is a value from **0** to **8**, which points to a coin in the node, as shown in the following figure.



For example, for node **56** in Figure 28.19, flip it at position **0**, and you will get node **51**. If you flip node **56** at position **1**, you will get node **47**.

The **flipACell(char[] node, int row, int column)** method flips a node at the specified row and column. For example, if you flip node **56** at row **0** and column **0**, the new node is **408**. If you flip node **56** at row **2** and column **0**, the new node is **30**.



**FIGURE 28.19** If node **u** becomes node **v** after cells are flipped, assign an edge from **v** to **u**.

| NineTailModel                                         |                                                                                                                |
|-------------------------------------------------------|----------------------------------------------------------------------------------------------------------------|
| #tree: AbstractGraph<Integer>.Tree                    | A tree rooted at node 511.                                                                                     |
| +NineTailModel()                                      | Constructs a model for the nine tails problem and obtains the tree.                                            |
| +getShortestPath(nodeIndex: int): List<Integer>       | Returns a path from the specified node to the root. The path returned consists of the node labels in a list.   |
| -getEdges(): List<AbstractGraph.Edge>                 | Returns a list of Edge objects for the graph.                                                                  |
| +getNode(index: int): char[]                          | Returns a node consisting of nine characters of Hs and Ts.                                                     |
| +getIndex(node: char[]): int                          | Returns the index of the specified node.                                                                       |
| +getFlippedNode(node: char[], position: int): int     | Flips the node at the specified position and its adjacent positions and returns the index of the flipped node. |
| +flipACell(node: char[], row: int, column: int): void | Flips the node at the specified row and column.                                                                |
| +printNode(node: char[]): void                        | Displays the node on the console.                                                                              |

**FIGURE 28.20** The **NineTailModel** class models the nine tails problem using a graph.

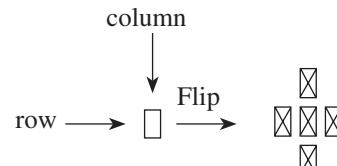
Listing 28.13 shows the source code for NineTailModel.java.

### LISTING 28.13 NineTailModel.java

```

1 import java.util.*;
2
3 public class NineTailModel {
4 public final static int NUMBER_OF_NODES = 512;
5 protected AbstractGraph<Integer>.Tree tree; // Define a tree declare a tree
6
7 /** Construct a model */
8 public NineTailModel() {
9 // Create edges
10 List<AbstractGraph.Edge> edges = getEdges(); create edges
11
12 // Create a graph
13 UnweightedGraph<Integer> graph = new UnweightedGraph<>(
14 edges, NUMBER_OF_NODES); create graph
15
16 // Obtain a BSF tree rooted at the target node
17 tree = graph.bfs(511); create tree
18 }
19
20 /** Create all edges for the graph */
21 private List<AbstractGraph.Edge> getEdges() { get edges
22 List<AbstractGraph.Edge> edges =
23 new ArrayList<>(); // Store edges
24
25 for (int u = 0; u < NUMBER_OF_NODES; u++) {
26 for (int k = 0; k < 9; k++) {
27 char[] node = getNode(u); // Get the node for vertex u
28 if (node[k] == 'H') {
29 int v = getFlippedNode(node, k);
30 // Add edge (v, u) for a legal move from node u to node v
31 edges.add(new AbstractGraph.Edge(v, u)); add an edge
32 }
33 }
34 }
35
36 return edges;
37 }
38
39 public static int getFlippedNode(char[] node, int position) { flip cells
40 int row = position / 3;
41 int column = position % 3;
42
43 flipACell(node, row, column); column
44 flipACell(node, row - 1, column); ↓
45 flipACell(node, row + 1, column); Flip
46 flipACell(node, row, column - 1); row → □ →
47 flipACell(node, row, column + 1); □□□
48
49 return getIndex(node);
50 }
51
52 public static void flipACell(char[] node, int row, int column) { flip a cell
53 if (row >= 0 && row <= 2 && column >= 0 && column <= 2) {
54 // Within the boundary
55 if (node[row * 3 + column] == 'H')
56 node[row * 3 + column] = 'T'; // Flip from H to T

```



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```

57 else
58 node[row * 3 + column] = 'H'; // Flip from T to H
59 }
60 }
61
get index for a node
62 public static int getIndex(char[] node) {
63 int result = 0;
64
65 for (int i = 0; i < 9; i++)
66 if (node[i] == 'T')
67 result = result * 2 + 1;
68 else
69 result = result * 2 + 0;
70
71 return result;
72 }
73
74 public static char[] getNode(int index) {
75 char[] result = new char[9];
76
77 for (int i = 0; i < 9; i++) {
78 int digit = index % 2;
79 if (digit == 0)
80 result[8 - i] = 'H';
81 else
82 result[8 - i] = 'T';
83 index = index / 2;
84 }
85
86 return result;
87 }
88
89 public List<Integer> getShortestPath(int nodeIndex) {
90 return tree.getPath(nodeIndex);
91 }
92
93 public static void printNode(char[] node) {
94 for (int i = 0; i < 9; i++)
95 if (i % 3 != 2)
96 System.out.print(node[i]);
97 else
98 System.out.println(node[i]);
99
100 System.out.println();
101 }
102 }
```

For example:  
index: 3  
node: HHHHHHHTT

|   |   |   |
|---|---|---|
| H | H | H |
| H | H | H |
| H | T | T |

For example:  
node: THHHHHHTT  
index: 259

|   |   |   |
|---|---|---|
| T | H | H |
| H | H | H |
| H | T | T |

shortest path

display a node

For example:  
node: THHHHHHTT  
Output:

|   |   |   |
|---|---|---|
| T | H | H |
| H | H | H |
| H | T | T |

The constructor (lines 8–18) creates a graph with 512 nodes, and each edge corresponds to the move from one node to the other (line 10). From the graph, a BFS tree rooted at the target node 511 is obtained (line 17).

To create edges, the `getEdges` method (lines 21–37) checks each node `u` to see if it can be flipped to another node `v`. If so, add `(v, u)` to the `Edge` list (line 31). The `getFlippedNode(node, position)` method finds a flipped node by flipping an `H` cell and its neighbors in a node (lines 43–47). The `flipACell(node, row, column)` method actually flips an `H` cell and its neighbors in a node (lines 52–60).

The `getIndex(node)` method is implemented in the same way as converting a binary number to a decimal number (lines 62–72). The `getNode(index)` method returns a node consisting of the letters `H` and `T` (lines 74–87).

The `getShortestpath(nodeIndex)` method invokes the `getPath(nodeIndex)` method to get a vertices in a shortest path from the specified node to the target node (lines 89–91).

The `printNode(node)` method displays a node on the console (lines 93–101).

Listing 28.14 gives a program that prompts the user to enter an initial node and displays the steps to reach the target node.

## LISTING 28.14 NineTail.java

```

1 import java.util.Scanner;
2
3 public class NineTail {
4 public static void main(String[] args) {
5 // Prompt the user to enter nine coins' Hs and Ts
6 System.out.print("Enter the initial nine coins Hs and Ts: ");
7 Scanner input = new Scanner(System.in);
8 String s = input.nextLine();
9 char[] initialNode = s.toCharArray(); initial node
10
11 NineTailModel model = new NineTailModel(); create model
12 java.util.List<Integer> path =
13 model.getShortestPath(NineTailModel.getIndex(initialNode)); get shortest path
14
15 System.out.println("The steps to flip the coins are ");
16 for (int i = 0; i < path.size(); i++)
17 NineTailModel.printNode(
18 NineTailModel.getNode(path.get(i).intValue()));
19 }
20 }
```

The program prompts the user to enter an initial node with nine letters with a combination of **H**s and **T**s as a string in line 8, obtains an array of characters from the string (line 9), creates a graph model to get a BFS tree (line 11), obtains a shortest path from the initial node to the target node (lines 12–13), and displays the nodes in the path (lines 16–18).

**28.26** How are the nodes created for the graph in `NineTailModel`?

**28.27** How are the edges created for the graph in `NineTailModel`?

**28.28** What is returned after invoking `getIndex("HTHTTHHH".toCharArray())` in Listing 28.13? What is returned after invoking `getNode(46)` in Listing 28.13?

**28.29** If lines 26 and 27 are swapped in Listing 28.13, `NineTailModel.java`, will the program work? Why?



## KEY TERMS

---

|                      |      |                             |      |
|----------------------|------|-----------------------------|------|
| adjacency list       | 1022 | incident edges              | 1018 |
| adjacency matrix     | 1021 | parallel edge               | 1018 |
| adjacent vertices    | 1018 | Seven Bridges of Königsberg | 1016 |
| breadth-first search | 1037 | simple graph                | 1018 |
| complete graph       | 1018 | spanning tree               | 1018 |
| cycle                | 1018 | tree                        | 1018 |
| degree               | 1018 | undirected graph            | 1017 |
| depth-first search   | 1037 | unweighted graph            | 1018 |
| directed graph       | 1017 | weighted graph              | 1018 |
| graph                | 1016 |                             |      |

## CHAPTER SUMMARY

---

1. A *graph* is a useful mathematical structure that represents relationships among entities in the real world. You learned how to model graphs using classes and interfaces, how to represent vertices and edges using arrays and linked lists, and how to implement operations for graphs.
2. Graph traversal is the process of visiting each vertex in the graph exactly once. You learned two popular ways for traversing a graph: the *depth-first search* (DFS) and *breadth-first search* (BFS).
3. DFS and BFS can be used to solve many problems such as detecting whether a graph is connected, detecting whether there is a cycle in the graph, and finding a shortest path between two vertices.

## Quiz

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Answer the quiz for this chapter online at [www.cs.armstrong.edu/liang/intro10e/quiz.html](http://www.cs.armstrong.edu/liang/intro10e/quiz.html).

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## PROGRAMMING EXERCISES

---

### Sections 28.6–28.10

- \*28.1** (*Test whether a graph is connected*) Write a program that reads a graph from a file and determines whether the graph is connected. The first line in the file contains a number that indicates the number of vertices (**n**). The vertices are labeled as **0, 1, ..., n-1**. Each subsequent line, with the format **u v1 v2 ...**, describes edges **(u, v1)**, **(u, v2)**, and so on. Figure 28.21 gives the examples of two files for their corresponding graphs.



**FIGURE 28.21** The vertices and edges of a graph can be stored in a file.

Your program should prompt the user to enter the name of the file, then it should read data from the file, create an instance **g** of **UnweightedGraph**, invoke **g.printEdges()** to display all edges, and invoke **dfs()** to obtain an instance **tree** of **AbstractGraph.Tree**. If **tree.getNumberOfVerticesFound()** is the same as the number of vertices in the graph, the graph is connected. Here is a sample run of the program:

```
Enter a file name: c:\exercise\GraphSample1.txt [Enter]
The number of vertices is 6
Vertex 0: (0, 1) (0, 2)
Vertex 1: (1, 0) (1, 3)
Vertex 2: (2, 0) (2, 3) (2, 4)
Vertex 3: (3, 1) (3, 2) (3, 4) (3, 5)
Vertex 4: (4, 2) (4, 3) (4, 5)
Vertex 5: (5, 3) (5, 4)
The graph is connected
```



(Hint: Use `new UnweightedGraph(list, numberOfVertices)` to create a graph, where `list` contains a list of `AbstractGraph.Edge` objects. Use `new AbstractGraph.Edge(u, v)` to create an edge. Read the first line to get the number of vertices. Read each subsequent line into a string `s` and use `s.split("[\\s+])` to extract the vertices from the string and create edges from the vertices.)

- \*28.2** (*Create a file for a graph*) Modify Listing 28.1, `TestGraph.java`, to create a file representing `graph1`. The file format is described in Programming Exercise 28.1. Create the file from the array defined in lines 8–21 in Listing 28.1. The number of vertices for the graph is `12`, which will be stored in the first line of the file. The contents of the file should be as follows:

```
12
0 1 3 5
1 0 2 3
2 1 3 4 10
3 0 1 2 4 5
4 2 3 5 7 8 10
5 0 3 4 6 7
6 5 7
7 4 5 6 8
8 4 7 9 10 11
9 8 11
10 2 4 8 11
11 8 9 10
```

- \*28.3** (*Implement DFS using a stack*) The depth-first search algorithm described in Listing 28.8 uses recursion. Design a new algorithm without using recursion. Describe it using pseudocode. Implement it by defining a new class named `UnweightedGraphWithNonrecursiveDFS` that extends `UnweightedGraph` and overriding the `dfs` method.

- \*28.4** (*Find connected components*) Create a new class named `MyGraph` as a subclass of `UnweightedGraph` that contains a method for finding all connected components in a graph with the following header:

```
public List<List<Integer>> getConnectedComponents();
```

The method returns a `List<List<Integer>>`. Each element in the list is another list that contains all the vertices in a connected component. For example, for the graph in Figure 28.21b, `getConnectedComponents()` returns `[[0, 1, 2, 3], [4, 5]]`.

- \*28.5** (*Find paths*) Add a new method in **AbstractGraph** to find a path between two vertices with the following header:

```
public List<Integer> getPath(int u, int v);
```

The method returns a **List<Integer>** that contains all the vertices in a path from **u** to **v** in this order. Using the BFS approach, you can obtain a shortest path from **u** to **v**. If there isn't a path from **u** to **v**, the method returns **null**.

- \*28.6** (*Detect cycles*) Add a new method in **AbstractGraph** to determine whether there is a cycle in the graph with the following header:

```
public boolean isCyclic();
```

- \*28.7** (*Find a cycle*) Add a new method in **AbstractGraph** to find a cycle in the graph with the following header:

```
public List<Integer> getACycle(int u);
```

The method returns a **List** that contains all the vertices in a cycle starting from **u**. If the graph doesn't have any cycles, the method returns **null**.

- \*\*28.8** (*Test bipartite*) Recall that a graph is bipartite if its vertices can be divided into two disjoint sets such that no edges exist between vertices in the same set. Add a new method in **AbstractGraph** with the following header to detect whether the graph is bipartite:

```
public boolean isBipartite();
```

- \*\*28.9** (*Get bipartite sets*) Add a new method in **AbstractGraph** with the following header to return two bipartite sets if the graph is bipartite:

```
public List<List<Integer>> getBipartite();
```

The method returns a **List** that contains two sublists, each of which contains a set of vertices. If the graph is not bipartite, the method returns **null**.

- 28.10** (*Find a shortest path*) Write a program that reads a connected graph from a file. The graph is stored in a file using the same format specified in Programming Exercise 28.1. Your program should prompt the user to enter the name of the file, then two vertices, and should display a shortest path between the two vertices. For example, for the graph in Figure 28.21a, a shortest path between **0** and **5** may be displayed as **0 1 3 5**.

Here is a sample run of the program:



```
Enter a file name: c:\exercise\GraphSample1.txt ↵ Enter
Enter two vertices (integer indexes): 0 5 ↵ Enter
The number of vertices is 6
Vertex 0: (0, 1) (0, 2)
Vertex 1: (1, 0) (1, 3)
Vertex 2: (2, 0) (2, 3) (2, 4)
Vertex 3: (3, 1) (3, 2) (3, 4) (3, 5)
Vertex 4: (4, 2) (4, 3) (4, 5)
Vertex 5: (5, 3) (5, 4)
The path is 0 1 3 5
```

- \*\*28.11** (*Revise Listing 28.14, NineTail.java*) The program in Listing 28.14 lets the user enter an input for the nine tails problem from the console and displays the result on the console. Write a program that lets the user set an initial state of the nine coins (see Figure 28.22a) and click the *Solve* button to display the solution, as shown in Figure 28.22b. Initially, the user can click the mouse button to flip a coin. Set a red color on the flipped cells.



FIGURE 28.22 The program solves the nine tails problem.

- \*\*28.12** (*Variation of the nine tails problem*) In the nine tails problem, when you flip a coin, the horizontal and vertical neighboring cells are also flipped. Rewrite the program, assuming that all neighboring cells including the diagonal neighbors are also flipped.

- \*\*28.13** (*4 × 4 16 tails problem*) Listing 28.14, NineTail.java, presents a solution for the nine tails problem. Revise this program for the  $4 \times 4$  16 tails problem. Note that it is possible that a solution may not exist for a starting pattern. If so, report that no solution exists.

- \*\*28.14** (*4 × 4 16 tails analysis*) The nine tails problem in the text uses a  $3 \times 3$  matrix. Assume that you have 16 coins placed in a  $4 \times 4$  matrix. Write a program to find out the number of the starting patterns that don't have a solution.

- \*28.15** (*4 × 4 16 tails GUI*) Rewrite Programming Exercise 28.14 to enable the user to set an initial pattern of the  $4 \times 4$  16 tails problem (see Figure 28.23a). The user can click the *Solve* button to display the solution, as shown in Figure 28.23b. Initially, the user can click the mouse button to flip a coin. If a solution does not exist, display a message to report it.

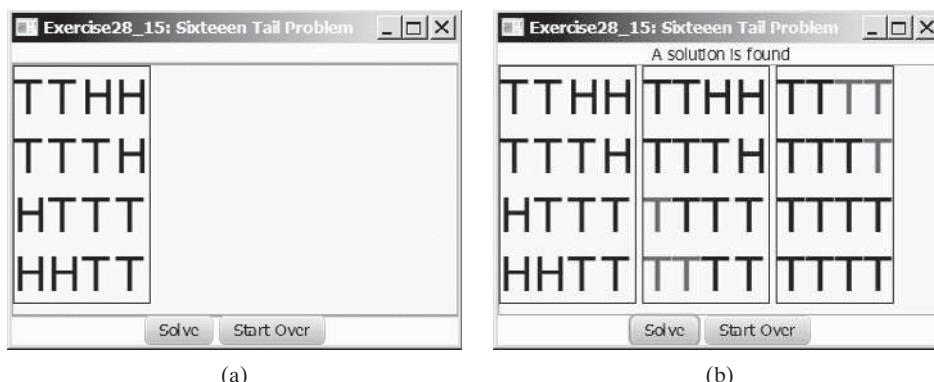


FIGURE 28.23 The problem solves the 16 tails problem.

- \*\*28.16** (*Induced subgraph*) Given an undirected graph  $G = (V, E)$  and an integer  $k$ , find an induced subgraph  $H$  of  $G$  of maximum size such that all vertices of  $H$  have a degree  $\geq k$ , or conclude that no such induced subgraph exists. Implement the method with the following header:

```
public static Graph maxInducedSubgraph(Graph g, int k)
```

The method returns `null` if such a subgraph does not exist.

(*Hint*: An intuitive approach is to remove vertices whose degree is less than  $k$ . As vertices are removed with their adjacent edges, the degrees of other vertices may be reduced. Continue the process until no vertices can be removed, or all the vertices are removed.)

- \*\*\*28.17** (*Hamiltonian cycle*) The Hamiltonian path algorithm is implemented in Supplement VI.E. Add the following `getHamiltonianCycle` method in the `Graph` interface and implement it in the `AbstractGraph` class:

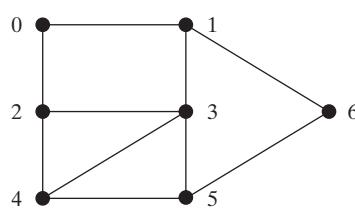
```
/** Return a Hamiltonian cycle
 * Return null if the graph doesn't contain a Hamiltonian cycle */
public List<Integer> getHamiltonianCycle()
```

- \*\*\*28.18** (*Knight's Tour cycle*) Rewrite `KnightTourApp.java` in the case study in Supplement VI.E to find a knight's tour that visits each square in a chessboard and returns to the starting square. Reduce the Knight's Tour cycle problem to the problem of finding a Hamiltonian cycle.

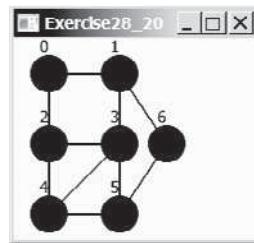
- \*\*28.19** (*Display a DFS/BFS tree in a graph*) Modify `GraphView` in Listing 28.6 to add a new data field `tree` with a set method. The edges in the tree are displayed in red. Write a program that displays the graph in Figure 28.1 and the DFS/BFS tree starting from a specified city, as shown in Figures 28.13 and 28.16. If a city not in the map is entered, the program displays an error message in the label.

- \*28.20** (*Display a graph*) Write a program that reads a graph from a file and displays it. The first line in the file contains a number that indicates the number of vertices (`n`). The vertices are labeled `0, 1, ..., n-1`. Each subsequent line, with the format `u x y v1 v2 ...`, describes the position of `u` at `(x, y)` and edges `(u, v1)`, `(u, v2)`, and so on. Figure 28.24a gives an example of the file for their corresponding graph. Your program prompts the user to enter the name of the file, reads data from the file, and displays the graph on a pane using `GraphView`, as shown in Figure 28.24b.

```
File
7
0 30 30 1 2
1 90 30 0 3 6
2 30 90 0 3 4
3 90 90 1 2 4 5
4 30 150 2 3 5
5 90 150 3 4 6
6 130 90 1 5
```



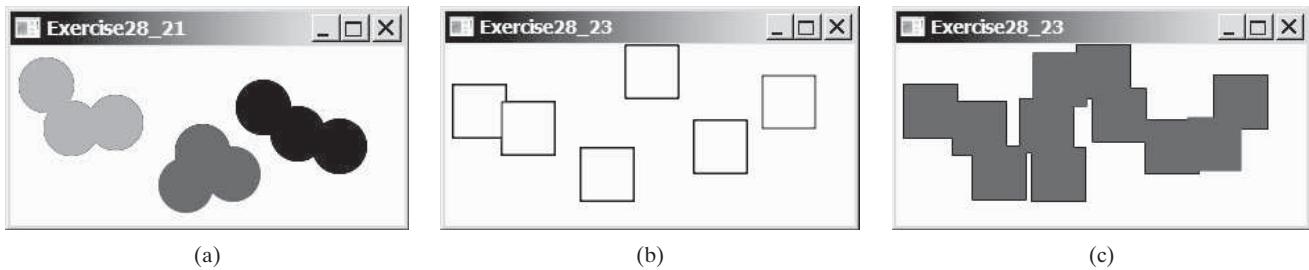
(a)



(b)

FIGURE 28.24 The program reads the information about the graph and displays it visually.

- \*\*28.21** (*Display sets of connected circles*) Modify Listing 28.10, ConnectedCircles.java, to display sets of connected circles in different colors. That is, if two circles are connected, they are displayed using the same color; otherwise, they are not in same color, as shown in Figure 28.25. (*Hint:* See Programming Exercise 28.4.)



**FIGURE 28.25** (a) Connected circles are displayed in the same color. (b) Rectangles are not filled with a color if they are not connected. (c) Rectangles are filled with a color if they are connected.

- \*28.22** (*Move a circle*) Modify Listing 28.10, ConnectedCircles.java, to enable the user to drag and move a circle.

- \*\*28.23** (*Connected rectangles*) Listing 28.10, ConnectedCircles.java, allows the user to create circles and determine whether they are connected. Rewrite the program for rectangles. The program lets the user create a rectangle by clicking a mouse in a blank area that is not currently covered by a rectangle. As the rectangles are added, the rectangles are repainted as filled if they are connected or are unfilled otherwise, as shown in Figure 28.25b–c.

- \*28.24** (*Remove a circle*) Modify Listing 28.10, ConnectedCircles.java, to enable the user to remove a circle when the mouse is clicked inside the circle.

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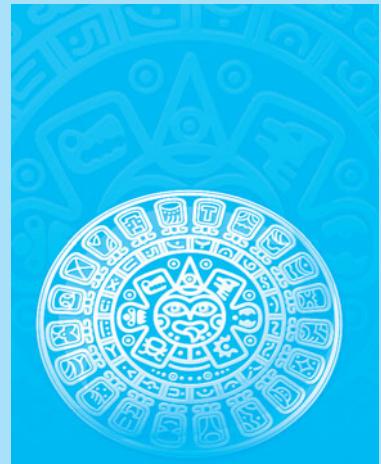
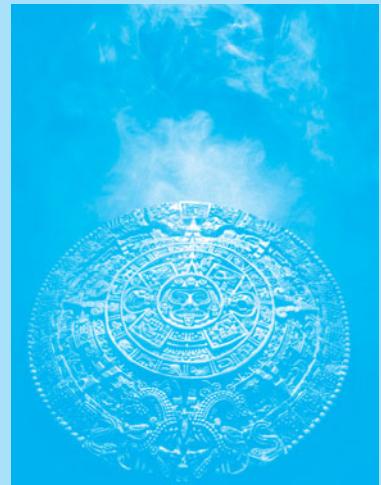
# CHAPTER

# 29

## WEIGHTED GRAPHS AND APPLICATIONS

### Objectives

- To represent weighted edges using adjacency matrices and adjacency lists (§29.2).
- To model weighted graphs using the **WeightedGraph** class that extends the **AbstractGraph** class (§29.3).
- To design and implement the algorithm for finding a minimum spanning tree (§29.4).
- To define the **MST** class that extends the **Tree** class (§29.4).
- To design and implement the algorithm for finding single-source shortest paths (§29.5).
- To define the **ShortestPathTree** class that extends the **Tree** class (§29.5).
- To solve the weighted nine tails problem using the shortest-path algorithm (§29.6).



## 29.1 Introduction



A graph is a weighted graph if each edge is assigned a weight. Weighted graphs have many practical applications.

Figure 28.1 assumes that the graph represents the number of flights among cities. You can apply the BFS to find the fewest number of flights between two cities. Assume that the edges represent the driving distances among the cities as shown in Figure 29.1. How do you find the minimal total distances for connecting all cities? How do you find the shortest path between two cities? This chapter will address these questions. The former is known as the *minimum spanning tree (MST) problem* and the latter as the *shortest path problem*.



**FIGURE 29.1** The graph models the distances among the cities.

The preceding chapter introduced the concept of graphs. You learned how to represent edges using edge arrays, edge lists, adjacency matrices, and adjacency lists, and how to model a graph using the `Graph` interface, the `AbstractGraph` class, and the `UnweightedGraph` class. The preceding chapter also introduced two important techniques for traversing graphs: depth-first search and breadth-first search, and applied traversal to solve practical problems. This chapter will introduce weighted graphs. You will learn the algorithm for finding a minimum spanning tree in Section 29.4 and the algorithm for finding shortest paths in Section 29.5.

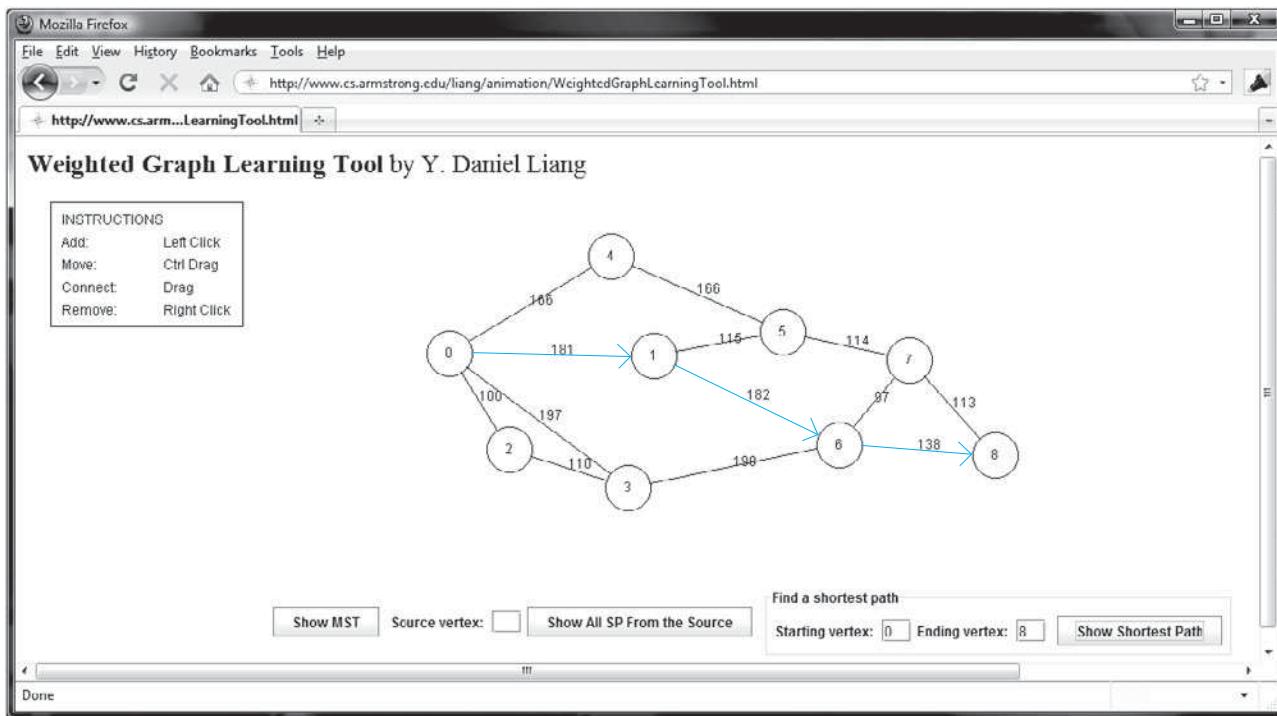


weighted graph learning tool  
on Companion Website



### Pedagogical Note

Before we introduce the algorithms and applications for weighted graphs, it is helpful to get acquainted with weighted graphs using the GUI interactive tool at [www.cs.armstrong.edu/liang/animation/WeightedGraphLearningTool.html](http://www.cs.armstrong.edu/liang/animation/WeightedGraphLearningTool.html), as shown in Figure 29.2. The tool allows you to enter vertices, specify edges and their weights, view the graph, and find an MST and all shortest paths from a single source, as shown in Figure 29.2.



**FIGURE 29.2** You can use the tool to create a weighted graph with mouse gestures and show the MST and shortest paths.

## 29.2 Representing Weighted Graphs

*Weighted edges can be stored in adjacency lists.*

There are two types of weighted graphs: vertex weighted and edge weighted. In a *vertex-weighted graph*, each vertex is assigned a weight. In an *edge-weighted graph*, each edge is assigned a weight. Of the two types, edge-weighted graphs have more applications. This chapter considers edge-weighted graphs.

Weighted graphs can be represented in the same way as unweighted graphs, except that you have to represent the weights on the edges. As with unweighted graphs, the vertices in weighted graphs can be stored in an array. This section introduces three representations for the edges in weighted graphs.

### 29.2.1 Representing Weighted Edges: Edge Array

Weighted edges can be represented using a two-dimensional array. For example, you can store all the edges in the graph in Figure 29.3a using the array in Figure 29.3b.



vertex-weighted graph  
edge-weighted graph

#### Note

Weights can be of any type: `Integer`, `Double`, `BigDecimal`, and so on. You can use a two-dimensional array of the `Object` type to represent weighted edges as follows:

```
Object[][] edges = {
 {new Integer(0), new Integer(1), new SomeTypeForWeight(2)},
 {new Integer(0), new Integer(3), new SomeTypeForWeight(8)},
 ...
};
```

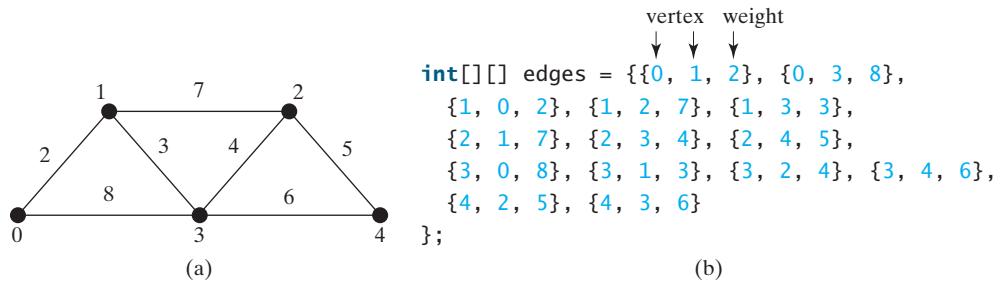


FIGURE 29.3 Each edge is assigned a weight in an edge-weighted graph.

### 29.2.2 Weighted Adjacency Matrices

Assume that the graph has  $n$  vertices. You can use a two-dimensional  $n \times n$  matrix, say **weights**, to represent the weights on edges. **weights[i][j]** represents the weight on edge (*i*, *j*). If vertices *i* and *j* are not connected, **weights[i][j]** is **null**. For example, the weights in the graph in Figure 29.3a can be represented using an adjacency matrix as follows:

```

Integer[][] adjacencyMatrix = {
 {null, 2, null, 8, null},
 {2, null, 7, 3, null},
 {null, 7, null, 4, 5},
 {8, 3, 4, null, 6},
 {null, null, 5, 6, null}
};

```

|   | 0    | 1    | 2    | 3    | 4    |
|---|------|------|------|------|------|
| 0 | null | 2    | null | 8    | null |
| 1 | 2    | null | 7    | 3    | null |
| 2 | null | 7    | null | 4    | 5    |
| 3 | 8    | 3    | 4    | null | 6    |
| 4 | null | null | 5    | 6    | null |

### 29.2.3 Adjacency Lists

Another way to represent the edges is to define edges as objects. The **AbstractGraph.Edge** class was defined to represent an unweighted edge in Listing 28.3. For weighted edges, we define the **WeightedEdge** class as shown in Listing 29.1.

#### LISTING 29.1 WeightedEdge.java

```

1 public class WeightedEdge extends AbstractGraph.Edge
2 implements Comparable<WeightedEdge> {
3 public double weight; // The weight on edge (u, v)
4
5 /** Create a weighted edge on (u, v) */
6 public WeightedEdge(int u, int v, double weight) {
7 super(u, v);
8 this.weight = weight;
9 }
10
11 @Override /** Compare two edges on weights */
12 public int compareTo(WeightedEdge edge) {
13 if (weight > edge.weight)
14 return 1;
15 else if (weight == edge.weight)
16 return 0;
17 else
18 return -1;
19 }
20 }

```

edge weight

constructor

compare edges

**AbstractGraph.Edge** is an inner class defined in the **AbstractGraph** class. It represents an edge from vertex **u** to **v**. **WeightedEdge** extends **AbstractGraph.Edge** with a new property **weight**.

To create a **WeightedEdge** object, use **new WeightedEdge(i, j, w)**, where **w** is the weight on edge **(i, j)**. Often you need to compare the weights of the edges. For this reason, the **WeightedEdge** class implements the **Comparable** interface.

For unweighted graphs, we use adjacency lists to represent edges. For weighted graphs, we still use adjacency lists, the adjacency lists for the vertices in the graph in Figure 29.3a can be represented as follows:

```
java.util.List<WeightedEdge>[] list = new java.util.List[5];
```

|         |                       |                       |                       |                       |
|---------|-----------------------|-----------------------|-----------------------|-----------------------|
| list[0] | WeightedEdge(0, 1, 2) | WeightedEdge(0, 3, 8) |                       |                       |
| list[1] | WeightedEdge(1, 0, 2) | WeightedEdge(1, 2, 3) | WeightedEdge(1, 2, 7) |                       |
| list[2] | WeightedEdge(2, 3, 4) | WeightedEdge(2, 4, 5) | WeightedEdge(2, 1, 7) |                       |
| list[3] | WeightedEdge(3, 1, 3) | WeightedEdge(3, 2, 4) | WeightedEdge(3, 4, 6) | WeightedEdge(3, 0, 8) |
| list[4] | WeightedEdge(4, 2, 5) | WeightedEdge(4, 3, 6) |                       |                       |

**list[i]** stores all edges adjacent to vertex **i**.

For flexibility, we will use an array list rather than a fixed-sized array to represent **list** as follows:

```
List<List<WeightedEdge>> list = new java.util.ArrayList<>();
```

**29.1** For the code **WeightedEdge edge = new WeightedEdge(1, 2, 3.5)**, what is **edge.u**, **edge.v**, and **edge.weight**?



**29.2** What is the output of the following code?

```
List<WeightedEdge> list = new ArrayList<>();
list.add(new WeightedEdge(1, 2, 3.5));
list.add(new WeightedEdge(2, 3, 4.5));
WeightedEdge e = java.util.Collections.max(list);
System.out.println(e.u);
System.out.println(e.v);
System.out.println(e.weight);
```

## 29.3 The WeightedGraph Class

The **WeightedGraph** class extends **AbstractGraph**.



The preceding chapter designed the **Graph** interface, the **AbstractGraph** class, and the **UnweightedGraph** class for modeling graphs. Following this pattern, we design **WeightedGraph** as a subclass of **AbstractGraph**, as shown in Figure 29.4.

**WeightedGraph** simply extends **AbstractGraph** with five constructors for creating concrete **WeightedGraph** instances. **WeightedGraph** inherits all methods from **AbstractGraph**, overrides the **clear** and **addVertex** methods, implements a new **addEdge** method for adding a weighted edge, and also introduces new methods for obtaining minimum spanning trees and for finding all single-source shortest paths. Minimum spanning trees and shortest paths will be introduced in Sections 29.4 and 29.5, respectively.

Listing 29.2 implements **WeightedGraph**. Edge adjacency lists (lines 38–63) are used internally to store adjacent edges for a vertex. When a **WeightedGraph** is constructed, its edge

FIGURE 29.4 `WeightedGraph` extends `AbstractGraph`.

adjacency lists are created (lines 47 and 57). The methods `getMinimumSpanningTree()` (lines 99–138) and `getShortestPath()` (lines 156–197) will be introduced in upcoming sections.

### LISTING 29.2 `WeightedGraph.java`

```

1 import java.util.*;
2
3 public class WeightedGraph<V> extends AbstractGraph<V> {
4 /** Construct an empty */
5 public WeightedGraph() {
6 }
7
8 /** Construct a WeightedGraph from vertices and edged in arrays */
9 public WeightedGraph(V[] vertices, int[][] edges) {
10 createWeightedGraph(java.util.Arrays.asList(vertices), edges);
11 }
12
13 /** Construct a WeightedGraph from vertices and edges in list */
14 public WeightedGraph(int[][] edges, int numberVertices) {
15 List<V> vertices = new ArrayList<>();
16 for (int i = 0; i < numberVertices; i++)
17 vertices.add((V)(new Integer(i)));
18
19 createWeightedGraph(vertices, edges);
20 }
21

```

no-arg constructor

constructor

constructor

```

22 /** Construct a WeightedGraph for vertices 0, 1, 2 and edge list */
23 public WeightedGraph(List<V> vertices, List<WeightedEdge> edges) { constructor
24 createWeightedGraph(vertices, edges);
25 }
26
27 /** Construct a WeightedGraph from vertices 0, 1, and edge array */
28 public WeightedGraph(List<WeightedEdge> edges, constructor
29 int numberofVertices) {
30 List<V> vertices = new ArrayList<>();
31 for (int i = 0; i < numberofVertices; i++)
32 vertices.add((V)(new Integer(i)));
33
34 createWeightedGraph(vertices, edges);
35 }
36
37 /** Create adjacency lists from edge arrays */
38 private void createWeightedGraph(List<V> vertices, int[][] edges) {
39 this.vertices = vertices;
40
41 for (int i = 0; i < vertices.size(); i++) {
42 neighbors.add(new ArrayList<Edge>()); // Create a list for vertices create list for vertices
43 }
44
45 for (int i = 0; i < edges.length; i++) {
46 neighbors.get(edges[i][0]).add(
47 new WeightedEdge(edges[i][0], edges[i][1], edges[i][2])); create a weighted edge
48 }
49 }
50
51 /** Create adjacency lists from edge lists */
52 private void createWeightedGraph(
53 List<V> vertices, List<WeightedEdge> edges) {
54 this.vertices = vertices;
55
56 for (int i = 0; i < vertices.size(); i++) {
57 neighbors.add(new ArrayList<Edge>()); // Create a list for vertices create list for vertices
58 }
59
60 for (WeightedEdge edge: edges) {
61 neighbors.get(edge.u).add(edge); // Add an edge into the list
62 }
63 }
64
65 /** Return the weight on the edge (u, v) */
66 public double getWeight(int u, int v) throws Exception { print edges
67 for (Edge edge : neighbors.get(u)) {
68 if (edge.v == v) {
69 return ((WeightedEdge)edge).weight;
70 }
71 }
72
73 throw new Exception("Edge does not exist");
74 }
75
76 /** Display edges with weights */
77 public void printWeightedEdges() {
78 for (int i = 0; i < getSize(); i++) {
79 System.out.print(getVertex(i) + " (" + i + "): ");
80 for (Edge edge : neighbors.get(i)) {
81 System.out.print("(" + edge.u +

```

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```
82 ", " + edge.v + ", " + ((WeightedEdge)edge).weight + ") ");
83 }
84 System.out.println();
85 }
86 }
87
88 /**
89 * Add edges to the weighted graph */
90 public boolean addEdge(int u, int v, double weight) {
91 return addEdge(new WeightedEdge(u, v, weight));
92 }
93
94 /**
95 * Get a minimum spanning tree rooted at vertex 0 */
96 public MST getMinimumSpanningTree() {
97 return getMinimumSpanningTree(0);
98 }
99
100 /**
101 * Get a minimum spanning tree rooted at a specified vertex */
102 public MST getMinimumSpanningTree(int startingVertex) {
103 // cost[v] stores the cost by adding v to the tree
104 double[] cost = new double[getSize()];
105 for (int i = 0; i < cost.length; i++) {
106 cost[i] = Double.POSITIVE_INFINITY; // Initial cost
107 }
108 cost[startingVertex] = 0; // Cost of source is 0
109
110 int[] parent = new int[getSize()]; // Parent of a vertex
111 parent[startingVertex] = -1; // startingVertex is the root
112 double totalWeight = 0; // Total weight of the tree thus far
113
114 List<Integer> T = new ArrayList<>();
115
116 // Expand T
117 while (T.size() < getSize()) {
118 // Find smallest cost v in V - T
119 int u = -1; // Vertex to be determined
120 double currentMinCost = Double.POSITIVE_INFINITY;
121 for (int i = 0; i < getSize(); i++) {
122 if (!T.contains(i) && cost[i] < currentMinCost) {
123 currentMinCost = cost[i];
124 u = i;
125 }
126 }
127
128 T.add(u); // Add a new vertex to T
129 totalWeight += cost[u]; // Add cost[u] to the tree
130
131 // Adjust cost[v] for v that is adjacent to u and v in V - T
132 for (Edge e : neighbors.get(u)) {
133 if (!T.contains(e.v) && cost[e.v] > ((WeightedEdge)e).weight) {
134 cost[e.v] = ((WeightedEdge)e).weight;
135 parent[e.v] = u;
136 }
137 }
138 } // End of while
139
140 return new MST(startingVertex, parent, T, totalWeight);
141 }
142
143 /**
144 * MST is an inner class in WeightedGraph */
145 public class MST extends Tree {
```

```

142 private double totalWeight; // Total weight of all edges in the tree total weight in tree
143
144 public MST(int root, int[] parent, List<Integer> searchOrder,
145 double totalWeight) {
146 super(root, parent, searchOrder);
147 this.totalWeight = totalWeight;
148 }
149
150 public double getTotalWeight() {
151 return totalWeight;
152 }
153 }
154
155 /** Find single source shortest paths */
156 public ShortestPathTree getShortestPath(int sourceVertex) { getShortestPath
157 // cost[v] stores the cost of the path from v to the source
158 double[] cost = newdouble[getSize()]; initialize cost
159 for (int i = 0; i < cost.length; i++) {
160 cost[i] = Double.POSITIVE_INFINITY; // Initial cost set to infinity
161 }
162 cost[sourceVertex] = 0; // Cost of source is 0
163
164 // parent[v] stores the previous vertex of v in the path
165 int[] parent = newint[getSize()];
166 parent[sourceVertex] = -1; // The parent of source is set to -1
167
168 // T stores the vertices whose path found so far
169 List<Integer> T = new ArrayList<>(); shortest path tree
170
171 // Expand T
172 while (T.size() < getSize()) { expand tree
173 // Find smallest cost v in V - T
174 int u = -1; // Vertex to be determined
175 double currentMinCost = Double.POSITIVE_INFINITY;
176 for (int i = 0; i < getSize(); i++) {
177 if (!T.contains(i) && cost[i] < currentMinCost) {
178 currentMinCost = cost[i];
179 u = i; vertex with smallest cost
180 }
181 }
182
183 T.add(u); // Add a new vertex to T add to T
184
185 // Adjust cost[v] for v that is adjacent to u and v in V - T
186 for (Edge e : neighbors.get(u)) {
187 if (!T.contains(e.v)
188 && cost[e.v] > cost[u] + ((WeightedEdge)e).weight) {
189 cost[e.v] = cost[u] + ((WeightedEdge)e).weight;
190 parent[e.v] = u; adjust cost
191 }
192 }
193 } // End of while adjust parent
194
195 // Create a ShortestPathTree
196 return new ShortestPathTree(sourceVertex, parent, T, cost); create a tree
197 }
198
199 /** ShortestPathTree is an inner class in WeightedGraph */
200 public class ShortestPathTree extends Tree {
201 private double[] cost; // cost[v] is the cost from v to source shortest path tree
202 }
```

```

202
203 /** Construct a path */
204 public ShortestPathTree(int source, int[] parent,
205 List<Integer> searchOrder, double[] cost) {
206 super(source, parent, searchOrder);
207 this.cost = cost;
208 }
209
210 /** Return the cost for a path from the root to vertex v */
211 public double getCost(int v) {
212 return cost[v];
213 }
214
215 /** Print paths from all vertices to the source */
216 public void printAllPaths() {
217 System.out.println("All shortest paths from " +
218 vertices.get(getRoot()) + " are:");
219 for (int i = 0; i < cost.length; i++) {
220 printPath(i); // Print a path from i to the source
221 System.out.println("(cost: " + cost[i] + ")");
222 }
223 }
224 }
225 }
```

print all paths

The `WeightedGraph` class extends the `AbstractGraph` class (line 3). The properties `vertices` and `neighbors` in `AbstractGraph` are inherited in `WeightedGraph`. `neighbors` is a list. Each element is the list is another list that contains edges. For unweighted graph, each edge is an instance of `AbstractGraph.Edge`. For a weighted graph, each edge is an instance of `WeightedEdge`. `WeightedEdge` is a subtype of `Edge`. So you can add a weighted edge into `neighbors.get(i)` for a weighted graph (line 47).

Listing 29.3 gives a test program that creates a graph for the one in Figure 29.1 and another graph for the one in Figure 29.3a.

### LISTING 29.3 TestWeightedGraph.java

```

1 public class TestWeightedGraph {
2 public static void main(String[] args) {
3 String[] vertices = {"Seattle", "San Francisco", "Los Angeles",
4 "Denver", "Kansas City", "Chicago", "Boston", "New York",
5 "Atlanta", "Miami", "Dallas", "Houston"};
6
7 int[][] edges = {
8 {0, 1, 807}, {0, 3, 1331}, {0, 5, 2097},
9 {1, 0, 807}, {1, 2, 381}, {1, 3, 1267},
10 {2, 1, 381}, {2, 3, 1015}, {2, 4, 1663}, {2, 10, 1435},
11 {3, 0, 1331}, {3, 1, 1267}, {3, 2, 1015}, {3, 4, 599},
12 {3, 5, 1003},
13 {4, 2, 1663}, {4, 3, 599}, {4, 5, 533}, {4, 7, 1260},
14 {4, 8, 864}, {4, 10, 496},
15 {5, 0, 2097}, {5, 3, 1003}, {5, 4, 533},
16 {5, 6, 983}, {5, 7, 787},
17 {6, 5, 983}, {6, 7, 214},
18 {7, 4, 1260}, {7, 5, 787}, {7, 6, 214}, {7, 8, 888},
19 {8, 4, 864}, {8, 7, 888}, {8, 9, 661},
20 {8, 10, 781}, {8, 11, 810},
21 {9, 8, 661}, {9, 11, 1187},
22 {10, 2, 1435}, {10, 4, 496}, {10, 8, 781}, {10, 11, 239},
23 {11, 8, 810}, {11, 9, 1187}, {11, 10, 239}}
```

vertices

edges

```

24 };
25
26 WeightedGraph<String> graph1 =
27 new WeightedGraph<>(vertices, edges); create graph
28 System.out.println("The number of vertices in graph1: "
29 + graph1.getSize());
30 System.out.println("The vertex with index 1 is "
31 + graph1.getVertex(1));
32 System.out.println("The index for Miami is " +
33 graph1.getIndex("Miami"));
34 System.out.println("The edges for graph1:");
35 graph1.printWeightedEdges(); print edges
36
37 edges = new int[][] {
38 {0, 1, 2}, {0, 3, 8}, edges
39 {1, 0, 2}, {1, 2, 7}, {1, 3, 3},
40 {2, 1, 7}, {2, 3, 4}, {2, 4, 5},
41 {3, 0, 8}, {3, 1, 3}, {3, 2, 4}, {3, 4, 6},
42 {4, 2, 5}, {4, 3, 6}
43 };
44 WeightedGraph<Integer> graph2 = new WeightedGraph<>(edges, 5); create graph
45 System.out.println("\nThe edges for graph2:");
46 graph2.printWeightedEdges(); print edges
47 }
48 }
```

```

The number of vertices in graph1: 12
The vertex with index 1 is San Francisco
The index for Miami is 9
The edges for graph1:
Vertex 0: (0, 1, 807) (0, 3, 1331) (0, 5, 2097)
Vertex 1: (1, 2, 381) (1, 0, 807) (1, 3, 1267)
Vertex 2: (2, 1, 381) (2, 3, 1015) (2, 4, 1663) (2, 10, 1435)
Vertex 3: (3, 4, 599) (3, 5, 1003) (3, 1, 1267)
 (3, 0, 1331) (3, 2, 1015)
Vertex 4: (4, 10, 496) (4, 8, 864) (4, 5, 533) (4, 2, 1663)
 (4, 7, 1260) (4, 3, 599)
Vertex 5: (5, 4, 533) (5, 7, 787) (5, 3, 1003)
 (5, 0, 2097) (5, 6, 983)
Vertex 6: (6, 7, 214) (6, 5, 983)
Vertex 7: (7, 6, 214) (7, 8, 888) (7, 5, 787) (7, 4, 1260)
Vertex 8: (8, 9, 661) (8, 10, 781) (8, 4, 864)
 (8, 7, 888) (8, 11, 810)
Vertex 9: (9, 8, 661) (9, 11, 1187)
Vertex 10: (10, 11, 239) (10, 4, 496) (10, 8, 781) (10, 2, 1435)
Vertex 11: (11, 10, 239) (11, 9, 1187) (11, 8, 810)

The edges for graph2:
Vertex 0: (0, 1, 2) (0, 3, 8)
Vertex 1: (1, 0, 2) (1, 2, 7) (1, 3, 3)
Vertex 2: (2, 3, 4) (2, 1, 7) (2, 4, 5)
Vertex 3: (3, 1, 3) (3, 4, 6) (3, 2, 4) (3, 0, 8)
Vertex 4: (4, 2, 5) (4, 3, 6)
```



The program creates `graph1` for the graph in Figure 29.1 in lines 3–27. The vertices for `graph1` are defined in lines 3–5. The edges for `graph1` are defined in lines 7–24. The edges are represented using a two-dimensional array. For each row `i` in the array, `edges[i][0]` and `edges[i][1]` indicate that there is an edge from vertex `edges[i][0]` to vertex

`edges[i][1]` and the weight for the edge is `edges[i][2]`. For example, `{0, 1, 807}` (line 8) represents the edge from vertex `0` (`edges[0][0]`) to vertex `1` (`edges[0][1]`) with weight `807` (`edges[0][2]`). `{0, 5, 2097}` (line 8) represents the edge from vertex `0` (`edges[2][0]`) to vertex `5` (`edges[2][1]`) with weight `2097` (`edges[2][2]`). Line 35 invokes the `printWeightedEdges()` method on `graph1` to display all edges in `graph1`.

The program creates the edges for `graph2` for the graph in Figure 29.3a in lines 37–44. Line 46 invokes the `printWeightedEdges()` method on `graph2` to display all edges in `graph2`.



- 29.3** If a priority queue is used to store weighted edges, what is the output of the following code?

```
PriorityQueue<WeightedEdge> q = new PriorityQueue<>();
q.offer(new WeightedEdge(1, 2, 3.5));
q.offer(new WeightedEdge(1, 6, 6.5));
q.offer(new WeightedEdge(1, 7, 1.5));
System.out.println(q.poll().weight);
System.out.println(q.poll().weight);
System.out.println(q.poll().weight);
```

- 29.4** If a priority queue is used to store weighted edges, what is wrong in the following code? Fix it and show the output.

```
List<PriorityQueue<WeightedEdge>> queues = new ArrayList<>();
queues.get(0).offer(new WeightedEdge(0, 2, 3.5));
queues.get(0).offer(new WeightedEdge(0, 6, 6.5));
queues.get(0).offer(new WeightedEdge(0, 7, 1.5));
queues.get(1).offer(new WeightedEdge(1, 0, 3.5));
queues.get(1).offer(new WeightedEdge(1, 5, 8.5));
queues.get(1).offer(new WeightedEdge(1, 8, 19.5));
System.out.println(queues.get(0).peek()
 .compareTo(queues.get(1).peek()));
```

## 29.4 Minimum Spanning Trees



A *minimum spanning tree of a graph* is a spanning tree with the minimum total weights.

minimum spanning tree

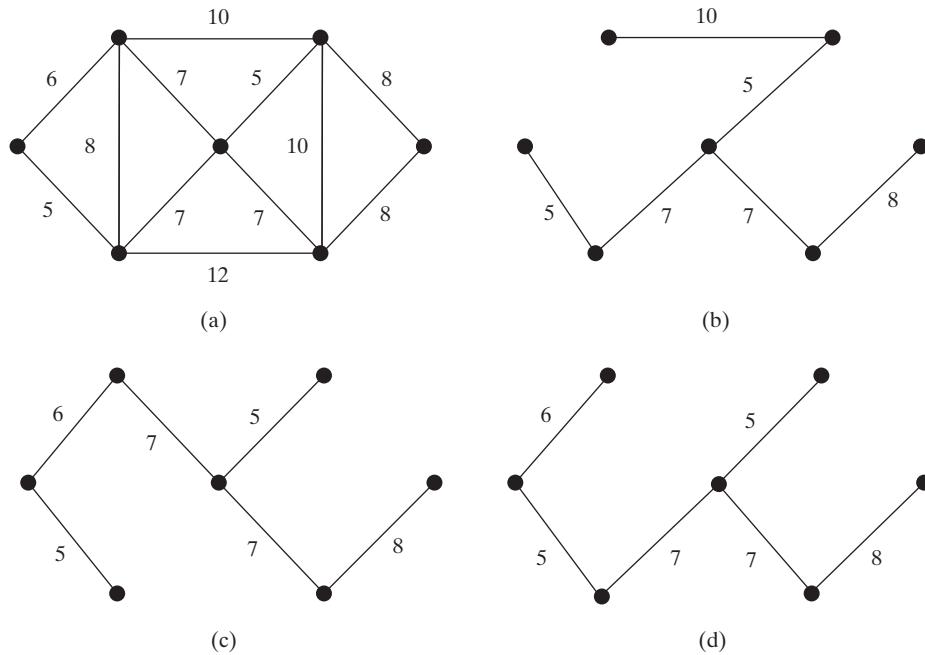
A graph may have many spanning trees. Suppose that the edges are weighted. A *minimum spanning tree* has the minimum total weights. For example, the trees in Figures 29.5b, 29.5c, 29.5d are spanning trees for the graph in Figure 29.5a. The trees in Figures 29.3c and 29.3d are minimum spanning trees.

The problem of finding a minimum spanning tree has many applications. Consider a company with branches in many cities. The company wants to lease telephone lines to connect all the branches together. The phone company charges different amounts of money to connect different pairs of cities. There are many ways to connect all branches together. The cheapest way is to find a spanning tree with the minimum total rates.

### 29.4.1 Minimum Spanning Tree Algorithms

Prim's algorithm

How do you find a minimum spanning tree? There are several well-known algorithms for doing so. This section introduces *Prim's algorithm*. Prim's algorithm starts with a spanning tree `T` that contains an arbitrary vertex. The algorithm expands the tree by repeatedly adding a vertex with the *lowest-cost* edge incident to a vertex already in the tree. Prim's algorithm is a greedy algorithm, and it is described in Listing 29.4.



**FIGURE 29.5** The trees in (c) and (d) are minimum spanning trees of the graph in (a).

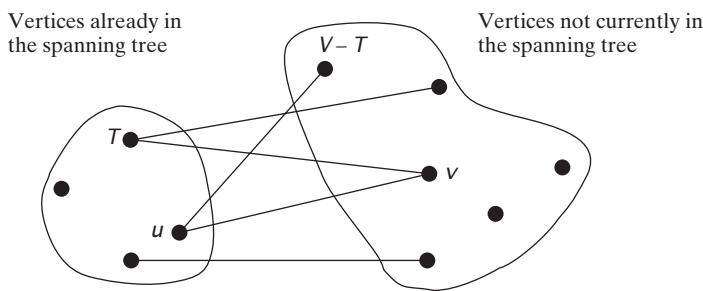
#### LISTING 29.4 Prim's Minimum Spanning Tree Algorithm

**Input:** A connected undirected weighted  $G = (V, E)$  with non-negative weights  
**Output:** MST (a minimum spanning tree)

```

1 MST minimumSpanningTree() {
2 Let T be a set for the vertices in the spanning tree;
3 Initially, add the starting vertex to T; add initial vertex
4
5 while (size of T < n) {
6 Find u in T and v in V - T with the smallest weight
7 on the edge (u, v), as shown in Figure 29.6;
8 Add v to T and set parent[v] = u; more vertices?
9 } find a vertex
10 }

```

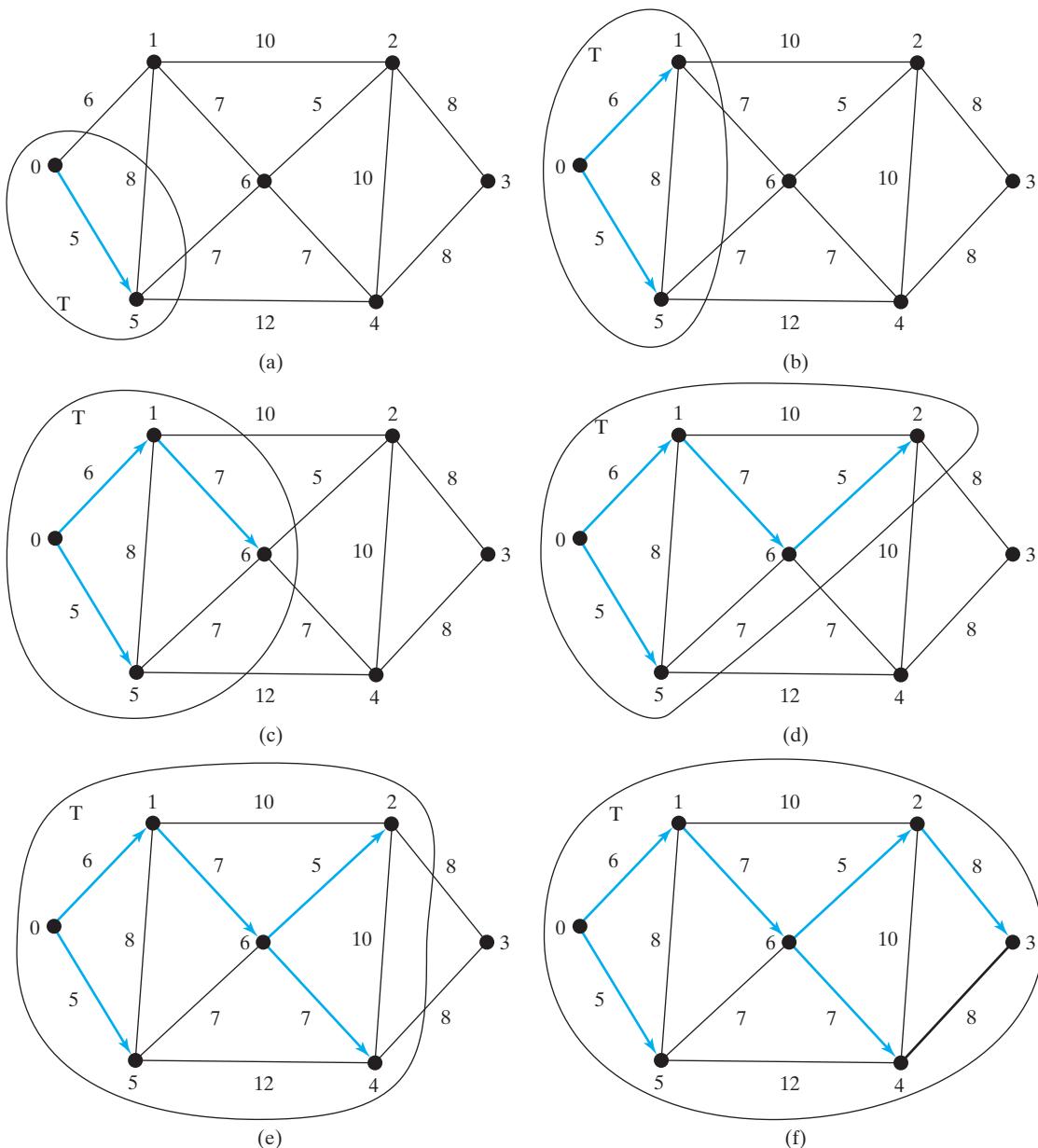


**FIGURE 29.6** Find a vertex  $u$  in  $T$  that connects a vertex  $v$  in  $V - T$  with the smallest weight.

The algorithm starts by adding the starting vertex into  $T$ . It then continuously adds a vertex (say  $v$ ) from  $V - T$  into  $T$ .  $v$  is the vertex that is adjacent to the vertex in  $T$  with the smallest weight on the edge. For example, there are five edges connecting vertices in  $T$  and  $V - T$  as example

shown in Figure 29.6, and  $(u, v)$  is the one with the smallest weight. Consider the graph in Figure 29.7. The algorithm adds the vertices to  $T$  in this order:

1. Add vertex **0** to  $T$ .
2. Add vertex **5** to  $T$ , since **Edge(5, 0, 5)** has the smallest weight among all edges incident to a vertex in  $T$ , as shown in Figure 29.7a. The arrow line from **0** to **5** indicates that **0** is the parent of **5**.
3. Add vertex **1** to  $T$ , since **Edge(1, 0, 6)** has the smallest weight among all edges incident to a vertex in  $T$ , as shown in Figure 29.7b.
4. Add vertex **6** to  $T$ , since **Edge(6, 1, 7)** has the smallest weight among all edges incident to a vertex in  $T$ , as shown in Figure 29.7c.



**FIGURE 29.7** The adjacent vertices with the smallest weight are added successively to  $T$ .

5. Add vertex **2** to **T**, since **Edge(2, 6, 5)** has the smallest weight among all edges incident to a vertex in **T**, as shown in Figure 29.7d.
6. Add vertex **4** to **T**, since **Edge(4, 6, 7)** has the smallest weight among all edges incident to a vertex in **T**, as shown in Figure 29.7e.
7. Add vertex **3** to **T**, since **Edge(3, 2, 8)** has the smallest weight among all edges incident to a vertex in **T**, as shown in Figure 29.7f.



### Note

A minimum spanning tree is not unique. For example, both (c) and (d) in Figure 29.5a are minimum spanning trees for the graph in Figure 29.5a. However, if the weights are distinct, the graph has a unique minimum spanning tree.

unique tree?



### Note

Assume that the graph is connected and undirected. If a graph is not connected or directed, the algorithm will not work. You can modify the algorithm to find a spanning forest for any undirected graph. A spanning forest is a graph in which each connected component is a tree.

connected and undirected

## 29.4.2 Refining Prim's MST Algorithm

To make it easy to identify the next vertex to add into the tree, we use **cost[v]** to store the cost of adding a vertex **v** to the spanning tree **T**. Initially **cost[s]** is **0** for a starting vertex and assign infinity to **cost[v]** for all other vertices. The algorithm repeatedly finds a vertex **u** in **V - T** with the smallest **cost[u]** and moves **u** to **T**. The refined version of the algorithm is given in Listing 29.5.

### LISTING 29.5 Refined Version of Prim's Algorithm

**Input:** A connected undirected weighted  $G = (V, E)$  with non-negative weights  
**Output:** a minimum spanning tree with the starting vertex  $s$  as the root

```

1 MST getMinimumSpanningTree(s) {
2 Let T be a set that contains the vertices in the spanning tree;
3 Initially T is empty;
4 Set cost[s] = 0; and cost[v] = infinity for all other vertices in V;
5
6 while (size of T < n) {
7 Find u not in T with the smallest cost[u];
8 Add u to T;
9 for (each v not in T and (u, v) in E)
10 if (cost[v] > w(u, v)) { // Adjust cost[v]
11 cost[v] = w(u, v); parent[v] = u;
12 }
13 }
14 }
```

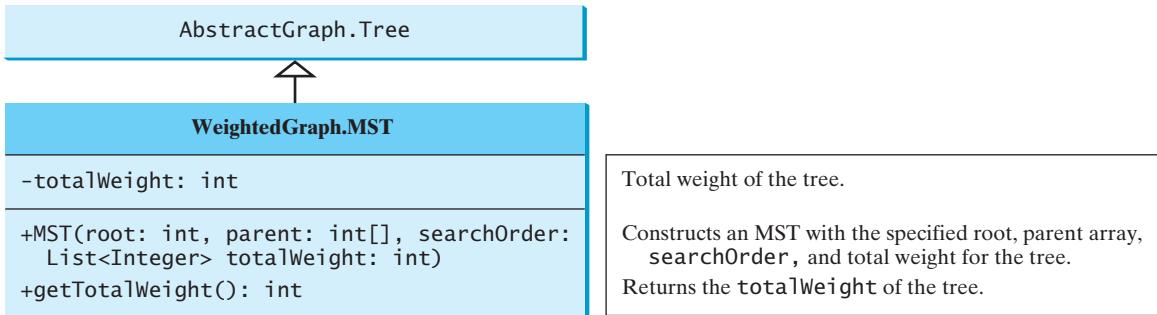
find next vertex  
add a vertex to T

adjust cost[v]

## 29.4.3 Implementation of the MST Algorithm

The **getMinimumSpanningTree(int v)** method is defined in the **WeightedGraph** class. It returns an instance of the **MST** class, as shown in Figure 29.4. The **MST** class is defined as an inner class in the **WeightedGraph** class, which extends the **Tree** class, as shown in Figure 29.8. The **Tree** class was shown in Figure 28.11. The **MST** class was implemented in lines 141–153 in Listing 29.2.

getMinimumSpanningTree()

**FIGURE 29.8** The `MST` class extends the `Tree` class.

The refined version of the Prim's algorithm greatly simplifies the implementation. The `getMinimumSpanningTree` method was implemented using the refined version of the Prim's algorithm in lines 99–138 in Listing 29.2. The `getMinimumSpanningTree(int startingVertex)` method sets `cost[startingVertex]` to 0 (line 105) and `cost[v]` to infinity for all other vertices (lines 102–104). The parent of `startingVertex` is set to `-1` (line 108). `T` is a list that stores the vertices added into the spanning tree (line 111). We use a list for `T` rather than a set in order to record the order of the vertices added to `T`.

Initially, `T` is empty. To expand `T`, the method performs the following operations:

1. Find the vertex `u` with the smallest `cost[u]` (lines 118–123 and add it into `T` (line 125).
2. After adding `u` in `T`, update `cost[v]` and `parent[v]` for each `v` adjacent to `u` in `V-T` if `cost[v] > w(u, v)` (lines 129–134).

After a new vertex is added to `T`, `totalWeight` is updated (line 126). Once all vertices are added to `T`, an instance of `MST` is created (line 137). Note that the method will not work if the graph is not connected. However, you can modify it to obtain a partial MST.

The `MST` class extends the `Tree` class (line 141). To create an instance of `MST`, pass `root`, `parent`, `T`, and `totalWeight` (lines 144–145). The data fields `root`, `parent`, and `searchOrder` are defined in the `Tree` class, which is an inner class defined in `AbstractGraph`.

time complexity

Note that testing whether a vertex `i` is in `T` by invoking `T.contains(i)` takes  $O(n)$  time, since `T` is a list. Therefore, the overall time complexity for this implementation is  $O(n^3)$ . Interested readers may see Programming Exercise 29.20 for improving the implementation and reduce the complexity to  $O(n^2)$ .

Listing 29.6 gives a test program that displays minimum spanning trees for the graph in Figure 29.1 and the graph in Figure 29.3a, respectively.

### LISTING 29.6 TestMinimumSpanningTree.java

create vertices

```

1 public class TestMinimumSpanningTree {
2 public static void main(String[] args) {
3 String[] vertices = {"Seattle", "San Francisco", "Los Angeles",
4 "Denver", "Kansas City", "Chicago", "Boston", "New York",
5 "Atlanta", "Miami", "Dallas", "Houston"};
6
7 int[][] edges = {
8 {0, 1, 807}, {0, 3, 1331}, {0, 5, 2097},
9 {1, 0, 807}, {1, 2, 381}, {1, 3, 1267},
10 {2, 1, 381}, {2, 3, 1015}, {2, 4, 1663}, {2, 10, 1435},
11 {3, 0, 1331}, {3, 1, 1267}, {3, 2, 1015}, {3, 4, 599},

```

create edges

```

12 {3, 5, 1003},
13 {4, 2, 1663}, {4, 3, 599}, {4, 5, 533}, {4, 7, 1260},
14 {4, 8, 864}, {4, 10, 496},
15 {5, 0, 2097}, {5, 3, 1003}, {5, 4, 533},
16 {5, 6, 983}, {5, 7, 787},
17 {6, 5, 983}, {6, 7, 214},
18 {7, 4, 1260}, {7, 5, 787}, {7, 6, 214}, {7, 8, 888},
19 {8, 4, 864}, {8, 7, 888}, {8, 9, 661},
20 {8, 10, 781}, {8, 11, 810},
21 {9, 8, 661}, {9, 11, 1187},
22 {10, 2, 1435}, {10, 4, 496}, {10, 8, 781}, {10, 11, 239},
23 {11, 8, 810}, {11, 9, 1187}, {11, 10, 239}
24 };
25
26 WeightedGraph<String> graph1 =
27 new WeightedGraph<>(vertices, edges);
28 WeightedGraph<String>.MST tree1 = graph1.getMinimumSpanningTree();
29 System.out.println("Total weight is " + tree1.getTotalWeight());
30 tree1.printTree();
31
32 edges = new int[][]{
33 {0, 1, 2}, {0, 3, 8},
34 {1, 0, 2}, {1, 2, 7}, {1, 3, 3},
35 {2, 1, 7}, {2, 3, 4}, {2, 4, 5},
36 {3, 0, 8}, {3, 1, 3}, {3, 2, 4}, {3, 4, 6},
37 {4, 2, 5}, {4, 3, 6}
38 };
39
40 WeightedGraph<Integer> graph2 = new WeightedGraph<>(edges, 5);
41 WeightedGraph<Integer>.MST tree2 =
42 graph2.getMinimumSpanningTree(1);
43 System.out.println("\nTotal weight is " + tree2.getTotalWeight());
44 tree2.printTree();
45 }
46 }
```

create graph1  
MST for graph1  
total weight  
print tree  
  
create edges  
  
create graph2  
MST for graph2  
total weight  
print tree

```

Total weight is 6513.0
Root is: Seattle
Edges: (Seattle, San Francisco) (San Francisco, Los Angeles)
(Los Angeles, Denver) (Denver, Kansas City) (Kansas City, Chicago)
(New York, Boston) (Chicago, New York) (Dallas, Atlanta)
(Atlanta, Miami) (Kansas City, Dallas) (Dallas, Houston)

Total weight is 14.0
Root is: 1
Edges: (1, 0) (3, 2) (1, 3) (2, 4)
```



The program creates a weighted graph for Figure 29.1 in line 27. It then invokes `getMinimumSpanningTree()` (line 28) to return an `MST` that represents a minimum spanning tree for the graph. Invoking `printTree()` (line 30) on the `MST` object displays the edges in the tree. Note that `MST` is a subclass of `Tree`. The `printTree()` method is defined in the `Tree` class.

The graphical illustration of the minimum spanning tree is shown in Figure 29.9. The vertices are added to the tree in this order: Seattle, San Francisco, Los Angeles, Denver, Kansas City, Dallas, Houston, Chicago, New York, Boston, Atlanta, and Miami.

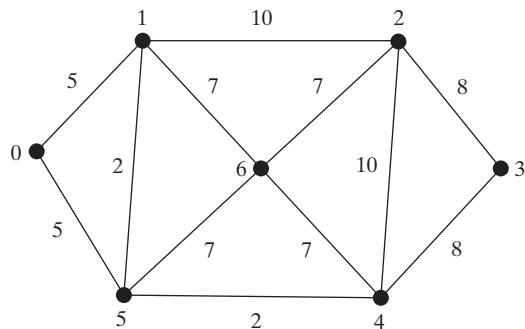
graphical illustration



**FIGURE 29.9** The edges in a minimum spanning tree for the cities are highlighted.



**29.5** Find a minimum spanning tree for the following graph.



**29.6** Is a minimum spanning tree unique if all edges have different weights?

**29.7** If you use an adjacency matrix to represent weighted edges, what will be the time complexity for Prim's algorithm?

**29.8** What happens to the `getMinimumSpanningTree()` method in `WeightedGraph` if the graph is not connected? Verify your answer by writing a test program that creates an unconnected graph and invokes the `getMinimumSpanningTree()` method. How do you fix the problem by obtaining a partial MST?

## 29.5 Finding Shortest Paths



*The shortest path between two vertices is a path with the minimum total weights.*

shortest path  
Dijkstra's algorithm

Given a graph with nonnegative weights on the edges, a well-known algorithm for finding a *shortest path* between two vertices was discovered by Edsger Dijkstra, a Dutch computer scientist. In order to find a shortest path from vertex **s** to vertex **v**, *Dijkstra's algorithm* finds the

shortest path from  $s$  to all vertices. So *Dijkstra's algorithm* is known as a *single-source shortest path* algorithm. The algorithm uses  $\text{cost}[v]$  to store the cost of a *shortest path* from vertex  $v$  to the source vertex  $s$ .  $\text{cost}[s]$  is 0. Initially assign infinity to  $\text{cost}[v]$  for all other vertices. The algorithm repeatedly finds a vertex  $u$  in  $V - T$  with the smallest  $\text{cost}[u]$  and moves  $u$  to  $T$ .

The algorithm is described in Listing 29.7.

### LISTING 29.7 Dijkstra's Single-Source Shortest-Path Algorithm

**Input:** a graph  $G = (V, E)$  with non-negative weights  
**Output:** a shortest path tree with the source vertex  $s$  as the root

```

1 ShortestPathTree getShortestPath(s) {
2 Let T be a set that contains the vertices whose
3 paths to s are known; Initially T is empty;
4 Set $\text{cost}[s] = 0$; and $\text{cost}[v] = \infty$ for all other vertices in V ;
5
6 while (size of $T < n$) {
7 Find u not in T with the smallest $\text{cost}[u]$;
8 Add u to T ;
9 for (each v not in T and (u, v) in E)
10 if ($\text{cost}[v] > \text{cost}[u] + w(u, v)$) {
11 $\text{cost}[v] = \text{cost}[u] + w(u, v)$; $\text{parent}[v] = u$;
12 }
13 }
14 }
```

find next vertex  
add a vertex to  $T$

adjust  $\text{cost}[v]$

This algorithm is very similar to Prim's for finding a minimum spanning tree. Both algorithms divide the vertices into two sets:  $T$  and  $V - T$ . In the case of Prim's algorithm, set  $T$  contains the vertices that are already added to the tree. In the case of Dijkstra's, set  $T$  contains the vertices whose shortest paths to the source have been found. Both algorithms repeatedly find a vertex from  $V - T$  and add it to  $T$ . In the case of Prim's algorithm, the vertex is adjacent to some vertex in the set with the minimum weight on the edge. In Dijkstra's algorithm, the vertex is adjacent to some vertex in the set with the minimum total cost to the source.

The algorithm starts by setting  $\text{cost}[s]$  to 0 (line 4), sets  $\text{cost}[v]$  to infinity for all other vertices. It then continuously adds a vertex (say  $u$ ) from  $V - T$  into  $T$  with smallest  $\text{cost}[u]$  (lines 7–8), as shown in Figure 29.10a. After adding  $u$  to  $T$ , the algorithm updates  $\text{cost}[v]$  and  $\text{parent}[v]$  for each  $v$  not in  $T$  if  $(u, v)$  is in  $E$  and  $\text{cost}[v] > \text{cost}[u] + w(u, v)$  (lines 10–11).



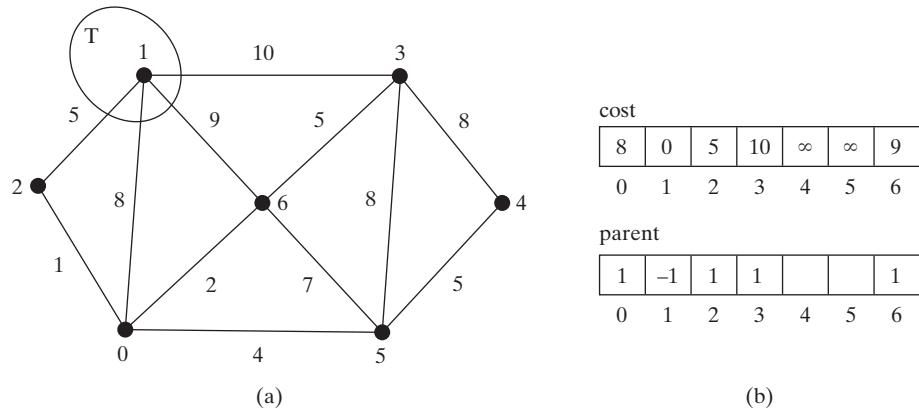
**FIGURE 29.10** (a) Find a vertex  $u$  in  $V - T$  with the smallest  $\text{cost}[u]$ . (b) Update  $\text{cost}[v]$  for  $v$  in  $V - T$  and  $v$  is adjacent to  $u$ .

Let us illustrate Dijkstra's algorithm using the graph in Figure 29.11a. Suppose the source vertex is **1**. Therefore, **cost[1] = 0** and the costs for all other vertices are initially  $\infty$ , as shown in Figure 29.11b. We use the **parent[i]** to denote the parent of **i** in the path. For convenience, set the parent of the source node to **-1**.



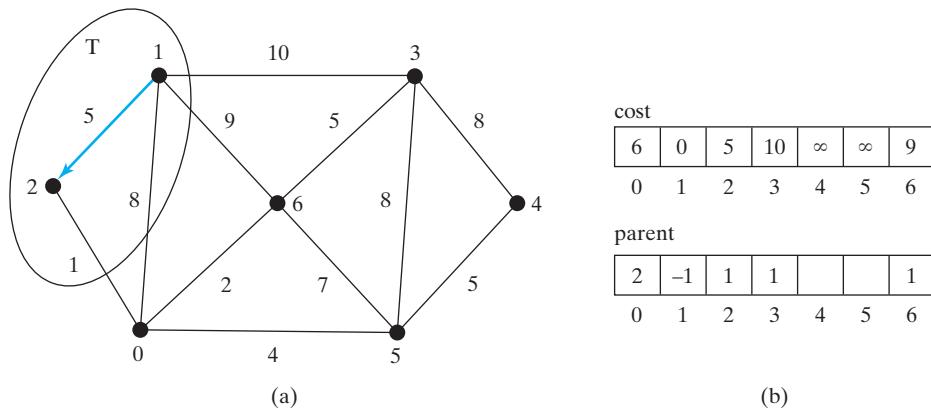
**FIGURE 29.11** The algorithm will find all shortest paths from source vertex **1**.

Initially set **T** is empty. The algorithm selects the vertex with the smallest cost. In this case, the vertex is **1**. The algorithm adds **1** to **T**, as shown in Figure 29.12a. Afterwards, it adjusts the cost for each vertex adjacent to **1**. The cost for vertices **2**, **0**, **6**, and **3** and their parents are now updated, as shown in Figure 29.12b.

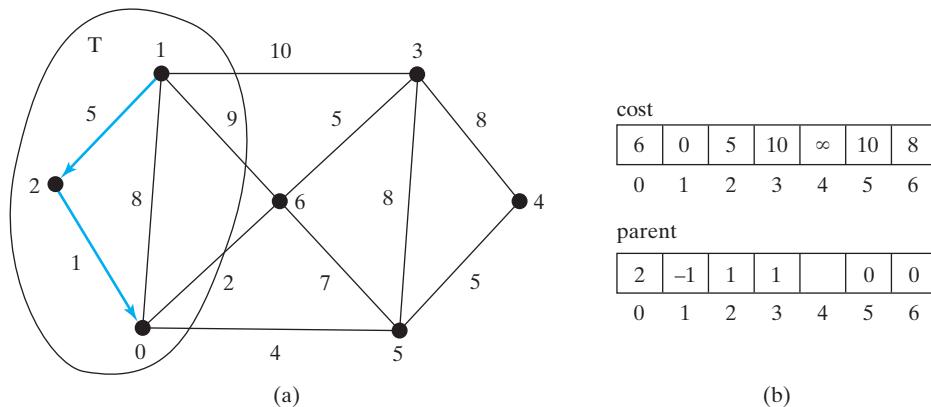


**FIGURE 29.12** Now vertex **1** is in set **T**.

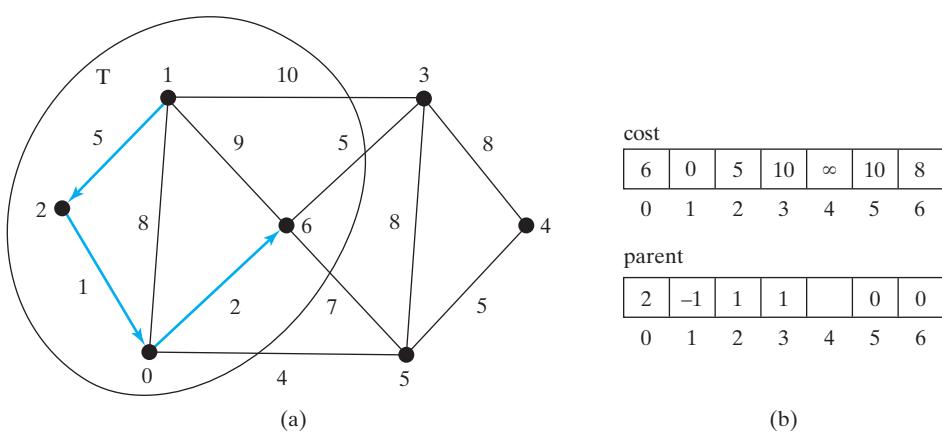
Vertices **2**, **0**, **6**, and **3** are adjacent to the source vertex, and vertex **2** is the one in **V-T** with the smallest cost, so add **2** to **T**, as shown in Figure 29.13 and update the cost and parent for vertices in **V-T** and adjacent to **2**. **cost[0]** is now updated to **6** and its parent is set to **2**. The arrow line from **1** to **2** indicates that **1** is the parent of **2** after **2** is added into **T**.

**FIGURE 29.13** Now vertices 1 and 2 are in set T.

Now  $T$  contains  $\{1, 2\}$ . Vertex 0 is the one in  $V-T$  with the smallest cost, so add 0 to  $T$ , as shown in Figure 29.14 and update the cost and parent for vertices in  $V-T$  and adjacent to 0 if applicable.  $\text{cost}[5]$  is now updated to 10 and its parent is set to 0 and  $\text{cost}[6]$  is now updated to 8 and its parent is set to 0.

**FIGURE 29.14** Now vertices  $\{1, 2, 0\}$  are in set T.

Now  $T$  contains  $\{1, 2, 0\}$ . Vertex 6 is the one in  $V-T$  with the smallest cost, so add 6 to  $T$ , as shown in Figure 29.15 and update the cost and parent for vertices in  $V-T$  and adjacent to 6 if applicable.

**FIGURE 29.15** Now vertices  $\{1, 2, 0, 6\}$  are in set T.

Now  $T$  contains  $\{1, 2, 0, 6\}$ . Vertex  $3$  or  $5$  is the one in  $V-T$  with the smallest cost. You may add either  $3$  or  $5$  into  $T$ . Let us add  $3$  to  $T$ , as shown in Figure 29.16 and update the cost and parent for vertices in  $V-T$  and adjacent to  $3$  if applicable. `cost[4]` is now updated to  $18$  and its parent is set to  $3$ .

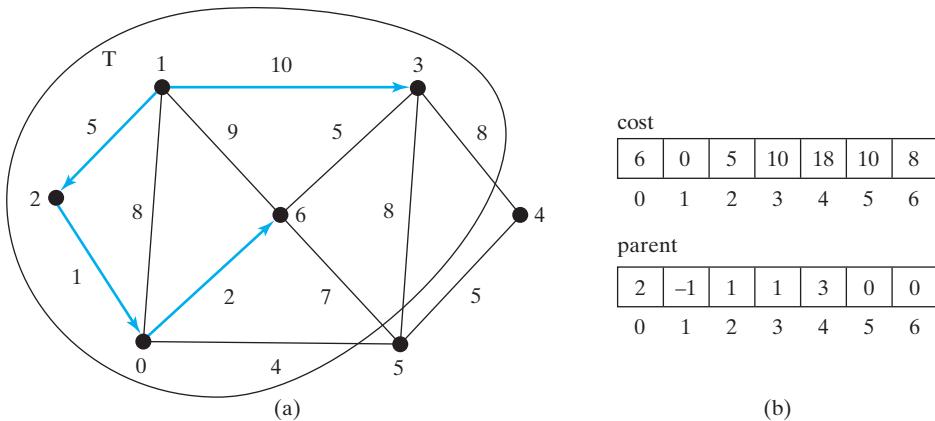


FIGURE 29.16 Now vertices  $\{1, 2, 0, 6, 3\}$  are in set  $T$ .

Now  $T$  contains  $\{1, 2, 0, 6, 3\}$ . Vertex  $5$  is the one in  $V-T$  with the smallest cost, so add  $5$  to  $T$ , as shown in Figure 29.17 and update the cost and parent for vertices in  $V-T$  and adjacent to  $5$  if applicable. `cost[4]` is now updated to  $10$  and its parent is set to  $5$ .

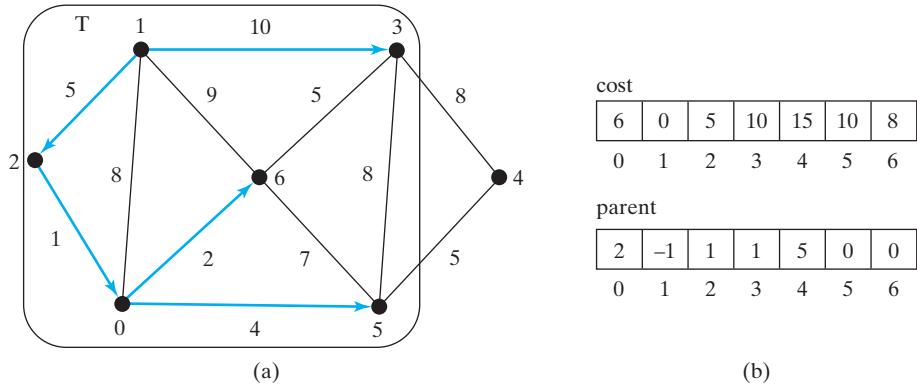


FIGURE 29.17 Now vertices  $\{1, 2, 0, 6, 3, 5\}$  are in set  $T$ .

Now  $T$  contains  $\{1, 2, 0, 6, 3, 5\}$ . Vertex  $4$  is the one in  $V-T$  with the smallest cost, so add  $4$  to  $T$ , as shown in Figure 29.18.

As you can see, the algorithm essentially finds all shortest paths from a source vertex, which produces a tree rooted at the source vertex. We call this tree a *single-source all-shortest-path tree* (or simply a *shortest-path tree*). To model this tree, define a class named `ShortestPathTree` that extends the `Tree` class, as shown in Figure 29.19. `ShortestPathTree` is defined as an inner class in `WeightedGraph` in lines 200–224 in Listing 29.2.

The `getShortestPath(int sourceVertex)` method was implemented in lines 156–197 in Listing 29.2. The method sets `cost[sourceVertex]` to `0` (line 162) and `cost[v]` to



FIGURE 29.18 Now vertices {1, 2, 6, 0, 3, 5, 4} are in set T.

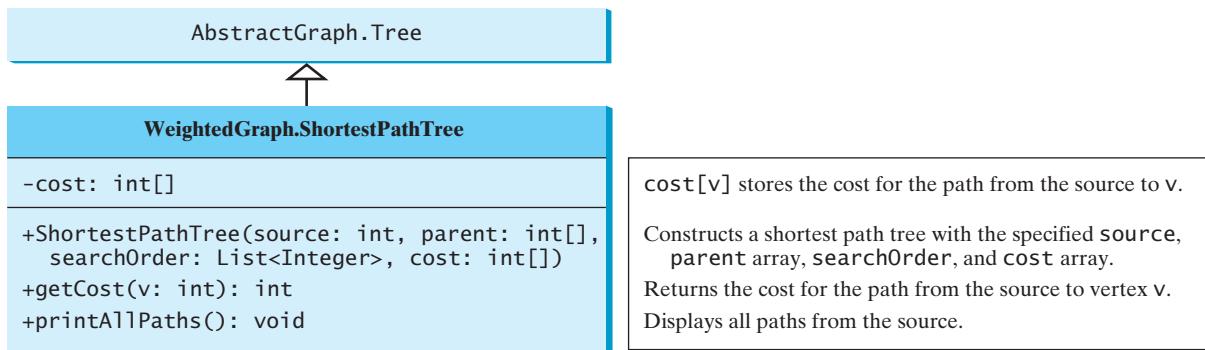


FIGURE 29.19 **WeightedGraph.ShortestPathTree** extends **AbstractGraph.Tree**.

infinity for all other vertices (lines 159–161). The parent of **sourceVertex** is set to **-1** (line 166). **T** is a list that stores the vertices added into the shortest path tree (line 169). We use a list for **T** rather than a set in order to record the order of the vertices added to **T**.

Initially, **T** is empty. To expand **T**, the method performs the following operations:

1. Find the vertex **u** with the smallest **cost[u]** (lines 175–181) and add it into **T** (line 183).
2. After adding **u** in **T**, update **cost[v]** and **parent[v]** for each **v** adjacent to **u** in **V-T** if **cost[v] > cost[u] + w(u, v)** (lines 186–192).

Once all vertices from **s** are added to **T**, an instance of **ShortestPathTree** is created (line 196).

The **ShortestPathTree** class extends the **Tree** class (line 200). To create an instance of **ShortestPathTree**, pass **sourceVertex**, **parent**, **T**, and **cost** (lines 204–205). **sourceVertex** becomes the root in the tree. The data fields **root**, **parent**, and **searchOrder** are defined in the **Tree** class, which is an inner class defined in **AbstractGraph**.

Note that testing whether a vertex **i** is in **T** by invoking **T.contains(i)** takes **O(n)** time, since **T** is a list. Therefore, the overall time complexity for this implementation is **O(n<sup>3</sup>)**. Interested readers may see Programming Exercise 29.20 for improving the implementation and reducing the complexity to **O(n<sup>2</sup>)**.

Dijkstra's algorithm is a combination of a greedy algorithm and dynamic programming. It is a greedy algorithm in the sense that it always adds a new vertex that has the shortest distance to the source. It stores the shortest distance of each known vertex to the source and uses it later to avoid redundant computing, so Dijkstra's algorithm also uses dynamic programming.

ShortestPathTree class

Dijkstra's algorithm time complexity

greedy and dynamic programming

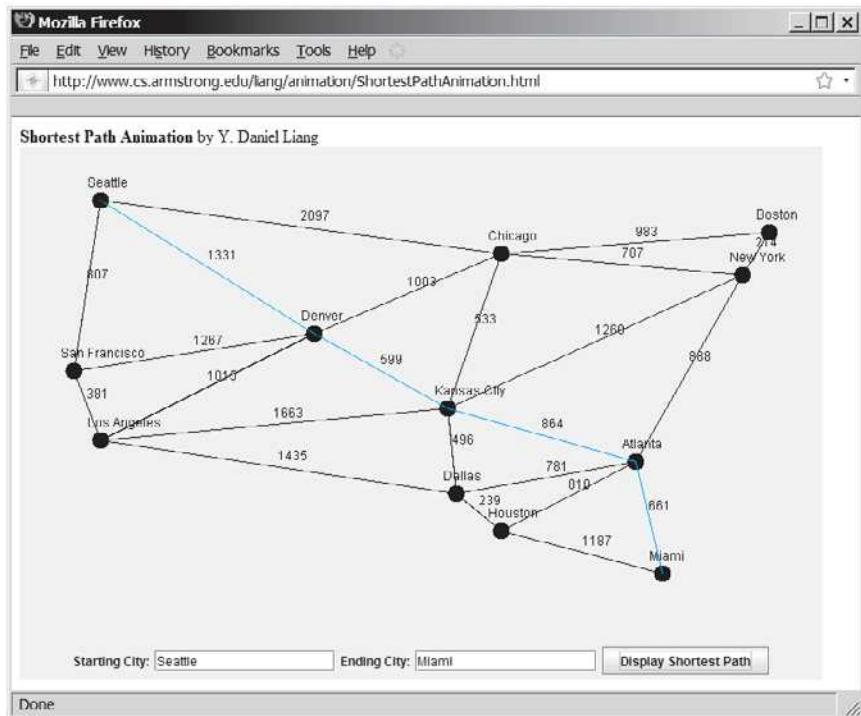


shortest path animation on  
Companion Website



### Pedagogical Note

Go to [www.cs.armstrong.edu/liang/animation/ShortestPathAnimation.html](http://www.cs.armstrong.edu/liang/animation/ShortestPathAnimation.html) to use a GUI interactive program to find a shortest path between any two cities, as shown in Figure 29.20.



**FIGURE 29.20** The animation tool displays a shortest path between two cities.

Listing 29.8 gives a test program that displays the shortest paths from Chicago to all other cities in Figure 29.1 and the shortest paths from vertex 3 to all vertices for the graph in Figure 29.3a, respectively.

### LISTING 29.8 TestShortestPath.java

```

vertices
1 public class TestShortestPath {
2 public static void main(String[] args) {
3 String[] vertices = {"Seattle", "San Francisco", "Los Angeles",
4 "Denver", "Kansas City", "Chicago", "Boston", "New York",
5 "Atlanta", "Miami", "Dallas", "Houston"};
6
edges
7 int[][][] edges = {
8 {0, 1, 807}, {0, 3, 1331}, {0, 5, 2097},
9 {1, 0, 807}, {1, 2, 381}, {1, 3, 1267},
10 {2, 1, 381}, {2, 3, 1015}, {2, 4, 1663}, {2, 10, 1435},
11 {3, 0, 1331}, {3, 1, 1267}, {3, 2, 1015}, {3, 4, 599},
12 {3, 5, 1003},
13 {4, 2, 1663}, {4, 3, 599}, {4, 5, 533}, {4, 7, 1260},
14 {4, 8, 864}, {4, 10, 496},
15 {5, 0, 2097}, {5, 3, 1003}, {5, 4, 533},
16 {5, 6, 983}, {5, 7, 787},
17 {6, 5, 983}, {6, 7, 214},
18 {7, 4, 1260}, {7, 5, 787}, {7, 6, 214}, {7, 8, 888},
19 {8, 4, 864}, {8, 7, 888}, {8, 9, 661},
20 {8, 10, 781}, {8, 11, 810},
21 {9, 8, 661}, {9, 11, 1187},

```

```

22 {10, 2, 1435}, {10, 4, 496}, {10, 8, 781}, {10, 11, 239},
23 {11, 8, 810}, {11, 9, 1187}, {11, 10, 239}
24 };
25
26 WeightedGraph<String> graph1 =
27 new WeightedGraph<>(vertices, edges); create graph1
28 WeightedGraph<String>.ShortestPathTree tree1 =
29 graph1.getShortestPath(graph1.getIndex("Chicago")); shortest path
30 tree1.printAllPaths();
31
32 // Display shortest paths from Houston to Chicago
33 System.out.print("Shortest path from Houston to Chicago: ");
34 java.util.List<String> path
35 = tree1.getPath(graph1.getIndex("Houston"));
36 for (String s: path) {
37 System.out.print(s + " ");
38 }
39
40 edges = new int[][] {
41 {0, 1, 2}, {0, 3, 8},
42 {1, 0, 2}, {1, 2, 7}, {1, 3, 3},
43 {2, 1, 7}, {2, 3, 4}, {2, 4, 5},
44 {3, 0, 8}, {3, 1, 3}, {3, 2, 4}, {3, 4, 6},
45 {4, 2, 5}, {4, 3, 6}
46 };
47 WeightedGraph<Integer> graph2 = new WeightedGraph<>(edges, 5); create graph2
48 WeightedGraph<Integer>.ShortestPathTree tree2 =
49 graph2.getShortestPath(3);
50 System.out.println("\n");
51 tree2.printAllPaths();
52 }
53 }
```

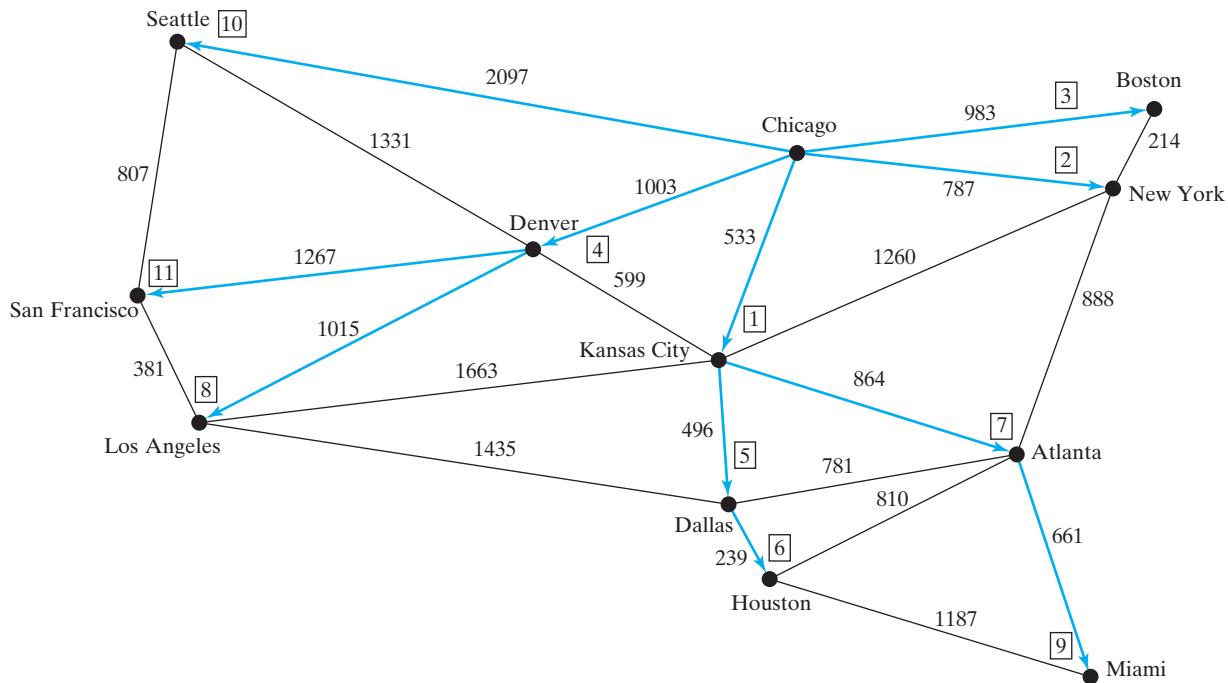
All shortest paths from Chicago are:  
A path from Chicago to Seattle: Chicago Seattle (cost: 2097.0)  
A path from Chicago to San Francisco:  
Chicago Denver San Francisco (cost: 2270.0)  
A path from Chicago to Los Angeles:  
Chicago Denver Los Angeles (cost: 2018.0)  
A path from Chicago to Denver: Chicago Denver (cost: 1003.0)  
A path from Chicago to Kansas City: Chicago Kansas City (cost: 533.0)  
A path from Chicago to Chicago: Chicago (cost: 0.0)  
A path from Chicago to Boston: Chicago Boston (cost: 983.0)  
A path from Chicago to New York: Chicago New York (cost: 787.0)  
A path from Chicago to Atlanta:  
Chicago Kansas City Atlanta (cost: 1397.0)  
A path from Chicago to Miami:  
Chicago Kansas City Atlanta Miami (cost: 2058.0)  
A path from Chicago to Dallas: Chicago Kansas City Dallas (cost: 1029.0)  
A path from Chicago to Houston:  
Chicago Kansas City Dallas Houston (cost: 1268.0)  
Shortest path from Houston to Chicago:  
Houston Dallas Kansas City Chicago

All shortest paths from 3 are:  
A path from 3 to 0: 3 1 0 (cost: 5.0)  
A path from 3 to 1: 3 1 (cost: 3.0)  
A path from 3 to 2: 3 2 (cost: 4.0)  
A path from 3 to 3: 3 (cost: 0.0)  
A path from 3 to 4: 3 4 (cost: 6.0)



The program creates a weighted graph for Figure 29.1 in line 27. It then invokes the `getShortestPath(graph1.getIndex("Chicago"))` method to return a `Path` object that contains all shortest paths from Chicago. Invoking `printAllPaths()` on the `ShortestPathTree` object displays all the paths (line 30).

The graphical illustration of all shortest paths from Chicago is shown in Figure 29.21. The shortest paths from Chicago to the cities are found in this order: Kansas City, New York, Boston, Denver, Dallas, Houston, Atlanta, Los Angeles, Miami, Seattle, and San Francisco.



**FIGURE 29.21** The shortest paths from Chicago to all other cities are highlighted.



- 29.9** Trace Dijkstra's algorithm for finding shortest paths from Boston to all other cities in Figure 29.1.

**29.10** Is a shortest path between two vertices unique if all edges have different weights?

**29.11** If you use an adjacency matrix to represent weighted edges, what would be the time complexity for Dijkstra's algorithm?

**29.12** What happens to the `getShortestPath()` method in `WeightedGraph` if the source vertex cannot reach all vertices in the graph? Verify your answer by writing a test program that creates an unconnected graph and invoke the `getShortestPath()` method. How do you fix the problem by obtaining a partial shortest path tree?

**29.13** If there is no path from vertex `v` to the source vertex, what will be `cost[v]`?

**29.14** Assume that the graph is connected; will the `getShortestPath` method find the shortest paths correctly if lines 159–161 in `WeightedGraph` are deleted?

## 29.6 Case Study: The Weighted Nine Tails Problem

The weighted nine tails problem can be reduced to the weighted shortest path problem.



Section 28.10 presented the nine tails problem and solved it using the BFS algorithm. This section presents a variation of the problem and solves it using the shortest-path algorithm.

The nine tails problem is to find the minimum number of the moves that lead to all coins facing down. Each move flips a head coin and its neighbors. The weighted nine tails problem assigns the number of flips as a weight on each move. For example, you can change the coins in Figure 29.22a to those in Figure 29.22b by flipping the first coin in the first row and its two neighbors. Thus, the weight for this move is 3. You can change the coins in Figure 29.22c to Figure 29.22d by flipping the center coin and its four neighbors. So the weight for this move is 5.



FIGURE 29.22 The weight for each move is the number of flips for the move.

The weighted nine tails problem can be reduced to finding a shortest path from a starting node to the target node in an edge-weighted graph. The graph has 512 nodes. Create an edge from node **v** to **u** if there is a move from node **u** to node **v**. Assign the number of flips to be the weight of the edge.

Recall that in Section 28.10 we defined a class **NineTailModel** for modeling the nine tails problem. We now define a new class named **WeightedNineTailModel** that extends **NineTailModel**, as shown in Figure 29.23.



FIGURE 29.23 The **WeightedNineTailModel** class extends **NineTailModel**.

The `NineTailModel` class creates a `Graph` and obtains a `Tree` rooted at the target node `511`. `WeightedNineTailModel` is the same as `NineTailModel` except that it creates a `WeightedGraph` and obtains a `ShortestPathTree` rooted at the target node `511`. `WeightedNineTailModel` extends `NineTailModel`. The method `getEdges()` finds all edges in the graph. The `getNumberOfFlips(int u, int v)` method returns the number of flips from node `u` to node `v`. The `getNumberOfFlips(int u)` method returns the number of flips from node `u` to the target node.

Listing 29.9 implements `WeightedNineTailModel`.

### LISTING 29.9 WeightedNineTailModel.java

```

1 import java.util.*;
2
3 public class WeightedNineTailModel extends NineTailModel {
4 /** Construct a model */
5 public WeightedNineTailModel() {
6 // Create edges
7 List<WeightedEdge> edges = getEdges();
8
9 // Create a graph
10 WeightedGraph<Integer> graph = new WeightedGraph<>(
11 edges, NUMBER_OF_NODES);
12
13 // Obtain a shortest path tree rooted at the target node
14 tree = graph.getShortestPath(511);
15 }
16
17 /** Create all edges for the graph */
18 private List<WeightedEdge> getEdges() {
19 // Store edges
20 List<WeightedEdge> edges = new ArrayList<>();
21
22 for (int u = 0; u < NUMBER_OF_NODES; u++) {
23 for (int k = 0; k < 9; k++) {
24 char[] node = getNode(u); // Get the node for vertex u
25 if (node[k] == 'H') {
26 int v = getFlippedNode(node, k);
27 int numberOffFlips = getNumberOfFlips(u, v);
28
29 // Add edge (v, u) for a legal move from node u to node v
30 edges.add(new WeightedEdge(v, u, numberOffFlips));
31 }
32 }
33 }
34
35 return edges;
36 }
37
38 private static int getNumberOfFlips(int u, int v) {
39 char[] node1 = getNode(u);
40 char[] node2 = getNode(v);
41
42 int count = 0; // Count the number of different cells
43 for (int i = 0; i < node1.length; i++)
44 if (node1[i] != node2[i]) count++;
45
46 return count;
47 }
48

```

```

49 public int getNumberOfFlips(int u) {
50 return ((int)((WeightedGraph<Integer>.ShortestPathTree)tree)
51 .getCost(u));
52 }
53 }
```

total number of flips

**WeightedNineTailModel** extends **NineTailModel** to build a **WeightedGraph** to model the weighted nine tails problem (lines 10–11). For each node **u**, the **getEdges()** method finds a flipped node **v** and assigns the number of flips as the weight for edge  $(v, u)$  (line 30). The **getNumberOfFlips(int u, int v)** method returns the number of flips from node **u** to node **v** (lines 38–47). The number of flips is the number of the different cells between the two nodes (line 44).

The **WeightedNineTailModel** obtains a **ShortestPathTree** rooted at the target node **511** (line 14). Note that **tree** is a protected data field defined in **NineTailModel** and **ShortestPathTree** is a subclass of **Tree**. The methods defined in **NineTailModel** use the **tree** property.

The **getNumberOfFlips(int u)** method (lines 49–52) returns the number of flips from node **u** to the target node, which is the cost of the path from node **u** to the target node. This cost can be obtained by invoking the **getCost(u)** method defined in the **ShortestPathTree** class (line 51).

Listing 29.10 gives a program that prompts the user to enter an initial node and displays the minimum number of flips to reach the target node.

### LISTING 29.10 WeightedNineTail.java

```

1 import java.util.Scanner;
2
3 public class WeightedNineTail {
4 public static void main(String[] args) {
5 // Prompt the user to enter the nine coins' Hs and Ts
6 System.out.print("Enter an initial nine coins' Hs and Ts: ");
7 Scanner input = new Scanner(System.in);
8 String s = input.nextLine();
9 char[] initialNode = s.toCharArray(); initial node
10
11 WeightedNineTailModel model = new WeightedNineTailModel(); create model
12 java.util.List<Integer> path =
13 model.getShortestPath(NineTailModel.getIndex(initialNode)); get shortest path
14
15 System.out.println("The steps to flip the coins are ");
16 for (int i = 0; i < path.size(); i++)
17 NineTailModel.printNode(NineTailModel.getNode(path.get(i))); print node
18
19 System.out.println("The number of flips is " +
20 model.getNumberOfFlips(NineTailModel.getIndex(initialNode))); number of flips
21
22 }
```

Enter an initial nine coins Hs and Ts: HHHTTTHHH

The steps to flip the coins are  
HHH  
TTT  
HHH



```

HHH
THT
TTT

TTT
TTT
TTT

```

The number of flips is 8

The program prompts the user to enter an initial node with nine letters with a combination of **H**s and **T**s as a string in line 8, obtains an array of characters from the string (line 9), creates a model (line 11), obtains the shortest path from the initial node to the target node (lines 12–13), displays the nodes in the path (lines 16–17), and invokes `getNumberOfFlips` to get the number of flips needed to reach the target node (line 20).



- 29.15** Why is the `tree` data field in `NineTailModel` in Listing 28.13 defined protected?
- 29.16** How are the nodes created for the graph in `WeightedNineTailModel`?
- 29.17** How are the edges created for the graph in `WeightedNineTailModel`?

## KEY TERMS

Dijkstra's algorithm 1078  
 edge-weighted graph 1063  
 minimum spanning tree 1072  
 Prim's algorithm 1072

shortest path 1078  
 single-source shortest path 1079  
 vertex-weighted graph 1063

## CHAPTER SUMMARY

1. You can use adjacency matrices or lists to store weighted edges in graphs.
2. A spanning tree of a graph is a subgraph that is a tree and connects all vertices in the graph.
3. Prim's algorithm for finding a minimum spanning tree works as follows: the algorithm starts with a spanning tree that contains an arbitrary vertex. The algorithm expands the tree by adding a vertex with the minimum-weight edge incident to a vertex already in the tree.
4. Dijkstra's algorithm starts search from the source vertex and keeps finding vertices that have the shortest path to the source until all vertices are found.

## QUIZ

Answer the quiz for this chapter online at [www.cs.armstrong.edu/liang/intro10e/quiz.html](http://www.cs.armstrong.edu/liang/intro10e/quiz.html).

- \*29.1** (*Kruskal's algorithm*) The text introduced Prim's algorithm for finding a minimum spanning tree. Kruskal's algorithm is another well-known algorithm for finding a minimum spanning tree. The algorithm repeatedly finds a minimum-weight edge and adds it to the tree if it does not cause a cycle. The process ends

when all vertices are in the tree. Design and implement an algorithm for finding an MST using Kruskal's algorithm.

- \*29.2 (*Implement Prim's algorithm using an adjacency matrix*) The text implements Prim's algorithm using lists for adjacent edges. Implement the algorithm using an adjacency matrix for weighted graphs.
- \*29.3 (*Implement Dijkstra's algorithm using an adjacency matrix*) The text implements Dijkstra's algorithm using lists for adjacent edges. Implement the algorithm using an adjacency matrix for weighted graphs.
- \*29.4 (*Modify weight in the nine tails problem*) In the text, we assign the number of the flips as the weight for each move. Assuming that the weight is three times of the number of flips, revise the program.
- \*29.5 (*Prove or disprove*) The conjecture is that both **NineTailModel** and **WeightedNineTailModel** result in the same shortest path. Write a program to prove or disprove it. (*Hint:* Let **tree1** and **tree2** denote the trees rooted at node **511** obtained from **NineTailModel** and **WeightedNineTailModel**, respectively. If the depth of a node **u** is the same in **tree1** and in **tree2**, the length of the path from **u** to the target is the same.)
- \*\*29.6 (*Weighted  $4 \times 4$  16 tails model*) The weighted nine tails problem in the text uses a  $3 \times 3$  matrix. Assume that you have 16 coins placed in a  $4 \times 4$  matrix. Create a new model class named **WeightedTailModel16**. Create an instance of the model and save the object into a file named **WeightedTailModel16.dat**.
- \*\*29.7 (*Weighted  $4 \times 4$  16 tails*) Revise Listing 29.9, **WeightedNineTail.java**, for the weighted  $4 \times 4$  16 tails problem. Your program should read the model object created from the preceding exercise.
- \*\*29.8 (*Traveling salesperson problem*) The traveling salesperson problem (TSP) is to find a shortest round-trip route that visits each city exactly once and then returns to the starting city. The problem is equivalent to finding a shortest Hamiltonian cycle in Programming Exercise 28.17. Add the following method in the **WeightedGraph** class:

```
// Return a shortest cycle
// Return null if no such cycle exists
public List<Integer> getShortestHamiltonianCycle()
```

- \*29.9 (*Find a minimum spanning tree*) Write a program that reads a connected graph from a file and displays its minimum spanning tree. The first line in the file contains a number that indicates the number of vertices (**n**). The vertices are labeled as **0, 1, ..., n-1**. Each subsequent line describes the edges in the form of **u1, v1, w1 | u2, v2, w2 | ...**. Each triplet in this form describes an edge and its weight. Figure 29.24 shows an example of the file for the corresponding graph. Note that we assume the graph is undirected. If the graph has



FIGURE 29.24 The vertices and edges of a weighted graph can be stored in a file.

an edge  $(u, v)$ , it also has an edge  $(v, u)$ . Only one edge is represented in the file. When you construct a graph, both edges need to be added.

Your program should prompt the user to enter the name of the file, read data from the file, create an instance `g` of `WeightedGraph`, invoke `g.printWeightedEdges()` to display all edges, invoke `getMinimumSpanningTree()` to obtain an instance `tree` of `WeightedGraph.MST`, invoke `tree.getTotalWeight()` to display the weight of the minimum spanning tree, and invoke `tree.printTree()` to display the tree. Here is a sample run of the program:



```
Enter a file name: c:\exercise\WeightedGraphSample.txt [Enter]
The number of vertices is 6
Vertex 0: (0, 2, 3) (0, 1, 100)
Vertex 1: (1, 3, 20) (1, 0, 100)
Vertex 2: (2, 4, 2) (2, 3, 40) (2, 0, 3)
Vertex 3: (3, 4, 5) (3, 5, 5) (3, 1, 20) (3, 2, 40)
Vertex 4: (4, 2, 2) (4, 3, 5) (4, 5, 9)
Vertex 5: (5, 3, 5) (5, 4, 9)
Total weight in MST is 35
Root is: 0
Edges: (3, 1) (0, 2) (4, 3) (2, 4) (3, 5)
```

(Hint: Use `new WeightedGraph(list, numberOfVertices)` to create a graph, where `List` contains a list of `WeightedEdge` objects. Use `new WeightedEdge(u, v, w)` to create an edge. Read the first line to get the number of vertices. Read each subsequent line into a string `s` and use `s.split("[\\|]")` to extract the triplets. For each triplet, use `triplet.split("[,]")` to extract vertices and weight.)

- \*29.10** (*Create a file for a graph*) Modify Listing 29.3, `TestWeightedGraph.java`, to create a file for representing `graph1`. The file format is described in Programming Exercise 29.9. Create the file from the array defined in lines 7–24 in Listing 29.3. The number of vertices for the graph is 12, which will be stored in the first line of the file. An edge  $(u, v)$  is stored if  $u < v$ . The contents of the file should be as follows:



```
12
0, 1, 807 | 0, 3, 1331 | 0, 5, 2097
1, 2, 381 | 1, 3, 1267
2, 3, 1015 | 2, 4, 1663 | 2, 10, 1435
3, 4, 599 | 3, 5, 1003
4, 5, 533 | 4, 7, 1260 | 4, 8, 864 | 4, 10, 496
5, 6, 983 | 5, 7, 787
6, 7, 214
7, 8, 888
8, 9, 661 | 8, 10, 781 | 8, 11, 810
9, 11, 1187
10, 11, 239
```

- \*29.11** (*Find shortest paths*) Write a program that reads a connected graph from a file. The graph is stored in a file using the same format specified in Programming Exercise 29.9. Your program should prompt the user to enter the name of the file then two vertices, and should display a shortest path between the two

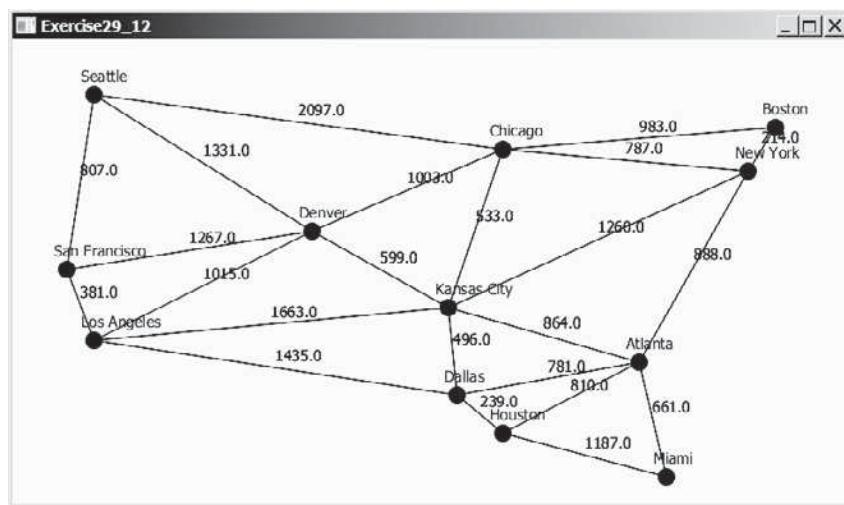
vertices. For example, for the graph in Figure 29.23, a shortest path between **0** and **1** can be displayed as **0 2 4 3 1**.

Here is a sample run of the program:

```
Enter a file name: WeightedGraphSample2.txt [Enter]
Enter two vertices (integer indexes): 0 1 [Enter]
The number of vertices is 6
Vertex 0: (0, 2, 3) (0, 1, 100)
Vertex 1: (1, 3, 20) (1, 0, 100)
Vertex 2: (2, 4, 2) (2, 3, 40) (2, 0, 3)
Vertex 3: (3, 4, 5) (3, 5, 5) (3, 1, 20) (3, 2, 40)
Vertex 4: (4, 2, 2) (4, 3, 5) (4, 5, 9)
Vertex 5: (5, 3, 5) (5, 4, 9)
A path from 0 to 1: 0 2 4 3 1
```

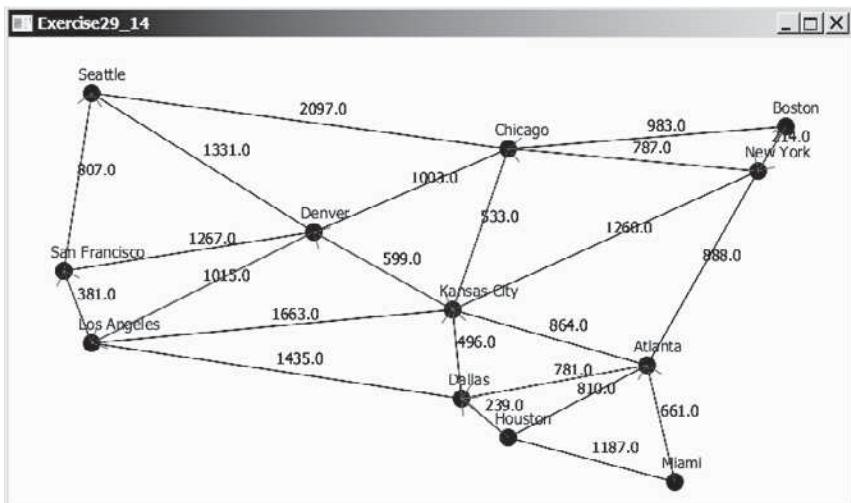


- \*29.12** (*Display weighted graphs*) Revise **GraphView** in Listing 28.6 to display a weighted graph. Write a program that displays the graph in Figure 29.1 as shown in Figure 29.25. (Instructors may ask students to expand this program by adding new cities with appropriate edges into the graph).

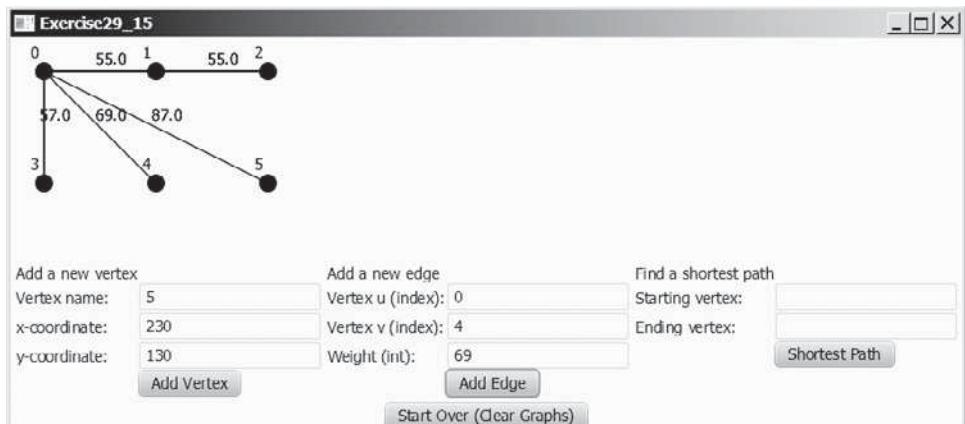


**FIGURE 29.25** Programming Exercise 29.12 displays a weighted graph.

- \*29.13** (*Display shortest paths*) Revise **GraphView** in Listing 28.6 to display a weighted graph and a shortest path between the two specified cities, as shown in Figure 29.19. You need to add a data field **path** in **GraphView**. If a **path** is not null, the edges in the path are displayed in red. If a city not in the map is entered, the program displays a text to alert the user.
- \*29.14** (*Display a minimum spanning tree*) Revise **GraphView** in Listing 28.6 to display a weighted graph and a minimum spanning tree for the graph in Figure 29.1, as shown in Figure 29.26. The edges in the MST are shown in red.
- \*\*\*29.15** (*Dynamic graphs*) Write a program that lets the users create a weighted graph dynamically. The user can create a vertex by entering its name and location, as shown in Figure 29.27. The user can also create an edge to connect two vertices. To simplify the program, assume that vertex names are the same as vertex



**FIGURE 29.26** Programming Exercise 29.14 displays an MST.



**FIGURE 29.27** The program can add vertices and edges and display a shortest path between two specified vertices.

indices. You have to add the vertex indices **0**, **1**, ..., and **n**, in this order. The user can specify two vertices and let the program display their shortest path in red.

**\*\*\*29.16** (*Display a dynamic MST*) Write a program that lets the user create a weighted graph dynamically. The user can create a vertex by entering its name and location, as shown in Figure 29.28. The user can also create an edge to connect two vertices. To simplify the program, assume that vertex names are the same as those of vertex indices. You have to add the vertex indices **0**, **1**, . . . , and **n**, in this order. The edges in the MST are displayed in red. As new edges are added, the MST is redisplayed.

**\*\*\*29.17** (*Weighted graph visualization tool*) Develop a GUI program as shown in Figure 29.2, with the following requirements: (1) The radius of each vertex is 20 pixels. (2) The user clicks the left mouse button to place a vertex centered at the mouse point, provided that the mouse point is not inside or too close to an existing vertex. (3) The user clicks the right mouse button inside an existing vertex to remove the vertex. (4) The user presses a mouse button inside a vertex and drags to another vertex and then releases the button to create an



**FIGURE 29.28** The program can add vertices and edges and display MST dynamically.

edge, and the distance between the two vertices is also displayed. (5) The user drags a vertex while pressing the *CTRL* key to move a vertex. (6) The vertices are numbers starting from **0**. When a vertex is removed, the vertices are renumbered. (7) You can click the *Show MST* or *Show All SP From the Source* button to display an MST or SP tree from a starting vertex. (8) You can click the *Show Shortest Path* button to display the shortest path between the two specified vertices.

**\*\*\*29.18** (*Alternative version of Dijkstra algorithm*) An alternative version of the Dijkstra algorithm can be described as follows:

Input: a weighted graph  $G = (V, E)$  with non-negative weights  
Output: A shortest path tree from a source vertex  $s$

```

1 ShortestPathTree getShortestPath(s) {
2 Let T be a set that contains the vertices whose
3 paths to s are known;
4 Initially T contains source vertex s with cost[s] = 0; add initial vertex
5 for (each u in V - T)
6 cost[u] = infinity;
7
8 while (size of T < n) {
9 Find v in V - T with the smallest cost[u] + w(u, v) value more vertex
10 among all u in T; find next vertex
11 Add v to T and set cost[v] = cost[u] + w(u, v); add a vertex
12 parent[v] = u;
13 }
14 }
```

The algorithm uses **cost[v]** to store the cost of a shortest path from vertex **v** to the source vertex **s**. **cost[s]** is **0**. Initially assign infinity to **cost[v]** to indicate that no path is found from **v** to **s**. Let **V** denote all vertices in the graph and **T** denote the set of the vertices whose costs are known. Initially, the source vertex **s** is in **T**. The algorithm repeatedly finds a vertex **u** in **T** and a vertex **v** in **V - T** such that **cost[u] + w(u, v)** is the smallest, and moves **v** to **T**. The shortest path algorithm given in the text continuously update the cost and parent for a vertex in **V - T**. This algorithm initializes the cost to infinity for each vertex and then changes the cost for a vertex only once when the vertex is added into **T**. Implement this algorithm and use Listing 29.7, TestShortestPath.java, to test your new algorithm.

**\*\*\*29.19** (*Find  $u$  with smallest  $\text{cost}[u]$  efficiently*) The `getShortestPath` method finds a  $u$  with the smallest `cost[u]` using a linear search, which takes  $O(|V|)$ . The search time can be reduced to  $O(\log |V|)$  using an AVL tree. Modify the method using an AVL tree to store the vertices in  $V - T$ . Use Listing 29.7, `TestShortestPath.java`, to test your new implementation.

**\*\*\*29.20** (*Test if a vertex  $u$  is in  $T$  efficiently*) Since  $T$  is implemented using a list in the `getMinimumSpanningTree` and `getShortestPath` methods in Listing 29.2 `WeightedGraph.java`, testing whether a vertex  $u$  is in  $T$  by invoking `T.contains(u)` takes  $O(n)$  time. Modify these two methods by introducing an array named `isInT`. Set `isInT[u]` to `true` when a vertex  $u$  is added to  $T$ . Testing whether a vertex  $u$  is in  $T$  can now be done in  $O(1)$  time. Write a test program using the following code, where `graph1` is created from Figure 29.1.

```
WeightedGraph<String> graph1 = new WeightedGraph<>(edges, vertices);
WeightedGraph<String>.MST tree1 = graph1.getMinimumSpanningTree();
System.out.println("Total weight is " + tree1.getTotalWeight());
tree1.printTree();
WeightedGraph<String>.ShortestPathTree tree2 =
 graph1.getShortestPath(graph1.getIndex("Chicago"));
tree2.printAllPaths();
```

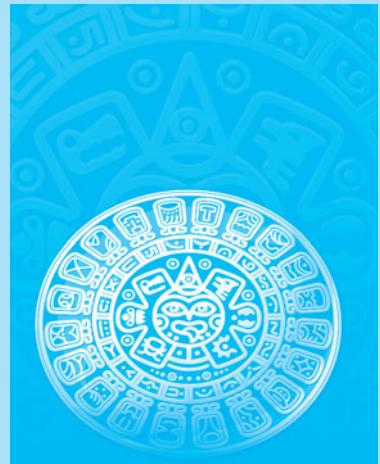
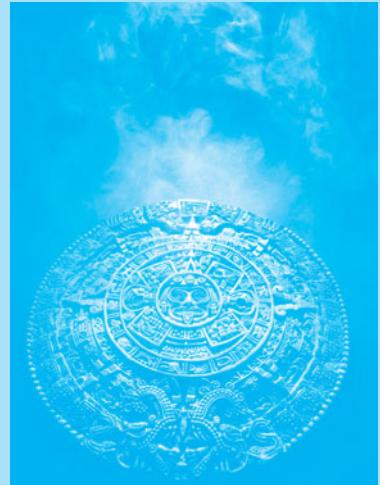
# CHAPTER

# 30

## MULTITHREADING AND PARALLEL PROGRAMMING

### Objectives

- To get an overview of multithreading (§30.2).
- To develop task classes by implementing the `Runnable` interface (§30.3).
- To create threads to run tasks using the `Thread` class (§30.3).
- To control threads using the methods in the `Thread` class (§30.4).
- To control animations using threads and use `Platform.runLater` to run the code in the application thread (§30.5).
- To execute tasks in a thread pool (§30.6).
- To use synchronized methods or blocks to synchronize threads to avoid race conditions (§30.7).
- To synchronize threads using locks (§30.8).
- To facilitate thread communications using conditions on locks (§§30.9 and 30.10).
- To use blocking queues (`ArrayBlockingQueue`, `LinkedBlockingQueue`, `PriorityBlockingQueue`) to synchronize access to a queue (§30.11).
- To restrict the number of concurrent tasks that access a shared resource using semaphores (§30.12).
- To use the resource-ordering technique to avoid deadlocks (§30.13).
- To describe the life cycle of a thread (§30.14).
- To create synchronized collections using the static methods in the `Collections` class (§30.15).
- To develop parallel programs using the Fork/Join Framework (§30.16).



## 30.1 Introduction



multithreading

*Multithreading enables multiple tasks in a program to be executed concurrently.*

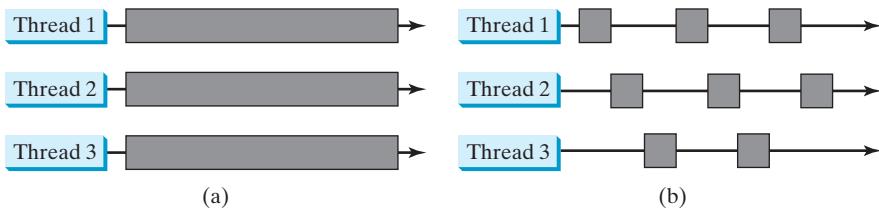
One of the powerful features of Java is its built-in support for *multithreading*—the concurrent running of multiple tasks within a program. In many programming languages, you have to invoke system-dependent procedures and functions to implement multithreading. This chapter introduces the concepts of threads and how multithreading programs can be developed in Java.

## 30.2 Thread Concepts

thread  
task

*A program may consist of many tasks that can run concurrently. A thread is the flow of execution, from beginning to end, of a task.*

A *thread* provides the mechanism for running a task. With Java, you can launch multiple threads from a program concurrently. These threads can be executed simultaneously in multi-processor systems, as shown in Figure 30.1a.



**FIGURE 30.1** (a) Here multiple threads are running on multiple CPUs. (b) Here multiple threads share a single CPU.

time sharing

In single-processor systems, as shown in Figure 30.1b, the multiple threads share CPU time, known as *time sharing*, and the operating system is responsible for scheduling and allocating resources to them. This arrangement is practical because most of the time the CPU is idle. It does nothing, for example, while waiting for the user to enter data.

task  
Runnable object  
thread

Multithreading can make your program more responsive and interactive, as well as enhance performance. For example, a good word processor lets you print or save a file while you are typing. In some cases, multithreaded programs run faster than single-threaded programs even on single-processor systems. Java provides exceptionally good support for creating and running threads and for locking resources to prevent conflicts.

You can create additional threads to run concurrent tasks in the program. In Java, each task is an instance of the **Runnable** interface, also called a *Runnable object*. A *thread* is essentially an object that facilitates the execution of a task.



**30.1** Why is multithreading needed? How can multiple threads run simultaneously in a single-processor system?

**30.2** What is a Runnable object? What is a thread?

## 30.3 Creating Tasks and Threads

Runnable interface  
run() method

*A task class must implement the **Runnable** interface. A task must be run from a thread.*

Tasks are objects. To create tasks, you have to first define a class for tasks, which implements the **Runnable** interface. The **Runnable** interface is rather simple. All it contains is the **run** method. You need to implement this method to tell the system how your thread is going to run. A template for developing a task class is shown in Figure 30.2a.



**FIGURE 30.2** Define a task class by implementing the `Runnable` interface.

Once you have defined a `TaskClass`, you can create a task using its constructor. For example,

```
TaskClass task = new TaskClass(...);
```

A task must be executed in a thread. The [Thread](#) class contains the constructors for creating threads and many useful methods for controlling threads. To create a thread for a task, use

```
Thread thread = new Thread(task);
```

You can then invoke the `start()` method to tell the JVM that the thread is ready to run, as follows:

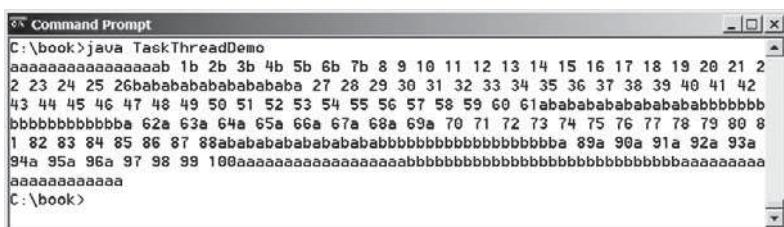
```
thread.start();
```

The JVM will execute the task by invoking the task's `run()` method. Figure 30.2b outlines the major steps for creating a task, a thread, and starting the thread.

Listing 30.1 gives a program that creates three tasks and three threads to run them.

- The first task prints the letter  $a$  100 times.
  - The second task prints the letter  $b$  100 times.
  - The third task prints the integers 1 through 100.

When you run this program, the three threads will share the CPU and take turns printing letters and numbers on the console. Figure 30.3 shows a sample run of the program.



**FIGURE 30.3** Tasks `printA`, `printB`, and `print100` are executed simultaneously to display the letter `a` 100 times, the letter `b` 100 times, and the numbers from 1 to 100.

**LISTING 30.1** TaskThreadDemo.java

```

1 public class TaskThreadDemo {
2 public static void main(String[] args) {
3 // Create tasks
4 Runnable printA = new PrintChar('a', 100);
5 Runnable printB = new PrintChar('b', 100);
6 Runnable print100 = new PrintNum(100);
7
8 // Create threads
9 Thread thread1 = new Thread(printA);
10 Thread thread2 = new Thread(printB);
11 Thread thread3 = new Thread(print100);
12
13 // Start threads
14 thread1.start();
15 thread2.start();
16 thread3.start();
17 }
18 }
19
20 // The task for printing a character a specified number of times
21 class PrintChar implements Runnable {
22 private char charToPrint; // The character to print
23 private int times; // The number of times to repeat
24
25 /** Construct a task with a specified character and number of
26 * times to print the character
27 */
28 public PrintChar(char c, int t) {
29 charToPrint = c;
30 times = t;
31 }
32
33 @Override /** Override the run() method to tell the system
34 * what task to perform
35 */
36 public void run() {
37 for (int i = 0; i < times; i++) {
38 System.out.print(charToPrint);
39 }
40 }
41 }
42
43 // The task class for printing numbers from 1 to n for a given n
44 class PrintNum implements Runnable {
45 private int lastNum;
46
47 /** Construct a task for printing 1, 2, ..., n */
48 public PrintNum(int n) {
49 lastNum = n;
50 }
51
52 @Override /** Tell the thread how to run */
53 public void run() {
54 for (int i = 1; i <= lastNum; i++) {
55 System.out.print(" " + i);
56 }
57 }
58 }
```

create tasks

create threads

start threads

task class

run

task class

run

The program creates three tasks (lines 4–6). To run them concurrently, three threads are created (lines 9–11). The `start()` method (lines 14–16) is invoked to start a thread that causes the `run()` method in the task to be executed. When the `run()` method completes, the thread terminates.

Because the first two tasks, `printA` and `printB`, have similar functionality, they can be defined in one task class `PrintChar` (lines 21–41). The `PrintChar` class implements `Runnable` and overrides the `run()` method (lines 36–40) with the print-character action. This class provides a framework for printing any single character a given number of times. The runnable objects, `printA` and `printB`, are instances of the `PrintChar` class.

The `PrintNum` class (lines 44–58) implements `Runnable` and overrides the `run()` method (lines 53–57) with the print-number action. This class provides a framework for printing numbers from  $l$  to  $n$ , for any integer  $n$ . The runnable object `print100` is an instance of the class `printNum` class.



### Note

If you don't see the effect of these three threads running concurrently, increase the number of characters to be printed. For example, change line 4 to

effect of concurrency

```
Runnable printA = new PrintChar('a', 10000);
```



### Important Note

The `run()` method in a task specifies how to perform the task. This method is automatically invoked by the JVM. You should not invoke it. Invoking `run()` directly merely executes this method in the same thread; no new thread is started.

run() method

**30.3** How do you define a task class? How do you create a thread for a task?

**30.4** What would happen if you replace the `start()` method with the `run()` method in lines 14–16 in Listing 30.1?



**30.5** What is wrong in the following two programs? Correct the errors.

```

public class Test implements Runnable {
 public static void main(String[] args) {
 new Test();
 }

 public Test() {
 Test task = new Test();
 new Thread(task).start();
 }

 public void run() {
 System.out.println("test");
 }
}

```

```

public class Test implements Runnable {
 public static void main(String[] args) {
 new Test();
 }

 public Test() {
 Thread t = new Thread(this);
 t.start();
 t.start();
 }

 public void run() {
 System.out.println("test");
 }
}

```

(a)

(b)

## 30.4 The Thread Class



*The **Thread** class contains the constructors for creating threads for tasks and the methods for controlling threads.*

Figure 30.4 shows the class diagram for the **Thread** class.

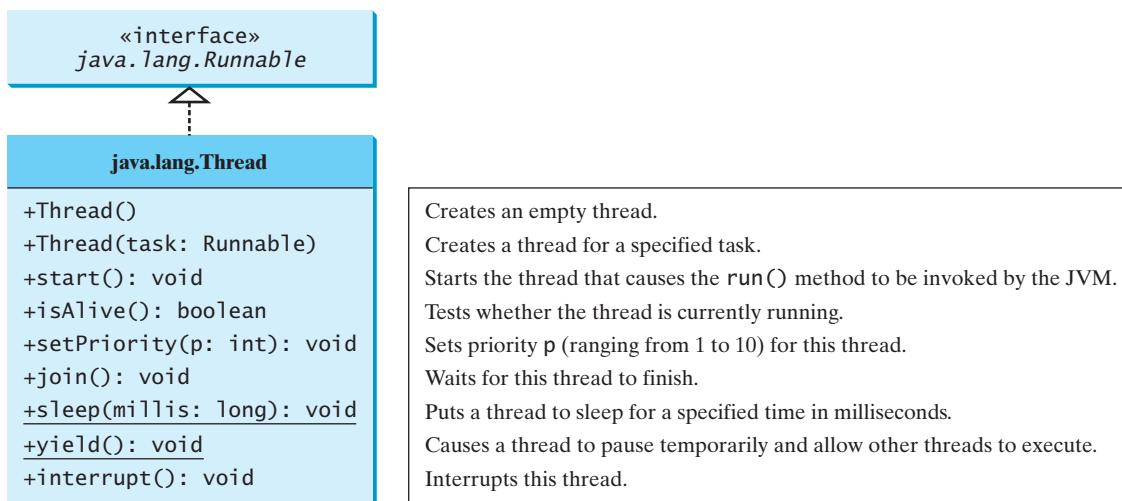


FIGURE 30.4 The **Thread** class contains the methods for controlling threads.

separating task from thread



### Note

Since the **Thread** class implements **Runnable**, you could define a class that extends **Thread** and implements the **run** method, as shown in Figure 30.5a, and then create an object from the class and invoke its **start** method in a client program to start the thread, as shown in Figure 30.5b.

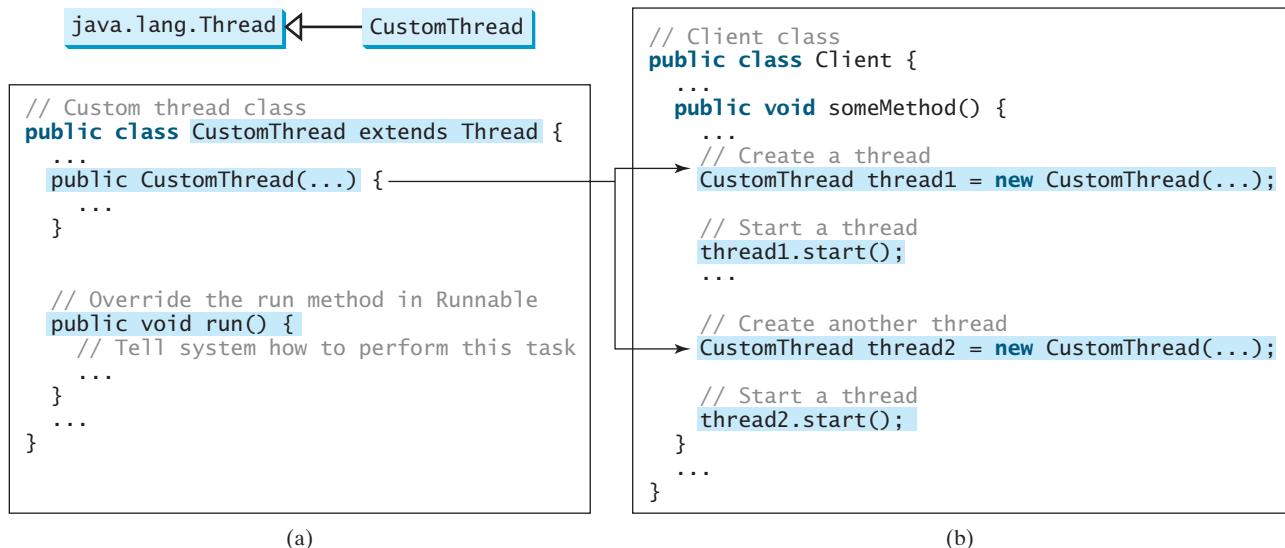


FIGURE 30.5 Define a thread class by extending the **Thread** class.

This approach is, however, not recommended because it mixes the task and the mechanism of running the task. Separating the task from the thread is a preferred design.



### Note

The `Thread` class also contains the `stop()`, `suspend()`, and `resume()` methods.

As of Java 2, these methods were *deprecated* (or *outdated*) because they are known to be inherently unsafe. Instead of using the `stop()` method, you should assign `null` to a `Thread` variable to indicate that has stopped.

deprecated method

You can use the `yield()` method to temporarily release time for other threads. For example, suppose you modify the code in the `run()` method in lines 53–57 for `PrintNum` in Listing 30.1 as follows:

`yield()`

```
public void run() {
 for (int i = 1; i <= lastNum; i++) {
 System.out.print(" " + i);
 Thread.yield();
 }
}
```

Every time a number is printed, the thread of the `print100` task is yielded to other threads.

The `sleep(long millis)` method puts the thread to sleep for a specified time in milliseconds to allow other threads to execute. For example, suppose you modify the code in lines 53–57 in Listing 30.1, as follows:

`sleep(long)`

```
public void run() {
 try {
 for (int i = 1; i <= lastNum; i++) {
 System.out.print(" " + i);
 if (i >= 50) Thread.sleep(1);
 }
 }
 catch (InterruptedException ex) {
 }
}
```

Every time a number ( $\geq 50$ ) is printed, the thread of the `print100` task is put to sleep for 1 millisecond.

The `sleep` method may throw an `InterruptedException`, which is a checked exception. Such an exception may occur when a sleeping thread's `interrupt()` method is called. The `interrupt()` method is very rarely invoked on a thread, so an `InterruptedException` is unlikely to occur. But since Java forces you to catch checked exceptions, you have to put it in a `try-catch` block. If a `sleep` method is invoked in a loop, you should wrap the loop in a `try-catch` block, as shown in (a) below. If the loop is outside the `try-catch` block, as shown in (b), the thread may continue to execute even though it is being interrupted.

`InterruptedException`

```
public void run() {
 try {
 while (...) {
 ...
 Thread.sleep(1000);
 }
 }
 catch (InterruptedException ex) {
 ex.printStackTrace();
 }
}
```

(a) correct

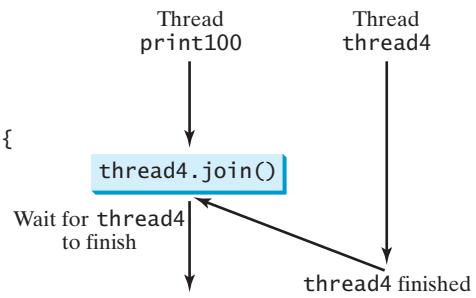
```
public void run() {
 while (...) {
 ...
 Thread.sleep(sleepTime);
 }
 catch (InterruptedException ex) {
 ex.printStackTrace();
 }
}
```

(b) Incorrect

join()

You can use the `join()` method to force one thread to wait for another thread to finish. For example, suppose you modify the code in lines 53–57 in Listing 30.1 as follows:

```
public void run() {
 Thread thread4 = new Thread(
 new PrintChar('c', 40));
 thread4.start();
 try {
 for (int i = 1; i <= lastNum; i++) {
 System.out.print (" " + i);
 if (i == 50) thread4.join();
 }
 } catch (InterruptedException ex) {
 }
}
```



setPriority(int)

round-robin scheduling

A new `thread4` is created and it prints character `c` 40 times. The numbers from `50` to `100` are printed after thread `thread4` is finished.

Java assigns every thread a priority. By default, a thread inherits the priority of the thread that spawned it. You can increase or decrease the priority of any thread by using the `setPriority` method, and you can get the thread's priority by using the `getPriority` method. Priorities are numbers ranging from `1` to `10`. The `Thread` class has the `int` constants `MIN_PRIORITY`, `NORM_PRIORITY`, and `MAX_PRIORITY`, representing `1`, `5`, and `10`, respectively. The priority of the main thread is `Thread.NORM_PRIORITY`.

The JVM always picks the currently runnable thread with the highest priority. A lower-priority thread can run only when no higher-priority threads are running. If all runnable threads have equal priorities, each is assigned an equal portion of the CPU time in a circular queue. This is called *round-robin scheduling*. For example, suppose you insert the following code in line 16 in Listing 30.1:

```
thread3.setPriority(Thread.MAX_PRIORITY);
```

The thread for the `print100` task will be finished first.



### Tip

The priority numbers may be changed in a future version of Java. To minimize the impact of any changes, use the constants in the `Thread` class to specify thread priorities.



### Tip

A thread may never get a chance to run if there is always a higher-priority thread running or a same-priority thread that never yields. This situation is known as *contention* or *starvation*. To avoid contention, the thread with higher priority must periodically invoke the `sleep` or `yield` method to give a thread with a lower or the same priority a chance to run.



contention or starvation

**30.6** Which of the following methods are instance methods in `java.lang.Thread`? Which method may throw an `InterruptedException`? Which of them are deprecated in Java?

`run`, `start`, `stop`, `suspend`, `resume`, `sleep`, `interrupt`, `yield`, `join`

**30.7** If a loop contains a method that throws an `InterruptedException`, why should the loop be placed inside a `try-catch` block?

**30.8** How do you set a priority for a thread? What is the default priority?



## 30.5 Case Study: Flashing Text

You can use a thread to control an animation.

The use of a **Timeline** object to control animations was introduced in Section 15.11, Animation. Alternatively, you can also use a thread to control animation. Listing 30.2 gives an example that displays flashing text on a label, as shown in Figure 30.6.



FIGURE 30.6 The text “Welcome” blinks.

### LISTING 30.2 FlashText.java

```

1 import javafx.application.Application;
2 import javafx.application.Platform;
3 import javafx.scene.Scene;
4 import javafx.scene.control.Label;
5 import javafx.scene.layout.StackPane;
6 import javafx.stage.Stage;
7
8 public class FlashText extends Application {
9 private String text = "";
10
11 @Override // Override the start method in the Application class
12 public void start(Stage primaryStage) {
13 StackPane pane = new StackPane();
14 Label lblText = new Label("Programming is fun");
15 pane.getChildren().add(lblText);
16
17 new Thread(new Runnable() {
18 @Override
19 public void run() {
20 try {
21 while (true) {
22 if (lblText.getText().trim().length() == 0)
23 text = "Welcome";
24 else
25 text = "";
26
27 Platform.runLater(new Runnable() { // Run from JavaFX GUI
28 @Override
29 public void run() {
30 lblText.setText(text);
31 }
32 });
33
34 Thread.sleep(200);
35 }
36 } catch (InterruptedException ex) {
37 }
38 }
39 }).start();
40 }
41

```

create a label  
label in a pane

create a thread

run thread

change text

Platform.runLater

update GUI

sleep

```

42 // Create a scene and place it in the stage
43 Scene scene = new Scene(pane, 200, 50);
44 primaryStage.setTitle("FlashText"); // Set the stage title
45 primaryStage.setScene(scene); // Place the scene in the stage
46 primaryStage.show(); // Display the stage
47 }
48 }

```

The program creates a **Runnable** object in an anonymous inner class (lines 17–40). This object is started in line 40 and runs continuously to change the text in the label. It sets a text in the label if the label is blank (line 23) and sets its text blank (line 25) if the label has a text. The text is set and unset to simulate a flashing effect.

JavaFX application thread

`Platform.runLater`

JavaFX GUI is run from the *JavaFX application thread*. The flashing control is run from a separate thread. The code in a nonapplication thread cannot update GUI in the application thread. To update the text in the label, a new **Runnable** object is created in lines 27–32. Invoking **Platform.runLater(Runnable r)** tells the system to run this **Runnable** object in the application thread.

The anonymous inner classes in this program can be simplified using lambda expressions as follows:

```

new Thread(() -> { // lambda expression
 try {
 while (true) {
 if (lblText.getText().trim().length() == 0)
 text = "Welcome";
 else
 text = "";
 Platform.runLater(() -> lblText.setText(text)); // lambda exp
 Thread.sleep(200);
 }
 } catch (InterruptedException ex) {
 }
}).start();

```



**30.9** What causes the text to flash?

**30.10** Is an instance of **FlashText** a runnable object?

**30.11** What is the purpose of using **Platform.runLater**?

**30.12** Can you replace the code in lines 27–32 using the following code?

```
Platform.runLater(e -> lblText.setText(text));
```

**30.13** What happens if line 34 (**Thread.sleep(200)**) is not used?

## 30.6 Thread Pools



*A thread pool can be used to execute tasks efficiently.*

In Section 30.3, Creating Tasks and Threads, you learned how to define a task class by implementing **java.lang.Runnable**, and how to create a thread to run a task like this:

```

Runnable task = new TaskClass(task);
new Thread(task).start();

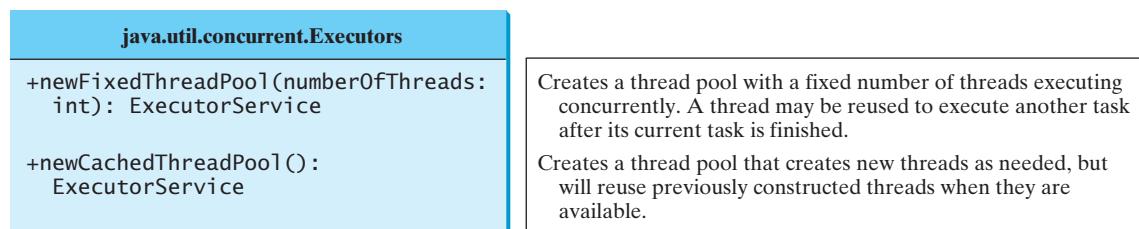
```

This approach is convenient for a single task execution, but it is not efficient for a large number of tasks because you have to create a thread for each task. Starting a new thread for each task could limit throughput and cause poor performance. Using a *thread pool* is an ideal way to manage the number of tasks executing concurrently. Java provides the **Executor** interface for executing tasks in a thread pool and the **ExecutorService** interface for managing and controlling tasks. **ExecutorService** is a subinterface of **Executor**, as shown in Figure 30.7.



**FIGURE 30.7** The **Executor** interface executes threads, and the **ExecutorService** subinterface manages threads.

To create an **Executor** object, use the static methods in the **Executors** class, as shown in Figure 30.8. The **newFixedThreadPool(int)** method creates a fixed number of threads in a pool. If a thread completes executing a task, it can be reused to execute another task. If a thread terminates due to a failure prior to shutdown, a new thread will be created to replace it if all the threads in the pool are not idle and there are tasks waiting for execution. The **newCachedThreadPool()** method creates a new thread if all the threads in the pool are not idle and there are tasks waiting for execution. A thread in a cached pool will be terminated if it has not been used for 60 seconds. A cached pool is efficient for many short tasks.



**FIGURE 30.8** The **Executors** class provides static methods for creating **Executor** objects.

Listing 30.3 shows how to rewrite Listing 30.1 using a thread pool.

### LISTING 30.3 ExecutorDemo.java

```

1 import java.util.concurrent.*;
2
3 public class ExecutorDemo {

```

```

4 public static void main(String[] args) {
5 // Create a fixed thread pool with maximum three threads
6 ExecutorService executor = Executors.newFixedThreadPool(3);
7
8 // Submit runnable tasks to the executor
9 executor.execute(new PrintChar('a', 100));
10 executor.execute(new PrintChar('b', 100));
11 executor.execute(new PrintNum(100));
12
13 // Shut down the executor
14 executor.shutdown();
15 }
16 }
```

Line 6 creates a thread pool executor with a total of three threads maximum. Classes `PrintChar` and `PrintNum` are defined in Listing 30.1. Line 9 creates a task, `new PrintChar('a', 100)`, and adds it to the pool. Similarly, another two runnable tasks are created and added to the same pool in lines 10 and 11. The executor creates three threads to execute three tasks concurrently.

Suppose that you replace line 6 with

```
ExecutorService executor = Executors.newFixedThreadPool(1);
```

What will happen? The three runnable tasks will be executed sequentially because there is only one thread in the pool.

Suppose you replace line 6 with

```
ExecutorService executor = Executors.newCachedThreadPool();
```

What will happen? New threads will be created for each waiting task, so all the tasks will be executed concurrently.

The `shutdown()` method in line 14 tells the executor to shut down. No new tasks can be accepted, but any existing tasks will continue to finish.



### Tip

If you need to create a thread for just one task, use the `Thread` class. If you need to create threads for multiple tasks, it is better to use a thread pool.



**30.14** What are the benefits of using a thread pool?

**30.15** How do you create a thread pool with three fixed threads? How do you submit a task to a thread pool? How do you know that all the tasks are finished?



## 30.7 Thread Synchronization

*Thread synchronization is to coordinate the execution of the dependent threads.*

A shared resource may become corrupted if it is accessed simultaneously by multiple threads. The following example demonstrates the problem.

Suppose you create and launch 100 threads, each of which adds a penny to an account. Define a class named `Account` to model the account, a class named `AddAPennyTask` to add a penny to the account, and a main class that creates and launches threads. The relationships of these classes are shown in Figure 30.9. The program is given in Listing 30.4.



FIGURE 30.9 `AccountWithoutSync` contains an instance of `Account` and 100 threads of `AddAPennyTask`.

#### LISTING 30.4 AccountWithoutSync.java

```

1 import java.util.concurrent.*;
2
3 public class AccountWithoutSync {
4 private static Account account = new Account();
5
6 public static void main(String[] args) {
7 ExecutorService executor = Executors.newCachedThreadPool(); create executor
8
9 // Create and launch 100 threads
10 for (int i = 0; i < 100; i++) {
11 executor.execute(new AddAPennyTask()); submit task
12 }
13
14 executor.shutdown(); shut down executor
15
16 // Wait until all tasks are finished
17 while (!executor.isTerminated()) { wait for all tasks to terminate
18 }
19
20 System.out.println("What is balance? " + account.getBalance());
21 }
22
23 // A thread for adding a penny to the account
24 private static class AddAPennyTask implements Runnable {
25 public void run() {
26 account.deposit(1);
27 }
28 }
29
30 // An inner class for account
31 private static class Account {
32 private int balance = 0;
33
34 public int getBalance() {
35 return balance;
36 }
37
38 public void deposit(int amount) {
39 int newBalance = balance + amount;
40 // This delay is deliberately added to magnify the

```

```

42 // data-corruption problem and make it easy to see.
43 try {
44 Thread.sleep(5);
45 }
46 catch (InterruptedException ex) {
47 }
48
49 balance = newBalance;
50 }
51 }
52 }
```

The classes `AddAPennyTask` and `Account` in lines 24–51 are inner classes. Line 4 creates an `Account` with initial balance 0. Line 11 creates a task to add a penny to the account and submits the task to the executor. Line 11 is repeated 100 times in lines 10–12. The program repeatedly checks whether all tasks are completed in lines 17 and 18. The account balance is displayed in line 20 after all tasks are completed.

The program creates 100 threads executed in a thread pool `executor` (lines 10–12). The `isTerminated()` method (line 17) is used to test whether the thread is terminated.

The balance of the account is initially 0 (line 32). When all the threads are finished, the balance should be 100 but the output is unpredictable. As can be seen in Figure 30.10, the answers are wrong in the sample run. This demonstrates the data-corruption problem that occurs when all the threads have access to the same data source simultaneously.



**FIGURE 30.10** The `AccountWithoutSync` program causes data inconsistency.

Lines 39–49 could be replaced by one statement:

```
balance = balance + amount;
```

It is highly unlikely, although plausible, that the problem can be replicated using this single statement. The statements in lines 39–49 are deliberately designed to magnify the data-corruption problem and make it easy to see. If you run the program several times but still do not see the problem, increase the sleep time in line 44. This will increase the chances for showing the problem of data inconsistency.

What, then, caused the error in this program? A possible scenario is shown in Figure 30.11.

| Step | Balance | Task 1                    | Task 2                    |
|------|---------|---------------------------|---------------------------|
| 1    | 0       | newBalance = balance + 1; |                           |
| 2    | 0       |                           | newBalance = balance + 1; |
| 3    | 1       | balance = newBalance;     |                           |
| 4    | 1       |                           | balance = newBalance;     |

**FIGURE 30.11** Task 1 and Task 2 both add 1 to the same balance.

In Step 1, Task 1 gets the balance from the account. In Step 2, Task 2 gets the same balance from the account. In Step 3, Task 1 writes a new balance to the account. In Step 4, Task 2 writes a new balance to the account.

The effect of this scenario is that Task 1 does nothing because in Step 4 Task 2 overrides Task 1's result. Obviously, the problem is that Task 1 and Task 2 are accessing a common resource in a way that causes a conflict. This is a common problem, known as a *race condition*, in multithreaded programs. A class is said to be *thread-safe* if an object of the class does not cause a race condition in the presence of multiple threads. As demonstrated in the preceding example, the **Account** class is not thread-safe.

race condition  
thread-safe

### 30.7.1 The **synchronized** Keyword

To avoid race conditions, it is necessary to prevent more than one thread from simultaneously entering a certain part of the program, known as the *critical region*. The critical region in Listing 30.4 is the entire **deposit** method. You can use the keyword **synchronized** to synchronize the method so that only one thread can access the method at a time. There are several ways to correct the problem in Listing 30.4. One approach is to make **Account** thread-safe by adding the keyword **synchronized** in the **deposit** method in line 38, as follows:

```
public synchronized void deposit(double amount)
```

A synchronized method acquires a lock before it executes. A lock is a mechanism for exclusive use of a resource. In the case of an instance method, the lock is on the object for which the method was invoked. In the case of a static method, the lock is on the class. If one thread invokes a synchronized instance method (respectively, static method) on an object, the lock of that object (respectively, class) is acquired first, then the method is executed, and finally the lock is released. Another thread invoking the same method of that object (respectively, class) is blocked until the lock is released.

With the **deposit** method synchronized, the preceding scenario cannot happen. If Task 1 enters the method, Task 2 is blocked until Task 1 finishes the method, as shown in Figure 30.12.

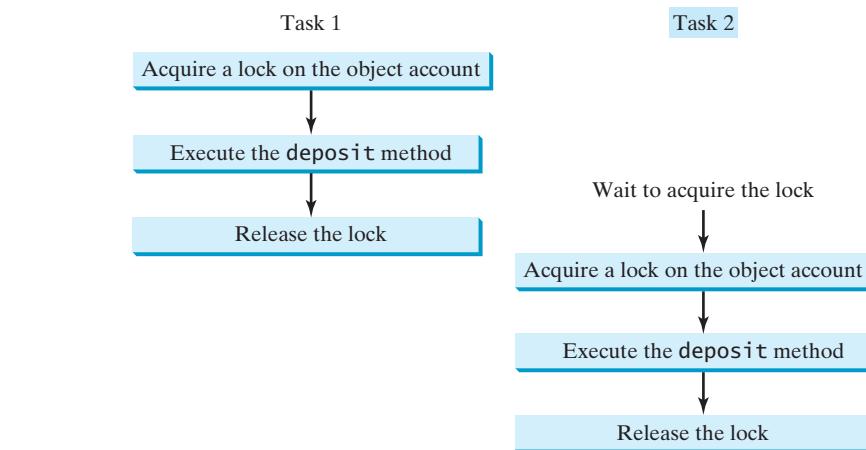


FIGURE 30.12 Task 1 and Task 2 are synchronized.

### 30.7.2 Synchronizing Statements

Invoking a synchronized instance method of an object acquires a lock on the object, and invoking a synchronized static method of a class acquires a lock on the class. A synchronized statement can be used to acquire a lock on any object, not just *this* object, when executing a

synchronized block

block of the code in a method. This block is referred to as a *synchronized block*. The general form of a synchronized statement is as follows:

```
synchronized (expr) {
 statements;
}
```

The expression **expr** must evaluate to an object reference. If the object is already locked by another thread, the thread is blocked until the lock is released. When a lock is obtained on the object, the statements in the synchronized block are executed and then the lock is released.

Synchronized statements enable you to synchronize part of the code in a method instead of the entire method. This increases concurrency. You can make Listing 30.4 thread-safe by placing the statement in line 26 inside a synchronized block:

```
synchronized (account) {
 account.deposit(1);
}
```



### Note

Any synchronized instance method can be converted into a synchronized statement.

For example, the following synchronized instance method in (a) is equivalent to (b):

```
public synchronized void xMethod() {
 // method body
}
```

(a)

```
public void xMethod() {
 synchronized (this) {
 // method body
 }
}
```

(b)



**30.16** Give some examples of possible resource corruption when running multiple threads. How do you synchronize conflicting threads?

**30.17** Suppose you place the statement in line 26 of Listing 30.4 inside a synchronized block to avoid race conditions, as follows:

```
synchronized (this) {
 account.deposit(1);
}
```

Will it work?

## 30.8 Synchronization Using Locks



*Locks and conditions can be explicitly used to synchronize threads.*

Recall that in Listing 30.4, 100 tasks deposit a penny to the same account concurrently, which causes conflicts. To avoid it, you use the **synchronized** keyword in the **deposit** method, as follows:

```
public synchronized void deposit(double amount)
```

lock

A synchronized instance method implicitly acquires a *lock* on the instance before it executes the method.

Java enables you to acquire locks explicitly, which give you more control for coordinating threads. A lock is an instance of the **Lock** interface, which defines the methods for acquiring and releasing locks, as shown in Figure 30.13. A lock may also use the **newCondition()** method to create any number of **Condition** objects, which can be used for thread communications.



**FIGURE 30.13** The `ReentrantLock` class implements the `Lock` interface to represent a lock.

`ReentrantLock` is a concrete implementation of `Lock` for creating mutually exclusive locks. You can create a lock with the specified *fairness policy*. True fairness policies guarantee that the longest-waiting thread will obtain the lock first. False fairness policies grant a lock to a waiting thread arbitrarily. Programs using fair locks accessed by many threads may have poorer overall performance than those using the default setting, but they have smaller variances in times to obtain locks and prevent starvation.

fairness policy

Listing 30.5 revises the program in Listing 30.7 to synchronize the account modification using explicit locks.

### LISTING 30.5 AccountWithSyncUsingLock.java

```

1 import java.util.concurrent.*;
2 import java.util.concurrent.locks.*;
3
4 public class AccountWithSyncUsingLock {
5 private static Account account = new Account();
6
7 public static void main(String[] args) {
8 ExecutorService executor = Executors.newCachedThreadPool();
9
10 // Create and launch 100 threads
11 for (int i = 0; i < 100; i++) {
12 executor.execute(new AddAPennyTask());
13 }
14
15 executor.shutdown();
16
17 // Wait until all tasks are finished
18 while (!executor.isTerminated()) {
19 }
20
21 System.out.println("What is balance? " + account.getBalance());
22 }
23
24 // A thread for adding a penny to the account
25 public static class AddAPennyTask implements Runnable {
26 public void run() {
27 account.deposit(1);
28 }
29 }

```

package for locks

```

31 // An inner class for Account
32 public static class Account {
33 private static Lock lock = new ReentrantLock(); // Create a lock
34 private int balance = 0;
35
36 public int getBalance() {
37 return balance;
38 }
39
40 public void deposit(int amount) {
41 lock.lock(); // Acquire the lock
42
43 try {
44 int newBalance = balance + amount;
45
46 // This delay is deliberately added to magnify the
47 // data-corruption problem and make it easy to see.
48 Thread.sleep(5);
49
50 balance = newBalance;
51 }
52 catch (InterruptedException ex) {
53 }
54 finally {
55 lock.unlock(); // Release the lock
56 }
57 }
58 }
59 }
```

release the lock

Line 33 creates a lock, line 41 acquires the lock, and line 55 releases the lock.

**Tip**

It is a good practice to always immediately follow a call to `lock()` with a `try-catch` block and release the lock in the `finally` clause, as shown in lines 41–56, to ensure that the lock is always released.

Listing 30.5 can be implemented using a synchronize method for `deposit` rather than using a lock. In general, using `synchronized` methods or statements is simpler than using explicit locks for mutual exclusion. However, using explicit locks is more intuitive and flexible to synchronize threads with conditions, as you will see in the next section.



**30.18** How do you create a lock object? How do you acquire a lock and release a lock?



## 30.9 Cooperation among Threads

*Conditions on locks can be used to coordinate thread interactions.*

condition

Thread synchronization suffices to avoid race conditions by ensuring the mutual exclusion of multiple threads in the critical region, but sometimes you also need a way for threads to cooperate. *Conditions* can be used to facilitate communications among threads. A thread can specify what to do under a certain condition. Conditions are objects created by invoking the `newCondition()` method on a `Lock` object. Once a condition is created, you can use its `await()`, `signal()`, and `signalAll()` methods for thread communications, as shown in Figure 30.14. The `await()` method causes the current thread to wait until the condition is signaled. The `signal()` method wakes up one waiting thread, and the `signalAll()` method wakes all waiting threads.

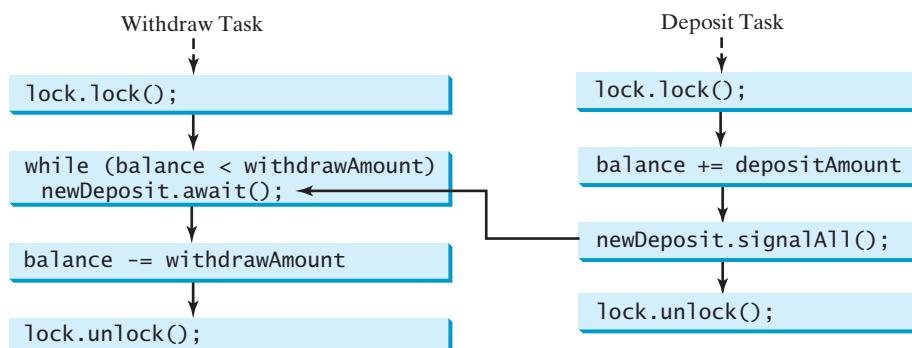


**FIGURE 30.14** The **Condition** interface defines the methods for performing synchronization.

Let us use an example to demonstrate thread communications. Suppose that you create and launch two tasks: one that deposits into an account and one that withdraws from the same account. The withdraw task has to wait if the amount to be withdrawn is more than the current balance. Whenever new funds are deposited into the account, the deposit task notifies the withdraw task to resume. If the amount is still not enough for a withdrawal, the withdraw thread has to continue to wait for a new deposit.

To synchronize the operations, use a lock with a condition: **newDeposit** (i.e., new deposit added to the account). If the balance is less than the amount to be withdrawn, the withdraw task will wait for the **newDeposit** condition. When the deposit task adds money to the account, the task signals the waiting withdraw task to try again. The interaction between the two tasks is shown in Figure 30.15.

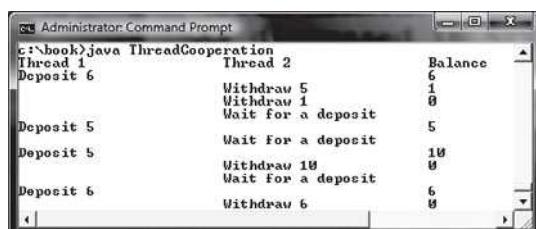
thread cooperation example



**FIGURE 30.15** The condition **newDeposit** is used for communications between the two threads.

You create a condition from a **Lock** object. To use a condition, you have to first obtain a lock. The **await()** method causes the thread to wait and automatically releases the lock on the condition. Once the condition is right, the thread reacquires the lock and continues executing.

Assume that the initial balance is **0** and the amount to deposit and withdraw are randomly generated. Listing 30.6 gives the program. A sample run of the program is shown in Figure 30.16.



**FIGURE 30.16** The withdraw task waits if there are not sufficient funds to withdraw.

**LISTING 30.6** ThreadCooperation.java

```

1 import java.util.concurrent.*;
2 import java.util.concurrent.locks.*;
3
4 public class ThreadCooperation {
5 private static Account account = new Account();
6
7 public static void main(String[] args) {
8 // Create a thread pool with two threads
9 ExecutorService executor = Executors.newFixedThreadPool(2);
10 executor.execute(new DepositTask());
11 executor.execute(new WithdrawTask());
12 executor.shutdown();
13
14 System.out.println("Thread 1\t\tThread 2\t\tBalance");
15 }
16
17 public static class DepositTask implements Runnable {
18 @Override // Keep adding an amount to the account
19 public void run() {
20 try { // Purposely delay it to let the withdraw method proceed
21 while (true) {
22 account.deposit((int)(Math.random() * 10) + 1);
23 Thread.sleep(1000);
24 }
25 } catch (InterruptedException ex) {
26 ex.printStackTrace();
27 }
28 }
29 }
30
31
32 public static class WithdrawTask implements Runnable {
33 @Override // Keep subtracting an amount from the account
34 public void run() {
35 while (true) {
36 account.withdraw((int)(Math.random() * 10) + 1);
37 }
38 }
39 }
40
41 // An inner class for account
42 private static class Account {
43 // Create a new lock
44 private static Lock lock = new ReentrantLock();
45
46 // Create a condition
47 private static Condition newDeposit = lock.newCondition();
48
49 private int balance = 0;
50
51 public int getBalance() {
52 return balance;
53 }
54
55 public void withdraw(int amount) {
56 lock.lock(); // Acquire the lock
57 try {
58 while (balance < amount) {

```

create two threads

create a lock

create a condition

acquire the lock

```

59 System.out.println("\t\t\tWait for a deposit");
60 newDeposit.await(); wait on the condition
61 }
62
63 balance -= amount;
64 System.out.println("\t\t\tWithdraw " + amount +
65 "\t\t" + getBalance());
66 }
67 catch (InterruptedException ex) {
68 ex.printStackTrace();
69 }
70 finally {
71 lock.unlock(); // Release the lock release the lock
72 }
73 }
74
75 public void deposit(int amount) {
76 lock.lock(); // Acquire the lock acquire the lock
77 try {
78 balance += amount;
79 System.out.println("Deposit " + amount +
80 "\t\t\t\t" + getBalance());
81
82 // Signal thread waiting on the condition
83 newDeposit.signalAll(); signal threads
84 }
85 finally {
86 lock.unlock(); // Release the lock release the lock
87 }
88 }
89 }
90 }
```

The example creates a new inner class named `Account` to model the account with two methods, `deposit(int)` and `withdraw(int)`, a class named `DepositTask` to add an amount to the balance, a class named `WithdrawTask` to withdraw an amount from the balance, and a main class that creates and launches two threads.

The program creates and submits the deposit task (line 10) and the withdraw task (line 11). The deposit task is purposely put to sleep (line 23) to let the withdraw task run. When there are not enough funds to withdraw, the withdraw task waits (line 59) for notification of the balance change from the deposit task (line 83).

A lock is created in line 44. A condition named `newDeposit` on the lock is created in line 47. A condition is bound to a lock. Before waiting or signaling the condition, a thread must first acquire the lock for the condition. The withdraw task acquires the lock in line 56, waits for the `newDeposit` condition (line 60) when there is not a sufficient amount to withdraw, and releases the lock in line 71. The deposit task acquires the lock in line 76 and signals all waiting threads (line 83) for the `newDeposit` condition after a new deposit is made.

What will happen if you replace the `while` loop in lines 58–61 with the following `if` statement?

```

if (balance < amount) {
 System.out.println("\t\t\tWait for a deposit");
 newDeposit.await();
}
```

The deposit task will notify the withdraw task whenever the balance changes. `(balance < amount)` may still be true when the withdraw task is awakened. Using the `if`

statement may lead to an incorrect withdraw. Using the loop statement, the withdraw task will have a chance to recheck the condition before performing a withdraw.

ever-waiting threads

`IllegalMonitorStateException`

Java's built-in monitor  
monitor



### Caution

Once a thread invokes `await()` on a condition, the thread waits for a signal to resume. If you forget to call `signal()` or `signalAll()` on the condition, the thread will wait forever.



### Caution

A condition is created from a `Lock` object. To invoke its method (e.g., `await()`, `signal()`, and `signalAll()`), you must first own the lock. If you invoke these methods without acquiring the lock, an `IllegalMonitorStateException` will be thrown.

Locks and conditions were introduced in Java 5. Prior to Java 5, thread communications were programmed using the object's built-in monitors. Locks and conditions are more powerful and flexible than the built-in monitor, so you will not need to use monitors. However, if you are working with legacy Java code, you may encounter Java's built-in monitor.

A *monitor* is an object with mutual exclusion and synchronization capabilities. Only one thread can execute a method at a time in the monitor. A thread enters the monitor by acquiring a lock on it and exits by releasing the lock. *Any object can be a monitor*. An object becomes a monitor once a thread locks it. Locking is implemented using the `synchronized` keyword on a method or a block. A thread must acquire a lock before executing a synchronized method or block. A thread can wait in a monitor if the condition is not right for it to continue executing in the monitor. You can invoke the `wait()` method on the monitor object to release the lock so that some other thread can get in the monitor and perhaps change the monitor's state. When the condition is right, the other thread can invoke the `notify()` or `notifyAll()` method to signal one or all waiting threads to regain the lock and resume execution. The template for invoking these methods is shown in Figure 30.17.



FIGURE 30.17 The `wait()`, `notify()`, and `notifyAll()` methods coordinate thread communication.

The `wait()`, `notify()`, and `notifyAll()` methods must be called in a synchronized method or a synchronized block on the receiving object of these methods. Otherwise, an `IllegalMonitorStateException` will occur.

When `wait()` is invoked, it pauses the thread and simultaneously releases the lock on the object. When the thread is restarted after being notified, the lock is automatically reacquired.

The `wait()`, `notify()`, and `notifyAll()` methods on an object are analogous to the `await()`, `signal()`, and `signalAll()` methods on a condition.



- 30.19** How do you create a condition on a lock? What are the `await()`, `signal()`, and `signalAll()` methods for?
- 30.20** What would happen if the `while` loop in line 58 of Listing 30.6 was changed to an `if` statement?



- 30.21** Why does the following class have a syntax error?

```

public class Test implements Runnable {
 public static void main(String[] args) {
 new Test();
 }

 public Test() throws InterruptedException {
 Thread thread = new Thread(this);
 thread.sleep(1000);
 }

 public synchronized void run() {
 }
}

```

- 30.22** What is a possible cause for `IllegalMonitorStateException`?
- 30.23** Can the `wait()`, `notify()`, and `notifyAll()` be invoked from any object? What is the purpose of these methods?
- 30.24** What is wrong in the following code?

```

synchronized (object1) {
 try {
 while (!condition) object2.wait();
 }
 catch (InterruptedException ex) {
 }
}

```

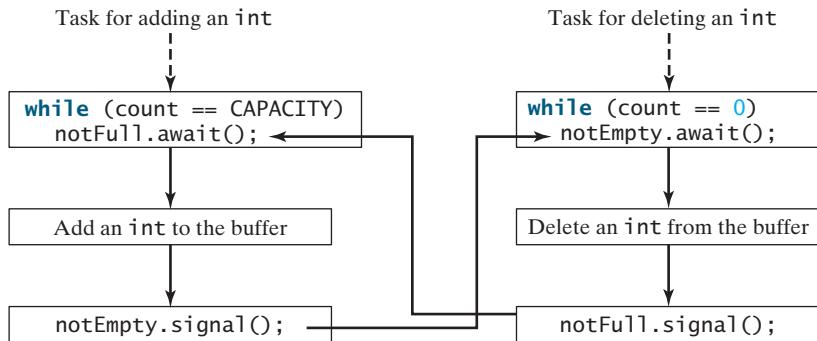
## 30.10 Case Study: Producer/Consumer

*This section gives the classic Consumer/Producer example for demonstrating thread coordination.*



Suppose you use a buffer to store integers and that the buffer size is limited. The buffer provides the method `write(int)` to add an `int` value to the buffer and the method `read()` to read and delete an `int` value from the buffer. To synchronize the operations, use a lock with two conditions: `notEmpty` (i.e., the buffer is not empty) and `notFull` (i.e., the buffer is not full). When a task adds an `int` to the buffer, if the buffer is full, the task will wait for the `notFull` condition. When a task reads an `int` from the buffer, if the buffer is empty, the task will wait for the `notEmpty` condition. The interaction between the two tasks is shown in Figure 30.18.

Listing 30.7 presents the complete program. The program contains the `Buffer` class (lines 50–101) and two tasks for repeatedly adding and consuming numbers to and from the buffer (lines 16–47). The `write(int)` method (lines 62–79) adds an integer to the buffer. The `read()` method (lines 81–100) deletes and returns an integer from the buffer.



**FIGURE 30.18** The conditions `notFull` and `notEmpty` are used to coordinate task interactions.

The buffer is actually a first-in, first-out queue (lines 52–53). The conditions `notEmpty` and `notFull` on the lock are created in lines 59–60. The conditions are bound to a lock. A lock must be acquired before a condition can be applied. If you use the `wait()` and `notify()` methods to rewrite this example, you have to designate two objects as monitors.

### LISTING 30.7 ConsumerProducer.java

```

1 import java.util.concurrent.*;
2 import java.util.concurrent.locks.*;
3
4 public class ConsumerProducer {
5 private static Buffer buffer = new Buffer();
6
7 public static void main(String[] args) {
8 // Create a thread pool with two threads
9 ExecutorService executor = Executors.newFixedThreadPool(2);
10 executor.execute(new ProducerTask());
11 executor.execute(new ConsumerTask());
12 executor.shutdown();
13 }
14
15 // A task for adding an int to the buffer
16 private static class ProducerTask implements Runnable {
17 public void run() {
18 try {
19 int i = 1;
20 while (true) {
21 System.out.println("Producer writes " + i);
22 buffer.write(i++); // Add a value to the buffer
23 // Put the thread into sleep
24 Thread.sleep((int)(Math.random() * 10000));
25 }
26 } catch (InterruptedException ex) {
27 ex.printStackTrace();
28 }
29 }
30 }
31
32 // A task for reading and deleting an int from the buffer
33 private static class ConsumerTask implements Runnable {
34 public void run() {
35

```

create a buffer

create two threads

producer task

consumer task

```

36 try {
37 while (true) {
38 System.out.println("\t\t\tConsumer reads " + buffer.read());
39 // Put the thread into sleep
40 Thread.sleep((int)(Math.random() * 10000));
41 }
42 }
43 catch (InterruptedException ex) {
44 ex.printStackTrace();
45 }
46 }
47 }

48 // An inner class for buffer
49 private static class Buffer {
50 private static final int CAPACITY = 1; // buffer size
51 private java.util.LinkedList<Integer> queue =
52 new java.util.LinkedList<>();
53
54 // Create a new lock
55 private static Lock lock = new ReentrantLock(); create a lock
56
57 // Create two conditions
58 private static Condition notEmpty = lock.newCondition(); create a condition
59 private static Condition notFull = lock.newCondition(); create a condition
60

61 public void write(int value) {
62 lock.lock(); // Acquire the lock acquire the lock
63 try {
64 while (queue.size() == CAPACITY) {
65 System.out.println("Wait for notFull condition"); wait for notFull
66 notFull.await();
67 }
68
69 queue.offer(value);
70 notEmpty.signal(); // Signal notEmpty condition signal notEmpty
71 }
72 catch (InterruptedException ex) {
73 ex.printStackTrace();
74 }
75 finally {
76 lock.unlock(); // Release the lock release the lock
77 }
78 }
79 }

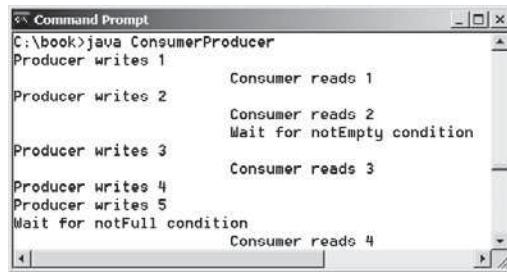
80
81 public int read() {
82 int value = 0;
83 lock.lock(); // Acquire the lock acquire the lock
84 try {
85 while (queue.isEmpty()) {
86 System.out.println("\t\t\tWait for notEmpty condition"); wait for notEmpty
87 notEmpty.await();
88 }
89
90 value = queue.remove();
91 notFull.signal(); // Signal notFull condition signal notFull
92 }
93 catch (InterruptedException ex) {
94 ex.printStackTrace();
95 }

```

```

96 finally {
97 lock.unlock(); // Release the lock
98 return value;
99 }
100 }
101 }
102 }
```

A sample run of the program is shown in Figure 30.19.



**FIGURE 30.19** Locks and conditions are used for communications between the Producer and Consumer threads.



**30.25** Can the `read` and `write` methods in the `Buffer` class be executed concurrently?

**30.26** When invoking the `read` method, what happens if the queue is empty?

**30.27** When invoking the `write` method, what happens if the queue is full?

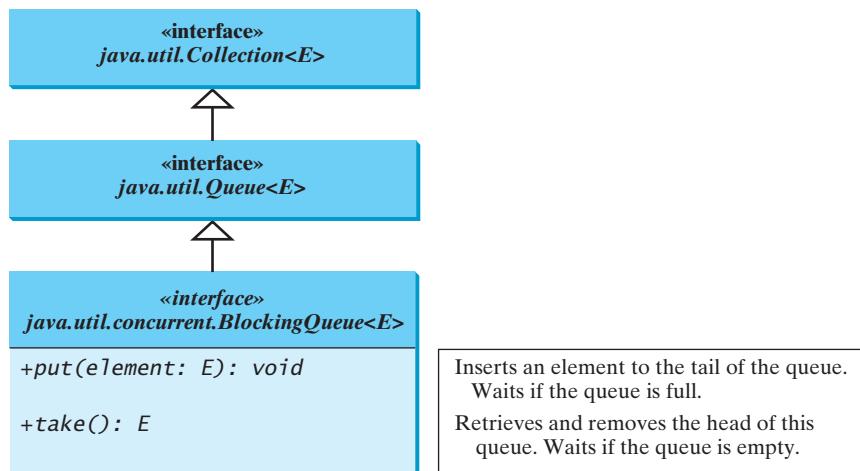


blocking queue

## 30.11 Blocking Queues

*Java Collections Framework provides `ArrayBlockingQueue`, `LinkedBlockingQueue`, and `PriorityBlockingQueue` for supporting blocking queues.*

Queues and priority queues are introduced in Section 20.9. A *blocking queue* causes a thread to block when you try to add an element to a full queue or to remove an element from an empty queue. The `BlockingQueue` interface extends `java.util.Queue` and provides the synchronized `put` and `take` methods for adding an element to the tail of the queue and for removing an element from the head of the queue, as shown in Figure 30.20.



**FIGURE 30.20** `BlockingQueue` is a subinterface of `Queue`.

Three concrete blocking queues—`ArrayBlockingQueue`, `LinkedBlockingQueue`, and `PriorityBlockingQueue`—are provided in Java, as shown in Figure 30.21. All are in the `java.util.concurrent` package. `ArrayBlockingQueue` implements a blocking queue using an array. You have to specify a capacity or an optional fairness to construct an `ArrayBlockingQueue`. `LinkedBlockingQueue` implements a blocking queue using a linked list. You can create an unbounded or bounded `LinkedBlockingQueue`. `PriorityBlockingQueue` is a priority queue. You can create an unbounded or bounded priority queue.



**FIGURE 30.21** `ArrayBlockingQueue`, `LinkedBlockingQueue`, and `PriorityBlockingQueue` are concrete blocking queues.



### Note

The `put` method will never block an unbounded `LinkedBlockingQueue` or `PriorityBlockingQueue`.

unbounded queue

Listing 30.8 gives an example of using an `ArrayBlockingQueue` to simplify the Consumer/Producer example in Listing 30.10. Line 5 creates an `ArrayBlockingQueue` to store integers. The Producer thread puts an integer into the queue (line 22), and the Consumer thread takes an integer from the queue (line 38).

### LISTING 30.8 ConsumerProducerUsingBlockingQueue.java

```

1 import java.util.concurrent.*;
2
3 public class ConsumerProducerUsingBlockingQueue {
4 private static ArrayBlockingQueue<Integer> buffer =
5 new ArrayBlockingQueue<>(2); // create a buffer
6
7 public static void main(String[] args) {
8 // Create a thread pool with two threads
9 ExecutorService executor = Executors.newFixedThreadPool(2); // create two threads
10 executor.execute(new ProducerTask());
11 executor.execute(new ConsumerTask());
12 executor.shutdown();
13 }
14
15 // A task for adding an int to the buffer
16 private static class ProducerTask implements Runnable { // producer task
17 public void run() {
18 try {
19 int i = 1;
20 while (true) {
21 System.out.println("Producer writes " + i);
22 buffer.put(i++); // Add any value to the buffer, say, 1 put
23 // Put the thread into sleep

```

```

24 Thread.sleep((int)(Math.random() * 10000));
25 }
26 }
27 catch (InterruptedException ex) {
28 ex.printStackTrace();
29 }
30 }
31
32
33 // A task for reading and deleting an int from the buffer
34 private static class ConsumerTask implements Runnable {
35 public void run() {
36 try {
37 while (true) {
38 System.out.println("\t\t\tConsumer reads " + buffer.take());
39 // Put the thread into sleep
40 Thread.sleep((int)(Math.random() * 10000));
41 }
42 }
43 catch (InterruptedException ex) {
44 ex.printStackTrace();
45 }
46 }
47 }
48 }
```

consumer task

take

In Listing 30.7, you used locks and conditions to synchronize the Producer and Consumer threads. This program does not use locks and conditions, because synchronization is already implemented in `ArrayBlockingQueue`.



- 30.28** What is a blocking queue? What blocking queues are supported in Java?
- 30.29** What method do you use to add an element to an `ArrayBlockingQueue`? What happens if the queue is full?
- 30.30** What method do you use to retrieve an element from an `ArrayBlockingQueue`? What happens if the queue is empty?

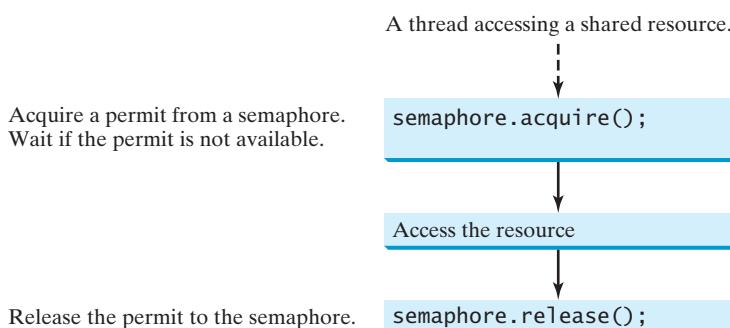
semaphore



## 30.12 Semaphores

*Semaphores can be used to restrict the number of threads that access a shared resource.*

In computer science, a *semaphore* is an object that controls the access to a common resource. Before accessing the resource, a thread must acquire a permit from the semaphore. After finishing with the resource, the thread must return the permit back to the semaphore, as shown in Figure 30.22.



**FIGURE 30.22** A limited number of threads can access a shared resource controlled by a semaphore.

To create a semaphore, you have to specify the number of permits with an optional fairness policy, as shown in Figure 30.23. A task acquires a permit by invoking the semaphore's `acquire()` method and releases the permit by invoking the semaphore's `release()` method. Once a permit is acquired, the total number of available permits in a semaphore is reduced by 1. Once a permit is released, the total number of available permits in a semaphore is increased by 1.

| java.util.concurrent.Semaphore                  |                                                                                                                 |
|-------------------------------------------------|-----------------------------------------------------------------------------------------------------------------|
| +Semaphore(numberOfPermits: int)                | Creates a semaphore with the specified number of permits. The fairness policy is false.                         |
| +Semaphore(numberOfPermits: int, fair: boolean) | Creates a semaphore with the specified number of permits and the fairness policy.                               |
| +acquire(): void                                | Acquires a permit from this semaphore. If no permit is available, the thread is blocked until one is available. |
| +release(): void                                | Releases a permit back to the semaphore.                                                                        |

FIGURE 30.23 The `Semaphore` class contains the methods for accessing a semaphore.

A semaphore with just one permit can be used to simulate a mutually exclusive lock. Listing 30.9 revises the `Account` inner class in Listing 30.9 using a semaphore to ensure that only one thread at a time can access the `deposit` method.

### LISTING 30.9 New Account Inner Class

```

1 // An inner class for Account
2 private static class Account {
3 // Create a semaphore
4 private static Semaphore semaphore = new Semaphore(1); create a semaphore
5 private int balance = 0;
6
7 public int getBalance() {
8 return balance;
9 }
10
11 public void deposit(int amount) {
12 try {
13 semaphore.acquire(); // Acquire a permit acquire a permit
14 int newBalance = balance + amount;
15
16 // This delay is deliberately added to magnify the
17 // data-corruption problem and make it easy to see
18 Thread.sleep(5);
19
20 balance = newBalance;
21 }
22 catch (InterruptedException ex) {
23 }
24 finally {
25 semaphore.release(); // Release a permit release a permit
26 }
27 }
28 }
```

A semaphore with one permit is created in line 4. A thread first acquires a permit when executing the `deposit` method in line 13. After the balance is updated, the thread releases the permit in line 25. It is a good practice to always place the `release()` method in the `finally` clause to ensure that the permit is finally released even in the case of exceptions.



- 30.31** What are the similarities and differences between a lock and a semaphore?  
**30.32** How do you create a semaphore that allows three concurrent threads? How do you acquire a semaphore? How do you release a semaphore?

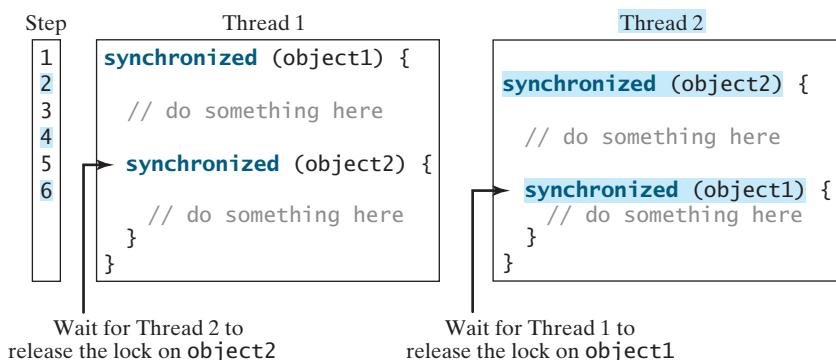


deadlock

### 30.13 Avoiding Deadlocks

*Deadlocks can be avoided by using a proper resource ordering.*

Sometimes two or more threads need to acquire the locks on several shared objects. This could cause a *deadlock*, in which each thread has the lock on one of the objects and is waiting for the lock on the other object. Consider the scenario with two threads and two objects, as shown in Figure 30.24. Thread 1 has acquired a lock on **object1**, and Thread 2 has acquired a lock on **object2**. Now Thread 1 is waiting for the lock on **object2**, and Thread 2 for the lock on **object1**. Each thread waits for the other to release the lock it needs and until that happens, neither can continue to run.



**FIGURE 30.24** Thread 1 and Thread 2 are deadlocked.

resource ordering

Deadlock is easily avoided by using a simple technique known as *resource ordering*. With this technique, you assign an order to all the objects whose locks must be acquired and ensure that each thread acquires the locks in that order. For the example in Figure 30.24, suppose that the objects are ordered as **object1** and **object2**. Using the resource ordering technique, Thread 2 must acquire a lock on **object1** first, then on **object2**. Once Thread 1 acquires a lock on **object1**, Thread 2 has to wait for a lock on **object1**. Thus, Thread 1 will be able to acquire a lock on **object2** and no deadlock will occur.



- 30.33** What is a deadlock? How can you avoid deadlock?



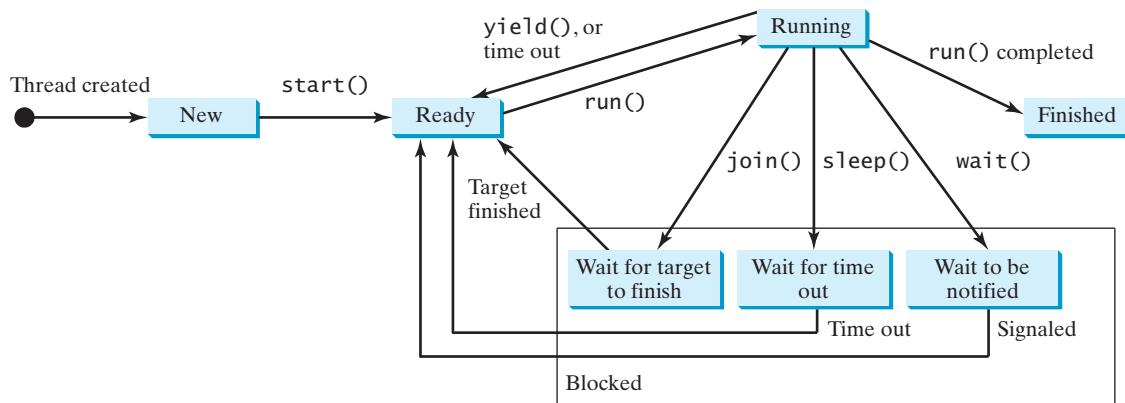
### 30.14 Thread States

*A thread state indicates the status of thread.*

Tasks are executed in threads. Threads can be in one of five states: New, Ready, Running, Blocked, or Finished (see Figure 30.25).

When a thread is newly created, it enters the *New state*. After a thread is started by calling its **start()** method, it enters the *Ready state*. A ready thread is runnable but may not be running yet. The operating system has to allocate CPU time to it.

When a ready thread begins executing, it enters the *Running state*. A running thread can enter the *Ready state* if its given CPU time expires or its **yield()** method is called.



**FIGURE 30.25** A thread can be in one of five states: New, Ready, Running, Blocked, or Finished.

A thread can enter the **Blocked** state (i.e., become inactive) for several reasons. It may have invoked the `join()`, `sleep()`, or `wait()` method. It may be waiting for an I/O operation to finish. A blocked thread may be reactivated when the action inactivating it is reversed. For example, if a thread has been put to sleep and the sleep time has expired, the thread is reactivated and enters the **Ready** state.

Finally, a thread is **Finished** if it completes the execution of its `run()` method.

The `isAlive()` method is used to find out the state of a thread. It returns `true` if a thread is in the **Ready**, **Blocked**, or **Running** state; it returns `false` if a thread is new and has not started or if it is finished.

The `interrupt()` method interrupts a thread in the following way: If a thread is currently in the **Ready** or **Running** state, its interrupted flag is set; if a thread is currently blocked, it is awakened and enters the **Ready** state, and a `java.lang.InterruptedIOException` is thrown.

**30.34** What is a thread state? Describe the states for a thread.



## 30.15 Synchronized Collections

*Java Collections Framework provides synchronized collections for lists, sets, and maps.*

The classes in the Java Collections Framework are not thread-safe; that is, their contents may become corrupted if they are accessed and updated concurrently by multiple threads. You can protect the data in a collection by locking the collection or by using synchronized collections.

The `Collections` class provides six static methods for wrapping a collection into a synchronized version, as shown in Figure 30.26. The collections created using these methods are called *synchronization wrappers*.



synchronized collection

synchronization wrapper

### java.util.Collections

|                                                                  |
|------------------------------------------------------------------|
| + <code>synchronizedCollection(c: Collection): Collection</code> |
| + <code>synchronizedList(list: List): List</code>                |
| + <code>synchronizedMap(m: Map): Map</code>                      |
| + <code>synchronizedSet(s: Set): Set</code>                      |
| + <code>synchronizedSortedMap(s: SortedMap): SortedMap</code>    |
| + <code>synchronizedSortedSet(s: SortedSet): SortedSet</code>    |

|                                                                  |
|------------------------------------------------------------------|
| Returns a synchronized collection.                               |
| Returns a synchronized list from the specified list.             |
| Returns a synchronized map from the specified map.               |
| Returns a synchronized set from the specified set.               |
| Returns a synchronized sorted map from the specified sorted map. |
| Returns a synchronized sorted set.                               |

**FIGURE 30.26** You can obtain synchronized collections using the methods in the `Collections` class.

Invoking `synchronizedCollection(Collection c)` returns a new `Collection` object, in which all the methods that access and update the original collection `c` are synchronized. These methods are implemented using the `synchronized` keyword. For example, the `add` method is implemented like this:

```
public boolean add(E o) {
 synchronized (this) {
 return c.add(o);
 }
}
```

Synchronized collections can be safely accessed and modified by multiple threads concurrently.



### Note

The methods in `java.util.Vector`, `java.util.Stack`, and `java.util.Hashtable` are already synchronized. These are old classes introduced in JDK 1.0. Starting with JDK 1.5, you should use `java.util.ArrayList` to replace `Vector`, `java.util.LinkedList` to replace `Stack`, and `java.util.Map` to replace `Hashtable`. If synchronization is needed, use a synchronization wrapper.

fail-fast

The synchronization wrapper classes are thread-safe, but the iterator is *fail-fast*. This means that if you are using an iterator to traverse a collection while the underlying collection is being modified by another thread, then the iterator will immediately fail by throwing `java.util.ConcurrentModificationException`, which is a subclass of `RuntimeException`. To avoid this error, you need to create a synchronized collection object and acquire a lock on the object when traversing it. For example, to traverse a set, you have to write the code like this:

```
Set hashSet = Collections.synchronizedSet(new HashSet());
synchronized (hashSet) { // Must synchronize it
 Iterator iterator = hashSet.iterator();
 while (iterator.hasNext()) {
 System.out.println(iterator.next());
 }
}
```

Failure to do so may result in nondeterministic behavior, such as a `ConcurrentModificationException`.



**30.35** What is a synchronized collection? Is `ArrayList` synchronized? How do you make it synchronized?

**30.36** Explain why an iterator is fail-fast.



## 30.16 Parallel Programming

*The Fork/Join Framework is used for parallel programming in Java.*

JDK 7 feature

Fork/Join Framework

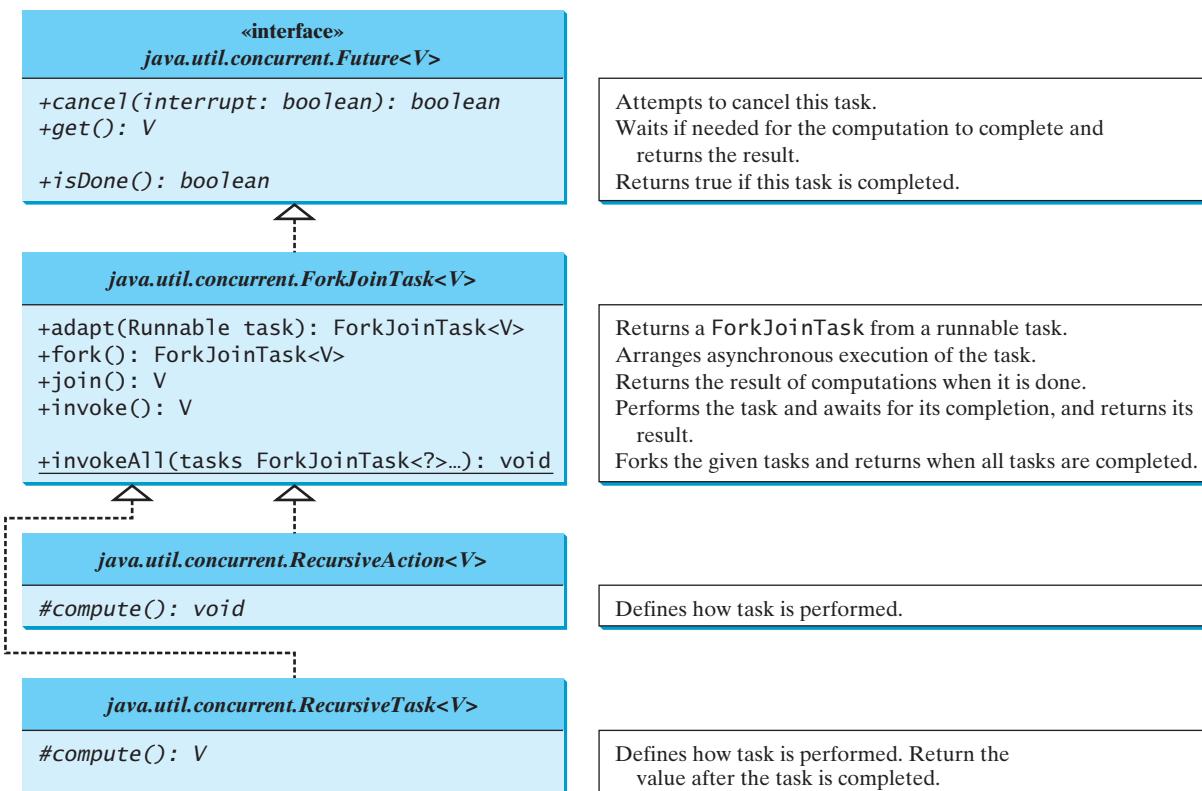
The widespread use of multicore systems has created a revolution in software. In order to benefit from multiple processors, software needs to run in parallel. JDK 7 introduces the new Fork/Join Framework for parallel programming, which utilizes the multicore processors.

The *Fork/Join Framework* is illustrated in Figure 30.27 (the diagram resembles a fork, hence its name). A problem is divided into nonoverlapping subproblems, which can be solved independently in parallel. The solutions to all subproblems are then joined to obtain an overall solution for the problem. This is the parallel implementation of the divide-and-conquer approach. In JDK 7's Fork/Join Framework, a *fork* can be viewed as an independent task that runs on a thread.

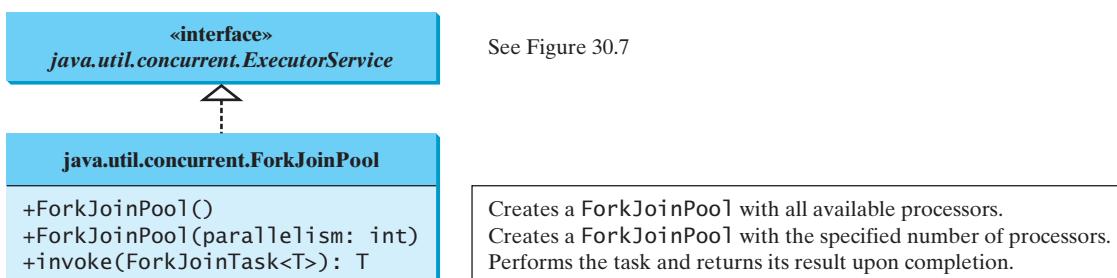


**FIGURE 30.27** The nonoverlapping subproblems are solved in parallel.

The framework defines a task using the `ForkJoinTask` class, as shown in Figure 30.28 and executes a task in an instance of `ForkJoinPool`, as shown in Figure 30.29.



**FIGURE 30.28** The `ForkJoinTask` class defines a task for asynchronous execution.



**FIGURE 30.29** The `ForkJoinPool` executes Fork/Join tasks.

**ForkJoinTask** is the abstract base class for tasks. A **ForkJoinTask** is a thread-like entity, but it is much lighter than a normal thread because huge numbers of tasks and sub-tasks can be executed by a small number of actual threads in a **ForkJoinPool**. The tasks are primarily coordinated using **fork()** and **join()**. Invoking **fork()** on a task arranges asynchronous execution, and invoking **join()** waits until the task is completed. The **invoke()** and **invokeAll(tasks)** methods implicitly invoke **fork()** to execute the task and **join()** to wait for the tasks to complete, and return the result, if any. Note that the static method **invokeAll** takes a variable number of **ForkJoinTask** arguments using the **...** syntax, which is introduced in Section 7.9.

RecursiveAction  
RecursiveTask

The Fork/Join Framework is designed to parallelize divide-and-conquer solutions, which are naturally recursive. **RecursiveAction** and **RecursiveTask** are two subclasses of **ForkJoinTask**. To define a concrete task class, your class should extend **RecursiveAction** or **RecursiveTask**. **RecursiveAction** is for a task that doesn't return a value, and **RecursiveTask** is for a task that does return a value. Your task class should override the **compute()** method to specify how a task is performed.

We now use a merge sort to demonstrate how to develop parallel programs using the Fork/Join Framework. The merge sort algorithm (introduced in Section 25.3) divides the array into two halves and applies a merge sort on each half recursively. After the two halves are sorted, the algorithm merges them. Listing 30.10 gives a parallel implementation of the merge sort algorithm and compares its execution time with a sequential sort.

### LISTING 30.10 ParallelMergeSort.java

invoke parallel sort

invoke sequential sort

create a ForkJoinTask  
create a ForkJoinPool  
execute a task

define concrete  
ForkJoinTask

```

1 import java.util.concurrent.RecursiveAction;
2 import java.util.concurrent.ForkJoinPool;
3
4 public class ParallelMergeSort {
5 public static void main(String[] args) {
6 final int SIZE = 7000000;
7 int[] list1 = new int[SIZE];
8 int[] list2 = new int[SIZE];
9
10 for (int i = 0; i < list1.length; i++)
11 list1[i] = list2[i] = (int)(Math.random() * 10000000);
12
13 long startTime = System.currentTimeMillis();
14 parallelMergeSort(list1); // Invoke parallel merge sort
15 long endTime = System.currentTimeMillis();
16 System.out.println("\nParallel time with "
17 + Runtime.getRuntime().availableProcessors() +
18 " processors is " + (endTime - startTime) + " milliseconds");
19
20 startTime = System.currentTimeMillis();
21 MergeSort.mergeSort(list2); // MergeSort is in Listing 23.5
22 endTime = System.currentTimeMillis();
23 System.out.println("\nSequential time is " +
24 (endTime - startTime) + " milliseconds");
25 }
26
27 public static void parallelMergeSort(int[] list) {
28 RecursiveAction mainTask = new SortTask(list);
29 ForkJoinPool pool = new ForkJoinPool();
30 pool.invoke(mainTask);
31 }
32
33 private static class SortTask extends RecursiveAction {
34 private final int THRESHOLD = 500;

```

```

35 private int[] list;
36
37 SortTask(int[] list) {
38 this.list = list;
39 }
40
41 @Override
42 protected void compute() {
43 if (list.length < THRESHOLD)
44 java.util.Arrays.sort(list);
45 else {
46 // Obtain the first half
47 int[] firstHalf = new int[list.length / 2];
48 System.arraycopy(list, 0, firstHalf, 0, list.length / 2);
49
50 // Obtain the second half
51 int secondHalfLength = list.length - list.length / 2;
52 int[] secondHalf = new int[secondHalfLength];
53 System.arraycopy(list, list.length / 2,
54 secondHalf, 0, secondHalfLength);
55
56 // Recursively sort the two halves
57 invokeAll(new SortTask(firstHalf),
58 new SortTask(secondHalf));
59
60 // Merge firstHalf with secondHalf into list
61 MergeSort.merge(firstHalf, secondHalf, list);
62 }
63 }
64 }
65 }
```

perform the task  
sort a small list  
split into two parts  
solve each part  
merge two parts

Parallel time with 2 processors is 2829 milliseconds  
 Sequential time is 4751 milliseconds



Since the sort algorithm does not return a value, we define a concrete `ForkJoinTask` class by extending `RecursiveAction` (lines 33–64). The `compute` method is overridden to implement a recursive merge sort (lines 42–63). If the list is small, it is more efficient to be solved sequentially (line 44). For a large list, it is split into two halves (lines 47–54). The two halves are sorted concurrently (lines 57 and 58) and then merged (line 61).

The program creates a main `ForkJoinTask` (line 28), a `ForkJoinPool` (line 29), and places the main task for execution in a `ForkJoinPool` (line 30). The `invoke` method will return after the main task is completed.

When executing the main task, the task is split into subtasks and the subtasks are invoked using the `invokeAll` method (lines 57 and 58). The `invokeAll` method will return after all the subtasks are completed. Note that each subtask is further split into smaller tasks recursively. Huge numbers of subtasks may be created and executed in the pool. The Fork/Join Framework automatically executes and coordinates all the tasks efficiently.

The `MergeSort` class is defined in Listing 23.5. The program invokes `MergeSort.merge` to merge two sorted sublists (line 61). The program also invokes `MergeSort.mergeSort` (line 21) to sort a list using merge sort sequentially. You can see that the parallel sort is much faster than the sequential sort.

Note that the loop for initializing the list can also be parallelized. However, you should avoid using `Math.random()` in the code because it is synchronized and cannot be executed in parallel (see Programming Exercise 30.12). The `parallelMergeSort` method only sorts

an array of `int` values, but you can modify it to become a generic method (see Programming Exercise 30.13).

In general, a problem can be solved in parallel using the following pattern:

```
if (the program is small)
 solve it sequentially;
else {
 divide the problem into nonoverlapping subproblems;
 solve the subproblems concurrently;
 combine the results from subproblems to solve the whole problem;
}
```

Listing 30.11 develops a parallel method that finds the maximal number in a list.

### LISTING 30.11 ParallelMax.java

```
1 import java.util.concurrent.*;
2
3 public class ParallelMax {
4 public static void main(String[] args) {
5 // Create a list
6 final int N = 9000000;
7 int[] list = new int[N];
8 for (int i = 0; i < list.length; i++)
9 list[i] = i;
10
11 long startTime = System.currentTimeMillis();
12 System.out.println("\nThe maximal number is " + max(list));
13 long endTime = System.currentTimeMillis();
14 System.out.println("The number of processors is " +
15 Runtime.getRuntime().availableProcessors());
16 System.out.println("Time is " + (endTime - startTime)
17 + " milliseconds");
18 }
19
20 public static int max(int[] list) {
21 RecursiveTask<Integer> task = new MaxTask(list, 0, list.length);
22 ForkJoinPool pool = new ForkJoinPool();
23 return pool.invoke(task);
24 }
25
26 private static class MaxTask extends RecursiveTask<Integer> {
27 private final static int THRESHOLD = 1000;
28 private int[] list;
29 private int low;
30 private int high;
31
32 public MaxTask(int[] list, int low, int high) {
33 this.list = list;
34 this.low = low;
35 this.high = high;
36 }
37
38 @Override
39 public Integer compute() {
40 if (high - low < THRESHOLD) {
41 int max = list[0];
42 for (int i = low; i < high; i++)
43 if (list[i] > max)
44 max = list[i];
45 return new Integer(max);
46 }
47 else {
48 int mid = (low + high) / 2;
49 MaxTask left = new MaxTask(list, low, mid);
50 MaxTask right = new MaxTask(list, mid, high);
51 invokeAll(left, right);
52 awaitDone(0, TimeUnit.MILLISECONDS);
53 return left.result();
54 }
55 }
56 }
57 }
```

invoke max

create a ForkJoinTask  
create a ForkJoinPool  
execute a task

define concrete  
ForkJoinTask

perform the task

solve a small problem

```

46 }
47 else {
48 int mid = (low + high) / 2;
49 RecursiveTask<Integer> left = new MaxTask(list, low, mid);
50 RecursiveTask<Integer> right = new MaxTask(list, mid, high); split into two parts
51
52 right.fork();
53 left.fork();
54 return new Integer(Math.max(left.join().intValue(),
55 right.join().intValue()));
56 }
57 }
58 }
59 }
```

The maximal number is 8999999  
 The number of processors is 2  
 Time is 44 milliseconds



Since the algorithm returns an integer, we define a task class for fork join by extending **RecursiveTask<Integer>** (lines 26–58). The **compute** method is overridden to return the max element in a **List[low..high]** (lines 39–57). If the list is small, it is more efficient to be solved sequentially (lines 40–46). For a large list, it is split into two halves (lines 48–50). The tasks **left** and **right** find the maximal element in the left half and right half, respectively. Invoking **fork()** on the task causes the task to be executed (lines 52 and 53). The **join()** method awaits for the task to complete and then returns the result (lines 54 and 55).

**30.37** How do you define a **ForkJoinTask**? What are the differences between **RecursiveAction** and **RecursiveTask**?



**30.38** How do you tell the system to execute a task?

**30.39** What method can you use to test if a task has been completed?

**30.40** How do you create a **ForkJoinPool**? How do you place a task into a **ForkJoinPool**?

## Key Terms

|                          |                              |
|--------------------------|------------------------------|
| condition 1114           | multithreading 1098          |
| deadlock 1126            | race condition 1111          |
| fail-fast 1128           | semaphore 1124               |
| fairness policy 1113     | synchronization wrapper 1127 |
| Fork/Join Framework 1128 | synchronized block 1112      |
| lock 1112                | thread 1098                  |
| monitor 1118             | thread-safe 1111             |

## CHAPTER SUMMARY

1. Each task is an instance of the **Runnable** interface. A *thread* is an object that facilitates the execution of a task. You can define a task class by implementing the **Runnable** interface and create a thread by wrapping a task using a **Thread** constructor.
2. After a thread object is created, use the **start()** method to start a thread, and the **sleep(long)** method to put a thread to sleep so that other threads get a chance to run.

3. A thread object never directly invokes the `run` method. The JVM invokes the `run` method when it is time to execute the thread. Your class must override the `run` method to tell the system what the thread will do when it runs.
4. To prevent threads from corrupting a shared resource, use *synchronized* methods or blocks. A *synchronized method* acquires a *lock* before it executes. In the case of an instance method, the lock is on the object for which the method was invoked. In the case of a static method, the lock is on the class.
5. A synchronized statement can be used to acquire a lock on any object, not just *this* object, when executing a block of the code in a method. This block is referred to as a *synchronized block*.
6. You can use explicit locks and *conditions* to facilitate communications among threads, as well as using the built-in monitor for objects.
7. The blocking queues (`ArrayBlockingQueue`, `LinkedBlockingQueue`, `PriorityBlockingQueue`) provided in the Java Collections Framework automatically synchronize access to a queue.
8. You can use semaphores to restrict the number of concurrent tasks that access a shared resource.
9. *Deadlock* occurs when two or more threads acquire locks on multiple objects and each has a lock on one object and is waiting for the lock on the other object. The *resource ordering technique* can be used to avoid deadlock.
10. The JDK 7's Fork/Join Framework is designed for developing parallel programs. You can define a task class that extends `RecursiveAction` or `RecursiveTask` and execute the tasks concurrently in `ForkJoinPool` and obtains the overall solution after all tasks are completed.

## Quiz

---

Answer the quiz for this chapter online at [www.cs.armstrong.edu/liang/intro10e/quiz.html](http://www.cs.armstrong.edu/liang/intro10e/quiz.html).

MyProgrammingLab™

## PROGRAMMING EXERCISES

---

### Sections 30.1–30.5

- \*30.1** (Revise Listing 30.1) Rewrite Listing 30.1 to display the output in a text area, as shown in Figure 30.30.

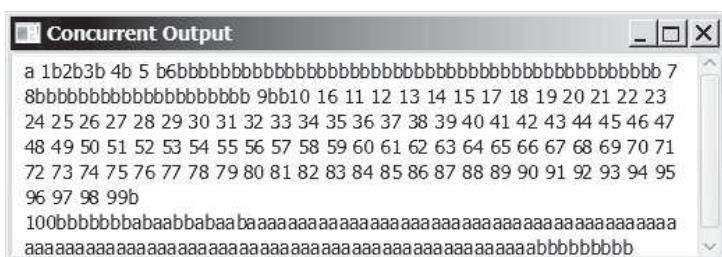


FIGURE 30.30 The output from three threads is displayed in a text area.

- 30.2** (*Racing cars*) Rewrite Programming Exercise 15.29 using a thread to control car racing. Compare the program with Programming Exercise 15.29 by setting the delay time to 10 in both programs. Which one runs the animation faster?
- 30.3** (*Raise flags*) Rewrite Listing 15.13 using a thread to animate a flag being raised. Compare the program with Listing 15.13 by setting the delay time to 10 in both programs. Which one runs the animation faster?

### Sections 30.8–30.12

- 30.4** (*Synchronize threads*) Write a program that launches 1,000 threads. Each thread adds 1 to a variable **sum** that initially is 0. Define an **Integer** wrapper object to hold **sum**. Run the program with and without synchronization to see its effect.
- 30.5** (*Display a running fan*) Rewrite Programming Exercise 15.28 using a thread to control the fan animation.
- 30.6** (*Bouncing balls*) Rewrite Listing 15.17 BallPane.java using a thread to animate bouncing ball movements.
- 30.7** (*Control a clock*) Rewrite Programming Exercise 15.32 using a thread to control the clock animation.
- 30.8** (*Account synchronization*) Rewrite Listing 30.6, ThreadCooperation.java, using the object's **wait()** and **notifyAll()** methods.
- 30.9** (*Demonstrate ConcurrentModificationException*) The iterator is *fail-fast*. Write a program to demonstrate it by creating two threads that concurrently access and modify a set. The first thread creates a hash set filled with numbers, and adds a new number to the set every second. The second thread obtains an iterator for the set and traverses the set back and forth through the iterator every second. You will receive a **ConcurrentModificationException** because the underlying set is being modified in the first thread while the set in the second thread is being traversed.
- \*30.10** (*Use synchronized sets*) Using synchronization, correct the problem in the preceding exercise so that the second thread does not throw a **ConcurrentModificationException**.

### Section 30.15

- \*30.11** (*Demonstrate deadlock*) Write a program that demonstrates deadlock.

### Section 30.18

- \*30.12** (*Parallel array initializer*) Implement the following method using the Fork/Join Framework to assign random values to the list.

```
public static void parallelAssignValues(double[] list)
```

Write a test program that creates a list with 9,000,000 elements and invokes **parallelAssignValues** to assign random values to the list. Also implement a sequential algorithm and compare the execution time of the two. Note that if you use **Math.random()**, your parallel code execution time will be worse than the sequential code execution time because **Math.random()** is synchronized and cannot be executed in parallel. To fix this problem, create a **Random** object for assigning random values to a small list.

- 30.13** (*Generic parallel merge sort*) Revise Listing 30.10, ParallelMergeSort.java, to define a generic parallelMergeSort method as follows:

```
public static <E extends Comparable<E>> void
 parallelMergeSort(E[] list)
```

- \*30.14** (*Parallel quick sort*) Implement the following method in parallel to sort a list using quick sort (see Listing 23.7).

```
public static void parallelQuickSort(int[] list)
```

Write a test program that times the execution time for a list of size 9,000,000 using this parallel method and a sequential method.

- \*30.15** (*Parallel sum*) Implement the following method using Fork/Join to find the sum of a list.

```
public static double parallelSum(double[] list)
```

Write a test program that finds the sum in a list of 9,000,000 double values.

- \*30.16** (*Parallel matrix addition*) Programming Exercise 8.5 describes how to perform matrix addition. Suppose you have multiple processors, so you can speed up the matrix addition. Implement the following method in parallel.

```
public static double[][] parallelAddMatrix(
 double[][] a, double[][] b)
```

Write a test program that measures the execution time for adding two  $2,000 \times 2,000$  matrices using the parallel method and sequential method, respectively.

- \*30.17** (*Parallel matrix multiplication*) Programming Exercise 7.6 describes how to perform matrix multiplication. Suppose you have multiple processors, so you can speed up the matrix multiplication. Implement the following method in parallel.

```
public static double[][] parallelMultiplyMatrix(
 double[][] a, double[][] b)
```

Write a test program that measures the execution time for multiplying two  $2,000 \times 2,000$  matrices using the parallel method and sequential method, respectively.

- \*30.18** (*Parallel Eight Queens*) Revise Listing 22.11, EightQueens.java, to develop a parallel algorithm that finds all solutions for the Eight Queens problem. (*Hint:* Launch eight subtasks, each of which places the queen in a different column in the first row.)

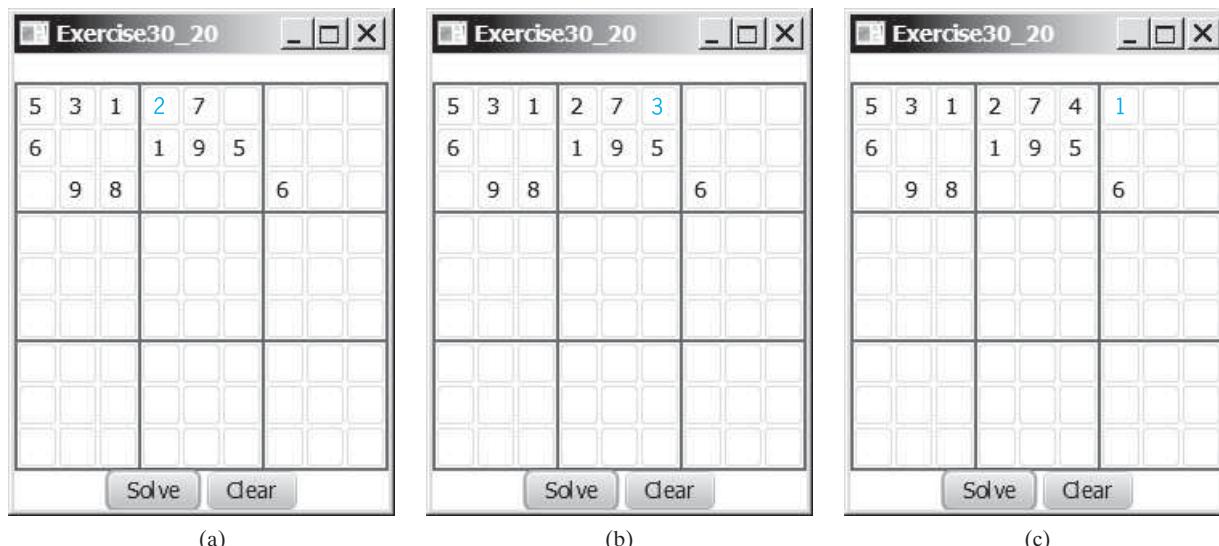
### Comprehensive

- \*\*\*30.19** (*Sorting animation*) Write an animation for selection sort, insertion sort, and bubble sort, as shown in Figure 30.31. Create an array of integers 1, 2, . . . , 50. Shuffle it randomly. Create a pane to display the array in a histogram. You should invoke each sort method in a separate thread. Each algorithm uses two nested loops. When the algorithm completes an iteration in the outer loop, put the thread to sleep for 0.5 seconds, and redisplay the array in the histogram. Color the last bar in the sorted subarray.



**FIGURE 30.31** Three sorting algorithms are illustrated in the animation.

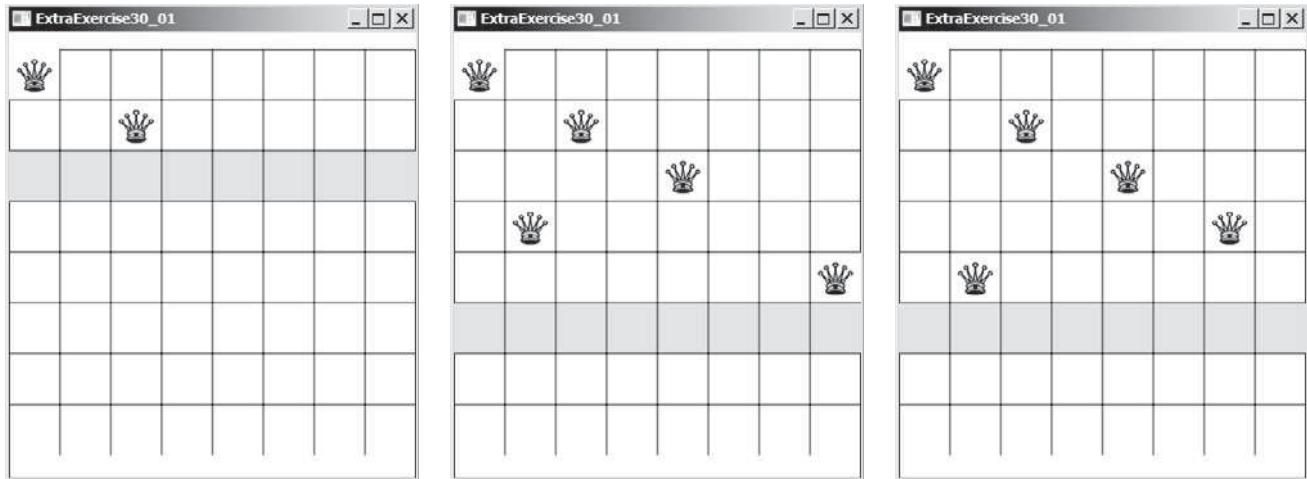
**\*\*\*30.20** (*Sudoku search animation*) Modify Programming Exercise 22.21 to display the intermediate results of the search. Figure 30.32 gives a snapshot of an animation in progress with number 2 placed in the cell in Figure 30.32a, number 3 placed in the cell in Figure 30.32b, and number 3 placed in the cell in Figure 30.32c. The animation displays all the search steps.



**FIGURE 30.32** The intermediate search steps are displayed in the animation for the Sudoku problem.

**30.21** (*Combine colliding bouncing balls*) Rewrite Programming Exercise 20.5 using a thread to animate bouncing ball movements.

**\*\*\*30.22** (*Eight Queens animation*) Modify Listing 22.11, EightQueens.java, to display the intermediate results of the search. As shown in Figure 30.33, the current row being searched is highlighted. Every one second, a new state of the chess board is displayed.



**FIGURE 30.33** The intermediate search steps are displayed in the animation for the Eight Queens problem.

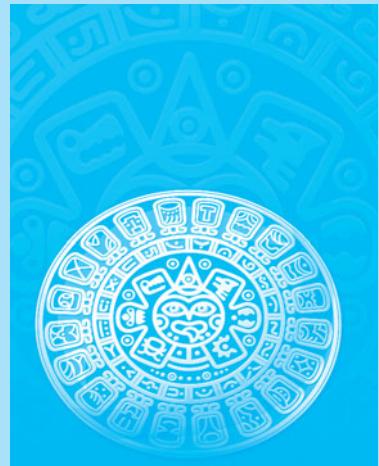
# CHAPTER

# 31

## NETWORKING

### Objectives

- To explain terms: TCP, IP, domain name, domain name server, stream-based communications, and packet-based communications (§31.2).
- To create servers using server sockets (§31.2.1) and clients using client sockets (§31.2.2).
- To implement Java networking programs using stream sockets (§31.2.3).
- To develop an example of a client/server application (§31.2.4).
- To obtain Internet addresses using the **InetAddress** class (§31.3).
- To develop servers for multiple clients (§31.4).
- To send and receive objects on a network (§31.5).
- To develop an interactive tic-tac-toe game played on the Internet (§31.6).



## 31.1 Introduction



*Computer networking is used to send and receive messages among computers on the Internet.*

IP address

domain name

domain name server

TCP

UDP

stream-based communication

packet-based communication

To browse the Web or send an email, your computer must be connected to the Internet. The *Internet* is the global network of millions of computers. Your computer can connect to the Internet through an Internet Service Provider (ISP) using a dialup, DSL, or cable modem, or through a local area network (LAN).

When a computer needs to communicate with another computer, it needs to know the other computer's address. An *Internet Protocol* (IP) address uniquely identifies the computer on the Internet. An IP address consists of four dotted decimal numbers between **0** and **255**, such as **130.254.204.31**. Since it is not easy to remember so many numbers, they are often mapped to meaningful names called *domain names*, such as [liang.armstrong.edu](http://liang.armstrong.edu). Special servers called *Domain Name Servers* (DNS) on the Internet translate host names into IP addresses. When a computer contacts [liang.armstrong.edu](http://liang.armstrong.edu), it first asks the DNS to translate this domain name into a numeric IP address and then sends the request using the IP address.

The Internet Protocol is a low-level protocol for delivering data from one computer to another across the Internet in packets. Two higher-level protocols used in conjunction with the IP are the *Transmission Control Protocol* (TCP) and the *User Datagram Protocol* (UDP). TCP enables two hosts to establish a connection and exchange streams of data. TCP guarantees delivery of data and also guarantees that packets will be delivered in the same order in which they were sent. UDP is a standard, low-overhead, connectionless, host-to-host protocol that is used over the IP. UDP allows an application program on one computer to send a datagram to an application program on another computer.

Java supports both stream-based and packet-based communications. *Stream-based communications* use TCP for data transmission, whereas *packet-based communications* use UDP. Since TCP can detect lost transmissions and resubmit them, transmissions are lossless and reliable. UDP, in contrast, cannot guarantee lossless transmission. Stream-based communications are used in most areas of Java programming and are the focus of this chapter. Packet-based communications are introduced in Supplement III.P, Networking Using Datagram Protocol.

## 31.2 Client/Server Computing



*Java provides the **ServerSocket** class for creating a server socket and the **Socket** class for creating a client socket. Two programs on the Internet communicate through a server socket and a client socket using I/O streams.*

socket

Networking is tightly integrated in Java. The Java API provides the classes for creating sockets to facilitate program communications over the Internet. *Sockets* are the endpoints of logical connections between two hosts and can be used to send and receive data. Java treats socket communications much as it treats I/O operations; thus, programs can read from or write to sockets as easily as they can read from or write to files.

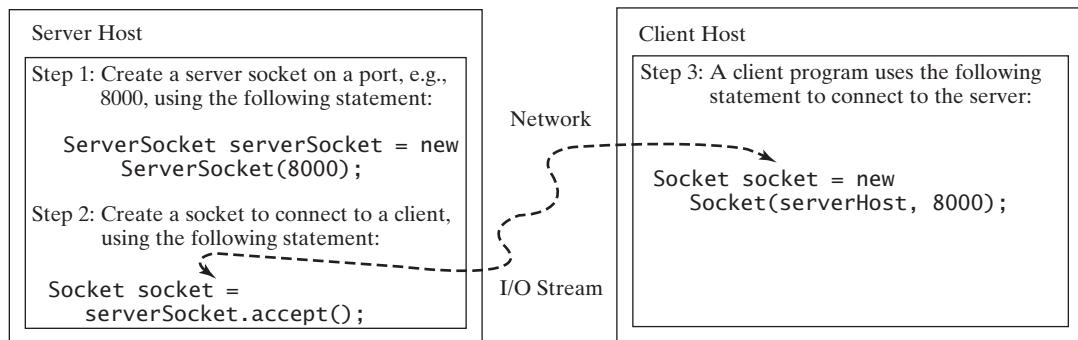
Network programming usually involves a server and one or more clients. The client sends requests to the server, and the server responds. The client begins by attempting to establish a connection to the server. The server can accept or deny the connection. Once a connection is established, the client and the server communicate through sockets.

The server must be running when a client attempts to connect to the server. The server waits for a connection request from the client. The statements needed to create sockets on a server and on a client are shown in Figure 31.1.

### 31.2.1 Server Sockets

server socket  
port

To establish a server, you need to create a *server socket* and attach it to a *port*, which is where the server listens for connections. The port identifies the TCP service on the socket. Port numbers range from 0 to 65536, but port numbers 0 to 1024 are reserved for privileged services.



**FIGURE 31.1** The server creates a server socket and, once a connection to a client is established, connects to the client with a client socket.

For instance, the email server runs on port 25, and the Web server usually runs on port 80. You can choose any port number that is not currently used by other programs. The following statement creates a server socket **serverSocket**:

```
ServerSocket serverSocket = new ServerSocket(port);
```



### Note

Attempting to create a server socket on a port already in use would cause a **java.net.BindException**.

**BindException**

## 31.2.2 Client Sockets

After a server socket is created, the server can use the following statement to listen for connections:

```
Socket socket = serverSocket.accept();
```

This statement waits until a client connects to the server socket. The client issues the following statement to request a connection to a server:

```
Socket socket = new Socket(serverName, port);
```

This statement opens a socket so that the client program can communicate with the server. **serverName** is the server's Internet host name or IP address. The following statement creates a socket on the client machine to connect to the host 130.254.204.33 at port 8000:

```
Socket socket = new Socket("130.254.204.33", 8000)
```

Alternatively, you can use the domain name to create a socket, as follows:

```
Socket socket = new Socket("liang.armstrong.edu", 8000);
```

When you create a socket with a host name, the JVM asks the DNS to translate the host name into the IP address.

connect to client

client socket  
use IP address

use domain name



### Note

A program can use the host name **localhost** or the IP address **127.0.0.1** to refer to the machine on which a client is running.

**localhost**

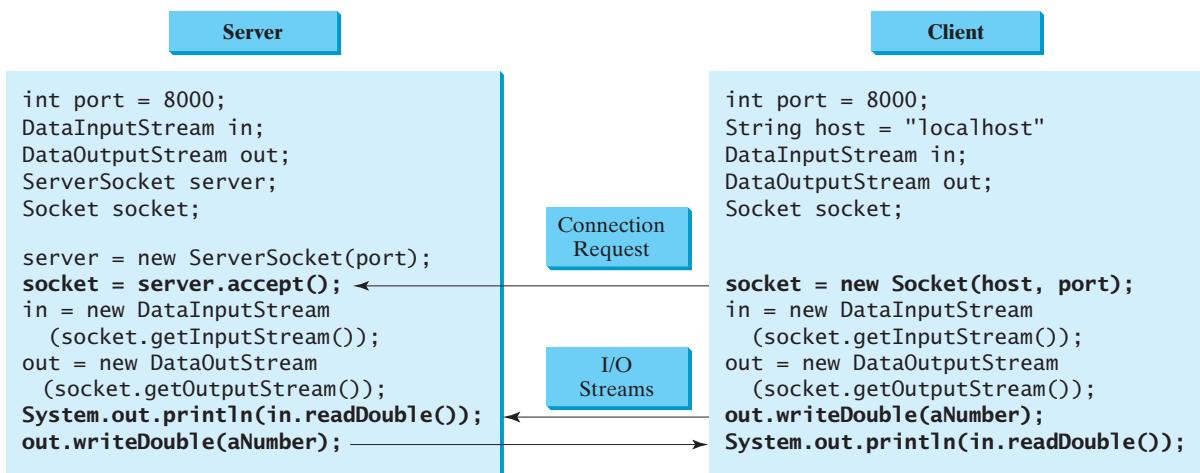
UnknownHostException

**Note**

The `Socket` constructor throws a `java.net.UnknownHostException` if the host cannot be found.

### 31.2.3 Data Transmission through Sockets

After the server accepts the connection, communication between the server and the client is conducted in the same way as for I/O streams. The statements needed to create the streams and to exchange data between them are shown in Figure 31.2.



**FIGURE 31.2** The server and client exchange data through I/O streams on top of the socket.

To get an input stream and an output stream, use the `getInputStream()` and `getOutputStream()` methods on a socket object. For example, the following statements create an `InputStream` stream called `input` and an `OutputStream` stream called `output` from a socket:

```
InputStream input = socket.getInputStream();
OutputStream output = socket.getOutputStream();
```

The `InputStream` and `OutputStream` streams are used to read or write bytes. You can use `DataInputStream`, `DataOutputStream`, `BufferedReader`, and `PrintWriter` to wrap on the `InputStream` and `OutputStream` to read or write data, such as `int`, `double`, or `String`. The following statements, for instance, create the `DataInputStream` stream `input` and the `DataOutput` stream `output` to read and write primitive data values:

```
DataInputStream input = new DataInputStream
 (socket.getInputStream());
DataOutputStream output = new DataOutputStream
 (socket.getOutputStream());
```

The server can use `input.readDouble()` to receive a `double` value from the client and `output.writeDouble(d)` to send the `double` value `d` to the client.

**Tip**

Recall that binary I/O is more efficient than text I/O because text I/O requires encoding and decoding. Therefore, it is better to use binary I/O for transmitting data between a server and a client to improve performance.

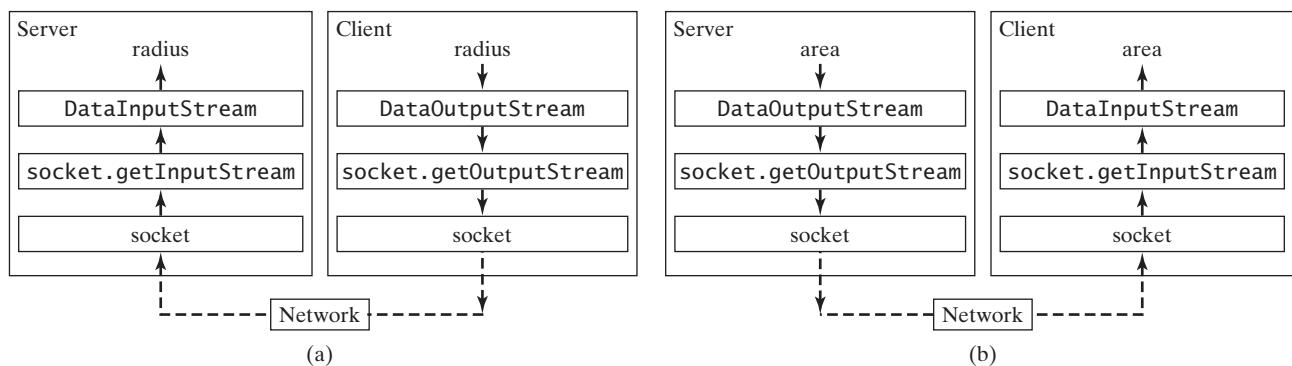
### 31.2.4 A Client/Server Example

This example presents a client program and a server program. The client sends data to a server. The server receives the data, uses it to produce a result, and then sends the result back to the client. The client displays the result on the console. In this example, the data sent from the client comprise the radius of a circle, and the result produced by the server is the area of the circle (see Figure 31.3).

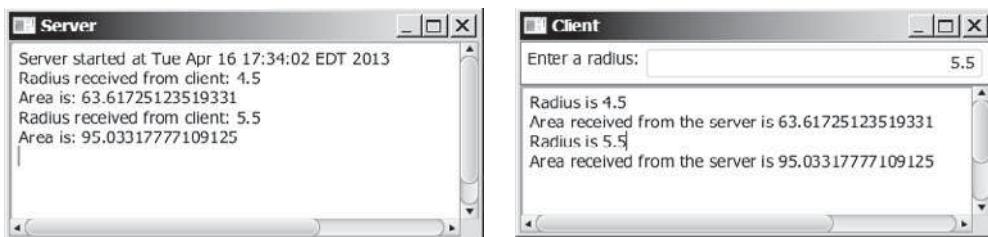


**FIGURE 31.3** The client sends the radius to the server; the server computes the area and sends it to the client.

The client sends the radius through a **DataOutputStream** on the output stream socket, and the server receives the radius through the **DataInputStream** on the input stream socket, as shown in Figure 31.4a. The server computes the area and sends it to the client through a **DataOutputStream** on the output stream socket, and the client receives the area through a **DataInputStream** on the input stream socket, as shown in Figure 31.4b. The server and client programs are given in Listings 31.1 and 31.2. Figure 31.5 contains a sample run of the server and client.



**FIGURE 31.4** (a) The client sends the radius to the server. (b) The server sends the area to the client.



**FIGURE 31.5** The client sends the radius to the server. The server receives it, computes the area, and sends the area to the client.

#### LISTING 31.1 Server.java

```

1 import java.io.*;
2 import java.net.*;
3 import java.util.Date;

```

```

4 import javafx.application.Application;
5 import javafx.application.Platform;
6 import javafx.scene.Scene;
7 import javafx.scene.control.ScrollPane;
8 import javafx.scene.control.TextArea;
9 import javafx.stage.Stage;
10
11 public class Server extends Application {
12 @Override // Override the start method in the Application class
13 public void start(Stage primaryStage) {
14 // Text area for displaying contents
15 TextArea ta = new TextArea();
16
17 // Create a scene and place it in the stage
18 Scene scene = new Scene(new ScrollPane(ta), 450, 200);
19 primaryStage.setTitle("Server"); // Set the stage title
20 primaryStage.setScene(scene); // Place the scene in the stage
21 primaryStage.show(); // Display the stage
22
23 new Thread(() -> {
24 try {
25 // Create a server socket
26 ServerSocket serverSocket = new ServerSocket(8000);
27 Platform.runLater(() ->
28 ta.appendText("Server started at " + new Date() + '\n'));
29
30 // Listen for a connection request
31 Socket socket = serverSocket.accept();
32
33 // Create data input and output streams
34 DataInputStream inputFromClient = new DataInputStream(
35 socket.getInputStream());
36 DataOutputStream outputToClient = new DataOutputStream(
37 socket.getOutputStream());
38
39 while (true) {
40 // Receive radius from the client
41 double radius = inputFromClient.readDouble();
42
43 // Compute area
44 double area = radius * radius * Math.PI;
45
46 // Send area back to the client
47 outputToClient.writeDouble(area);
48
49 Platform.runLater(() -> {
50 ta.appendText("Radius received from client: "
51 + radius + '\n');
52 ta.appendText("Area is: " + area + '\n');
53 });
54 }
55 } catch(IOException ex) {
56 ex.printStackTrace();
57 }
58 }).start();
59 }
60 }

```

create server UI

server socket update UI

connect client

input from client

output to client

read radius

write area

update UI

**LISTING 31.2 Client.java**

```

1 import java.io.*;
2 import java.net.*;
3 import javafx.application.Application;
4 import javafx.geometry.Insets;
5 import javafx.geometry.Pos;
6 import javafx.scene.Scene;
7 import javafx.scene.control.Label;
8 import javafx.scene.control.ScrollPane;
9 import javafx.scene.control.TextArea;
10 import javafx.scene.control.TextField;
11 import javafx.scene.layout.BorderPane;
12 import javafx.stage.Stage;
13
14 public class Client extends Application {
15 // IO streams
16 DataOutputStream toServer = null;
17 DataInputStream fromServer = null;
18
19 @Override // Override the start method in the Application class
20 public void start(Stage primaryStage) {
21 // Panel p to hold the label and text field
22 BorderPane paneForTextField = new BorderPane(); create UI
23 paneForTextField.setPadding(new Insets(5, 5, 5, 5));
24 paneForTextField.setStyle("-fx-border-color: green");
25 paneForTextField.setLeft(new Label("Enter a radius: "));
26
27 TextField tf = new TextField();
28 tf.setAlignment(Pos.BOTTOM_RIGHT);
29 paneForTextField.setCenter(tf);
30
31 BorderPane mainPane = new BorderPane();
32 // Text area to display contents
33 TextArea ta = new TextArea();
34 mainPane.setCenter(new ScrollPane(ta));
35 mainPane.setTop(paneForTextField);
36
37 // Create a scene and place it in the stage
38 Scene scene = new Scene(mainPane, 450, 200);
39 primaryStage.setTitle("Client"); // Set the stage title
40 primaryStage.setScene(scene); // Place the scene in the stage
41 primaryStage.show(); // Display the stage
42
43 tf.setOnAction(e -> { handle action event
44 try {
45 // Get the radius from the text field
46 double radius = Double.parseDouble(tf.getText().trim()); read radius
47
48 // Send the radius to the server
49 toServer.writeDouble(radius); write radius
50 toServer.flush();
51
52 // Get area from the server
53 double area = fromServer.readDouble(); read area
54
55 // Display to the text area
56 ta.appendText("Radius is " + radius + "\n");
57 ta.appendText("Area received from the server is "
58 + area + '\n');

```

```

59 }
60 catch (IOException ex) {
61 System.err.println(ex);
62 }
63 });
64
65 try {
66 // Create a socket to connect to the server
67 Socket socket = new Socket("localhost", 8000);
68 // Socket socket = new Socket("130.254.204.36", 8000);
69 // Socket socket = new Socket("drake.Armstrong.edu", 8000);
70
71 // Create an input stream to receive data from the server
72 fromServer = new DataInputStream(socket.getInputStream());
73
74 // Create an output stream to send data to the server
75 toServer = new DataOutputStream(socket.getOutputStream());
76 }
77 catch (IOException ex) {
78 ta.appendText(ex.toString() + '\n');
79 }
80 }
81 }

```

request connection

input from server

output to server

You start the server program first and then start the client program. In the client program, enter a radius in the text field and press *Enter* to send the radius to the server. The server computes the area and sends it back to the client. This process is repeated until one of the two programs terminates.

The networking classes are in the package **java.net**. You should import this package when writing Java network programs.

The **Server** class creates a **ServerSocket serverSocket** and attaches it to port 8000 using this statement (line 26 in Server.java):

```
ServerSocket serverSocket = new ServerSocket(8000);
```

The server then starts to listen for connection requests, using the following statement (line 31 in Server.java):

```
Socket socket = serverSocket.accept();
```

The server waits until the client requests a connection. After it is connected, the server reads the radius from the client through an input stream, computes the area, and sends the result to the client through an output stream. The **ServerSocket accept()** method takes time to execute. It is not appropriate to run this method in the JavaFX application thread. So, we place it in a separate thread (lines 23–59). The statements for updating GUI need to run from the JavaFX application thread using the **Platform.runLater** method (lines 27–28, 49–53).

The **Client** class uses the following statement to create a socket that will request a connection to the server on the same machine (localhost) at port 8000 (line 67 in Client.java).

```
Socket socket = new Socket("localhost", 8000);
```

If you run the server and the client on different machines, replace **localhost** with the server machine's host name or IP address. In this example, the server and the client are running on the same machine.

If the server is not running, the client program terminates with a **java.net.ConnectException**. After it is connected, the client gets input and output streams—wrapped by data input and output streams—in order to receive and send data to the server.

If you receive a `java.net.BindException` when you start the server, the server port is currently in use. You need to terminate the process that is using the server port and then restart the server.

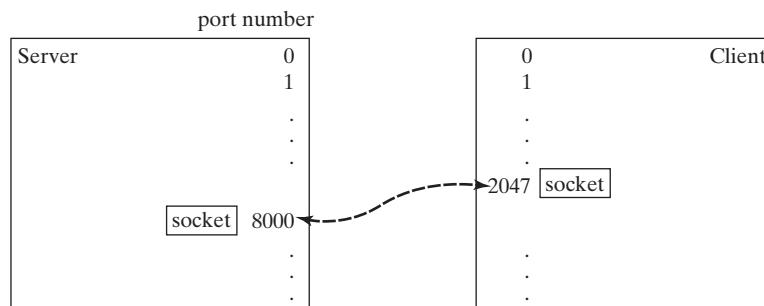


## Note

When you create a server socket, you have to specify a port (e.g., 8000) for the socket.

When a client connects to the server (line 67 in Client.java), a socket is created on the client. This socket has its own local port. This port number (e.g., 2047) is automatically chosen by the JVM, as shown in Figure 31.6.

client socket port



**FIGURE 31.6** The JVM automatically chooses an available port to create a socket for the client.

To see the local port on the client, insert the following statement in line 70 in Client.java.

```
System.out.println("local port: " + socket.getLocalPort());
```



- 31.1** How do you create a server socket? What port numbers can be used? What happens if a requested port number is already in use? Can a port connect to multiple clients?
  - 31.2** What are the differences between a server socket and a client socket?
  - 31.3** How does a client program initiate a connection?
  - 31.4** How does a server accept a connection?
  - 31.5** How are data transferred between a client and a server?

### 31.3 The InetAddress Class

The server program can use the `InetAddress` class to obtain the information about the IP address and host name for the client.



Occasionally, you would like to know who is connecting to the server. You can use the `InetAddress` class to find the client's host name and IP address. The `InetAddress` class models an IP address. You can use the following statement in the server program to get an instance of `InetAddress` on a socket that connects to the client.

```
InetAddress inetAddress = socket.getInetAddress();
```

Next, you can display the client's host name and IP address, as follows:

```
System.out.println("Client's host name is " +
 inetAddress.getHostName());
```

```
System.out.println("Client's IP Address is " +
 inetAddress.getHostAddress());
```

You can also create an instance of `InetAddress` from a host name or IP address using the static `getByName` method. For example, the following statement creates an `InetAddress` for the host `Liang.armstrong.edu`.

```
InetAddress address = InetAddress.getByName("Liang.armstrong.edu");
```

Listing 31.3 gives a program that identifies the host name and IP address of the arguments you pass in from the command line. Line 7 creates an `InetAddress` using the `getByName` method. Lines 8 and 9 use the `getHostName` and `getHostAddress` methods to get the host's name and IP address. Figure 31.7 shows a sample run of the program.



**FIGURE 31.7** The program identifies host names and IP addresses.

### LISTING 31.3 IdentifyHostNameIP.java

```
1 import java.net.*;
2
3 public class IdentifyHostNameIP {
4 public static void main(String[] args) {
5 for (int i = 0; i < args.length; i++) {
6 try {
7 InetAddress address = InetAddress.getByName(args[i]);
8 System.out.print("Host name: " + address.getHostName() + " ");
9 System.out.println("IP address: " + address.getHostAddress());
10 }
11 catch (UnknownHostException ex) {
12 System.err.println("Unknown host or IP address " + args[i]);
13 }
14 }
15 }
16 }
```

get an `InetAddress`  
get host name  
get host IP



**31.6** How do you obtain an instance of `InetAddress`?

**31.7** What methods can you use to get the IP address and hostname from an `InetAddress`?

### 31.4 Serving Multiple Clients



*A server can serve multiple clients. The connection to each client is handled by one thread.*

Multiple clients are quite often connected to a single server at the same time. Typically, a server runs continuously on a server computer, and clients from all over the Internet can connect to it. You can use threads to handle the server's multiple clients simultaneously—simply

create a thread for each connection. Here is how the server handles the establishment of a connection:

```
while (true) {
 Socket socket = serverSocket.accept(); // Connect to a client
 Thread thread = new ThreadClass(socket);
 thread.start();
}
```

The server socket can have many connections. Each iteration of the `while` loop creates a new connection. Whenever a connection is established, a new thread is created to handle communication between the server and the new client, and this allows multiple connections to run at the same time.

Listing 31.4 creates a server class that serves multiple clients simultaneously. For each connection, the server starts a new thread. This thread continuously receives input (the radius of a circle) from clients and sends the results (the area of the circle) back to them (see Figure 31.8). The client program is the same as in Listing 31.2. A sample run of the server with two clients is shown in Figure 31.9.

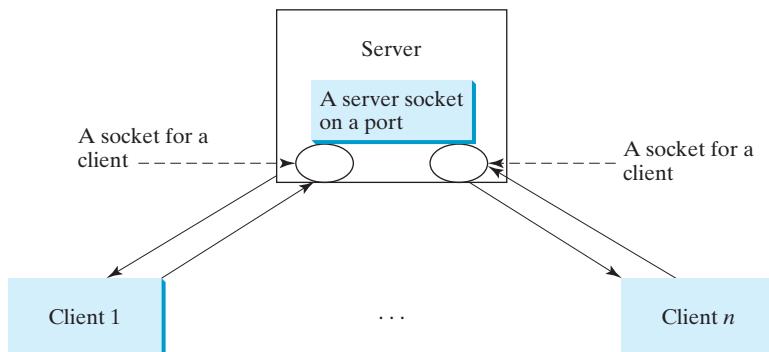


FIGURE 31.8 Multithreading enables a server to handle multiple independent clients.

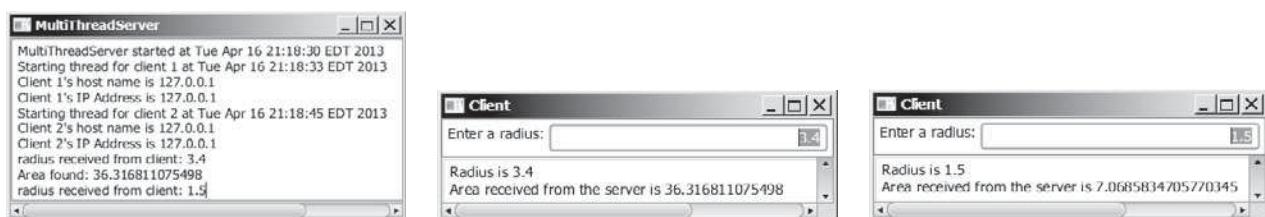


FIGURE 31.9 The server spawns a thread in order to serve a client.

#### LISTING 31.4 MultiThreadServer.java

```
1 import java.io.*;
2 import java.net.*;
3 import java.util.Date;
4 import javafx.application.Application;
5 import javafx.application.Platform;
6 import javafx.scene.Scene;
7 import javafx.scene.control.ScrollPane;
8 import javafx.scene.control.TextArea;
9 import javafx.stage.Stage;
```

```

11 public class MultiThreadServer extends Application {
12 // Text area for displaying contents
13 private TextArea ta = new TextArea();
14
15 // Number a client
16 private int clientNo = 0;
17
18 @Override // Override the start method in the Application class
19 public void start(Stage primaryStage) {
20 // Create a scene and place it in the stage
21 Scene scene = new Scene(new ScrollPane(ta), 450, 200);
22 primaryStage.setTitle("MultiThreadServer"); // Set the stage title
23 primaryStage.setScene(scene); // Place the scene in the stage
24 primaryStage.show(); // Display the stage
25
26 new Thread(() -> {
27 try {
28 // Create a server socket
29 ServerSocket serverSocket = new ServerSocket(8000);
30 ta.appendText("MultiThreadServer started at "
31 + new Date() + "\n");
32
33 while (true) {
34 // Listen for a new connection request
35 Socket socket = serverSocket.accept();
36
37 // Increment clientNo
38 clientNo++;
39
40 Platform.runLater(() -> {
41 // Display the client number
42 ta.appendText("Starting thread for client " + clientNo +
43 " at " + new Date() + "\n");
44
45 // Find the client's host name, and IP address
46 InetAddress inetAddress = socket.getInetAddress();
47 ta.appendText("Client " + clientNo + "'s host name is "
48 + inetAddress.getHostName() + "\n");
49 ta.appendText("Client " + clientNo + "'s IP Address is "
50 + inetAddress.getHostAddress() + "\n");
51 });
52
53 // Create and start a new thread for the connection
54 new Thread(new HandleAClient(socket)).start();
55 }
56 } catch(IOException ex) {
57 System.err.println(ex);
58 }
59 }).start();
60 }
61
62
63 // Define the thread class for handling new connection
64 class HandleAClient implements Runnable {
65 private Socket socket; // A connected socket
66
67 /** Construct a thread */
68 public HandleAClient(Socket socket) {
69 this.socket = socket;
70 }
71 }

```

server socket

connect client

update GUI

network information

create task

start thread

task class

```

72 /** Run a thread */
73 public void run() {
74 try {
75 // Create data input and output streams
76 DataInputStream inputFromClient = new DataInputStream(
77 socket.getInputStream()); I/O
78 DataOutputStream outputToClient = new DataOutputStream(
79 socket.getOutputStream());
80
81 // Continuously serve the client
82 while (true) {
83 // Receive radius from the client
84 double radius = inputFromClient.readDouble();
85
86 // Compute area
87 double area = radius * radius * Math.PI;
88
89 // Send area back to the client
90 outputToClient.writeDouble(area);
91
92 Platform.runLater(() -> {
93 ta.appendText("radius received from client: " +
94 radius + '\n');
95 ta.appendText("Area found: " + area + '\n');
96 });
97 }
98 } catch(IOException e) {
99 ex.printStackTrace();
100 }
101 }
102 }
103 }
104 }
```

The server creates a server socket at port 8000 (line 29) and waits for a connection (line 35). When a connection with a client is established, the server creates a new thread to handle the communication (line 54). It then waits for another connection in an infinite **while** loop (lines 33–55).

The threads, which run independently of one another, communicate with designated clients. Each thread creates data input and output streams that receive and send data to a client.

### 31.8 How do you make a server serve multiple clients?



## 31.5 Sending and Receiving Objects

*A program can send and receive objects from another program.*



In the preceding examples, you learned how to send and receive data of primitive types. You can also send and receive objects using **ObjectOutputStream** and **ObjectInputStream** on socket streams. To enable passing, the objects must be serializable. The following example demonstrates how to send and receive objects.

The example consists of three classes: **StudentAddress.java** (Listing 31.5), **StudentClient.java** (Listing 31.6), and **StudentServer.java** (Listing 31.7). The client program collects student information from the client and sends it to a server, as shown in Figure 31.10.

The **StudentAddress** class contains the student information: name, street, city, state, and zip. The **StudentAddress** class implements the **Serializable** interface. Therefore, a **StudentAddress** object can be sent and received using the object output and input streams.



**FIGURE 31.10** The client sends the student information in an object to the server.

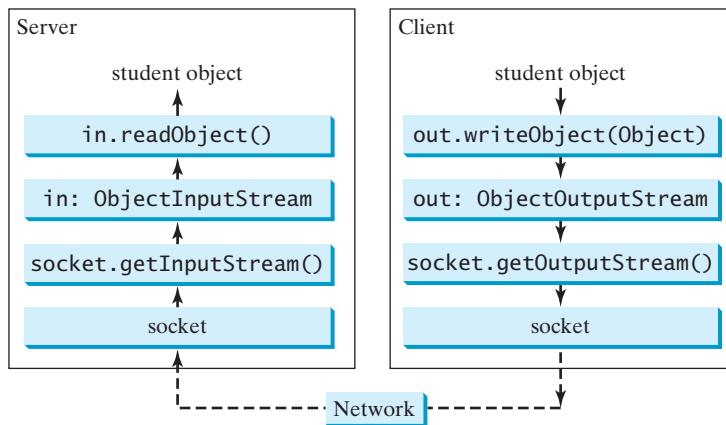
### LISTING 31.5 StudentAddress.java

serialized

```

1 public class StudentAddress implements java.io.Serializable {
2 private String name;
3 private String street;
4 private String city;
5 private String state;
6 private String zip;
7
8 public StudentAddress(String name, String street, String city,
9 String state, String zip) {
10 this.name = name;
11 this.street = street;
12 this.city = city;
13 this.state = state;
14 this.zip = zip;
15 }
16
17 public String getName() {
18 return name;
19 }
20
21 public String getStreet() {
22 return street;
23 }
24
25 public String getCity() {
26 return city;
27 }
28
29 public String getState() {
30 return state;
31 }
32
33 public String getZip() {
34 return zip;
35 }
36 }
```

The client sends a `StudentAddress` object through an `ObjectOutputStream` on the output stream socket, and the server receives the `Student` object through the `ObjectInputStream` on the input stream socket, as shown in Figure 31.11. The client uses the `writeObject` method in the `ObjectOutputStream` class to send data about a student to the server, and the server receives the student's information using the `readObject` method in the `ObjectInputStream` class. The server and client programs are given in Listings 31.6 and 31.7.



**FIGURE 31.11** The client sends a **StudentAddress** object to the server.

### LISTING 31.6 StudentClient.java

```

1 import java.io.*;
2 import java.net.*;
3 import javafx.application.Application;
4 import javafx.event.ActionEvent;
5 import javafx.event.EventHandler;
6 import javafx.geometry.HPos;
7 import javafx.geometry.Pos;
8 import javafx.scene.Scene;
9 import javafx.scene.control.Button;
10 import javafx.scene.control.Label;
11 import javafx.scene.control.TextField;
12 import javafx.scene.layout.GridPane;
13 import javafx.scene.layout.HBox;
14 import javafx.stage.Stage;
15
16 public class StudentClient extends Application {
17 private TextField tfName = new TextField();
18 private TextField tfStreet = new TextField();
19 private TextField tfCity = new TextField();
20 private TextField tfState = new TextField();
21 private TextField tfZip = new TextField();
22
23 // Button for sending a student to the server
24 private Button btRegister = new Button("Register to the Server");
25
26 // Host name or ip
27 String host = "localhost";
28
29 @Override // Override the start method in the Application class
30 public void start(Stage primaryStage) {
31 GridPane pane = new GridPane(); create UI
32 pane.add(new Label("Name"), 0, 0);
33 pane.add(tfName, 1, 0);
34 pane.add(new Label("Street"), 0, 1);
35 pane.add(tfStreet, 1, 1);
36 pane.add(new Label("City"), 0, 2);
37

```

```

38 HBox hBox = new HBox(2);
39 pane.add(hBox, 1, 2);
40 hBox.getChildren().addAll(tfCity, new Label("State"), tfState,
41 new Label("Zip"), tfZip);
42 pane.add(btRegister, 1, 3);
43 GridPane.setAlignment(btRegister, HPos.RIGHT);
44
45 pane.setAlignment(Pos.CENTER);
46 tfName.setPrefColumnCount(15);
47 tfStreet.setPrefColumnCount(15);
48 tfCity.setPrefColumnCount(10);
49 tfState.setPrefColumnCount(2);
50 tfZip.setPrefColumnCount(3);
51
52 btRegister.setOnAction(new ButtonListener());
53
54 // Create a scene and place it in the stage
55 Scene scene = new Scene(pane, 450, 200);
56 primaryStage.setTitle("StudentClient"); // Set the stage title
57 primaryStage.setScene(scene); // Place the scene in the stage
58 primaryStage.show(); // Display the stage
59 }
60
61 /**
62 * Handle button action */
63 private class ButtonListener implements EventHandler<ActionEvent> {
64 @Override
65 public void handle(ActionEvent e) {
66 try {
67 // Establish connection with the server
68 Socket socket = new Socket(host, 8000);
69
70 // Create an output stream to the server
71 ObjectOutputStream toServer =
72 new ObjectOutputStream(socket.getOutputStream());
73
74 // Get text field
75 String name = tfName.getText().trim();
76 String street = tfStreet.getText().trim();
77 String city = tfCity.getText().trim();
78 String state = tfState.getText().trim();
79 String zip = tfZip.getText().trim();
80
81 // Create a Student object and send to the server
82 StudentAddress s =
83 new StudentAddress(name, street, city, state, zip);
84 toServer.writeObject(s);
85 } catch (IOException ex) {
86 ex.printStackTrace();
87 }
88 }
89 }
90 }

```

**LISTING 31.7** StudentServer.java

```

1 import java.io.*;
2 import java.net.*;
3
4 public class StudentServer {

```

```

5 private ObjectOutputStream outputToFile;
6 private ObjectInputStream inputFromClient;
7
8 public static void main(String[] args) {
9 new StudentServer();
10 }
11
12 public StudentServer() {
13 try {
14 // Create a server socket
15 ServerSocket serverSocket = new ServerSocket(8000); server socket
16 System.out.println("Server started ");
17
18 // Create an object output stream
19 outputToFile = new ObjectOutputStream(
20 new FileOutputStream("student.dat", true)); output to file
21
22 while (true) {
23 // Listen for a new connection request
24 Socket socket = serverSocket.accept(); connect to client
25
26 // Create an input stream from the socket
27 inputFromClient = input stream
28 new ObjectInputStream(socket.getInputStream());
29
30 // Read from input
31 Object object = inputFromClient.readObject(); get from client
32
33 // Write to the file
34 outputToFile.writeObject(object); write to file
35 System.out.println("A new student object is stored");
36 }
37 } catch(ClassNotFoundException ex) {
38 ex.printStackTrace();
39 } catch(IOException ex) {
40 ex.printStackTrace();
41 } finally {
42 try {
43 inputFromClient.close();
44 outputToFile.close();
45 } catch (Exception ex) {
46 ex.printStackTrace();
47 }
48 }
49 }
50 }
51 }
52 }
53 }
54 }

```

On the client side, when the user clicks the *Register to the Server* button, the client creates a socket to connect to the host (line 67), creates an **ObjectOutputStream** on the output stream of the socket (lines 70 and 71), and invokes the **writeObject** method to send the **StudentAddress** object to the server through the object output stream (line 83).

On the server side, when a client connects to the server, the server creates an **ObjectInputStream** on the input stream of the socket (lines 27 and 28), invokes the **readObject** method to receive the **StudentAddress** object through the object input stream (line 31), and writes the object to a file (line 34).



- 31.9** How does a server receive connection from a client? How does a client connect to a server?
- 31.10** How do you find the host name of a client program from the server?
- 31.11** How do you send and receive an object?



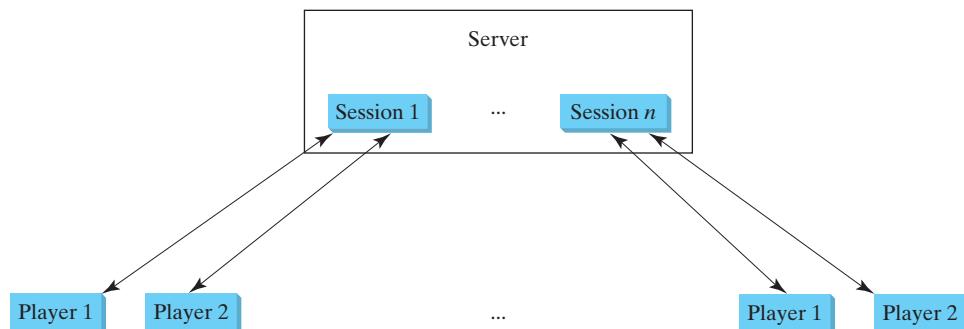
## 31.6 Case Study: Distributed Tic-Tac-Toe Games

*This section develops a program that enables two players to play the tic-tac-toe game on the Internet.*

In Section 16.12, Case Study: Developing a Tic-Tac-Toe Game, you developed a program for a tic-tac-toe game that enables two players to play the game on the same machine. In this section, you will learn how to develop a distributed tic-tac-toe game using multithreads and networking with socket streams. A distributed tic-tac-toe game enables users to play on different machines from anywhere on the Internet.

You need to develop a server for multiple clients. The server creates a server socket and accepts connections from every two players to form a session. Each session is a thread that communicates with the two players and determines the status of the game. The server can establish any number of sessions, as shown in Figure 31.13.

For each session, the first client connecting to the server is identified as player 1 with token **X**, and the second client connecting is identified as player 2 with token **O**. The server notifies the players of their respective tokens. Once two clients are connected to it, the server starts a thread to facilitate the game between the two players by performing the steps repeatedly, as shown in Figure 31.13.



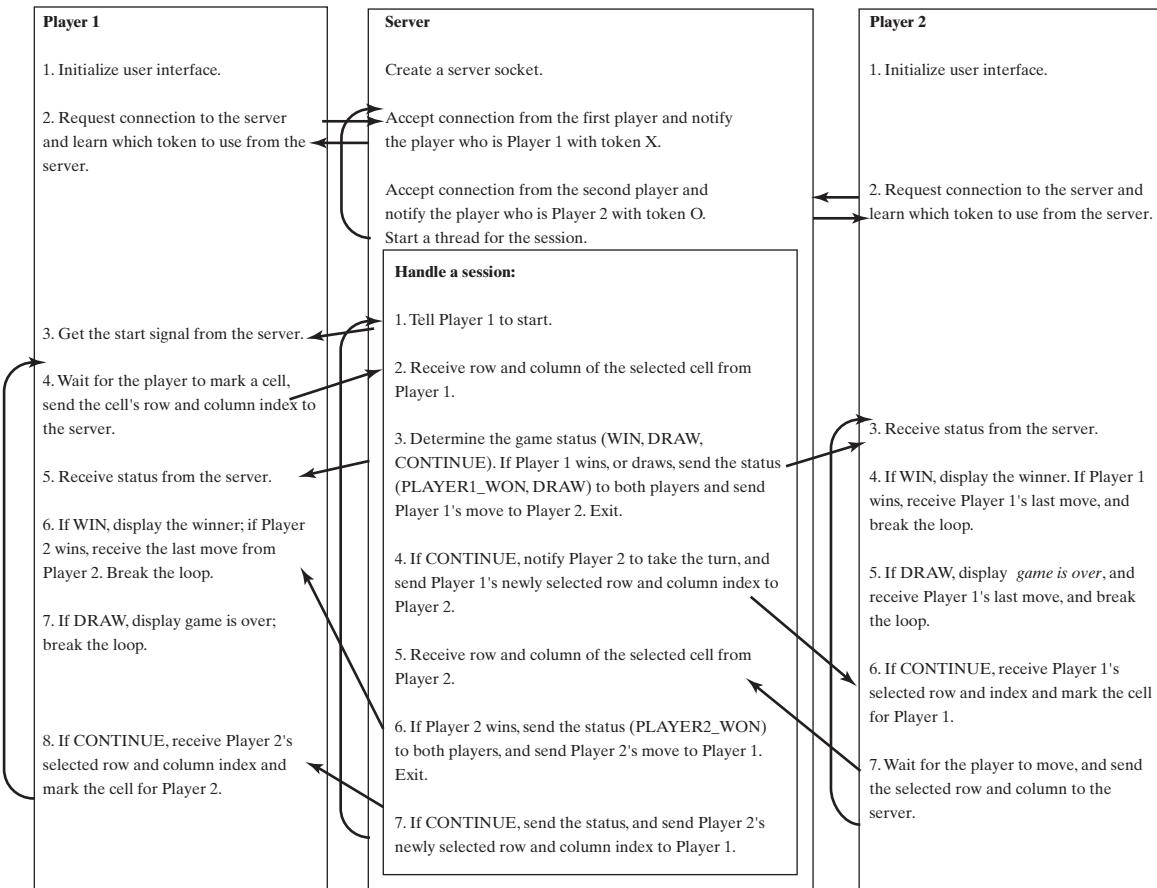
**FIGURE 31.12** The server can create many sessions, each of which facilitates a tic-tac-toe game for two players.

The server does not have to be a graphical component, but creating it in a GUI in which game information can be viewed is user-friendly. You can create a scroll pane to hold a text area in the GUI and display game information in the text area. The server creates a thread to handle a game session when two players are connected to the server.

The client is responsible for interacting with the players. It creates a user interface with nine cells and displays the game title and status to the players in the labels. The client class is very similar to the **TicTacToe** class presented in the case study in Listing 16.13. However, the client in this example does not determine the game status (win or draw); it simply passes the moves to the server and receives the game status from the server.

Based on the foregoing analysis, you can create the following classes:

- **TicTacToeServer** serves all the clients in Listing 31.9.
- **HandleASession** facilitates the game for two players. This class is defined in **TicTacToeServer.java**.



**FIGURE 31.13** The server starts a thread to facilitate communications between the two players.

- **TicTacToeClient** models a player in Listing 31.10.
- **Cell** models a cell in the game. It is an inner class in **TicTacToeClient**.
- **TicTacToeConstants** is an interface that defines the constants shared by all the classes in the example in Listing 31.8.

The relationships of these classes are shown in Figure 31.14.

### LISTING 31.8 TicTacToeConstants.java

```

1 public interface TicTacToeConstants {
2 public static int PLAYER1 = 1; // Indicate player 1
3 public static int PLAYER2 = 2; // Indicate player 2
4 public static int PLAYER1_WON = 1; // Indicate player 1 won
5 public static int PLAYER2_WON = 2; // Indicate player 2 won
6 public static int DRAW = 3; // Indicate a draw
7 public static int CONTINUE = 4; // Indicate to continue
8 }

```

### LISTING 31.9 TicTacToeServer.java

```

1 import java.io.*;
2 import java.net.*;
3 import java.util.Date;
4 import javafx.application.Application;

```

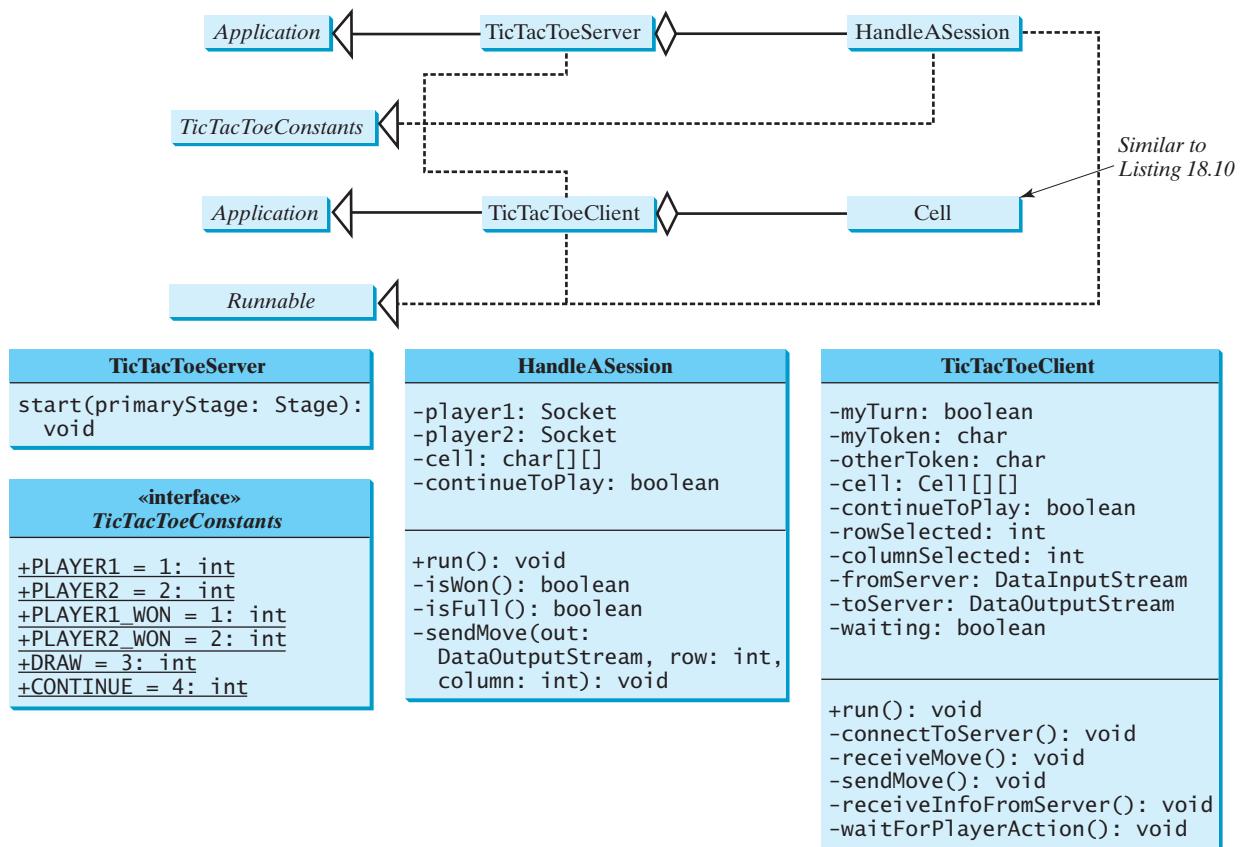


FIGURE 31.14 **TicTacToeServer** creates an instance of **HandleASession** for each session of two players. **TicTacToeClient** creates nine cells in the UI.

```

5 import javafx.application.Platform;
6 import javafx.scene.Scene;
7 import javafx.scene.control.ScrollPane;
8 import javafx.scene.control.TextArea;
9 import javafx.stage.Stage;
10
11 public class TicTacToeServer extends Application
12 implements TicTacToeConstants {
13 private int sessionNo = 1; // Number a session
14
15 @Override // Override the start method in the Application class
16 public void start(Stage primaryStage) {
17 TextArea taLog = new TextArea();
18
19 // Create a scene and place it in the stage
20 Scene scene = new Scene(new ScrollPane(taLog), 450, 200);
21 primaryStage.setTitle("TicTacToeServer"); // Set the stage title
22 primaryStage.setScene(scene); // Place the scene in the stage
23 primaryStage.show(); // Display the stage
24
25 new Thread(() -> {
26 try {
27 // Create a server socket
28 ServerSocket serverSocket = new ServerSocket(8000);

```

create UI

server socket

```

29 Platform.runLater(() -> taLog.appendText(new Date() +
30 ": Server started at socket 8000\n"));
31
32 // Ready to create a session for every two players
33 while (true) {
34 Platform.runLater(() -> taLog.appendText(new Date() +
35 ": Wait for players to join session " + sessionNo + '\n'));
36
37 // Connect to player 1
38 Socket player1 = serverSocket.accept(); connect to client
39
40 Platform.runLater(() -> {
41 taLog.appendText(new Date() + ": Player 1 joined session "
42 + sessionNo + '\n');
43 taLog.appendText("Player 1's IP address" +
44 player1.getInetAddress().getHostAddress() + '\n');
45 });
46
47 // Notify that the player is Player 1 to player1
48 new DataOutputStream(
49 player1.getOutputStream()).writeInt(PLAYER1);
50
51 // Connect to player 2
52 Socket player2 = serverSocket.accept(); connect to client
53
54 Platform.runLater(() -> {
55 taLog.appendText(new Date() +
56 ": Player 2 joined session " + sessionNo + '\n');
57 taLog.appendText("Player 2's IP address" +
58 player2.getInetAddress().getHostAddress() + '\n');
59 });
60
61 // Notify that the player is Player 2 to player2
62 new DataOutputStream(
63 player2.getOutputStream()).writeInt(PLAYER2);
64
65 // Display this session and increment session number
66 Platform.runLater(() ->
67 taLog.appendText(new Date() +
68 ": Start a thread for session " + sessionNo++ + '\n'));
69
70 // Launch a new thread for this session of two players a session for two players
71 new Thread(new HandleASession(player1, player2)).start();
72 }
73 }
74 catch(IOException ex) {
75 ex.printStackTrace();
76 }
77 }.start();
78 }
79
80 // Define the thread class for handling a new session for two players
81 class HandleASession implements Runnable, TicTacToeConstants {
82 private Socket player1;
83 private Socket player2;
84
85 // Create and initialize cells
86 private char[][] cell = new char[3][3];
87
88 private DataInputStream fromPlayer1;

```

```

89 private DataOutputStream toPlayer1;
90 private DataInputStream fromPlayer2;
91 private DataOutputStream toPlayer2;
92
93 // Continue to play
94 private boolean continueToPlay = true;
95
96 /** Construct a thread */
97 public HandleASession(Socket player1, Socket player2) {
98 this.player1 = player1;
99 this.player2 = player2;
100
101 // Initialize cells
102 for (int i = 0; i < 3; i++)
103 for (int j = 0; j < 3; j++)
104 cell[i][j] = ' ';
105 }
106
107 /** Implement the run() method for the thread */
108 public void run() {
109 try {
110 // Create data input and output streams
111 DataInputStream fromPlayer1 = new DataInputStream(
112 player1.getInputStream());
113 DataOutputStream toPlayer1 = new DataOutputStream(
114 player1.getOutputStream());
115 DataInputStream fromPlayer2 = new DataInputStream(
116 player2.getInputStream());
117 DataOutputStream toPlayer2 = new DataOutputStream(
118 player2.getOutputStream());
119
120 // Write anything to notify player 1 to start
121 // This is just to let player 1 know to start
122 toPlayer1.writeInt(1);
123
124 // Continuously serve the players and determine and report
125 // the game status to the players
126 while (true) {
127 // Receive a move from player 1
128 int row = fromPlayer1.readInt();
129 int column = fromPlayer1.readInt();
130 cell[row][column] = 'X';
131
132 // Check if Player 1 wins
133 if (isWon('X')) {
134 toPlayer1.writeInt(PLAYER1_WON);
135 toPlayer2.writeInt(PLAYER1_WON);
136 sendMove(toPlayer2, row, column);
137 break; // Break the loop
138 }
139 else if (isFull()) { // Check if all cells are filled
140 toPlayer1.writeInt(DRAW);
141 toPlayer2.writeInt(DRAW);
142 sendMove(toPlayer2, row, column);
143 break;
144 }
145 else {
146 // Notify player 2 to take the turn
147 toPlayer2.writeInt(CONTINUE);
148

```

IO streams

X won?

Is full?

```

149 // Send player 1's selected row and column to player 2
150 sendMove(toPlayer2, row, column);
151 }
152
153 // Receive a move from Player 2
154 row = fromPlayer2.readInt();
155 column = fromPlayer2.readInt();
156 cell[row][column] = 'O';
157
158 // Check if Player 2 wins
159 if (isWon('O')) { O won?
160 toPlayer1.writeInt(PLAYER2_WON);
161 toPlayer2.writeInt(PLAYER2_WON);
162 sendMove(toPlayer1, row, column);
163 break;
164 }
165 else {
166 // Notify player 1 to take the turn
167 toPlayer1.writeInt(CONTINUE);
168
169 // Send player 2's selected row and column to player 1
170 sendMove(toPlayer1, row, column);
171 }
172 }
173
174 catch(IOException ex) {
175 ex.printStackTrace();
176 }
177 }
178
179 /** Send the move to other player */
180 private void sendMove(DataOutputStream out, int row, int column) send a move
181 throws IOException {
182 out.writeInt(row); // Send row index
183 out.writeInt(column); // Send column index
184 }
185
186 /** Determine if the cells are all occupied */
187 private boolean isFull() {
188 for (int i = 0; i < 3; i++)
189 for (int j = 0; j < 3; j++)
190 if (cell[i][j] == ' ')
191 return false; // At least one cell is not filled
192
193 // All cells are filled
194 return true;
195 }
196
197 /** Determine if the player with the specified token wins */
198 private boolean isWon(char token) {
199 // Check all rows
200 for (int i = 0; i < 3; i++)
201 if ((cell[i][0] == token)
202 && (cell[i][1] == token)
203 && (cell[i][2] == token)) {
204 return true;
205 }
206
207 /** Check all columns */
208 for (int j = 0; j < 3; j++)

```

```

209 if ((cell[0][j] == token)
210 && (cell[1][j] == token)
211 && (cell[2][j] == token)) {
212 return true;
213 }
214
215 /** Check major diagonal */
216 if ((cell[0][0] == token)
217 && (cell[1][1] == token)
218 && (cell[2][2] == token)) {
219 return true;
220 }
221
222 /** Check subdiagonal */
223 if ((cell[0][2] == token)
224 && (cell[1][1] == token)
225 && (cell[2][0] == token)) {
226 return true;
227 }
228
229 /** All checked, but no winner */
230 return false;
231 }
232 }
233 }
```

**LISTING 31.10 TicTacToeClient.java**

```

1 import java.io.*;
2 import java.net.*;
3 import java.util.Date;
4 import javafx.application.Application;
5 import javafx.application.Platform;
6 import javafx.scene.Scene;
7 import javafx.scene.control.Label;
8 import javafx.scene.control.ScrollPane;
9 import javafx.scene.control.TextArea;
10 import javafx.scene.layout.BorderPane;
11 import javafx.scene.layout.GridPane;
12 import javafx.scene.layout.Pane;
13 import javafx.scene.paint.Color;
14 import javafx.scene.shape.Ellipse;
15 import javafx.scene.shape.Line;
16 import javafx.stage.Stage;
17
18 public class TicTacToeClient extends Application
19 implements TicTacToeConstants {
20 // Indicate whether the player has the turn
21 private boolean myTurn = false;
22
23 // Indicate the token for the player
24 private char myToken = ' ';
25
26 // Indicate the token for the other player
27 private char otherToken = ' ';
28
29 // Create and initialize cells
30 private Cell[][] cell = new Cell[3][3];
31 }
```

```

32 // Create and initialize a title label
33 private Label lblTitle = new Label();
34
35 // Create and initialize a status label
36 private Label lblStatus = new Label();
37
38 // Indicate selected row and column by the current move
39 private int rowSelected;
40 private int columnSelected;
41
42 // Input and output streams from/to server
43 private DataInputStream fromServer;
44 private DataOutputStream toServer;
45
46 // Continue to play?
47 private boolean continueToPlay = true;
48
49 // Wait for the player to mark a cell
50 private boolean waiting = true;
51
52 // Host name or ip
53 private String host = "localhost";
54
55 @Override // Override the start method in the Application class
56 public void start(Stage primaryStage) {
57 // Pane to hold cell
58 GridPane pane = new GridPane(); create UI
59 for (int i = 0; i < 3; i++)
60 for (int j = 0; j < 3; j++)
61 pane.add(cell[i][j] = new Cell(i, j), j, i);
62
63 BorderPane borderPane = new BorderPane();
64 borderPane.setTop(lblTitle);
65 borderPane.setCenter(pane);
66 borderPane.setBottom(lblStatus);
67
68 // Create a scene and place it in the stage
69 Scene scene = new Scene(borderPane, 320, 350);
70 primaryStage.setTitle("TicTacToeClient"); // Set the stage title
71 primaryStage.setScene(scene); // Place the scene in the stage
72 primaryStage.show(); // Display the stage
73
74 // Connect to the server
75 connectToServer(); connect to server
76 }
77
78 private void connectToServer() {
79 try {
80 // Create a socket to connect to the server
81 Socket socket = new Socket(host, 8000);
82
83 // Create an input stream to receive data from the server
84 fromServer = new DataInputStream(socket.getInputStream()); input from server
85
86 // Create an output stream to send data to the server
87 toServer = new DataOutputStream(socket.getOutputStream()); output to server
88 }
89 catch (Exception ex) {
90 ex.printStackTrace();
91 }

```

```

92
93 // Control the game on a separate thread
94 new Thread(() -> {
95 try {
96 // Get notification from the server
97 int player = fromServer.readInt();
98
99 // Am I player 1 or 2?
100 if (player == PLAYER1) {
101 myToken = 'X';
102 otherToken = 'O';
103 Platform.runLater(() -> {
104 lblTitle.setText("Player 1 with token 'X'");
105 lblStatus.setText("Waiting for player 2 to join");
106 });
107
108 // Receive startup notification from the server
109 fromServer.readInt(); // Whatever read is ignored
110
111 // The other player has joined
112 Platform.runLater(() ->
113 lblStatus.setText("Player 2 has joined. I start first"));
114
115 // It is my turn
116 myTurn = true;
117 }
118 else if (player == PLAYER2) {
119 myToken = 'O';
120 otherToken = 'X';
121 Platform.runLater(() -> {
122 lblTitle.setText("Player 2 with token 'O'");
123 lblStatus.setText("Waiting for player 1 to move");
124 });
125 }
126
127 // Continue to play
128 while (continueToPlay) {
129 if (player == PLAYER1) {
130 waitForPlayerAction(); // Wait for player 1 to move
131 sendMove(); // Send the move to the server
132 receiveInfoFromServer(); // Receive info from the server
133 }
134 else if (player == PLAYER2) {
135 receiveInfoFromServer(); // Receive info from the server
136 waitForPlayerAction(); // Wait for player 2 to move
137 sendMove(); // Send player 2's move to the server
138 }
139 }
140 }
141 catch (Exception ex) {
142 ex.printStackTrace();
143 }
144}.start();
145}
146
147 /** Wait for the player to mark a cell */
148 private void waitForPlayerAction() throws InterruptedException {
149 while (waiting) {
150 Thread.sleep(100);
151 }

```

```

152 waiting = true;
153 }
154
155 /**
156 * Send this player's move to the server */
157 private void sendMove() throws IOException {
158 toServer.writeInt(rowSelected); // Send the selected row
159 toServer.writeInt(columnSelected); // Send the selected column
160 }
161
162 /**
163 * Receive info from the server */
164 private void receiveInfoFromServer() throws IOException {
165 // Receive game status
166 int status = fromServer.readInt();
167
168 if (status == PLAYER1_WON) {
169 // Player 1 won, stop playing
170 continueToPlay = false;
171 if (myToken == 'X') {
172 Platform.runLater(() -> lblStatus.setText("I won! (X)"));
173 }
174 else if (myToken == 'O') {
175 Platform.runLater(() ->
176 lblStatus.setText("Player 1 (X) has won!"));
177 receiveMove();
178 }
179 } else if (status == PLAYER2_WON) {
180 // Player 2 won, stop playing
181 continueToPlay = false;
182 if (myToken == 'O') {
183 Platform.runLater(() -> lblStatus.setText("I won! (O)"));
184 }
185 else if (myToken == 'X') {
186 Platform.runLater(() ->
187 lblStatus.setText("Player 2 (O) has won!"));
188 receiveMove();
189 }
190 } else if (status == DRAW) {
191 // No winner, game is over
192 continueToPlay = false;
193 Platform.runLater(() ->
194 lblStatus.setText("Game is over, no winner!"));
195
196 if (myToken == 'O') {
197 receiveMove();
198 }
199 } else {
200 receiveMove();
201 Platform.runLater(() -> lblStatus.setText("My turn"));
202 myTurn = true; // It is my turn
203 }
204 }
205
206
207
208 private void receiveMove() throws IOException {
209 // Get the other player's move
210 int row = fromServer.readInt();
211 int column = fromServer.readInt();

```

```

212 Platform.runLater(() -> cell[row][column].setToken(otherToken));
213 }
214
215 // An inner class for a cell
216 public class Cell extends Pane {
217 // Indicate the row and column of this cell in the board
218 private int row;
219 private int column;
220
221 // Token used for this cell
222 private char token = ' ';
223
224 public Cell(int row, int column) {
225 this.row = row;
226 this.column = column;
227 this.setPrefSize(2000, 2000); // What happens without this?
228 setStyle("-fx-border-color: black"); // Set cell's border
229 this.setOnMouseClicked(e -> handleMouseClick());
230 }
231
232 /** Return token */
233 public char getToken() {
234 return token;
235 }
236
237 /** Set a new token */
238 public void setToken(char c) {
239 token = c;
240 repaint();
241 }
242
243 protected void repaint() {
244 if (token == 'X') {
245 Line line1 = new Line(10, 10,
246 this.getWidth() - 10, this.getHeight() - 10);
247 line1.endXProperty().bind(this.widthProperty().subtract(10));
248 line1.endYProperty().bind(this.heightProperty().subtract(10));
249 Line line2 = new Line(10, this.getHeight() - 10,
250 this.getWidth() - 10, 10);
251 line2.startYProperty().bind(
252 this.heightProperty().subtract(10));
253 line2.endXProperty().bind(this.widthProperty().subtract(10));
254
255 // Add the lines to the pane
256 this.getChildren().addAll(line1, line2);
257 }
258 else if (token == 'O') {
259 Ellipse ellipse = new Ellipse(this.getWidth() / 2,
260 this.getHeight() / 2, this.getWidth() / 2 - 10,
261 this.getHeight() / 2 - 10);
262 ellipse.centerXProperty().bind(
263 this.widthProperty().divide(2));
264 ellipse.centerYProperty().bind(
265 this.heightProperty().divide(2));
266 ellipse.radiusXProperty().bind(
267 this.widthProperty().divide(2).subtract(10));
268 ellipse.radiusYProperty().bind(
269 this.heightProperty().divide(2).subtract(10));
270 ellipse.setStroke(Color.BLACK);
271 ellipse.setFill(Color.WHITE);
}

```

model a cell

register listener

draw X

draw O

```

272 getChildren().add(ellipse); // Add the ellipse to the pane
273 }
274 }
275 }
276
277 /* Handle a mouse click event */
278 private void handleMouseClick() {
279 // If cell is not occupied and the player has the turn
280 if (token == ' ' && myTurn) {
281 setToken(myToken); // Set the player's token in the cell
282 myTurn = false;
283 rowSelected = row;
284 columnSelected = column;
285 lblStatus.setText("Waiting for the other player to move");
286 waiting = false; // Just completed a successful move
287 }
288 }
289 }
290 }

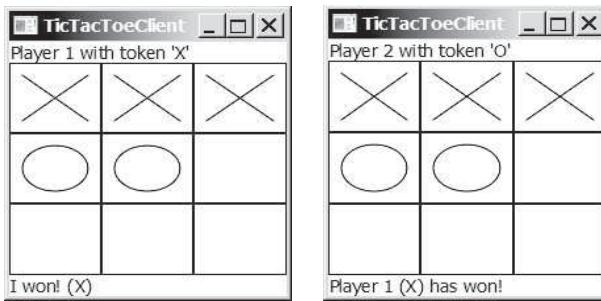
```

mouse clicked handler

The server can serve any number of sessions simultaneously. Each session takes care of two players. The client can be deployed to run as a Java applet. To run a client as a Java applet from a Web browser, the server must run from a Web server. Figures 31.15 and 31.16 show sample runs of the server and the clients.



**FIGURE 31.15** **TicTacToeServer** accepts connection requests and creates sessions to serve pairs of players.



**FIGURE 31.16** **TicTacToeClient** can run as an applet or standalone.

The **TicTacToeConstants** interface defines the constants shared by all the classes in the project. Each class that uses the constants needs to implement the interface. Centrally defining constants in an interface is a common practice in Java.

Once a session is established, the server receives moves from the players in alternation. Upon receiving a move from a player, the server determines the status of the game. If the game is not finished, the server sends the status (**CONTINUE**) and the player's move to

the other player. If the game is won or a draw, the server sends the status (`PLAYER1_WON`, `PLAYER2_WON`, or `DRAW`) to both players.

The implementation of Java network programs at the socket level is tightly synchronized. An operation to send data from one machine requires an operation to receive data from the other machine. As shown in this example, the server and the client are tightly synchronized to send or receive data.



**33.11** What would happen if the preferred size for a cell is not set in line 227 in Listing 31.10?

**33.12** If a player does not have the turn but clicks on an empty cell, what will the client program in Listing 31.10 do?

## KEY TERMS

|                         |                                 |
|-------------------------|---------------------------------|
| client socket 1141      | packet-based communication 1140 |
| domain name 1140        | server socket 1140              |
| domain name server 1140 | socket 1140                     |
| localhost 1141          | stream-based communication 1140 |
| IP address 1140         | TCP 1140                        |
| port 1140               | UDP 1140                        |

## CHAPTER SUMMARY

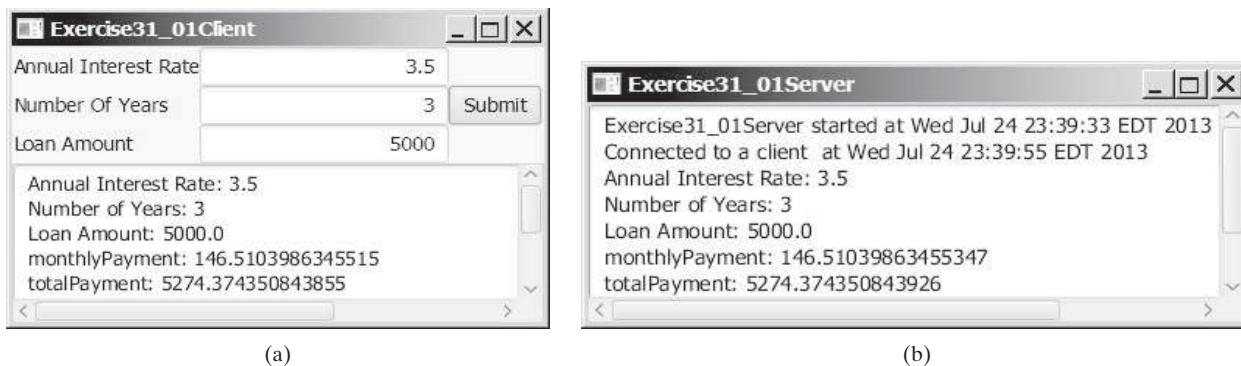
- Java supports stream sockets and datagram sockets. *Stream sockets* use TCP (Transmission Control Protocol) for data transmission, whereas *datagram sockets* use UDP (User Datagram Protocol). Since TCP can detect lost transmissions and resubmit them, transmissions are lossless and reliable. UDP, in contrast, cannot guarantee lossless transmission.
- To create a server, you must first obtain a server socket, using `new ServerSocket(port)`. After a server socket is created, the server can start to listen for connections, using the `accept()` method on the server socket. The client requests a connection to a server by using `new Socket(serverName, port)` to create a client socket.
- Stream socket communication is very much like input/output stream communication after the connection between a server and a client is established. You can obtain an input stream using the `getInputStream()` method and an output stream using the `getOutputStream()` method on the socket.
- A server must often work with multiple clients at the same time. You can use threads to handle the server's multiple clients simultaneously by creating a thread for each connection.

## QUIZ

Answer the quiz for this chapter online at [www.cs.armstrong.edu/liang/intro10e/quiz.html](http://www.cs.armstrong.edu/liang/intro10e/quiz.html).

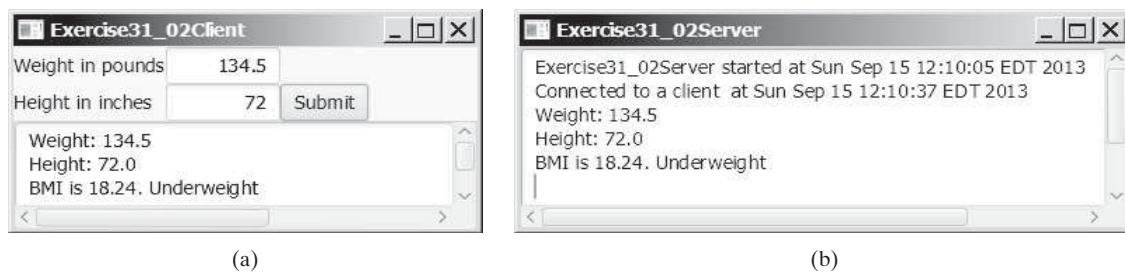
**PROGRAMMING EXERCISES****Section 31.2**

- \*31.1** (*Loan server*) Write a server for a client. The client sends loan information (annual interest rate, number of years, and loan amount) to the server (see Figure 31.17a). The server computes monthly payment and total payment, and sends them back to the client (see Figure 31.17b). Name the client Exercise31\_01Client and the server Exercise31\_01Server.



**FIGURE 31.17** The client in (a) sends the annual interest rate, number of years, and loan amount to the server and receives the monthly payment and total payment from the server in (b).

- \*31.2** (*BMI server*) Write a server for a client. The client sends the weight and height for a person to the server (see Figure 31.18a). The server computes BMI (Body Mass Index) and sends back to the client a string that reports the BMI (see Figure 31.18b). See Section 3.8 for computing BMI. Name the client Exercise31\_02Client and the server Exercise31\_02Server.



**FIGURE 31.18** The client in (a) sends the weight and height of a person to the server and receives the BMI from the server in (b).

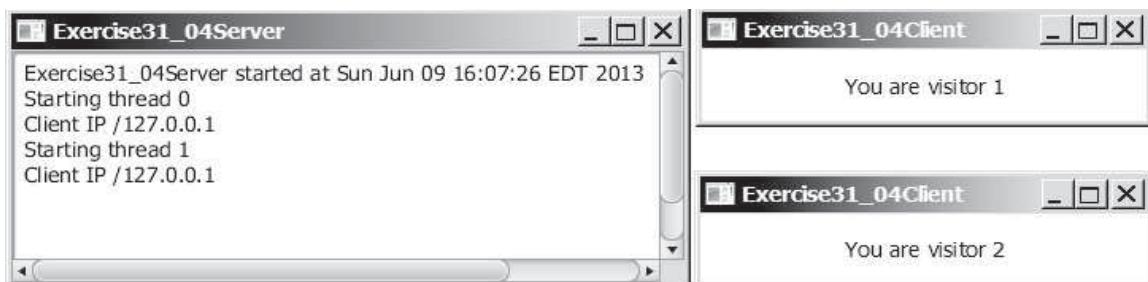
**Sections 31.3 and 31.4**

- \*31.3** (*Loan server for multiple clients*) Revise Programming Exercise 31.1 to write a server for multiple clients.

**Section 31.5**

- 31.4** (*Count clients*) Write a server that tracks the number of the clients connected to the server. When a new connection is established, the count is incremented by 1. The count is stored using a random-access file. Write a client program that

receives the count from the server and display a message, such as You are visitor number 11, as shown in Figure 31.19. Name the client Exercise31\_04Client and the server Exercise31\_04Server.



**FIGURE 31.19** The client displays how many times the server has been accessed. The server stores the count.

- 31.5** (*Send loan information in an object*) Revise Exercise 31.1 for the client to send a loan object that contains annual interest rate, number of years, and loan amount and for the server to send the monthly payment and total payment.

### Section 31.6

- 31.6** (*Display and add addresses*) Develop a client/server application to view and add addresses, as shown in Figure 31.20.



**FIGURE 31.20** You can view and add an address.

- Use the **StudentAddress** class defined in Listing 31.5 to hold the name, street, city, state, and zip in an object.
- The user can use the buttons *First*, *Next*, *Previous*, and *Last* to view an address, and the *Add* button to add a new address.
- Limit the concurrent connections to two clients.

Name the client Exercise31\_06Client and the server Exercise31\_06Server.

- \*31.7** (*Transfer last 100 numbers in an array*) Programming Exercise 22.12 retrieves the last 100 prime numbers from a file **PrimeNumbers.dat**. Write a client program that requests the server to send the last 100 prime numbers in an array. Name the server program Exercise31\_07Server and the client program Exercise31\_07Client. Assume that the numbers of the **Long** type are stored in **PrimeNumbers.dat** in binary format.

- \*31.8** (*Transfer last 100 numbers in an ArrayList*) Programming Exercise 24.12 retrieves the last 100 prime numbers from a file **PrimeNumbers.dat**. Write a client program that requests the server to send the last 100 prime numbers in an **ArrayList**. Name the server program Exercise31\_08Server and the client program Exercise31\_08Client. Assume that the numbers of the **Long** type are stored in **PrimeNumbers.dat** in binary format.

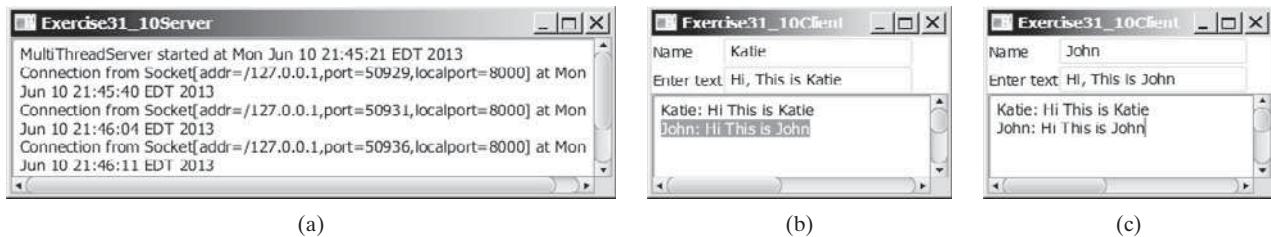
### Section 31.7

- \*\*31.9** (*Chat*) Write a program that enables two users to chat. Implement one user as the server (Figure 31.21a) and the other as the client (Figure 31.21b). The server has two text areas: one for entering text and the other (noneditable) for displaying text received from the client. When the user presses the *Enter* key, the current line is sent to the client. The client has two text areas: one (noneditable) for displaying text from the server and the other for entering text. When the user presses the *Enter* key, the current line is sent to the server. Name the client Exercise31\_09Client and the server Exercise31\_09Server.



**FIGURE 31.21** The server and client send text to and receive text from each other.

- \*\*\*31.10** (*Multiple client chat*) Write a program that enables any number of clients to chat. Implement one server that serves all the clients, as shown in Figure 31.22. Name the client Exercise31\_10Client and the server Exercise31\_10Server.



**FIGURE 31.22** The server starts in (a) with three clients in (b) and (c).

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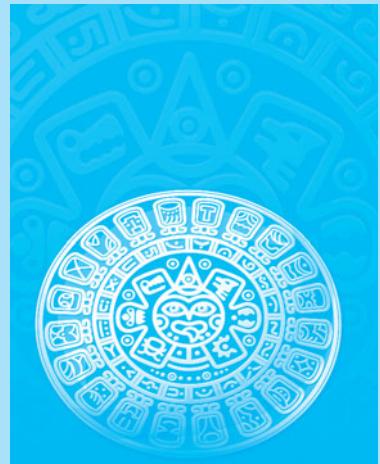
# CHAPTER

# 32

## JAVA DATABASE PROGRAMMING

### Objectives

- To understand the concepts of databases and database management systems (§32.2).
- To understand the relational data model: relational data structures, constraints, and languages (§32.2).
- To use SQL to create and drop tables and to retrieve and modify data (§32.3).
- To learn how to load a driver, connect to a database, execute statements, and process result sets using JDBC (§32.4).
- To use prepared statements to execute precompiled SQL statements (§32.5).
- To use callable statements to execute stored SQL procedures and functions (§32.6).
- To explore database metadata using the **DatabaseMetaData** and **ResultSetMetaData** interfaces (§32.7).



## 32.1 Introduction



*Java provides the API for developing database applications that works with any relational database systems.*

You may have heard a lot about database systems. Database systems are everywhere. Your social security information is stored in a database by the government. If you shop online, your purchase information is stored in a database by the company. If you attend a university, your academic information is stored in a database by the university. Database systems not only store data, they also provide means of accessing, updating, manipulating, and analyzing data. Your social security information is updated periodically, and you can register for courses online. Database systems play an important role in society and in commerce.

This chapter introduces database systems, the SQL language, and how database applications can be developed using Java. If you already know SQL, you can skip Sections 32.2 and 32.3.

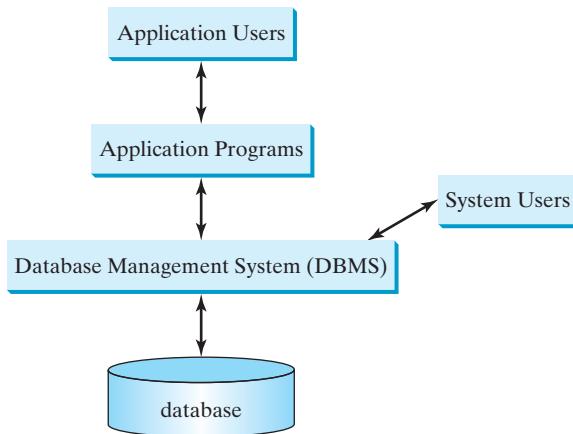
## 32.2 Relational Database Systems



database system

*SQL is the standard database language for defining and accessing databases.*

A *database system* consists of a database, the software that stores and manages data in the database, and the application programs that present data and enable the user to interact with the database system, as shown in Figure 32.1.

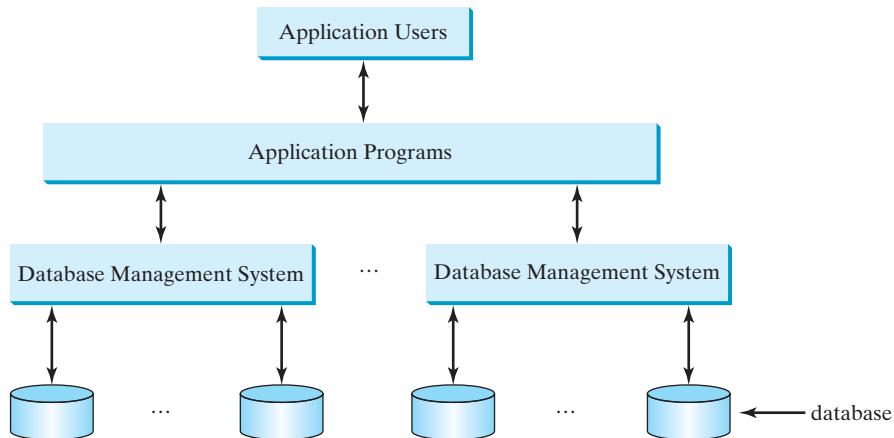


**FIGURE 32.1** A database system consists of data, database management software, and application programs.

DBMS

A *database* is a repository of data that form information. When you purchase a database system—such as MySQL, Oracle, IBM’s DB2 and Informix, Microsoft SQL Server, or Sybase—from a software vendor, you actually purchase the software comprising a *database management system* (DBMS). Database management systems are designed for use by professional programmers and are not suitable for ordinary customers. Application programs are built on top of the DBMS for customers to access and update the database. Thus, application programs can be viewed as the *interfaces* between the database system and its users. Application programs may be stand-alone GUI applications or Web applications and may access several different database systems in the network, as shown in Figure 32.2.

Most of today’s database systems are *relational database systems*. They are based on the relational data model, which has three key components: structure, integrity, and language.



**FIGURE 32.2** An application program can access multiple database systems.

*Structure* defines the representation of the data. *Integrity* imposes constraints on the data. *Language* provides the means for accessing and manipulating data.

### 32.2.1 Relational Structures

The relational model is built around a simple and natural structure. A *relation* is actually a table that consists of nonduplicate rows. Tables are easy to understand and use. The relational model provides a simple yet powerful way to represent data.

A row of a table represents a *record*, and a column of a table represents the *value of a single attribute* of the record. In relational database theory, a row is called a *tuple* and a column is called an *attribute*. Figure 32.3 shows a sample table that stores information about the courses offered by a university. The table has eight tuples, and each tuple has five attributes.

relational model

tuple  
attribute

| Relation/Table Name |              | Columns/Attributes |           |              |                         |              |
|---------------------|--------------|--------------------|-----------|--------------|-------------------------|--------------|
|                     |              | courseId           | subjectId | courseNumber | title                   | numOfCredits |
| Tuples/<br>Rows     | Course Table | 11111              | CSCI      | 1301         | Introduction to Java I  | 4            |
|                     |              | 11112              | CSCI      | 1302         | Introduction to Java II | 3            |
|                     |              | 11113              | CSCI      | 3720         | Database Systems        | 3            |
|                     |              | 11114              | CSCI      | 4750         | Rapid Java Application  | 3            |
|                     |              | 11115              | MATH      | 2750         | Calculus I              | 5            |
|                     |              | 11116              | MATH      | 3750         | Calculus II             | 5            |
|                     |              | 11117              | EDUC      | 1111         | Reading                 | 3            |
|                     |              | 11118              | ITEC      | 1344         | Database Administration | 3            |

**FIGURE 32.3** A table has a table name, column names, and rows.

Tables describe the relationship among data. Each row in a table represents a record of related data. For example, “11111,” “CSCI,” “1301,” “Introduction to Java I,” and “4” are related to form a record (the first row in Figure 32.3) in the **Course** table. Just as the data in the same row are related, so too data in different tables may be related through common attributes. Suppose the database has two other tables, **Student** and **Enrollment**, as shown in

Figures 32.4 and 32.5. The **Course** table and the **Enrollment** table are related through their common attribute **courseId**, and the **Enrollment** table and the **Student** table are related through **ssn**.

| Student Table |           |    |           |            |            |      |                 |         |        |  |
|---------------|-----------|----|-----------|------------|------------|------|-----------------|---------|--------|--|
| ssn           | firstName | mi | lastName  | phone      | birthDate  |      | street          | zipCode | deptID |  |
| 44411110      | Jacob     | R  | Smith     | 9129219434 | 1985-04-09 | 99   | Kingston Street | 31435   | BIOL   |  |
| 44411111      | John      | K  | Stevenson | 9129219434 | null       | 100  | Main Street     | 31411   | BIOL   |  |
| 44411112      | George    | K  | Smith     | 9129213454 | 1974-10-10 | 1200 | Abercorn St.    | 31419   | CS     |  |
| 44411113      | Frank     | E  | Jones     | 9125919434 | 1970-09-09 | 100  | Main Street     | 31411   | BIOL   |  |
| 44411114      | Jean      | K  | Smith     | 9129219434 | 1970-02-09 | 100  | Main Street     | 31411   | CHEM   |  |
| 44411115      | Josh      | R  | Woo       | 7075989434 | 1970-02-09 | 555  | Franklin St.    | 31411   | CHEM   |  |
| 44411116      | Josh      | R  | Smith     | 9129219434 | 1973-02-09 | 100  | Main Street     | 31411   | BIOL   |  |
| 44411117      | Joy       | P  | Kennedy   | 9129229434 | 1974-03-19 | 103  | Bay Street      | 31412   | CS     |  |
| 44411118      | Toni      | R  | Peterson  | 9129229434 | 1964-04-29 | 103  | Bay Street      | 31412   | MATH   |  |
| 44411119      | Patrick   | R  | Stoneman  | 9129229434 | 1969-04-29 | 101  | Washington St.  | 31435   | MATH   |  |
| 44411120      | Rick      | R  | Carter    | 9125919434 | 1986-04-09 | 19   | West Ford St.   | 31411   | BIOL   |  |

FIGURE 32.4 A **Student** table stores student information.

| Enrollment Table |          |                |       |
|------------------|----------|----------------|-------|
| ssn              | courseId | dateRegistered | grade |
| 44411110         | 11111    | 2004-03-19     | A     |
| 44411110         | 11112    | 2004-03-19     | B     |
| 44411110         | 11113    | 2004-03-19     | C     |
| 44411111         | 11111    | 2004-03-19     | D     |
| 44411111         | 11112    | 2004-03-19     | F     |
| 44411111         | 11113    | 2004-03-19     | A     |
| 44411112         | 11114    | 2004-03-19     | B     |
| 44411112         | 11115    | 2004-03-19     | C     |
| 44411112         | 11116    | 2004-03-19     | D     |
| 44411113         | 11111    | 2004-03-19     | A     |
| 44411113         | 11113    | 2004-03-19     | A     |
| 44411114         | 11115    | 2004-03-19     | B     |
| 44411115         | 11115    | 2004-03-19     | F     |
| 44411115         | 11116    | 2004-03-19     | F     |
| 44411116         | 11111    | 2004-03-19     | D     |
| 44411117         | 11111    | 2004-03-19     | D     |
| 44411118         | 11111    | 2004-03-19     | A     |
| 44411118         | 11112    | 2004-03-19     | D     |
| 44411118         | 11113    | 2004-03-19     | B     |

FIGURE 32.5 An **Enrollment** table stores student enrollment information.

### 32.2.2 Integrity Constraints

integrity constraint

An *integrity constraint* imposes a condition that all the legal values in a table must satisfy. Figure 32.6 shows an example of some integrity constraints in the **Subject** and **Course** tables.

In general, there are three types of constraints: domain constraints, primary key constraints, and foreign key constraints. *Domain constraints* and *primary key constraints* are known as *intrarelational constraints* meaning that a constraint involves only one relation. The *foreign key constraint* is *interrelational* meaning that a constraint involves more than one relation.



FIGURE 32.6 The `Enrollment` table and the `Course` table have integrity constraints.

## Domain Constraints

*Domain constraints* specify the permissible values for an attribute. Domains can be specified using standard data types, such as integers, floating-point numbers, fixed-length strings, and variant-length strings. The standard data type specifies a broad range of values. Additional constraints can be specified to narrow the ranges. For example, you can specify that the `numOfCredits` attribute (in the `Course` table) must be greater than 0 and less than 5. You can also specify whether an attribute can be `null`, which is a special value in a database meaning unknown or not applicable. As shown in the `Student` table, `birthDate` may be `null`.

domain constraint

## Primary Key Constraints

To understand *primary keys*, it is helpful to know superkeys, keys, and candidate keys. A *superkey* is an attribute or a set of attributes that uniquely identifies the relation. That is, no two tuples have the same values on a superkey. By definition, a relation consists of a set of distinct tuples. The set of all attributes in the relation forms a superkey.

superkey

A *key* **K** is a minimal superkey, meaning that any proper subset of **K** is not a superkey. A relation can have several keys. In this case, each of the keys is called a *candidate key*. The *primary key* is one of the candidate keys designated by the database designer. The primary key is often used to identify tuples in a relation. As shown in Figure 32.6, `courseId` is the primary key in the `Course` table.

candidate key  
primary key

## Foreign Key Constraints

In a *relational database*, data are related. Tuples in a relation are related, and tuples in different relations are related through their common attributes. Informally speaking, the common attributes are foreign keys. The *foreign key constraints* define the relationships among relations.

relational database

Formally, a set of attributes *FK* is a *foreign key* in a relation *R* that references relation *T* if it satisfies the following two rules:

foreign key constraint

- The attributes in *FK* have the same domain as the primary key in *T*.
- A nonnull value on *FK* in *R* must match a primary key value in *T*.

foreign key

As shown in Figure 32.6, `courseId` is the foreign key in `Enrollment` that references the primary key `courseId` in `Course`. Every `courseId` value must match a `courseId` value in `Course`.

### Enforcing Integrity Constraints

auto enforcement

The database management system enforces integrity constraints and rejects operations that would violate them. For example, if you attempt to insert the new record (“11115,” “CSCI,” “2490,” “C++ Programming,” 0) into the `Course` table, it would fail because the credit hours must be greater than 0; if you attempted to insert a record with the same primary key as an existing record in the table, the DBMS would report an error and reject the operation; if you attempted to delete a record from the `Course` table whose primary key value is referenced by the records in the `Enrollment` table, the DBMS would reject this operation.



#### Note

All relational database systems support primary key constraints and foreign key constraints but not all database systems support domain constraints. In the Microsoft Access database, for example, you cannot specify the constraint that `numOfCredits` is greater than 0 and less than 5.



- 32.1** What are superkeys, candidate keys, and primary keys?
- 32.2** What is a foreign key?
- 32.3** Can a relation have more than one primary key or foreign key?
- 32.4** Does a foreign key need to be a primary key in the same relation?
- 32.5** Does a foreign key need to have the same name as its referenced primary key?
- 32.6** Can a foreign key value be null?

## 32.3 SQL



*Structured Query Language (SQL) is the language for defining tables and integrity constraints, and for accessing and manipulating data.*

SQL

database language

standard SQL

SQL (pronounced “S-Q-L” or “sequel”) is the universal language for accessing relational database systems. Application programs may allow users to access a database without directly using SQL, but these applications themselves must use SQL to access the database. This section introduces some basic SQL commands.



#### Note

There are many relational database management systems. They share the common SQL language but do not all support every feature of SQL. Some systems have their own extensions to SQL. This section introduces standard SQL supported by all systems.

SQL can be used on MySQL, Oracle, Sybase, IBM DB2, IBM Informix, MS Access, or any other relational database system. This chapter uses MySQL to demonstrate SQL and uses MySQL, Oracle, and Access to demonstrate Java database programming. The Companion Website contains the following supplements on how to install and use three popular databases: MySQL, Oracle, and Access:

MySQL Tutorial  
Oracle Tutorial  
Access Tutorial

- Supplement IV.B: Tutorial for MySQL
- Supplement IV.C: Tutorial for Oracle
- Supplement IV.D: Tutorial for Microsoft Access

### 32.3.1 Creating a User Account on MySQL

Assume that you have installed MySQL 5 with the default configuration. To match all the examples in this book, you should create a user named *scott* with the password *tiger*. You can perform the administrative tasks using the MySQL Workbench or using the command line. MySQL Workbench is a GUI tool for managing MySQL databases. Here are the steps to create a user from the command line:

1. From the DOS command prompt, type

```
mysql -uroot -p
```

You will be prompted to enter the root password, as shown in Figure 32.7.

2. At the mysql prompt, enter

```
use mysql;
```

3. To create user **scott** with password **tiger**, enter

```
create user 'scott'@'localhost' identified by 'tiger';
```

4. To grant privileges to **scott**, enter

```
grant select, insert, update, delete, create, create view, drop,
execute, references on *.* to 'scott'@'localhost';
```

- If you want to enable remote access of the account from any IP address, enter

```
grant all privileges on *.* to 'scott'@'%'
identified by 'tiger';
```

- If you want to restrict the account's remote access to just one particular IP address, enter

```
grant all privileges on *.* to 'scott'@'ipAddress'
identified by 'tiger';
```

5. Enter

```
exit;
```

to exit the MySQL console.

```
C:\>mysql -uroot -p
Enter password: *****
Welcome to the MySQL monitor. Commands end with ; or \g.
Your MySQL connection id is 29
Server version: 5.0.37-community-nt MySQL Community Edition (GPL)

Type 'help;' or '\h' for help. Type '\c' to clear the buffer.

mysql> use mysql;
Database changed
mysql> create user 'scott'@'localhost' identified by 'tiger';
Query OK, 0 rows affected (0.02 sec)

mysql> grant select, insert, update, delete, create, create view, drop,
-> execute, references on *.* to 'scott'@'localhost';
Query OK, 0 rows affected (0.00 sec)

mysql> exit;
```

**FIGURE 32.7** You can access a MySQL database server from the command window.

stop mysql  
start mysql

**Note**

On Windows, your MySQL database server starts every time your computer starts. You can stop it by typing the command **net stop mysql** and restart it by typing the command **net start mysql**.

By default, the server contains two databases named **mysql** and **test**. The **mysql** database contains the tables that store information about the server and its users. This database is intended for the server administrator to use. For example, the administrator can use it to create users and grant or revoke user privileges. Since you are the owner of the server installed on your system, you have full access to the **mysql** database. However, you should not create user tables in the **mysql** database. You can use the **test** database to store data or create new databases. You can also create a new database using the command **create database databasename** or delete an existing database using the command **drop database databasename**.

### 32.3.2 Creating a Database

To match the examples in this book, you should create a database named **javabook**. Here are the steps to create it:

1. From the DOS command prompt, type

```
mysql -uscott -ptiger
```

to login to **mysql**, as shown in Figure 32.8.

2. At the **mysql** prompt, enter

```
create database javabook;
```

```
C:\>mysql -uscott -ptiger
Welcome to the MySQL monitor. Commands end with ; or \g.
Your MySQL connection id is 33
Server version: 5.0.37-community-nt MySQL Community Edition (GPL)

Type 'help;' or '\h' for help. Type '\c' to clear the buffer.

mysql> create database javabook;
Query OK, 1 row affected (0.02 sec)

mysql> show databases;
1|
```

**FIGURE 32.8** You can create databases in MySQL.

For your convenience, the SQL statements for creating and initializing tables used in this book are provided in Supplement IV.A. You can download the script for MySQL and save it to **script.sql**. To execute the script, first switch to the **javabook** database using the following command:

```
use javabook;
```

and then type

```
source script.sql;
```

as shown in Figure 32.9.

run script file

```

Administrator: Command Prompt - mysql -uroot -ptiger
Welcome to the MySQL monitor. Commands end with ; or \g.
Your MySQL connection id is 2
Server version: 5.1.35-community MySQL Community Server (GPL)

Type 'help;' or '\h' for help. Type '\c' to clear the current input statement.

mysql> create database javabook;
Query OK, 1 row affected (0.03 sec)

mysql> use javabook;
Database changed
mysql> source script.sql;

```

**FIGURE 32.9** You can run SQL commands in a script file.



### Note

You can populate the javabook database using the script from Supplement IV.A.

populating database

### 32.3.3 Creating and Dropping Tables

Tables are the essential objects in a database. To create a table, use the `create table` statement to specify a table name, attributes, and types, as in the following example:

```

create table Course (
 courseId char(5),
 subjectId char(4) not null,
 courseNumber integer,
 title varchar(50) not null,
 numOfCredits integer,
 primary key (courseId)
);

```

This statement creates the `Course` table with attributes `courseId`, `subjectId`, `courseNumber`, `title`, and `numOfCredits`. Each attribute has a data type that specifies the type of data stored in the attribute. `char(5)` specifies that `courseId` consists of five characters. `varchar(50)` specifies that `title` is a variant-length string with a maximum of 50 characters. `integer` specifies that `courseNumber` is an integer. The primary key is `courseId`.

The tables `Student` and `Enrollment` can be created as follows:

```

create table Student (
 ssn char(9),
 firstName varchar(25),
 mi char(1),
 lastName varchar(25),
 birthDate date,
 street varchar(25),
 phone char(11),
 zipCode char(5),
 deptId char(4),
 primary key (ssn)
);

create table Enrollment (
 ssn char(9),
 courseId char(5),
 dateRegistered date,
 grade char(1),
 primary key (ssn, courseId),
 foreign key (ssn) references
 Student(ssn),
 foreign key (courseId) references
 Course(courseId)
);

```



### Note

SQL keywords are not case sensitive. This book adopts the following naming conventions: tables are named in the same way as Java classes, and attributes are named in the same way as Java variables. SQL keywords are named in the same way as Java keywords.

naming convention

If a table is no longer needed, it can be dropped permanently using the `drop table` command. For example, the following statement drops the `Course` table:

```
drop table
```

If a table to be dropped is referenced by other tables, you have to drop the other tables first. For example, if you have created the tables `Course`, `Student`, and `Enrollment` and want to drop `Course`, you have to first drop `Enrollment`, because `Course` is referenced by `Enrollment`.

Figure 32.10 shows how to enter the `create table` statement from the MySQL console.

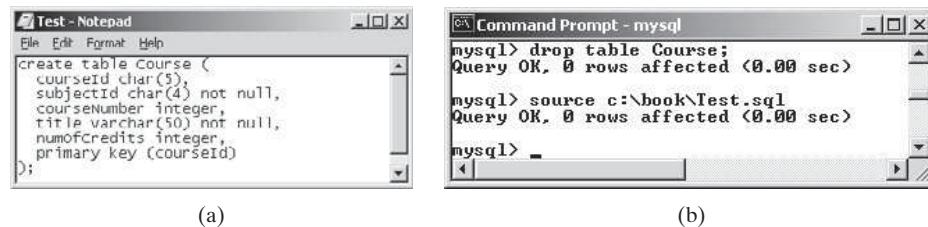
```
mysql> use javabook;
Database changed
mysql> drop table Course;
Query OK, 0 rows affected (0.08 sec)

mysql> create table Course(
-> courseId char(5),
-> subjectId char(4) not null,
-> courseNumber integer,
-> title varchar(50) not null,
-> numOfCredits integer,
-> primary key (courseId)
->);
Query OK, 0 rows affected (0.11 sec)

mysql>
```

**FIGURE 32.10** A table is created using the `create table` statement.

If you make typing errors, you have to retype the whole command. To avoid retyping, you can save the command in a file, and then run the command from the file. To do so, create a text file to contain commands, named, for example, `test.sql`. You can create the text file using any text editor, such as Notepad, as shown in Figure 32.11a. To comment a line, precede it with two dashes. You can now run the script file by typing `source test.sql` from the SQL command prompt, as shown in Figure 32.11b.



**FIGURE 32.11** (a) You can use Notepad to create a text file for SQL commands. (b) You can run the SQL commands in a script file from MySQL.

### 32.3.4 Simple Insert, Update, and Delete

Once a table is created, you can insert data into it. You can also update and delete records. This section introduces simple insert, update, and delete statements.

The syntax to insert a record into a table is:

```
insert into tableName [(column1, column2, ..., column)]
values (value1, value2, ..., valuen);
```

For example, the following statement inserts a record into the `Course` table. The new record has the `courseId` ‘11113’, `subjectId` ‘CSCI’, `courseNumber` ‘3720’, `title` ‘Database Systems’, and `creditHours` 3.

```
insert into Course (courseId, subjectId, courseNumber, title, numOfCredits)
values ('11113', 'CSCI', '3720', 'Database Systems', 3);
```

The column names are optional. If they are omitted, all the column values for the record must be entered, even though the columns have default values. String values are case sensitive and enclosed inside single quotation marks in SQL.

The syntax to update a table is:

```
update tableName
set column1 = newValue1 [, column2 = newValue2, ...]
[where condition];
```

For example, the following statement changes the `numOfCredits` for the course whose `title` is Database Systems to 4.

```
update Course
set numOfCredits = 4
where title = 'Database Systems';
```

The syntax to delete records from a table is:

```
delete from tableName
[where condition];
```

For example, the following statement deletes the Database Systems course from the `Course` table:

```
delete from Course
where title = 'Database Systems';
```

The following statement deletes all the records from the `Course` table:

```
delete from Course;
```

### 32.3.5 Simple Queries

To retrieve information from tables, use a `select` statement with the following syntax:

```
select column-list
from table-list
[where condition];
```

The `select` clause lists the columns to be selected. The `from` clause refers to the tables involved in the query. The optional `where` clause specifies the conditions for the selected rows.

*Query 1:* Select all the students in the CS department, as shown in Figure 32.12.

```
select firstName, mi, lastName
from Student
where deptId = 'CS';
```

The screenshot shows a Windows-style window titled "Command Prompt - mysql". Inside, a SQL query is run:

```
mysql> select firstName, mi, lastName
 -> from Student
 -> where deptId = 'CS';
+-----+---+-----+
| firstName | mi | lastName |
+-----+---+-----+
| George | R | Heintz |
| Jny | P | Kennedy |
+-----+---+-----+
2 rows in set (0.16 sec)
```

At the bottom, the MySQL prompt "mysql>" is visible.

**FIGURE 32.12** The result of the `select` statement is displayed in the MySQL console.

### 32.3.6 Comparison and Boolean Operators

SQL has six comparison operators, as shown in Table 32.1, and three Boolean operators, as shown in Table 32.2.

**TABLE 32.1** Comparison Operators

| Operator | Description              |
|----------|--------------------------|
| =        | Equal to                 |
| <> or != | Not equal to             |
| <        | Less than                |
| <=       | Less than or equal to    |
| >        | Greater than             |
| >=       | Greater than or equal to |

**TABLE 32.2** Boolean Operators

| Operator | Description         |
|----------|---------------------|
| not      | Logical negation    |
| and      | Logical conjunction |
| or       | Logical disjunction |



#### Note

The comparison and Boolean operators in SQL have the same meanings as in Java. In SQL the `equal to` operator is `=`, but in Java it is `==`. In SQL the `not equal to` operator is `<>` or `!=`, but in Java it is `!=`. The `not`, `and`, and `or` operators are `!`, `&&` (`&`), and `||` (`|`) in Java.

**Query 2:** Get the names of the students who are in the CS dept and live in the ZIP code 31411.

```
select firstName, mi, lastName
from Student
where deptId = 'CS' and zipCode = '31411';
```



#### Note

To select all the attributes from a table, you don't have to list all the attribute names in the select clause. Instead, you can just use an asterisk (\*), which stands for all the attributes. For example, the following query displays all the attributes of the students who are in the CS dept and live in ZIP code 31411.

```
select *
from Student
where deptId = 'CS' and zipCode = '31411';
```

### 32.3.7 The `Like`, `between-and`, and `is null` Operators

SQL has a `Like` operator that can be used for pattern matching. The syntax to check whether a string `s` has a pattern `p` is

`s like p` or `s not like p`

You can use the wildcard characters `%` (percent symbol) and `_` (underline symbol) in the pattern `p`. `%` matches zero or more characters, and `_` matches any single character in `s`. For example, `LastName Like '_mi'` matches any string whose second and third letters are `m` and `i`. `LastName not like '_mi%` excludes any string whose second and third letters are `m` and `i`.



#### Note

In earlier versions of MS Access, the wildcard character is `*`, and the character `?` matches any single character.

The `between-and` operator checks whether a value `v` is between two other values, `v1` and `v2`, using the following syntax:

`v between v1 and v2` or `v not between v1 and v2`

`v between v1 and v2` is equivalent to `v >= v1 and v <= v2`, and `v not between v1 and v2` is equivalent to `v < v1 or v > v2`.

The `is null` operator checks whether a value `v` is `null` using the following syntax:

`v is null` or `v is not null`

**Query 3:** Get the Social Security numbers of the students whose grades are between ‘C’ and ‘A’.

```
select ssn
from Enrollment
where grade between 'C' and 'A';
```

### 32.3.8 Column Alias

When a query result is displayed, SQL uses the column names as column headings. Usually the user gives abbreviated names for the columns, and the columns cannot have spaces when the table is created. Sometimes it is desirable to give more descriptive names in the result heading. You can use the column aliases with the following syntax:

`select columnName [as] alias`

**Query 4:** Get the last name and ZIP code of the students in the CS department. Display the column headings as “Last Name” for `lastName` and “Zip Code” for `zipCode`. The query result is shown in Figure 32.13.

```
mysql> select lastName as "Last Name", zipCode as "Zip Code"
-> from Student
-> where deptId = 'CS';
+-----+-----+
| Last Name | Zip Code |
+-----+-----+
| Heintz | 31419 |
| Kennedy | 31412 |
+-----+-----+
2 rows in set (0.00 sec)

mysql>
```

**FIGURE 32.13** You can use a column alias in the display.

```
select lastName as "Last Name", zipCode as "Zip Code"
from Student
where deptId = 'CS';
```

**Note**

The `as` keyword is optional in MySQL and Oracle, but it is required in MS Access.

### 32.3.9 The Arithmetic Operators

You can use the arithmetic operators `*` (multiplication), `/` (division), `+` (addition), and `-` (subtraction) in SQL.

**Query 5:** Assume that a credit hour is 50 minutes of lectures and get the total minutes for each course with the subject CSCI. The query result is shown in Figure 32.14.

```
select title, 50 * numOfCredits as "Lecture Minutes Per Week"
from Course
where subjectId = 'CSCI';
```

| Command Prompt - mysql                                                                                                                                                                                                                                                                                                                 |                          |       |                          |                 |     |                  |     |                  |     |                        |     |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------|-------|--------------------------|-----------------|-----|------------------|-----|------------------|-----|------------------------|-----|
| mysql> select title, 50 * numOfCredits as "Lecture Minutes Per Week"                                                                                                                                                                                                                                                                   |                          |       |                          |                 |     |                  |     |                  |     |                        |     |
| -> from Course                                                                                                                                                                                                                                                                                                                         |                          |       |                          |                 |     |                  |     |                  |     |                        |     |
| -> where subjectId = 'CSCI';                                                                                                                                                                                                                                                                                                           |                          |       |                          |                 |     |                  |     |                  |     |                        |     |
| <table border="1"> <thead> <tr> <th>title</th> <th>Lecture Minutes Per Week</th> </tr> </thead> <tbody> <tr> <td>Intro to Java I</td> <td>200</td> </tr> <tr> <td>Intro to Java II</td> <td>150</td> </tr> <tr> <td>Database Systems</td> <td>150</td> </tr> <tr> <td>Rapid Java Application</td> <td>150</td> </tr> </tbody> </table> |                          | title | Lecture Minutes Per Week | Intro to Java I | 200 | Intro to Java II | 150 | Database Systems | 150 | Rapid Java Application | 150 |
| title                                                                                                                                                                                                                                                                                                                                  | Lecture Minutes Per Week |       |                          |                 |     |                  |     |                  |     |                        |     |
| Intro to Java I                                                                                                                                                                                                                                                                                                                        | 200                      |       |                          |                 |     |                  |     |                  |     |                        |     |
| Intro to Java II                                                                                                                                                                                                                                                                                                                       | 150                      |       |                          |                 |     |                  |     |                  |     |                        |     |
| Database Systems                                                                                                                                                                                                                                                                                                                       | 150                      |       |                          |                 |     |                  |     |                  |     |                        |     |
| Rapid Java Application                                                                                                                                                                                                                                                                                                                 | 150                      |       |                          |                 |     |                  |     |                  |     |                        |     |
| 4 rows in set <0.00 sec>                                                                                                                                                                                                                                                                                                               |                          |       |                          |                 |     |                  |     |                  |     |                        |     |
| mysql>                                                                                                                                                                                                                                                                                                                                 |                          |       |                          |                 |     |                  |     |                  |     |                        |     |

FIGURE 32.14 You can use arithmetic operators in SQL.

### 32.3.10 Displaying Distinct Tuples

SQL provides the `distinct` keyword, which can be used to eliminate duplicate tuples in the result. Figure 32.15a displays all the subject IDs used by the courses, and Figure 32.15b displays all the distinct subject IDs used by the courses using the following statement.

```
select distinct subjectId as "Subject ID"
from Course;
```

| Command Prompt - mysql -uscott -p                                                                                                                                                                                                                                                                    |  |            |      |      |      |      |      |      |      |      |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|------------|------|------|------|------|------|------|------|------|
| mysql> select subjectId as "Subject ID" from Course;                                                                                                                                                                                                                                                 |  |            |      |      |      |      |      |      |      |      |
| <table border="1"> <thead> <tr> <th>Subject ID</th> </tr> </thead> <tbody> <tr> <td>CSCI</td> </tr> <tr> <td>CSCI</td> </tr> <tr> <td>CSCI</td> </tr> <tr> <td>CSCI</td> </tr> <tr> <td>EDUC</td> </tr> <tr> <td>ITEC</td> </tr> <tr> <td>MATH</td> </tr> <tr> <td>MATH</td> </tr> </tbody> </table> |  | Subject ID | CSCI | CSCI | CSCI | CSCI | EDUC | ITEC | MATH | MATH |
| Subject ID                                                                                                                                                                                                                                                                                           |  |            |      |      |      |      |      |      |      |      |
| CSCI                                                                                                                                                                                                                                                                                                 |  |            |      |      |      |      |      |      |      |      |
| CSCI                                                                                                                                                                                                                                                                                                 |  |            |      |      |      |      |      |      |      |      |
| CSCI                                                                                                                                                                                                                                                                                                 |  |            |      |      |      |      |      |      |      |      |
| CSCI                                                                                                                                                                                                                                                                                                 |  |            |      |      |      |      |      |      |      |      |
| EDUC                                                                                                                                                                                                                                                                                                 |  |            |      |      |      |      |      |      |      |      |
| ITEC                                                                                                                                                                                                                                                                                                 |  |            |      |      |      |      |      |      |      |      |
| MATH                                                                                                                                                                                                                                                                                                 |  |            |      |      |      |      |      |      |      |      |
| MATH                                                                                                                                                                                                                                                                                                 |  |            |      |      |      |      |      |      |      |      |
| 8 rows in set <0.00 sec>                                                                                                                                                                                                                                                                             |  |            |      |      |      |      |      |      |      |      |
| mysql>                                                                                                                                                                                                                                                                                               |  |            |      |      |      |      |      |      |      |      |

(a)

| Command Prompt - mysql -uscott -p                                                                                                                                                                |  |            |      |      |      |      |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|------------|------|------|------|------|
| mysql> select distinct subjectId as "Subject ID" from Course;                                                                                                                                    |  |            |      |      |      |      |
| <table border="1"> <thead> <tr> <th>Subject ID</th> </tr> </thead> <tbody> <tr> <td>CSCI</td> </tr> <tr> <td>EDUC</td> </tr> <tr> <td>ITEC</td> </tr> <tr> <td>MATH</td> </tr> </tbody> </table> |  | Subject ID | CSCI | EDUC | ITEC | MATH |
| Subject ID                                                                                                                                                                                       |  |            |      |      |      |      |
| CSCI                                                                                                                                                                                             |  |            |      |      |      |      |
| EDUC                                                                                                                                                                                             |  |            |      |      |      |      |
| ITEC                                                                                                                                                                                             |  |            |      |      |      |      |
| MATH                                                                                                                                                                                             |  |            |      |      |      |      |
| 4 rows in set <0.00 sec>                                                                                                                                                                         |  |            |      |      |      |      |
| mysql>                                                                                                                                                                                           |  |            |      |      |      |      |

(b)

FIGURE 32.15 (a) The duplicate tuples are displayed. (b) The distinct tuples are displayed.

When there is more than one column in the `select` clause, the `distinct` keyword applies to the whole tuple in the result. For example, the following statement displays all tuples with distinct `subjectId` and `title`, as shown in Figure 32.16. Note that some tuples may have the same `subjectId` but different `title`. These tuples are distinct.

```
select distinct subjectId, title
from Course;
```

```
mysql> select distinct subjectId, title from Course;
+-----+-----+
| subjectId | title |
+-----+-----+
| CSCI | Intro to Java I
| CSCI | Intro to Java II
| CSCI | Database Systems
| CSCI | Rapid Java Application
| MATH | Calculus I
| MATH | Calculus II
| EDUC | Reading
| ITEC | Database Administration
+-----+-----+
8 rows in set (0.00 sec)

mysql>
```

FIGURE 32.16 The keyword `distinct` applies to the entire tuple.

### 32.3.11 Displaying Sorted Tuples

SQL provides the `order by` clause to sort the output using the following syntax:

```
select column-list
from table-list
[where condition]
[order by columns-to-be-sorted];
```

In the syntax, `columns-to-be-sorted` specifies a column or a list of columns to be sorted. By default, the order is ascending. To sort in a descending order, append the `desc` keyword. You could also append the `asc` keyword after `columns-to-be-sorted`, but it is not necessary. When multiple columns are specified, the rows are sorted based on the first column, then the rows with the same values on the first column are sorted based on the second column, and so on.

**Query 6:** List the full names of the students in the CS department, ordered primarily on their last names in descending order and secondarily on their first names in ascending order. The query result is shown in Figure 32.17.

```
mysql> select lastName, firstName, deptId
-> from Student
-> where deptId = 'CS'
-> order by lastName desc, firstName asc;
+-----+-----+-----+
| lastName | firstName | deptId |
+-----+-----+-----+
| Kennedy | Joy | CS |
| Heintz | George | CS |
+-----+-----+-----+
2 rows in set (0.02 sec)

mysql>
```

FIGURE 32.17 You can sort results using the `order by` clause.

```
select lastName, firstName, deptId
from Student
where deptId = 'CS'
order by lastName desc, firstName asc;
```

### 32.3.12 Joining Tables

Often you need to get information from multiple tables, as demonstrated in the next query.

**Query 7:** List the courses taken by the student Jacob Smith. To solve this query, you need to join tables **Student** and **Enrollment**, as shown in Figure 32.18.



FIGURE 32.18 **Student** and **Enrollment** are joined on **ssn**.

You can write the query in SQL:

```
select distinct lastName, firstName, courseId
from Student, Enrollment
where Student.ssn = Enrollment.ssn and
lastName = 'Smith' and firstName = 'Jacob';
```

The tables **Student** and **Enrollment** are listed in the **from** clause. The query examines every pair of rows, each made of one item from **Student** and another from **Enrollment** and selects the pairs that satisfy the condition in the **where** clause. The rows in **Student** have the last name, Smith, and the first name, Jacob, and both rows from **Student** and **Enrollment** have the same **ssn** values. For each pair selected, **lastName** and **firstName** from **Student** and **courseId** from **Enrollment** are used to produce the result, as shown in Figure 32.19. **Student** and **Enrollment** have the same attribute **ssn**. To distinguish them in a query, use **Student.ssn** and **Enrollment.ssn**.

A screenshot of a Windows Command Prompt window titled "Command Prompt - mysql". The window displays the following SQL query and its results:

```
mysql> select distinct lastName, firstName, courseId
-> from Student, Enrollment
-> where Student.ssn = Enrollment.ssn and
-> lastName = 'Smith' and firstName = 'Jacob';
+ lastName + firstName + courseId +
| Smith | Jacob | 11111 |
| Smith | Jacob | 11112 |
| Smith | Jacob | 11113 |
+-----+-----+-----+
3 rows in set (0.06 sec)
```

FIGURE 32.19 Query 7 demonstrates queries involving multiple tables.

For more features of SQL, see Supplements IV.H and IV.I.



- 32.7** Create the tables **Course**, **Student**, and **Enrollment** using the **create table** statements in Section 32.3.3, Creating and Dropping Tables. Insert rows into the **Course**, **Student**, and **Enrollment** tables using the data in Figures 32.3–32.5.
- 32.8** List all CSCI courses with at least four credit hours.
- 32.9** List all students whose last names contain the letter *e* two times.
- 32.10** List all students whose birthdays are null.
- 32.11** List all students who take Math courses.
- 32.12** List the number of courses in each subject.
- 32.13** Assume that each credit hour is 50 minutes of lectures. Get the total minutes for the courses that each student takes.



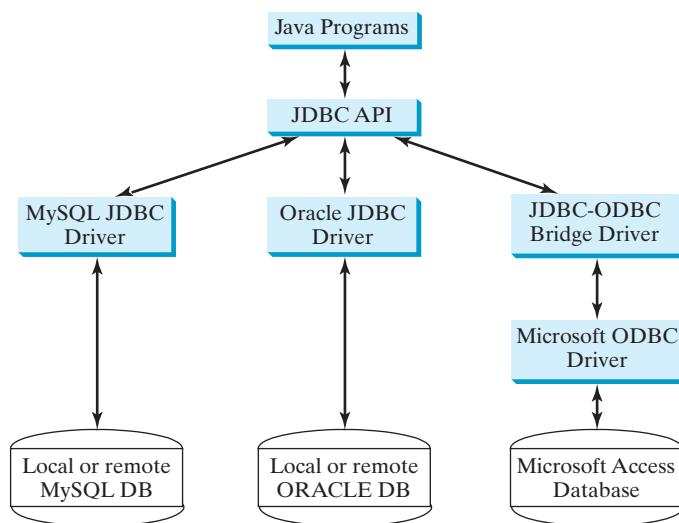
## 32.4 JDBC

*JDBC is the Java API for accessing relational database.*

The Java API for developing Java database applications is called **JDBC**. JDBC is the trademarked name of a Java API that supports Java programs that access relational databases. JDBC is not an acronym, but it is often thought to stand for Java Database Connectivity.

JDBC provides Java programmers with a uniform interface for accessing and manipulating relational databases. Using the JDBC API, applications written in the Java programming language can execute SQL statements, retrieve results, present data in a user-friendly interface, and propagate changes back to the database. The JDBC API can also be used to interact with multiple data sources in a distributed, heterogeneous environment.

The relationships between Java programs, JDBC API, JDBC drivers, and relational databases are shown in Figure 32.20. The JDBC API is a set of Java interfaces and classes used to write Java programs for accessing and manipulating relational databases. Since a JDBC driver serves as the interface to facilitate communications between JDBC and a proprietary database, JDBC drivers are database specific and are normally provided by the database vendors. You need MySQL JDBC drivers to access the MySQL database, and Oracle JDBC drivers



**FIGURE 32.20** Java programs access and manipulate databases through JDBC drivers.

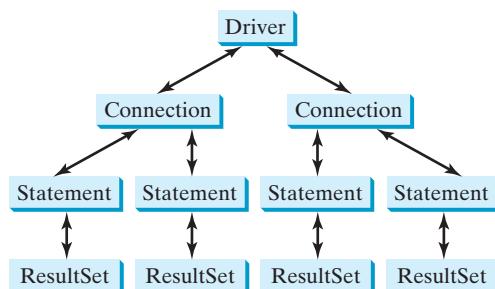
to access the Oracle database. For the Access database, use the JDBC-ODBC bridge driver included in the JDK. ODBC is a technology developed by Microsoft for accessing databases on the Windows platform. An ODBC driver is preinstalled on Windows. The JDBC-ODBC bridge driver allows a Java program to access any ODBC data source.

### 32.4.1 Developing Database Applications Using JDBC

The JDBC API is a Java application program interface to generic SQL databases that enables Java developers to develop DBMS-independent Java applications using a uniform interface.

The JDBC API consists of classes and interfaces for establishing connections with databases, sending SQL statements to databases, processing the results of SQL statements, and obtaining database metadata. Four key interfaces are needed to develop any database application using Java: **Driver**, **Connection**, **Statement**, and **ResultSet**. These interfaces define a framework for generic SQL database access. The JDBC API defines these interfaces, and the JDBC driver vendors provide the implementation for the interfaces. Programmers use these interfaces.

The relationship of these interfaces is shown in Figure 32.21. A JDBC application loads an appropriate driver using the **Driver** interface, connects to the database using the **Connection** interface, creates and executes SQL statements using the **Statement** interface, and processes the result using the **ResultSet** interface if the statements return results. Note that some statements, such as SQL data definition statements and SQL data modification statements, do not return results.



**FIGURE 32.21** JDBC classes enable Java programs to connect to the database, send SQL statements, and process results.

The JDBC interfaces and classes are the building blocks in the development of Java database programs. A typical Java program takes the following steps to access a database.

1. Loading drivers.

An appropriate driver must be loaded using the statement shown below before connecting to a database.

```
Class.forName("JDBC_DRIVER_CLASS");
```

A driver is a concrete class that implements the **java.sql.Driver** interface. The drivers for Access, MySQL, and Oracle are listed in Table 32.3. If your program accesses several different databases, all their respective drivers must be loaded.

The JDBC-ODBC driver for Access is bundled in JDK. The most recent platform independent version of MySQL JDBC driver is **mysql-connector-java-5.1.26.jar**. This file is contained in a ZIP file downloadable from [dev.mysql.com/downloads/connector/j/](http://dev.mysql.com/downloads/connector/j/). The most recent version of Oracle JDBC driver is **ojdbc6.jar** (downloadable from [www.oracle.com/technetwork/database/enterprise-edition/jdbc-112010-090769.html](http://www.oracle.com/technetwork/database/enterprise-edition/jdbc-112010-090769.html)). To use the MySQL and

**TABLE 32.3** JDBC Drivers

| Database | Driver Class                                 | Source                          |
|----------|----------------------------------------------|---------------------------------|
| Access   | <code>sun.jdbc.odbc.JdbcOdbcDriver</code>    | Already in JDK                  |
| MySQL    | <code>com.mysql.jdbc.Driver</code>           | mysql-connector-java-5.1.26.jar |
| Oracle   | <code>oracle.jdbc.driver.OracleDriver</code> | ojdbc6.jar                      |

Oracle drivers, you have to add **mysql-connector-java-5.1.26.jar** and **ojdbc6.jar** in the classpath using the following DOS command on Windows:

```
set classpath=%classpath%;c:\book\lib\mysql-connector-java-5.1.26.jar;
c:\book\lib\ojdbc6.jar
```

If you use an IDE such as Eclipse or NetBeans, you need to add these jar files into the library in the IDE.



### Note

`com.mysql.jdbc.Driver` is a class in **mysql-connector-java-5.1.26.jar**, and `oracle.jdbc.driver.OracleDriver` is a class in **ojdbc6.jar**. **mysql-connector-java-5.1.26.jar**, and **ojdbc6.jar** contains many classes to support the driver. These classes are used by JDBC but not directly by JDBC programmers. When you use a class explicitly in the program, it is automatically loaded by the JVM. The driver classes, however, are not used explicitly in the program, so you have to write the code to tell the JVM to load them.

why load a driver?



### Note

Java 6 supports automatic driver discovery, so you don't have to load the driver explicitly. At the time of this writing, however, this feature is not supported for all database drivers. To be safe, load the driver explicitly.

automatic driver discovery

## 2. Establishing connections.

To connect to a database, use the static method `getConnection(databaseURL)` in the `DriverManager` class, as follows:

```
Connection connection = DriverManager.getConnection(databaseURL);
```

where `databaseURL` is the unique identifier of the database on the Internet. Table 32.4 lists the URL patterns for the Access, MySQL, and Oracle databases.

**TABLE 32.4** JDBC URLs

| Database | URL Pattern                                               |
|----------|-----------------------------------------------------------|
| Access   | <code>jdbc:odbc:dataSource</code>                         |
| MySQL    | <code>jdbc:mysql://hostname/dbname</code>                 |
| Oracle   | <code>jdbc:oracle:thin:@hostname:port#:oracleDBSID</code> |

For an ODBC data source, the `databaseURL` is `jdbc:odbc:dataSource`. An ODBC data source can be created using the ODBC Data Source Administrator on Windows. See Supplement IV.D, Tutorial for Microsoft Access, on how to create an ODBC data source for an Access database.

connect Access DB

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connect MySQL DB

Suppose a data source named ExampleMDBDataSource has been created for an Access database. The following statement creates a **Connection** object:

```
Connection connection = DriverManager.getConnection
 ("jdbc:odbc:ExampleMDBDataSource");
```

The **databaseURL** for a MySQL database specifies the host name and database name to locate a database. For example, the following statement creates a **Connection** object for the local MySQL database **javabook** with username **scott** and password **tiger**:

```
Connection connection = DriverManager.getConnection
 ("jdbc:mysql://localhost/javabook", "scott", "tiger");
```

connect Oracle DB

Recall that by default, MySQL contains two databases named *mysql* and *test*. Section 32.3.2, Creating a Database, created a custom database named **javabook**. We will use **javabook** in the examples.

The **databaseURL** for an Oracle database specifies the *hostname*, the *port#* where the database listens for incoming connection requests, and the *oracleDBSID* database name to locate a database. For example, the following statement creates a **Connection** object for the Oracle database on [liang.armstrong.edu](http://liang.armstrong.edu) with the username **scott** and password **tiger**:

```
Connection connection = DriverManager.getConnection
 ("jdbc:oracle:thin:@liang.armstrong.edu:1521:orcl",
 "scott", "tiger");
```

### 3. Creating statements.

If a **Connection** object can be envisioned as a cable linking your program to a database, an object of **Statement** can be viewed as a cart that delivers SQL statements for execution by the database and brings the result back to the program. Once a **Connection** object is created, you can create statements for executing SQL statements as follows:

```
Statement statement = connection.createStatement();
```

### 4. Executing statements.

SQL data definition language (DDL) and update statements can be executed using **executeUpdate(String sql)**, and an SQL query statement can be executed using **executeQuery(String sql)**. The result of the query is returned in **ResultSet**. For example, the following code executes the SQL statement **create table Temp (col1 char(5), col2 char(5))**:

```
statement.executeUpdate
 ("create table Temp (col1 char(5), col2 char(5))");
```

This next code executes the SQL query **select firstName, mi, lastName from Student where lastName = 'Smith'**:

```
// Select the columns from the Student table
ResultSet resultSet = statement.executeQuery
 ("select firstName, mi, lastName from Student where LastName "
 + " = 'Smith'");
```

### 5. Processing **ResultSet**.

The **ResultSet** maintains a table whose current row can be retrieved. The initial row position is **null**. You can use the **next** method to move to the next row and the various getter methods to retrieve values from a current row. For example, the following code displays all the results from the preceding SQL query.

```
// Iterate through the result and print the student names
while (resultSet.next())
```

```
System.out.println(resultSet.getString(1) + " " +
 resultSet.getString(2) + " " + resultSet.getString(3));
```

The `getString(1)`, `getString(2)`, and `getString(3)` methods retrieve the column values for `firstName`, `mi`, and `lastName`, respectively. Alternatively, you can use `getString("firstName")`, `getString("mi")`, and `getString("lastName")` to retrieve the same three column values. The first execution of the `next()` method sets the current row to the first row in the result set, and subsequent invocations of the `next()` method set the current row to the second row, third row, and so on, to the last row.

Listing 32.1 is a complete example that demonstrates connecting to a database, executing a simple query, and processing the query result with JDBC. The program connects to a local MySQL database and displays the students whose last name is `Smith`.

### LISTING 32.1 SimpleJDBC.java

```

1 import java.sql.*;
2
3 public class SimpleJdbc {
4 public static void main(String[] args)
5 throws SQLException, ClassNotFoundException {
6 // Load the JDBC driver
7 Class.forName("com.mysql.jdbc.Driver");
8 System.out.println("Driver loaded"); load driver
9
10 // Connect to a database
11 Connection connection = DriverManager.getConnection
12 ("jdbc:mysql://localhost/javabook", "scott", "tiger");
13 System.out.println("Database connected"); connect database
14
15 // Create a statement
16 Statement statement = connection.createStatement(); create statement
17
18 // Execute a statement
19 ResultSet resultSet = statement.executeQuery
20 ("select firstName, mi, lastName from Student where lastName "
21 + " = 'Smith'"); execute statement
22
23 // Iterate through the result and print the student names
24 while (resultSet.next()) get result
25 System.out.println(resultSet.getString(1) + "\t" +
26 resultSet.getString(2) + "\t" + resultSet.getString(3));
27
28 // Close the connection
29 connection.close(); close connection
30 }
31 }
```

The statement in line 7 loads a JDBC driver for MySQL, and the statement in lines 11–13 connects to a local MySQL database. You can change them to connect to an Access or Oracle database. The program creates a `Statement` object (line 16), executes an SQL statement and returns a `ResultSet` object (lines 19–21), and retrieves the query result from the `ResultSet` object (lines 24–26). The last statement (line 29) closes the connection and releases resources related to the connection. You can rewrite this program using the try-with-resources syntax. See [www.cs.armstrong.edu/liang/intro10e/html/SimpleJdbcWithAutoClose.html](http://www.cs.armstrong.edu/liang/intro10e/html/SimpleJdbcWithAutoClose.html).



#### Note

If you run this program from the DOS prompt, specify the appropriate driver in the classpath, as shown in Figure 32.22.

run from DOS prompt



**FIGURE 32.22** You must include the driver file to run Java database programs.

The classpath directory and jar files are separated by commas. The period (.) represents the current directory. For convenience, the driver files are placed under the **c:\book\lib** directory.

the semicolon issue



### Caution

Do not use a semicolon (;) to end the Oracle SQL command in a Java program. The semicolon may not work with the Oracle JDBC drivers. It does work, however, with the other drivers used in this book.

auto commit



### Note

The **Connection** interface handles transactions and specifies how they are processed. By default, a new connection is in autocommit mode, and all its SQL statements are executed and committed as individual transactions. The commit occurs when the statement completes or the next execute occurs, whichever comes first. In the case of statements returning a result set, the statement completes when the last row of the result set has been retrieved or the result set has been closed. If a single statement returns multiple results, the commit occurs when all the results have been retrieved. You can use the **setAutoCommit(false)** method to disable autocommit, so that all SQL statements are grouped into one transaction that is terminated by a call to either the **commit()** or the **rollback()** method. The **rollback()** method undoes all the changes made by the transaction.

#### 32.4.2 Accessing a Database from JavaFX

This section gives an example that demonstrates connecting to a database from a JavaFX program. The program lets the user enter the SSN and the course ID to find a student's grade, as shown in Figure 32.23. The code in Listing 32.2 uses the MySQL database on the localhost.



**FIGURE 32.23** A JavaFX client can access the database on the server.

#### LISTING 32.2 FindGrade.java

```

1 import javafx.application.Application;
2 import javafx.scene.Scene;
3 import javafx.scene.control.Button;
4 import javafx.scene.control.Label;
5 import javafx.scene.control.TextField;
6 import javafx.scene.layout.HBox;
7 import javafx.scene.layout.VBox;
8 import javafx.stage.Stage;
9 import java.sql.*;
```

```

10 public class FindGrade extends Application {
11 // Statement for executing queries
12 private Statement stmt;
13 private TextField tfSSN = new TextField();
14 private TextField tfCourseId = new TextField();
15 private Label lblStatus = new Label();
16
17 @Override // Override the start method in the Application class
18 public void start(Stage primaryStage) {
19 // Initialize database connection and create a Statement object
20 initializeDB();
21
22 Button btShowGrade = new Button("Show Grade");
23 HBox hBox = new HBox(5);
24 hBox.getChildren().addAll(new Label("SSN"), tfSSN,
25 new Label("Course ID"), tfCourseId, (btShowGrade));
26
27 VBox vBox = new VBox(10);
28 vBox.getChildren().addAll(hBox, lblStatus);
29
30 tfSSN.setPrefColumnCount(6);
31 tfCourseId.setPrefColumnCount(6);
32 btShowGrade.setOnAction(e -> showGrade()); button listener
33
34 // Create a scene and place it in the stage
35 Scene scene = new Scene(vBox, 420, 80);
36 primaryStage.setTitle("FindGrade"); // Set the stage title
37 primaryStage.setScene(scene); // Place the scene in the stage
38 primaryStage.show(); // Display the stage
39 }
40
41 private void initializeDB() {
42 try {
43 // Load the JDBC driver
44 Class.forName("com.mysql.jdbc.Driver");
45 Class.forName("oracle.jdbc.driver.OracleDriver");
46 System.out.println("Driver loaded"); load driver
47
48 // Establish a connection
49 Connection connection = DriverManager.getConnection
50 ("jdbc:mysql://localhost/javabook", "scott", "tiger");
51 ("jdbc:oracle:thin:@liang.armstrong.edu:1521:orcl",
52 "scott", "tiger");
53 System.out.println("Database connected"); connect to MySQL database
54
55 // Create a statement
56 stmt = connection.createStatement(); connect to Oracle commented
57
58 } catch (Exception ex) {
59 ex.printStackTrace();
60 }
61 }
62
63
64 private void showGrade() { show result
65 String ssn = tfSSN.getText();
66 String courseId = tfCourseId.getText();
67 try {
68 String queryString = "select firstName, mi, " +
69 "lastName, title, grade from Student, Enrollment, Course " + execute statement

```

```

70 "where Student.ssn = '" + ssn + "' and Enrollment.courseId "
71 + "=" + courseId +
72 "' and Enrollment.courseId = Course.courseId " +
73 " and Enrollment.ssn = Student.ssn";
74
75 ResultSet rset = stmt.executeQuery(queryString);
76
77 if (rset.next()) {
78 String lastName = rset.getString(1);
79 String mi = rset.getString(2);
80 String firstName = rset.getString(3);
81 String title = rset.getString(4);
82 String grade = rset.getString(5);
83
84 // Display result in a label
85 lblStatus.setText(firstName + " " + mi +
86 " " + lastName + "'s grade on course " + title + " is " +
87 grade);
88 } else {
89 lblStatus.setText("Not found");
90 }
91 }
92 catch (SQLException ex) {
93 ex.printStackTrace();
94 }
95 }
96 }
```

The `initializeDB()` method (lines 42–62) loads the MySQL driver (line 45), connects to the MySQL database on host `Tiang.armstrong.edu` (lines 50–51) and creates a statement (line 57).

security hole



### Note

There is a *security hole* in this program. If you enter `'1' or true or '1'` in the `SSN` field, you will get the first student's score, because the query string now becomes

```

select firstName, mi, lastName, title, grade
from Student, Enrollment, Course
where Student.ssn = '1' or true or '1' and
 Enrollment.courseId = ' ' and
 Enrollment.courseId = Course.courseId and
 Enrollment.ssn = Student.ssn;
```

You can avoid this problem by using the `PreparedStatement` interface, which is discussed in the next section.



- 32.14** What are the advantages of developing database applications using Java?
- 32.15** Describe the following JDBC interfaces: `Driver`, `Connection`, `Statement`, and `ResultSet`.
- 32.16** How do you load a JDBC driver? What are the driver classes for MySQL, Access, and Oracle?
- 32.17** How do you create a database connection? What are the URLs for MySQL, Access, and Oracle?
- 32.18** How do you create a `Statement` and execute an SQL statement?
- 32.19** How do you retrieve values in a `ResultSet`?
- 32.20** Does JDBC automatically commit a transaction? How do you set autocommit to false?

## 32.5 PreparedStatement

**PreparedStatement** enables you to create parameterized SQL statements.

Once a connection to a particular database is established, it can be used to send SQL statements from your program to the database. The **Statement** interface is used to execute static SQL statements that don't contain any parameters. The **PreparedStatement** interface, extending **Statement**, is used to execute a precompiled SQL statement with or without parameters. Since the SQL statements are precompiled, they are efficient for repeated executions.

A **PreparedStatement** object is created using the **prepareStatement** method in the **Connection** interface. For example, the following code creates a **PreparedStatement** for an SQL **insert** statement:

```
PreparedStatement preparedStatement = connection.prepareStatement
("insert into Student (firstName, mi, lastName) " +
 "values (?, ?, ?);");
```

This **insert** statement has three question marks as placeholders for parameters representing values for **firstName**, **mi**, and **lastName** in a record of the **Student** table.

As a subinterface of **Statement**, the **PreparedStatement** interface inherits all the methods defined in **Statement**. It also provides the methods for setting parameters in the object of **PreparedStatement**. These methods are used to set the values for the parameters before executing statements or procedures. In general, the setter methods have the following name and signature:

```
setX(int parameterIndex, X value);
```

where *X* is the type of the parameter, and **parameterIndex** is the index of the parameter in the statement. The index starts from 1. For example, the method **setString(int parameterIndex, String value)** sets a **String** value to the specified parameter.

The following statements pass the parameters "Jack", "A", and "Ryan" to the placeholders for **firstName**, **mi**, and **lastName** in **preparedStatement**:

```
preparedStatement.setString(1, "Jack");
preparedStatement.setString(2, "A");
preparedStatement.setString(3, "Ryan");
```

After setting the parameters, you can execute the prepared statement by invoking **executeQuery()** for a SELECT statement and **executeUpdate()** for a DDL or update statement.

The **executeQuery()** and **executeUpdate()** methods are similar to the ones defined in the **Statement** interface except that they don't have any parameters, because the SQL statements are already specified in the **prepareStatement** method when the object of **PreparedStatement** is created.

Using a prepared SQL statement, Listing 32.2 can be improved as in Listing 32.3.

### LISTING 32.3 FindGradeUsingPreparedStatement.java

```
1 import javafx.application.Application;
2 import javafx.scene.Scene;
3 import javafx.scene.control.Button;
4 import javafx.scene.control.Label;
5 import javafx.scene.control.TextField;
6 import javafx.scene.layout.HBox;
7 import javafx.scene.layout.VBox;
8 import javafx.stage.Stage;
9 import java.sql.*;
```

10



```

11 public class FindGradeUsingPreparedStatement extends Application {
12 // PreparedStatement for executing queries
13 private PreparedStatement preparedStatement;
14 private TextField tfSSN = new TextField();
15 private TextField tfCourseId = new TextField();
16 private Label lblStatus = new Label();
17
18 @Override // Override the start method in the Application class
19 public void start(Stage primaryStage) {
20 // Initialize database connection and create a Statement object
21 initializeDB();
22
23 Button btShowGrade = new Button("Show Grade");
24 HBox hBox = new HBox(5);
25 hBox.getChildren().addAll(new Label("SSN"), tfSSN,
26 new Label("Course ID"), tfCourseId, (btShowGrade));
27
28 VBox vBox = new VBox(10);
29 vBox.getChildren().addAll(hBox, lblStatus);
30
31 tfSSN.setPrefColumnCount(6);
32 tfCourseId.setPrefColumnCount(6);
33 btShowGrade.setOnAction(e -> showGrade());
34
35 // Create a scene and place it in the stage
36 Scene scene = new Scene(vBox, 420, 80);
37 primaryStage.setTitle("FindGrade"); // Set the stage title
38 primaryStage.setScene(scene); // Place the scene in the stage
39 primaryStage.show(); // Display the stage
40 }
41
42 private void initializeDB() {
43 try {
44 // Load the JDBC driver
45 Class.forName("com.mysql.jdbc.Driver");
46 // Class.forName("oracle.jdbc.driver.OracleDriver");
47 System.out.println("Driver Loaded");
48
49 // Establish a connection
50 Connection connection = DriverManager.getConnection
51 ("jdbc:mysql://localhost/javabook", "scott", "tiger");
52 // ("jdbc:oracle:thin:@liang.armstrong.edu:1521:orcl",
53 // "scott", "tiger");
54 System.out.println("Database connected");
55
56 String queryString = "select firstName, mi, "
57 +"lastName, title, grade from Student, Enrollment, Course "
58 +"where Student.ssn = ? and Enrollment.courseId = ? "
59 +"and Enrollment.courseId = Course.courseId";
60
61 // Create a statement
62 preparedStatement = connection.prepareStatement(queryString);
63 }
64 catch (Exception ex) {
65 ex.printStackTrace();
66 }
67 }
68
69 private void showGrade() {
70 String ssn = tfSSN.getText();

```

load driver

connect database

placeholder

prepare statement

```

71 String courseId = tfCourseId.getText();
72 try {
73 preparedStatement.setString(1, ssn);
74 preparedStatement.setString(2, courseId);
75 ResultSet rset = preparedStatement.executeQuery(); execute statement
76
77 if (rset.next()) {
78 String lastName = rset.getString(1);
79 String mi = rset.getString(2);
80 String firstName = rset.getString(3);
81 String title = rset.getString(4);
82 String grade = rset.getString(5);
83
84 // Display result in a label
85 lblStatus.setText(firstName + " " + mi +
86 " " + lastName + "'s grade on course " + title + " is " +
87 grade); show result
88 } else {
89 lblStatus.setText("Not found");
90 }
91 }
92 catch (SQLException ex) {
93 ex.printStackTrace();
94 }
95 }
96 }
```

This example does exactly the same thing as Listing 32.2 except that it uses the prepared statement to dynamically set the parameters. The code in this example is almost the same as in the preceding example. The new code is highlighted.

A prepared query string is defined in lines 56–59 with `ssn` and `courseId` as parameters. An SQL prepared statement is obtained in line 62. Before executing the query, the actual values of `ssn` and `courseId` are set to the parameters in lines 73–74. Line 75 executes the prepared statement.

**32.21** Describe prepared statements. How do you create instances of `PreparedStatement`? How do you execute a `PreparedStatement`? How do you set parameter values in a `PreparedStatement`?



**32.22** What are the benefits of using prepared statements?

## 32.6 CallableStatement

`CallableStatement` enables you to execute SQL stored procedures.

The `CallableStatement` interface is designed to execute SQL-stored procedures. The procedures may have `IN`, `OUT` or `IN OUT` parameters. An `IN` parameter receives a value passed to the procedure when it is called. An `OUT` parameter returns a value after the procedure is completed, but it doesn't contain any value when the procedure is called. An `IN OUT` parameter contains a value passed to the procedure when it is called and returns a value after it is completed. For example, the following procedure in Oracle PL/SQL has `IN` parameter `p1`, `OUT` parameter `p2`, and `IN OUT` parameter `p3`.



IN parameter

OUT parameter

IN OUT parameter

```

create or replace procedure sampleProcedure
 (p1 in varchar, p2 out number, p3 in out integer) is
begin
 /* do something */
end sampleProcedure;
/
```

**Note**

The syntax of stored procedures is vendor specific. We use both Oracle and MySQL for demonstrations of stored procedures in this book.

A `CallableStatement` object can be created using the `prepareCall(String call)` method in the `Connection` interface. For example, the following code creates a `CallableStatement cstmt` on `Connection connection` for the procedure `sampleProcedure`.

```
CallableStatement callableStatement = connection.prepareCall(
 "{call sampleProcedure(?, ?, ?)}");
```

`{call sampleProcedure(?, ?, ...)}` is referred to as the *SQL escape syntax*, which signals the driver that the code within it should be handled differently. The driver parses the escape syntax and translates it into code that the database understands. In this example, `sampleProcedure` is an Oracle procedure. The call is translated to the string `begin sampleProcedure(?, ?, ?); end` and passed to an Oracle database for execution.

You can call procedures as well as functions. The syntax to create an SQL callable statement for a function is:

```
{? = call functionName(?, ?, ...)}
```

`CallableStatement` inherits `PreparedStatement`. Additionally, the `CallableStatement` interface provides methods for registering the `OUT` parameters and for getting values from the `OUT` parameters.

Before calling an SQL procedure, you need to use appropriate setter methods to pass values to `IN` and `IN OUT` parameters, and use `registerOutParameter` to register `OUT` and `IN OUT` parameters. For example, before calling procedure `sampleProcedure`, the following statements pass values to parameters `p1 (IN)` and `p3 (IN OUT)` and register parameters `p2 (OUT)` and `p3 (IN OUT)`:

```
callableStatement.setString(1, "Dallas"); // Set Dallas to p1
callableStatement.setLong(3, 1); // Set 1 to p3
// Register OUT parameters
callableStatement.registerOutParameter(2, java.sql.Types.DOUBLE);
callableStatement.registerOutParameter(3, java.sql.Types.INTEGER);
```

You can use `execute()` or `executeUpdate()` to execute the procedure depending on the type of SQL statement, then use getter methods to retrieve values from the `OUT` parameters. For example, the next statements retrieve the values from parameters `p2` and `p3`.

```
double d = callableStatement.getDouble(2);
int i = callableStatement.getInt(3);
```

Let us define a MySQL function that returns the number of the records in the table that match the specified `firstName` and `lastName` in the `Student` table.

```
/* For the callable statement example. Use MySQL version 5 */
drop function if exists studentFound;

delimiter //

create function studentFound(first varchar(20), last varchar(20))
 returns int
begin
 declare result int;
 select count(*) into result
```

```

from Student
where Student.firstName = first and
 Student.lastName = last;

 return result;
end;
//

delimiter ;
/* Please note that there is a space between delimiter and ; */

```

If you use an Oracle database, the function can be defined as follows:

```

create or replace function studentFound
(first varchar2, last varchar2)
/* Do not name firstName and lastName. */
return number is
numberOfSelectedRows number := 0;
begin
select count(*) into numberOfSelectedRows
from Student
where Student.firstName = first and
 Student.lastName = last;

 return numberOfSelectedRows;
end studentFound;
/

```

Suppose the function **studentFound** is already created in the database. Listing 32.4 gives an example that tests this function using callable statements.

#### LISTING 32.4 TestCallableStatement.java

```

1 import java.sql.*;
2
3 public class TestCallableStatement {
4 /** Creates new form TestTableEditor */
5 public static void main(String[] args) throws Exception {
6 Class.forName("com.mysql.jdbc.Driver");
7 Connection connection = DriverManager.getConnection(
8 "jdbc:mysql://localhost/javabook",
9 "scott", "tiger");
10 // Connection connection = DriverManager.getConnection(
11 // ("jdbc:oracle:thin:@liang.armstrong.edu:1521:orcl",
12 // "scott", "tiger");
13
14 // Create a callable statement
15 CallableStatement callableStatement = connection.prepareCall(
16 "{? = call studentFound(?, ?)}");
17
18 java.util.Scanner input = new java.util.Scanner(System.in);
19 System.out.print("Enter student's first name: ");
20 String firstName = input.nextLine();
21 System.out.print("Enter student's last name: ");
22 String lastName = input.nextLine();
23
24 callableStatement.setString(2, firstName);
25 callableStatement.setString(3, lastName);
26 callableStatement.registerOutParameter(1, Types.INTEGER);
27 callableStatement.execute();

```

load driver  
connect database

create callable statement

enter fistName

enter lastName

set IN parameter

set IN parameter

register OUT parameter

execute statement

```

28
29 if (callableStatement.getInt(1) >= 1)
30 System.out.println(firstName + " " + lastName +
31 " is in the database");
32 else
33 System.out.println(firstName + " " + lastName +
34 " is not in the database");
35 }
36 }
```



Enter student's first name: Jacob  ↵ Enter  
 Enter student's last name: Smith  ↵ Enter  
 Jacob Smith is in the database



Enter student's first name: John  ↵ Enter  
 Enter student's last name: Smith  ↵ Enter  
 John Smith is not in the database

The program loads a MySQL driver (line 6), connects to a MySQL database (lines 7–9), and creates a callable statement for executing the function **studentFound** (lines 15–16).

The function's first parameter is the return value; its second and third parameters correspond to the first and last names. Before executing the callable statement, the program sets the first name and last name (lines 24–25) and registers the **OUT** parameter (line 26). The statement is executed in line 27.

The function's return value is obtained in line 29. If the value is greater than or equal to 1, the student with the specified first and last name is found in the table.



**32.23** Describe callable statements. How do you create instances of **CallableStatement**? How do you execute a **CallableStatement**? How do you register **OUT** parameters in a **CallableStatement**?



database metadata

## 32.7 Retrieving Metadata

*The database metadata such as database URL, username, JDBC driver name can be obtained using the **DatabaseMetaData** interface and result set metadata such as table column count and column names can be obtained using the **ResultSetMetaData** interface.*

JDBC provides the **DatabaseMetaData** interface for obtaining database-wide information, and the **ResultSetMetaData** interface for obtaining information on a specific **ResultSet**.

### 32.7.1 Database Metadata

The **Connection** interface establishes a connection to a database. It is within the context of a connection that SQL statements are executed and results are returned. A connection also provides access to database metadata information that describes the capabilities of the database, supported SQL grammar, stored procedures, and so on. To obtain an instance of **DatabaseMetaData** for a database, use the **getMetaData** method on a **Connection** object like this:

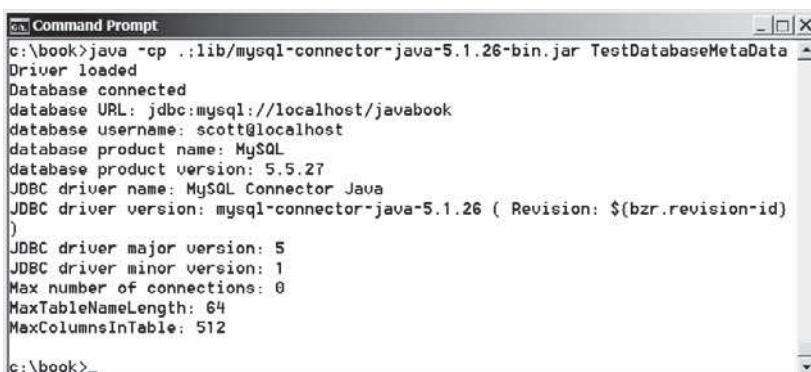
```
DatabaseMetaData dbMetaData = connection.getMetaData();
```

If your program connects to a local MySQL database, the program in Listing 32.5 displays the database information statements shown in Figure 32.24.

**LISTING 32.5** TestDatabaseMetaData.java

```

1 import java.sql.*;
2
3 public class TestDatabaseMetaData {
4 public static void main(String[] args)
5 throws SQLException, ClassNotFoundException {
6 // Load the JDBC driver
7 Class.forName("com.mysql.jdbc.Driver"); load driver
8 System.out.println("Driver loaded");
9
10 // Connect to a database
11 Connection connection = DriverManager.getConnection
12 ("jdbc:mysql://localhost/javabook", "scott", "tiger");
13 System.out.println("Database connected"); connect database
14
15 DatabaseMetaData dbMetaData = connection.getMetaData(); database metadata
16 System.out.println("database URL: " + dbMetaData.getURL()); get metadata
17 System.out.println("database username: " +
18 dbMetaData.getUserName());
19 System.out.println("database product name: " +
20 dbMetaData.getDatabaseProductName());
21 System.out.println("database product version: " +
22 dbMetaData.getDatabaseProductVersion());
23 System.out.println("JDBC driver name: " +
24 dbMetaData.getDriverName());
25 System.out.println("JDBC driver version: " +
26 dbMetaData.getDriverVersion());
27 System.out.println("JDBC driver major version: " +
28 dbMetaData.getDriverMajorVersion());
29 System.out.println("JDBC driver minor version: " +
30 dbMetaData.getDriverMinorVersion());
31 System.out.println("Max number of connections: " +
32 dbMetaData.getMaxConnections());
33 System.out.println("MaxTableNameLength: " +
34 dbMetaData.getMaxTableNameLength());
35 System.out.println("MaxColumnsInTable: " +
36 dbMetaData.getMaxColumnsInTable());
37
38 // Close the connection
39 connection.close();
40 }
41 }
```

**FIGURE 32.24** The **DatabaseMetaData** interface enables you to obtain database information.

### 32.7.2 Obtaining Database Tables

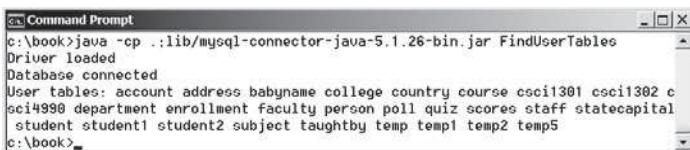
You can identify the tables in the database through database metadata using the `getTables` method. Listing 32.6 displays all the user tables in the javabook database on a local MySQL database. Figure 32.25 shows a sample output of the program.

#### LISTING 32.6 FindUserTables.java

```

1 import java.sql.*;
2
3 public class FindUserTables {
4 public static void main(String[] args)
5 throws SQLException, ClassNotFoundException {
6 // Load the JDBC driver
7 Class.forName("com.mysql.jdbc.Driver");
8 System.out.println("Driver loaded");
9
10 // Connect to a database
11 Connection connection = DriverManager.getConnection
12 ("jdbc:mysql://localhost/javabook", "scott", "tiger");
13 System.out.println("Database connected");
14
15 DatabaseMetaData dbMetaData = connection.getMetaData();
16
17 ResultSet rsTables = dbMetaData.getTables(null, null, null,
18 new String[] {"TABLE"});
19 System.out.print("User tables: ");
20 while (rsTables.next())
21 System.out.print(rsTables.getString("TABLE_NAME") + " ");
22
23 // Close the connection
24 connection.close();
25 }
26}

```



**FIGURE 32.25** You can find all the tables in the database.

Line 17 obtains table information in a result set using the `getTables` method. One of the columns in the result set is `TABLE_NAME`. Line 21 retrieves the table name from this result set column.

### 32.7.3 Result Set Metadata

The `ResultSetMetaData` interface describes information pertaining to the result set. A `ResultSetMetaData` object can be used to find the types and properties of the columns in a `ResultSet`. To obtain an instance of `ResultSetMetaData`, use the `getMetaData` method on a result set like this.

```
ResultSetMetaData rsMetaData = resultSet.getMetaData();
```

You can use the `getColumnName()` method to find the number of columns in the result and the `getColumnName(int)` method to get the column names. For example, Listing 32.7 displays all the column names and contents resulting from the SQL SELECT statement `select * from Enrollment`. The output is shown in Figure 32.26.

### LISTING 32.7 TestResultSetMetaData.java

```

1 import java.sql.*;
2
3 public class TestResultSetMetaData {
4 public static void main(String[] args)
5 throws SQLException, ClassNotFoundException {
6 // Load the JDBC driver
7 Class.forName("com.mysql.jdbc.Driver");
8 System.out.println("Driver loaded");
9
10 // Connect to a database
11 Connection connection = DriverManager.getConnection
12 ("jdbc:mysql://localhost/javabook", "scott", "tiger");
13 System.out.println("Database connected");
14
15 // Create a statement
16 Statement statement = connection.createStatement();
17
18 // Execute a statement
19 ResultSet resultSet = statement.executeQuery
20 ("select * from Enrollment");
21
22 ResultSetMetaData rsMetaData = resultSet.getMetaData();
23 for (int i = 1; i <= rsMetaData.getColumnCount(); i++)
24 System.out.printf("%-12s\t", rsMetaData.getColumnName(i));
25 System.out.println();
26
27 // Iterate through the result and print the students' names
28 while (resultSet.next()) {
29 for (int i = 1; i <= rsMetaData.getColumnCount(); i++)
30 System.out.printf("%-12s\t", resultSet.getObject(i));
31 System.out.println();
32 }
33
34 // Close the connection
35 connection.close();
36 }
37 }
```

The screenshot shows a Windows Command Prompt window titled 'Command Prompt'. The command entered is `c:\book>java -cp .;lib/mysql-connector-java-5.1.26-bin.jar TestResultSetMetaData`. The output displayed is:

```

Driver loaded
Database connected
ssn courseId dateRegistered grade
444111110 11111 2013-04-18 A
444111110 11112 2013-04-18 B

```

**FIGURE 32.26** The `ResultSetMetaData` interface enables you to obtain result set information.



- 32.24** What is **DatabaseMetaData** for? Describe the methods in **DatabaseMetaData**. How do you get an instance of **DatabaseMetaData**?
- 32.25** What is **ResultSetMetaData** for? Describe the methods in **ResultSetMetaData**. How do you get an instance of **ResultSetMetaData**?
- 32.26** How do you find the number of columns in a result set? How do you find the column names in a result set?

## KEY TERMS

---

|                        |      |                                 |      |
|------------------------|------|---------------------------------|------|
| candidate key          | 1177 | integrity constraint            | 1176 |
| database system        | 1174 | primary key                     | 1177 |
| domain constraint      | 1177 | relational database             | 1177 |
| foreign key            | 1177 | Structured Query Language (SQL) | 1178 |
| foreign key constraint | 1177 | superkey                        | 1177 |

## CHAPTER SUMMARY

---

1. This chapter introduced the concepts of *database systems*, *relational databases*, *relational data models*, *data integrity*, and *SQL*. You learned how to develop database applications using Java.
2. The Java API for developing Java database applications is called *JDBC*. JDBC provides Java programmers with a uniform interface for accessing and manipulating relational databases.
3. The JDBC API consists of classes and interfaces for establishing connections with databases, sending SQL statements to databases, processing the results of SQL statements, and obtaining database metadata.
4. Since a JDBC driver serves as the interface to facilitate communications between JDBC and a proprietary database, JDBC drivers are database specific. A JDBC-ODBC bridge driver is included in JDK to support Java programs that access databases through ODBC drivers. If you use a driver other than the JDBC-ODBC bridge driver, make sure it is in the classpath before running the program.
5. Four key interfaces are needed to develop any database application using Java: **Driver**, **Connection**, **Statement**, and **ResultSet**. These interfaces define a framework for generic SQL database access. The JDBC driver vendors provide implementation for them.
6. A JDBC application loads an appropriate driver using the **Driver** interface, connects to the database using the **Connection** interface, creates and executes SQL statements using the **Statement** interface, and processes the result using the **ResultSet** interface if the statements return results.
7. The **PreparedStatement** interface is designed to execute dynamic SQL statements with parameters. These SQL statements are precompiled for efficient use when repeatedly executed.
8. Database *metadata* is information that describes the database itself. JDBC provides the **DatabaseMetaData** interface for obtaining database-wide information and the **ResultSetMetaData** interface for obtaining information on the specific **ResultSet**.

## Quiz

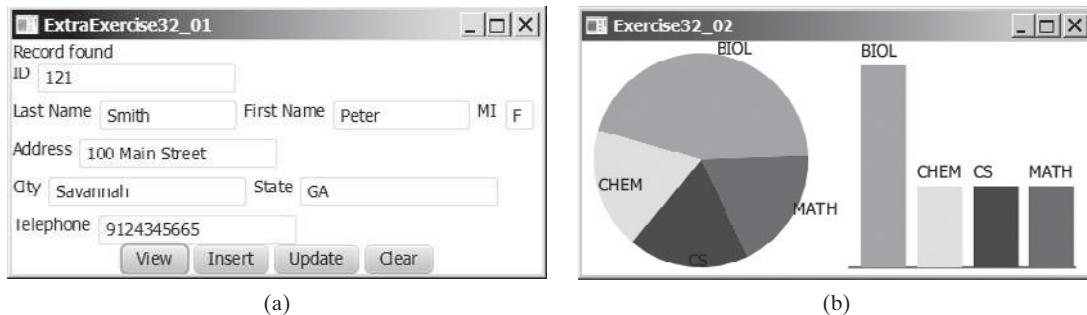
Answer the quiz for this chapter online at [www.cs.armstrong.edu/liang/intro10e/quiz.html](http://www.cs.armstrong.edu/liang/intro10e/quiz.html).

## PROGRAMMING EXERCISES

MyProgrammingLab™

- \*32.1** (Access and update a **Staff** table) Write a program that views, inserts, and updates staff information stored in a database, as shown in Figure 32.27a. The *View* button displays a record with a specified ID. The *Insert* button inserts a new record. The *Update* button updates the record for the specified ID. The **Staff** table is created as follows:

```
create table Staff (
 id char(9) not null,
 lastName varchar(15),
 firstName varchar(15),
 mi char(1),
 address varchar(20),
 city varchar(20),
 state char(2),
 telephone char(10),
 email varchar(40),
 primary key (id)
);
```

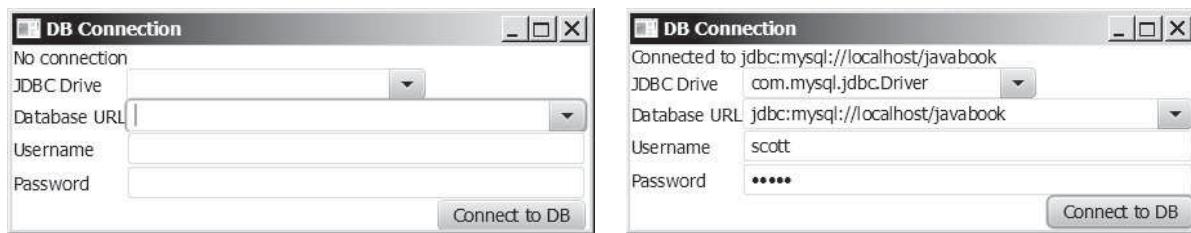


**FIGURE 32.27** (a) The program lets you view, insert, and update staff information. (b) The **PieChart** and **BarChart** components display the query data obtained from the data module.

- \*\*32.2** (Visualize data) Write a program that displays the number of students in each department in a pie chart and a bar chart, as shown in Figure 32.27b. The number of students for each department can be obtained from the **Student** table (see Figure 32.4) using the following SQL statement:

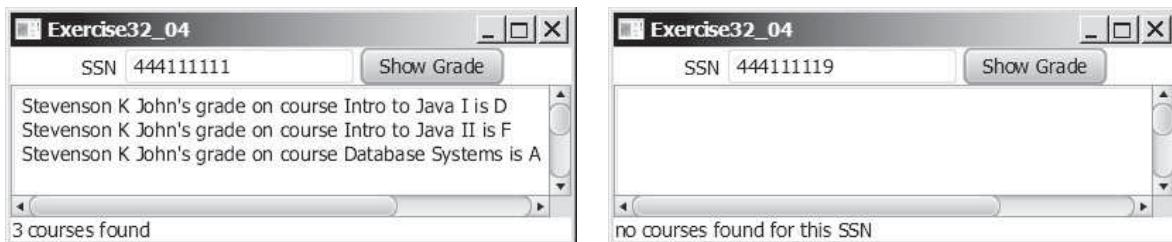
```
select deptId, count(*)
from Student
where deptId is not null
group by deptId;
```

- \*32.3** (Connection dialog) Develop a subclass of **BorderPane** named **DBConnectionPane** that enables the user to select or enter a JDBC driver and a URL and to enter a username and password, as shown in Figure 32.28. When the *Connect to DB* button is clicked, a **Connection** object for the database is stored in the **connection** property. You can then use the **getConnection()** method to return the connection.



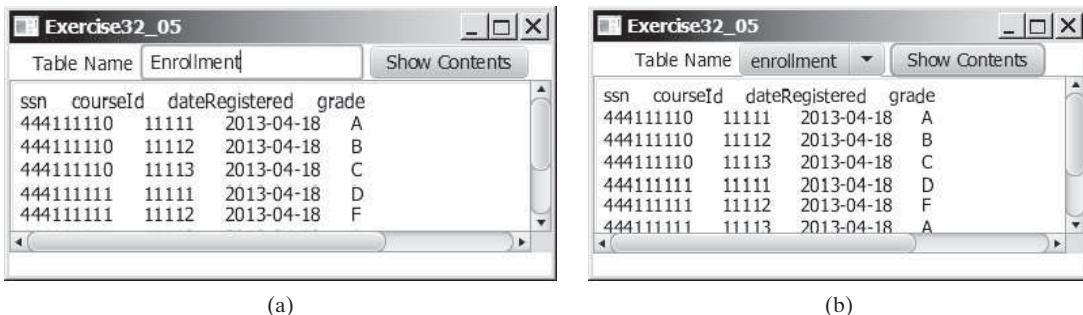
**FIGURE 32.28** The **DBConnectionPane** component enables the user to enter database information.

**\*32.4** (*Find grades*) Listing 32.2, *FindGrade.java*, presented a program that finds a student's grade for a specified course. Rewrite the program to find all the grades for a specified student, as shown in Figure 32.29.



**FIGURE 32.29** The program displays the grades for the courses for a specified student.

**\*32.5** (*Display table contents*) Write a program that displays the content for a given table. As shown in Figure 32.30a, you enter a table and click the *Show Contents* button to display the table contents in the text area.



**FIGURE 32.30** (a) Enter a table name to display the table contents. (b) Select a table name from the combo box to display its contents.

**\*32.6** (*Find tables and showing their contents*) Write a program that fills in table names in a combo box, as shown in Figure 32.30b. You can select a table from the combo box to display its contents in the text area.

**\*\*32.7** (*Populate Quiz table*) Create a table named **Quiz** as follows:

```
create table Quiz(
 questionId int,
 question varchar(4000),
 choicea varchar(1000),
```

```
choiceb varchar(1000),
choiced varchar(1000),
choiced varchar(1000),
answer varchar(5));
```

The **Quiz** table stores multiple-choice questions. Suppose the multiple-choice questions are stored in a text file accessible from [www.cs.armstrong.edu/liang/data/Quiz.txt](http://www.cs.armstrong.edu/liang/data/Quiz.txt) in the following format:

1. question1

- a. choice a
- b. choice b
- c. choice c
- d. choice d

Answer:cd

2. question2

- a. choice a
- b. choice b
- c. choice c
- d. choice d

Answer:a

...

Write a program that reads the data from the file and populate it into the **Quiz** table.

**\*32.8** (*Populate Salary table*) Create a table named **Salary** as follows:

```
create table Salary(
 firstName varchar(100),
 lastName varchar(100),
 rank varchar(15),
 salary float);
```

Obtain the data for salary from <http://cs.armstrong.edu/liang/data/Salary.txt> and populate it into the **Salary** table in the database.

**\*32.9** (*Copy table*) Suppose the database contains a student table defined as follows:

```
create table Student1 (
 username varchar(50) not null,
 password varchar(50) not null,
 fullname varchar(200) not null,
 constraint pkStudent primary key (username)
);
```

Create a new table named **Student2** as follows:

```
create table Student2 (
 username varchar(50) not null,
 password varchar(50) not null,
 firstname varchar(100),
 lastname varchar(100),
 constraint pkStudent primary key (username)
);
```

A full name is in the form of **firstname mi lastname** or **firstname lastname**. For example, **John K Smith** is a full name. Write a program that

copies table **Student1** into **Student2**. Your task is to split a full name into **firstname**, **mi**, and **lastname** for each record in **Student1** and store a new record into **Student2**.

- \*32.10** (*Record unsubmitted exercises*) The following three tables store information on students, assigned exercises, and exercise submission in LiveLab. LiveLab is an automatic grading system for grading programming exercises.

```
create table AGSStudent (
 username varchar(50) not null,
 password varchar(50) not null,
 fullname varchar(200) not null,
 instructorEmail varchar(100) not null,
 constraint pkAGSStudent primary key (username)
);

create table ExerciseAssigned (
 instructorEmail varchar(100),
 exerciseName varchar(100),
 maxscore double default 10,
 constraint pkCustomExercise primary key
 (instructorEmail, exerciseName)
);

create table AGSLog (
 username varchar(50), /* This is the student's user name */
 exerciseName varchar(100), /* This is the exercise */
 score double default null,
 submitted bit default 0,
 constraint pkLog primary key (username, exerciseName)
);
```

The **AGSStudent** table stores the student information. The **ExerciseAssigned** table assigns the exercises by an instructor. The **AGSLog** table stores the grading results. When a student submits an exercise, a record is stored in the **AGSLog** table. However, there is no record in **AGSLog** if a student did not submit the exercise.

Write a program that adds a new record for each student and an assigned exercise to the student in the **AGSLog** table if a student has not submitted the exercise. The record should have 0 on **score** and **submitted**. For example, if the tables contain the following data in **AGSLog** before you run this program, the **AGSLog** table now contains the new records after the program runs.

**AGSStudent**

| username | password | fullname | instructorEmail |
|----------|----------|----------|-----------------|
| abc      | p1       | John Roo | t@gmail.com     |
| cde      | p2       | Yao Mi   | c@gmail.com     |
| wbc      | p3       | F3       | t@gmail.com     |

**ExerciseAssigned**

| instructorEmail | exerciseName | maxScore |
|-----------------|--------------|----------|
| t@gmail.com     | e1           | 10       |
| t@gmail.com     | e2           | 10       |
| c@gmail.com     | e1           | 4        |
| c@gmail.com     | e4           | 20       |

**AGSLog**

| username | exerciseName | score | submitted |
|----------|--------------|-------|-----------|
| abc      | e1           | 9     | 1         |
| wbc      | e2           | 7     | 1         |

**AGSLog after the program runs**

| username | exerciseName | score | submitted |
|----------|--------------|-------|-----------|
| abc      | e1           | 9     | 1         |
| wbc      | e2           | 7     | 1         |
| abc      | e2           | 0     | 0         |
| wbc      | e1           | 0     | 0         |
| cde      | e1           | 0     | 0         |
| cde      | e4           | 0     | 0         |

\*32.11 (*Baby names*) Create the following table:

```
create table Babyname (
 year integer,
 name varchar(50),
 gender char(1),
 count integer,
 constraint pkBabyname primary key (year, name, gender)
);
```

The baby name ranking data was described in Programming Exercise 12.31. Write a program to read data from the following URL and store into the **Babyname** table.

<http://www.cs.armstrong.edu/liang/data/babynamesranking2001.txt>,

...

<http://www.cs.armstrong.edu/liang/data/babynamesranking2010.txt>.

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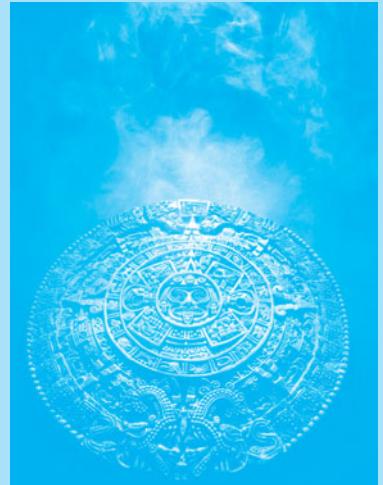
# CHAPTER

# 33

## JAVASERVER FACES

### Objectives

- To explain what JSF is (§33.1).
- To create a JSF project in NetBeans (§33.2.1).
- To create a JSF page (§33.2.2).
- To create a JSF managed bean (§33.2.3).
- To use JSF expressions in a facelet (§33.2.4).
- To use JSF GUI components (§33.3).
- To obtain and process input from a form (§33.4).
- To develop a calculator using JSF (§33.5).
- To track sessions in application, session, view, and request scopes (§33.6).
- To validate input using the JSF validators (§33.7).
- To bind database with facelets (§33.8).
- To open a new JSF page from the current page (§33.9).



## 33.1 Introduction



*JavaServer Faces (JSF) is a new technology for developing server-side Web applications using Java.*

JSF

JSF enables you to completely separate Java code from HTML. You can quickly build Web applications by assembling reusable UI components in a page, connecting these components to Java programs and wiring client-generated events to server-side event handlers. The application developed using JSF is easy to debug and maintain.

JSF 2.2  
XHTML  
CSS

NetBeans 7.4  
GlassFish 4  
J2EE 7



### Note

This chapter introduces JSF 2.2, the latest standard for JavaServer Faces. You need to know XHTML (eXtensible HyperText Markup Language) and CSS (Cascading Style Sheet) to start this chapter. For information on XHTML and CSS, see Supplements V.A and V.B on the Companion Website.



### Caution

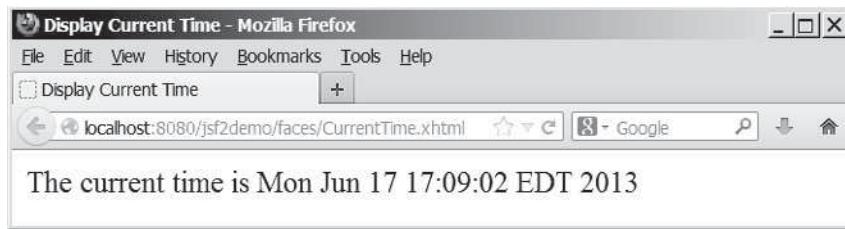
The examples and exercises in this chapter were tested using NetBeans 7.4, GlassFish 4, JSF2.2, and J2EE 7. You need to use NetBeans 7.4 or a higher version with GlassFish 4, JSF 2.2, and J2EE to develop your JSF projects.

## 33.2 Getting Started with JSF



*NetBeans is an effective tool for developing JSF applications.*

We begin with a simple example that illustrates the basics of developing JSF projects using NetBeans. The example is to display the date and time on the server, as shown in Figure 33.1.



**FIGURE 33.1** The application displays the date and time on the server.

### 33.2.1 Creating a JSF Project

Here are the steps to create the application.

create a project

Step 1: Choose **File, New Project** to display the New Project dialog box. In this box, choose *Java Web* in the Categories pane and *Web Application* in the Projects pane. Click **Next** to display the New Web Application dialog box.

choose server and J2EE 7

In the New Web Application dialog box, enter and select the following fields, as shown in Figure 33.2a:

Project Name: **jsf2demo**  
Project Location: **c:\book**

Step 2: Click **Next** to display the dialog box for choosing servers and settings. Select the following fields as shown in Figure 33.2b. (Note: You can use any server such as GlassFish 4.x that supports Java EE 7.)

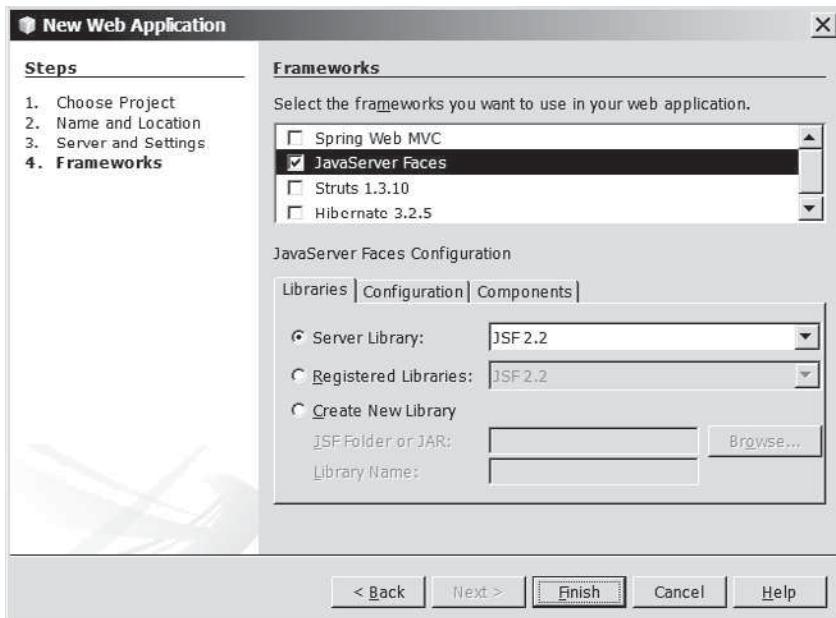
Server: **GlassFish 4**  
Java EE Version: **Java EE 7 Web**

Step 3: Click *Next* to display the dialog box for choosing frameworks, as shown in Figure 33.3. Check *JavaServer Faces* and JSF 2.2 as Server Library. Click *Finish* to create the project, as shown in Figure 33.4.

choose JavaServer Faces  
and JSF 2.2



**FIGURE 33.2** The New Web Application dialog box enables you to create a new Web project.



**FIGURE 33.3** Check JavaServer Faces and JSF 2.2 to create a Web project.

### 33.2.2 A Basic JSF Page

A new project was just created with a default page named *index.xhtml*, as shown in Figure 33.4. This page is known as a *facelet*, which mixes JSF tags with XHTML tags. Listing 33.1 lists the contents of *index.xhtml*.

#### LISTING 33.1 index.xhtml

```

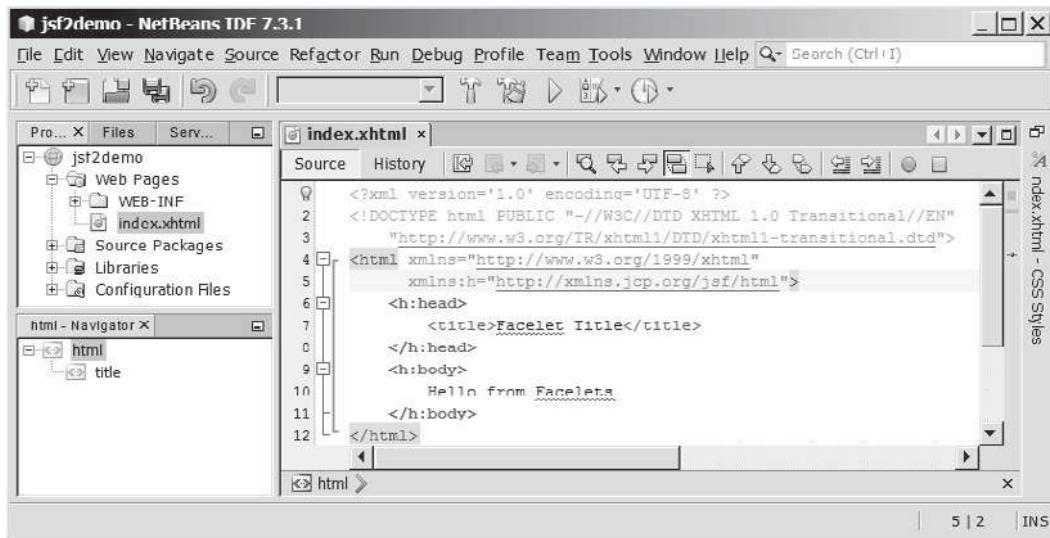
1 <?xml version='1.0' encoding='UTF-8' ?>
2 <!-- index.xhtml -->
3 <!DOCTYPE html PUBLIC "-//W3C//DTD XHTML 1.0 Transitional//EN"
4 "http://www.w3.org/TR/xhtml1/DTD/xhtml1-transitional.dtd">
5 <html xmlns="http://www.w3.org/1999/xhtml">
```

xml version

comment

DOCTYPE

default namespace



**FIGURE 33.4** A default JSF page is created in a new Web project.

|                 |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |
|-----------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| JSF namespace   | 6            xmlns:h="http://xmlns.jcp.org/jsf/html">                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
| h:head          | 7            <h:head>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
|                 | 8            <title>Facelet Title</title>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
|                 | 9            </h:head>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
| h:body          | 10          <h:body>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
|                 | 11          Hello from Facelets                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |
|                 | 12          </h:body>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
|                 | 13          </html>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
| XML declaration | Line 1 is an XML declaration to state that the document conforms to the XML version 1.0 and uses the UTF-8 encoding. The declaration is optional, but it is a good practice to use it. A document without the declaration may be assumed of a different version, which may lead to errors. If an XML declaration is present, it must be the first item to appear in the document. This is because an XML processor looks for the first line to obtain information about the document so that it can be processed correctly.                                                                                               |
| XML comment     | Line 2 is a comment for documenting the contents in the file. XML comment always begins with <code>&lt;!--</code> and ends with <code>--&gt;</code> .                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
| DOCTYPE         | Lines 3 and 4 specify the version of XHTML used in the document. This can be used by the Web browser to validate the syntax of the document.                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |
| element         | An XML document consists of elements described by tags. An element is enclosed between a start tag and an end tag. XML elements are organized in a tree-like hierarchy. Elements may contain subelements, but there is only one root element in an XML document. All the elements must be enclosed inside the root tag. The root element in XHTML is defined using the <code>html</code> tag (line 5).                                                                                                                                                                                                                    |
| tag             | Each tag in XML must be used in a pair of the start tag and the end tag. A start tag begins with <code>&lt;</code> followed by the tag name and ends with <code>&gt;</code> . An end tag is the same as its start tag except that it begins with <code>&lt;/</code> . The start tag and end tag for <code>html</code> are <code>&lt;html&gt;</code> and <code>&lt;/html&gt;</code> .                                                                                                                                                                                                                                      |
| html tag        | The <code>html</code> element is the root element that contains all other elements in an XHTML page. The starting <code>&lt;html&gt;</code> tag (lines 5 and 6) may contain one or more <code>xmlns</code> (XML namespace) attributes to specify the namespace for the elements used in the document. Namespaces are like Java packages. Java packages are used to organize classes and to avoid naming conflict. XHTML namespaces are used to organize tags and resolve naming conflict. If an element with the same name is defined in two namespaces, the fully qualified tag names can be used to differentiate them. |

Each `xmlns` attribute has a name and a value separated by an equal sign (=). The following `xmlns` declaration (line 5)

```
xmlns="http://www.w3.org/1999/xhtml"
```

specifies that any unqualified tag names are defined in the default standard XHTML namespace.

The following declaration (line 6)

```
xmlns:h="http://xmlns.jcp.org/jsf/html"
```

allows the tags defined in the JSF tag library to be used in the document. These tags must have a prefix `h`.

An `html` element contains a head and a body. The `h:head` element (lines 7–9) defines an `h:head` HTML `title` element. The title is usually displayed in the browser window's title bar.

A `h:body` element defines the page's content. In this simple example, it contains a string `h:body` to be displayed in the Web browser.



### Note

The XML tag names are case sensitive, whereas HTML tags are not. So, `<html>` is different from `<HTML>` in XML. Every start tag in XML must have a matching end tag, whereas some tags in HTML do not need end tags.

You can now display the page in `index.xhtml` by right-clicking on `index.xhtml` in the projects pane and choose *Run File*. The page is displayed in a browser, as shown in Figure 33.5.

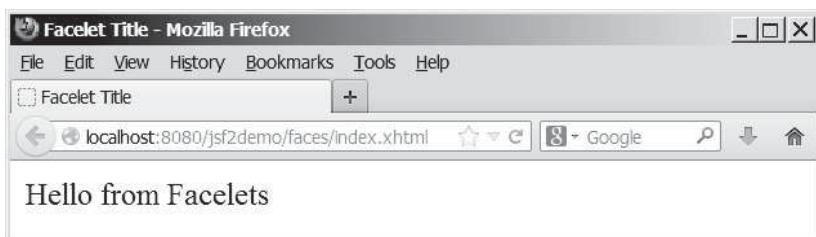


FIGURE 33.5 The `index.xhtml` is displayed in the browser.

### 33.2.3 Managed JavaBeans for JSF

JSF applications are developed using the Model-View-Controller (MVC) architecture, which separates the application's data (contained in the model) from the graphical presentation (the view). The controller is the JSF framework that is responsible for coordinating interactions between view and the model.

In JSF, the facelets are the view for presenting data. Data are obtained from Java objects. Objects are defined using Java classes. In JSF, the objects that are accessed from a facelet are JavaBeans objects. A `JavaBean` class is simply a public Java class with a no-arg constructor. JavaBeans may contain properties. By convention, a property is defined with a getter and a setter method. If a property only has a getter method, the property is called a read-only property. If a property only has a setter method, the property is called a write-only property. A property does not need to be defined as a data field in the class.

Our example in this section is to develop a JSF facelet to display current time. We will create a JavaBean with a `getTime()` method that returns the current time as a string. The facelet will invoke this method to obtain current time.

Here are the steps to create a JavaBean named `TimeBean`.

JavaBean

Step 1. Right-click the project node jsf2demo to display a context menu as shown in Figure 33.6. Choose *New, JSF Managed Bean* to display the New JSF Managed Bean dialog box, as shown in Figure 33.7. (Note: if you don't see JSF Managed Bean in the menu, choose *Other* to locate it in the JavaServer Faces category.)

Step 2. Enter and select the following fields, as shown in Figure 33.7:

Class Name: **TimeBean**

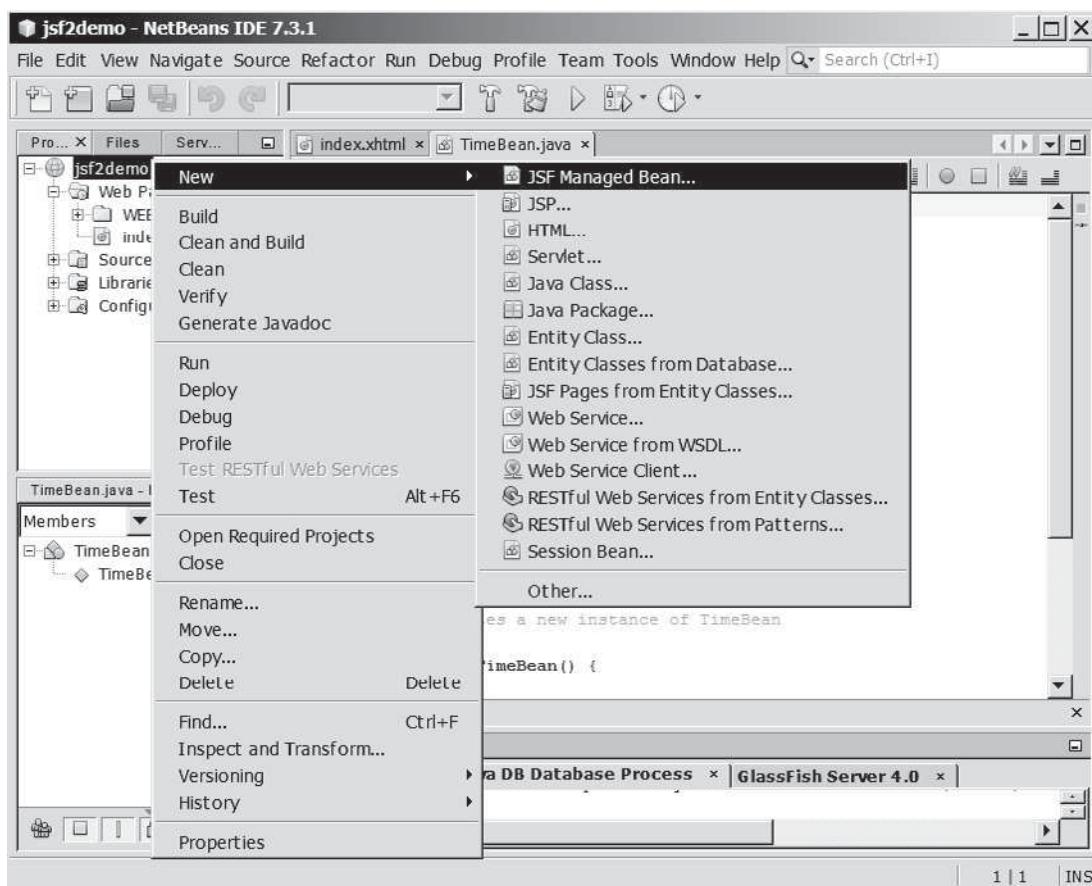
Package: **jsf2demo**

Name: **timeBean**

Scope: **request**

Click *Finish* to create TimeBean.java, as shown in Figure 33.8.

Step 3. Add the **getTime()** method to return the current time, as shown in Listing 33.2.



**FIGURE 33.6** Choose JSF Managed Bean to create a JavaBean for JSF.

### LISTING 33.2 TimeBean.java

```

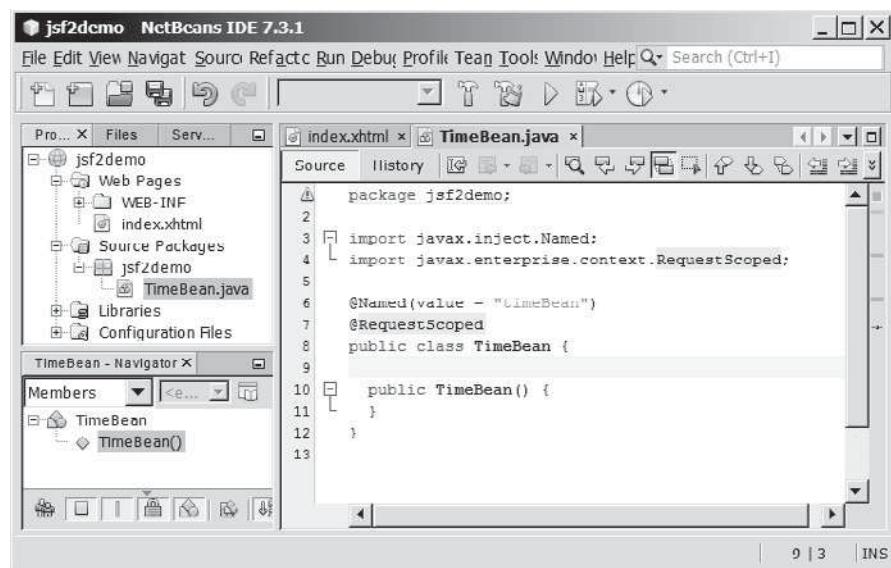
1 package jsf2demo;
2
3 import javax.inject.Named;
4 import javax.enterprise.context.RequestScoped;
5
6 @Named
7 @RequestScoped
8 public class TimeBean {

```

@Named  
@RequestScoped



**FIGURE 33.7** Specify the name, location, scope for the bean.



**FIGURE 33.8** A JavaBean for JSF was created.

```

9 public TimeBean() {
10 }
11
12 public String getTime() {
13 return new java.util.Date().toString();
14 }
15 }
```

time property

@RequestScope

**TimeBean** is a JavaBeans with the **@Named** annotation, which indicates that the JSF framework will create and manage the **TimeBean** objects used in the application. You have learned to use the **@Override** annotation in Chapter 11. The **@Override** annotation tells the compiler that the annotated method is required to override a method in a superclass. The **@Named** annotation tells the compiler to generate the code to enable the bean to be used by JSF facelets.

The **@RequestScope** annotation specifies that the scope of the JavaBeans object is within a request. You can also use **@ViewScope**, **@SessionScope** or **@ApplicationScope** to specify the scope for a session or for the entire application.

### 33.2.4 JSF Expressions

We demonstrate JSF expressions by writing a simple application that displays the current time. You can display current time by invoking the **getTime()** method in a **TimeBean** object using a JSF expression.

To keep index.xhtml intact, we create a new JSF page named CurrentTime.xhtml as follows:

Step 1. Right-click the **jsf2demo** node in the project pane to display a context menu and choose *New, JSF Page* to display the New JSF File dialog box, as shown in Figure 33.9.

Step 2. Enter **CurrentTime** in the File Name field, choose Facelets and click *Finish* to generate CurrentTime.xhtml, as shown in Figure 33.10.

Step 3. Add a JSF expression to obtain the current time, as shown in Listing 33.3.

Step 4. Right-click on CurrentTime.xhtml in the project to display a context menu and choose *Run File* to display the page in a browser as shown in Figure 33.1.

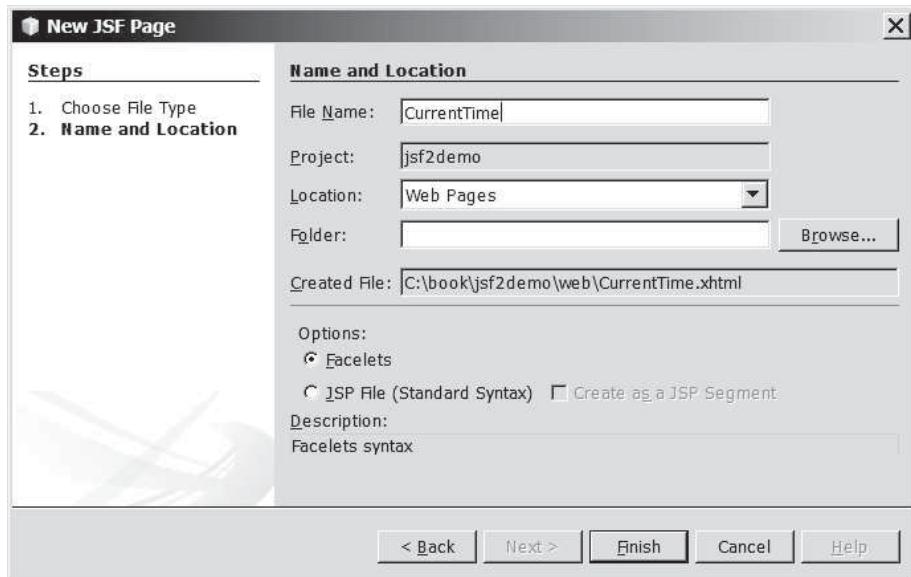


FIGURE 33.9 The New JSF Page dialog is used to create a JSF page.

#### LISTING 33.3 CurrentTime.xhtml

```

1 <?xml version='1.0' encoding='UTF-8' ?>
2 <!DOCTYPE html PUBLIC "-//W3C//DTD XHTML 1.0 Transitional//EN"
3 "http://www.w3.org/TR/xhtml1/DTD/xhtml1-transitional.dtd">
4 <html xmlns="http://www.w3.org/1999/xhtml">
```



**FIGURE 33.10** A New JSF page CurrentTime was created.

```

5 xmlns:h="http://xmlns.jcp.org/jsf/html">
6 <h:head>
7 <title>Display Current Time</title>
8 <meta http-equiv="refresh" content ="60" /> refresh page
9 </h:head>
10 <h:body>
11 The current time is #{timeBean.time} JSF expression
12 </h:body>
13 </html>

```

Line 8 defines a **meta** tag inside the **h:head** tag to tell the browser to refresh every 60 seconds. This line can also be written as

```
<meta http-equiv="refresh" content ="60"></ meta>
```

An element is called an *empty element* if there are no contents between the start tag and end tag. In an empty element, data are typically specified as attributes in the start tag. You can close an empty element by placing a slash immediately preceding the start tag's right angle bracket, as shown in line 8, for brevity.

Line 11 uses a JSF expression **#{timeBean.time}** to obtain the current time. **timeBean** is an object of the **TimeBean** class. The object name can be changed in the **@Named** annotation (line 6 in Listing 33.2) using the following syntax:

```
@Named(name = "anyObjectName")
```

By default, the object name is the class name with the first letter in lowercase.

Note that **time** is a JavaBeans property because the **getTime()** method is defined in **TimeBeans**. The JSF expression can either use the property name or invoke the method to obtain the current time. So the following two expressions are both fine.

```
#{timeBean.time}
#{timeBean.getTime()}
```

The syntax of a JSF expression is

```
#{expression}
```

JSF expressions bind JavaBeans objects with facelets. You will see more use of JSF expressions in the upcoming examples in this chapter.



- 33.1** What is JSF?
- 33.2** How do you create a JSF project in NetBeans?
- 33.3** How do you create a JSF page in a JSF project?
- 33.4** What is a facelet?
- 33.5** What is the file extension name for a facelet?
- 33.6** What is a managed bean?
- 33.7** What is the `@Named` annotation for?
- 33.8** What is the `@RequestScope` annotation for?



### 33.3 JSF GUI Components

*JSF provides many elements for displaying GUI components.*

Table 33.1 lists some of the commonly used elements. The tags with the `h` prefix are in the JSF HTML Tag library. The tags with the `f` prefix are in the JSF Core Tag library.

**TABLE 33.1** JSF GUI Form Elements

| JSF Tag                           | Description                                                                                                                  |
|-----------------------------------|------------------------------------------------------------------------------------------------------------------------------|
| <code>h:form</code>               | inserts an XHTML form into a page.                                                                                           |
| <code>h:panelGroup</code>         | similar to a JavaFX FlowPane.                                                                                                |
| <code>h:panelGrid</code>          | similar to a JavaFX GridPane.                                                                                                |
| <code>h:inputText</code>          | displays a textbox for entering input.                                                                                       |
| <code>h:outputText</code>         | displays a textbox for displaying output.                                                                                    |
| <code>h:inputTextArea</code>      | displays a textarea for entering input.                                                                                      |
| <code>h:inputSecret</code>        | displays a textbox for entering password.                                                                                    |
| <code>h:outputLabel</code>        | displays a label.                                                                                                            |
| <code>h:outputLink</code>         | displays a hypertext link.                                                                                                   |
| <code>h:selectOneMenu</code>      | displays a combo box for selecting one item.                                                                                 |
| <code>h:selectOneRadio</code>     | displays a set of radio button.                                                                                              |
| <code>h:selectManyCheckbox</code> | displays checkboxes.                                                                                                         |
| <code>h:selectOneListbox</code>   | displays a list for selecting one item.                                                                                      |
| <code>h:selectManyListbox</code>  | displays a list for selecting multiple items.                                                                                |
| <code>f:selectItem</code>         | specifies an item in an <code>h:selectOneMenu</code> , <code>h:selectOneRadio</code> , or <code>h:selectManyListbox</code> . |
| <code>h:message</code>            | displays a message for validating input.                                                                                     |
| <code>h:dataTable</code>          | displays a data table.                                                                                                       |
| <code>h:column</code>             | specifies a column in a data table.                                                                                          |
| <code>h:graphicImage</code>       | displays an image.                                                                                                           |

Listing 33.4 is an example that uses some of these elements to display a student registration form, as shown in Figure 33.11.

The screenshot shows a student registration form titled "Student Registration Form". It includes fields for Last Name, First Name, and MI (Middle Initial). A gender selection section with radio buttons for Male and Female. A dropdown menu for Major with "Computer Science" selected, and another dropdown for Minor with "Mathematics" selected. A hobby section with checkboxes for Tennis, Golf, and Ping Pong. A remarks section with a text area. A "Register" button at the bottom.

**FIGURE 33.11** A student registration form is displayed using JSF elements.

#### LISTING 33.4 StudentRegistrationForm.xhtml

```

1 <?xml version='1.0' encoding='UTF-8' ?>
2 <!DOCTYPE html PUBLIC "-//W3C//DTD XHTML 1.0 Transitional//EN"
3 "http://www.w3.org/TR/xhtml1/DTD/xhtml1-transitional.dtd">
4 <html xmlns="http://www.w3.org/1999/xhtml"
5 xmlns:h="http://xmlns.jcp.org/jsf/html"
6 xmlns:f="http://xmlns.jcp.org/jsf/core"> jsf core namespace
7 <h:head>
8 <title>Student Registration Form</title>
9 </h:head>
10 <h:body>
11 <h:form>
12 <!-- Use h:graphicImage -->
13 <h3>Student Registration Form
14 <h:graphicImage name="usIcon.gif" library="image"/> graphicImage
15 </h3>
16
17 <!-- Use h:panelGrid -->
18 <h:panelGrid columns="6" style="color:green"> h:panelGrid
19 <h:outputLabel value="Last Name"/> h:outputLabel
20 <h:inputText id="lastNameInputText" /> h:inputText
21 <h:outputLabel value="First Name" />
22 <h:inputText id="firstNameInputText" />
23 <h:outputLabel value="MI" />
24 <h:inputText id="miInputText" size="1" />
25 </h:panelGrid>
26
27 <!-- Use radio buttons -->
28 <h:panelGrid columns="2">
29 <h:outputLabel>Gender </h:outputLabel>

```

```

h:selectOneRadio 30 <h:selectOneRadio id="genderSelectOneRadio">
f:selectItem 31 <f:selectItem itemValue="Male"
 itemLabel="Male"/>
f:selectItem 32 <f:selectItem itemValue="Female"
 itemLabel="Female"/>
33 </h:selectOneRadio>
34 </h:panelGrid>
35
36
37
38 <!-- Use combo box and list -->
39 <h:panelGrid columns="4">
40 <h:outputLabel value="Major "/>
41 <h:selectOneMenu id="majorSelectOneMenu">
42 <f:selectItem itemValue="Computer Science"/>
43 <f:selectItem itemValue="Mathematics"/>
44 </h:selectOneMenu>
45 <h:outputLabel value="Minor "/>
46 <h:selectManyListbox id="minorSelectManyListbox">
47 <f:selectItem itemValue="Computer Science"/>
48 <f:selectItem itemValue="Mathematics"/>
49 <f:selectItem itemValue="English"/>
50 </h:selectManyListbox>
51 </h:panelGrid>
52
53 <!-- Use check boxes -->
54 <h:panelGrid columns="4">
55 <h:outputLabel value="Hobby: "/>
56 <h:selectManyCheckbox id="hobbySelectManyCheckbox">
57 <f:selectItem itemValue="Tennis"/>
58 <f:selectItem itemValue="Golf"/>
59 <f:selectItem itemValue="Ping Pong"/>
60 </h:selectManyCheckbox>
61 </h:panelGrid>
62
63 <!-- Use text area -->
64 <h:panelGrid columns="1">
65 <h:outputLabel>Remarks:</h:outputLabel>
66 <h:inputTextarea id="remarksInputTextarea"
67 style="width:400px; height:50px;" />
68 </h:panelGrid>
69
70 <!-- Use command button -->
71 <h:commandButton value="Register" />
72 </h:form>
73 </h:body>
74 </html>

```

jsf core xmlns

The tags with prefix **f** are in the JSF core tag library. Line 6`xmlns:f="http://xmlns.jcp.org/jsf/core">`

locates the library for these tags.

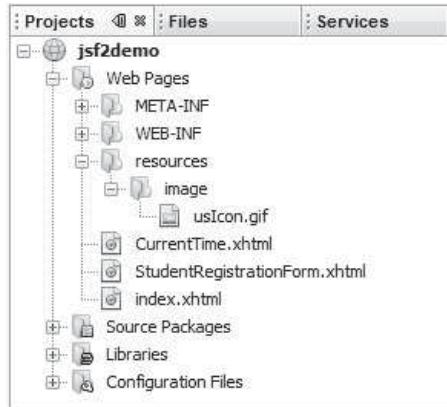
h:graphicImage

The **h:graphicImage** tag displays an image in the file usIcon.gif (line 14). The file is located in the /resources/image folder. In JSF 2.2, all resources (image files, audio files, CCS files) should be placed under the resources folder under the **Web Pages** node. You can create these folders as follows:

Step 1: Right-click the Web Pages node in the project pane to display a context menu and choose *New, Folder* to display the New Folder dialog box. (If *Folder* is not in the context menu, choose *Other* to locate it.)

Step 2: Enter **resources** as the Folder Name and click *Finish* to create the **resources** folder, as shown in Figure 33.12.

Step 3: Right-click the **resources** node in the project pane to create the image folder under resources. You can now place usIcon.gif under the image folder.



**FIGURE 33.12** The resources folder was created.

JSF provides **h:panelGrid** and **h:panelGroup** elements to contain and layout subelements. **h:panelGrid** places the elements in a grid like the JavaFX **GridPane**. **h:panelGroup** places the elements like a JavaFX **FlowPane**. Lines 18–25 places six elements (labels and input texts) are in a **h:panelGrid**. The **columns** attribute specifies that each row in the grid has **6** columns. The elements are placed into a row from left to right in the order they appear in the facelet. When a row is full, a new row is created to hold the elements. We used **h:panelGrid** in this example. You may replace it with **h:panelGroup** to see how the elements would be arranged.

You may use the **style** attribute with a JSF html tag to specify the CSS style for the element and its subelements. The **style** attribute in line 18 specifies color green for all elements in this **h:panelGrid** element.

The **h:outputLabel** element is for displaying a label (line 19). The **value** attribute specifies the label's text.

The **h:inputText** element is for displaying a text input box for the user to enter a text (line 20). The **id** attribute is useful for other elements or the server program to reference this element.

The **h:selectOneRadio** element is for displaying a group of radio buttons (line 30). Each radio button is defined using an **f:selectItem** element (lines 31–34).

The **h:selectOneMenu** element is for displaying a combo box (line 41). Each item in the combo box is defined using an **f:selectItem** element (lines 42 and 43).

The **h:selectManyListbox** element is for displaying a list for the user to choose multiple items in a list (line 46). Each item in the list is defined using an **f:selectItem** element (lines 47–49).

The **h:selectManyCheckbox** element is for displaying a group of check boxes (line 56). Each item in the check box is defined using an **f:selectItem** element (lines 57–59).

The **h:selectTextarea** element is for displaying a text area for multiple lines of input (line 66). The **style** attribute is used to specify the width and height of the text area (line 67).

The **h:commandButton** element is for displaying a button (line 71). When the button is clicked, an action is performed. The default action is to request the same page from the server. The next section shows how to process the form.

**h:panelGrid**

the **style** attribute

**h:outputLabel**

**h:inputText**

**h:selectOneRadio**

**h:selectOneMenu**

**h:selectManyListbox**

**h:selectManyCheckbox**

**h:selectTextarea**

**h:commandButton**



**33.9** What is the name space for JSF tags with prefix **h** and prefix **f**?

**33.10** Describe the use of the following tags?

**h:form, h:panelGroup, h:panelGrid, h:inputText, h:outputText,  
h:inputTextArea, h:inputSecret, h:outputLabel, h:outputLink,  
h:selectOneMenu, h:selectOneRadio, h:selectManyCheckbox,  
h:selectOneListbox, h:selectManyListbox, h:selectItem, h:message,  
h:dataTable, h:column, h:graphicImage**



## 33.4 Processing the Form

*Processing forms is a common task for Web programming. JSF provides tools for processing forms.*

The preceding section introduced how to display a form using common JSF elements. This section shows how to obtain and process the input.

To obtain input from the form, simply bind each input element with a property in a managed bean. We now define a managed bean named **registration** as shown in Listing 33.5.

### LISTING 33.5 RegistrationJSFBean.java

managed bean  
request scope

property lastName

```

1 package jsf2demo;
2
3 import javax.enterprise.context.RequestScoped;
4 import javax.inject.Named;
5
6 @Named(value = "registration")
7 @RequestScoped
8 public class RegistrationJSFBean {
9 private String lastName;
10 private String firstName;
11 private String mi;
12 private String gender;
13 private String major;
14 private String[] minor;
15 private String[] hobby;
16 private String remarks;
17
18 public RegistrationJSFBean() {
19 }
20
21 public String getLastName() {
22 return lastName;
23 }
24
25 public void setLastName(String lastName) {
26 this.lastName = lastName;
27 }
28
29 public String getFirstName() {
30 return firstName;
31 }
32
33 public void setFirstName(String firstName) {
34 this.firstName = firstName;
35 }
36

```

```
37 public String getMi() {
38 return mi;
39 }
40
41 public void setMi(String mi) {
42 this.mi = mi;
43 }
44
45 public String getGender() {
46 return gender;
47 }
48
49 public void setGender(String gender) {
50 this.gender = gender;
51 }
52
53 public String getMajor() {
54 return major;
55 }
56
57 public void setMajor(String major) {
58 this.major = major;
59 }
60
61 public String[] getMinor() {
62 return minor;
63 }
64
65 public void setMinor(String[] minor) {
66 this.minor = minor;
67 }
68
69 public String[] getHobby() {
70 return hobby;
71 }
72
73 public void setHobby(String[] hobby) {
74 this.hobby = hobby;
75 }
76
77 public String getRemarks() {
78 return remarks;
79 }
80
81 public void setRemarks(String remarks) {
82 this.remarks = remarks;
83 }
84
85 public String getResponse() { getResponse()
86 if (lastName == null)
87 return ""; // Request has not been made
88 else {
89 String allMinor = "";
90 for (String s: minor) {
91 allMinor += s + " ";
92 }
93
94 String allHobby = "";
95 for (String s: hobby) {
96 allHobby += s + " ";
97 }
98 }
```

```

99 return "<p style=\"color:red\">You entered
" +
100 "Last Name: " + lastName + "
" +
101 "First Name: " + firstName + "
" +
102 "MI: " + mi + "
" +
103 "Gender: " + gender + "
" +
104 "Major: " + major + "
" +
105 "Minor: " + allMinor + "
" +
106 "Hobby: " + allHobby + "
" +
107 "Remarks: " + remarks + "</p>";
108 }
109 }
110 }
```

bean properties

The `RegistrationJSFBean` class is a managed bean that defines the properties `lastName`, `firstName`, `mi`, `gender`, `major`, `minor`, and `remarks`, which will be bound to the elements in the JSF registration form.

The registration form can now be revised as shown in Listing 33.6. Figure 33.13 shows that new JSF page displays the user input upon clicking the *Register* button.

### LISTING 33.6 ProcessStudentRegistrationForm.xhtml

jsf core namespace

bind lastName

bind firstName

bind mi

bind gender

```

1 <?xml version='1.0' encoding='UTF-8' ?>
2 <!DOCTYPE html PUBLIC "-//W3C//DTD XHTML 1.0 Transitional//EN"
3 "http://www.w3.org/TR/xhtml1/DTD/xhtml1-transitional.dtd">
4 <html xmlns="http://www.w3.org/1999/xhtml"
5 xmlns:h="http://xmlns.jcp.org/jsf/html"
6 xmlns:f="http://xmlns.jcp.org/jsf/core">
7 <h:head>
8 <title>Student Registration Form</title>
9 </h:head>
10 <h:body>
11 <h:form>
12 <!-- Use h:graphicImage -->
13 <h3>Student Registration Form
14 <h:graphicImage name="usIcon.gif" library="image"/>
15 </h3>
16
17 <!-- Use h:panelGrid -->
18 <h:panelGrid columns="6" style="color:green">
19 <h:outputLabel value="Last Name"/>
20 <h:inputText id="lastNameInputText"
21 value="#{registration.lastName}" />
22 <h:outputLabel value="First Name" />
23 <h:inputText id="firstNameInputText"
24 value="#{registration.firstName}" />
25 <h:outputLabel value="MI" />
26 <h:inputText id="miInputText" size="1"
27 value="#{registration.mi}" />
28 </h:panelGrid>
29
30 <!-- Use radio buttons -->
31 <h:panelGrid columns="2">
32 <h:outputLabel>Gender </h:outputLabel>
33 <h:selectOneRadio id="genderSelectOneRadio"
34 value="#{registration.gender}">
35 <f:selectItem itemValue="Male"
36 itemLabel="Male"/>
37 <f:selectItem itemValue="Female"
38 itemLabel="Female"/>
39 </h:selectOneRadio>
```

```

40 </h:panelGrid>
41
42 <!-- Use combo box and list -->
43 <h:panelGrid columns="4">
44 <h:outputLabel value="Major "/>
45 <h:selectOneMenu id="majorSelectOneMenu"
46 value="#{registration.major}"> bind major
47 <f:selectItem itemValue="Computer Science"/>
48 <f:selectItem itemValue="Mathematics"/>
49 </h:selectOneMenu>
50 <h:outputLabel value="Minor "/>
51 <h:selectManyListbox id="minorSelectManyListbox"
52 value="#{registration.minor}"> bind minor
53 <f:selectItem itemValue="Computer Science"/>
54 <f:selectItem itemValue="Mathematics"/>
55 <f:selectItem itemValue="English"/>
56 </h:selectManyListbox>
57 </h:panelGrid>
58
59 <!-- Use check boxes -->
60 <h:panelGrid columns="4">
61 <h:outputLabel value="Hobby: "/>
62 <h:selectManyCheckbox id="hobbySelectManyCheckbox"
63 value="#{registration.hobby}"> bind hobby
64 <f:selectItem itemValue="Tennis"/>
65 <f:selectItem itemValue="Golf"/>
66 <f:selectItem itemValue="Ping Pong"/>
67 </h:selectManyCheckbox>
68 </h:panelGrid>
69
70 <!-- Use text area -->
71 <h:panelGrid columns="1">
72 <h:outputLabel>Remarks:</h:outputLabel>
73 <h:inputTextarea id="remarksInputTextarea"
74 style="width:400px; height:50px;" bind remarks
75 value="#{registration.remarks}"/>
76 </h:panelGrid>
77
78 <!-- Use command button -->
79 <h:commandButton value="Register" />
80

81 <h:outputText escape="false" style="color:red"
82 value="#{registration.response}" /> bind response
83 </h:form>
84 </h:body>
85 </html>

```

The new JSF form in this listing binds the `h:inputText` element for last name, first name, and mi with the properties `lastName`, `firstName`, and `mi` in the managed bean (lines 21, 24, 27). When the *Register* button is clicked, the page is sent to the server, which invokes the setter methods to set the properties in the managed bean.

The `h:selectOneRadio` element is bound to the `gender` property (line 34). Each radio button has an `itemValue`. The selected radio button's `itemValue` is set to the `gender` property in the bean when the page is sent to the server.

The `h:selectOneMenu` element is bound to the `major` property (line 46). When the page is sent to the server, the selected item is returned as a string and is set to the `major` property.

The `h:selectManyListbox` element is bound to the `minor` property (line 52). When the page is sent to the server, the selected items are returned as an array of strings and set to the `minor` property.

binding input texts

binding radio buttons

binding combo box

binding list box

Last Name  First Name  MI

Gender  Male  Female

Major  Minor

Hobby:  Tennis  Golf  Ping Pong

Remarks:

You entered  
 Last Name: Yao  
 First Name: John  
 MI: P  
 Gender: Male  
 Major: Mathematics  
 Minor: Computer Science English  
 Hobby: Tennis Ping Pong  
 Remarks: Done

**FIGURE 33.13** The user input is collected and displayed after clicking the Register button.

binding check boxes

The `h:selectManyCheckbox` element is bound to the `hobby` property (line 63). When the page is sent to the server, the checked boxes are returned as an array of `itemValues` and set to the `hobby` property.

binding text area

The `h:selectTextarea` element is bound to the `remarks` property (line 75). When the page is sent to the server, the content in the text area is returned as a string and set to the `remarks` property.

binding response

The `h:outputText` element is bound to the `response` property (line 82). This is a read-only property in the bean. It is `""` if `lastName` is `null` (lines 86–87 in Listing 33.5). When the page is returned to the client, the `response` property value is displayed in the output text element (line 82).

escape attribute

The `h:outputText` element's `escape` attribute is set to `false` (line 81) to enable the contents to be displayed in HTML. By default, the `escape` attribute is `true`, which indicates the contents are considered as regular text.



**33.11** In the `h:outputText` tag, what is the `escape` attribute for?

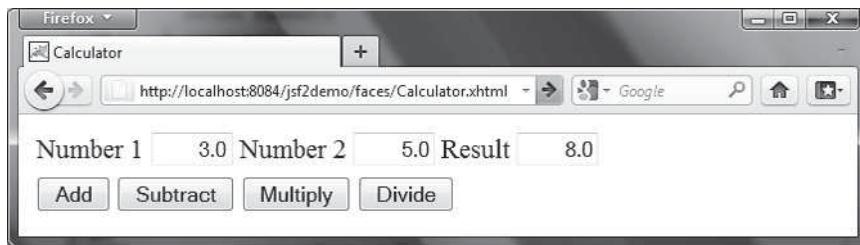
**33.12** Does every GUI component tag in JSF have the `style` attribute?

## 33.5 Case Study: Calculator



*This section gives a case study on using GUI elements and processing forms.*

This section uses JSF to develop a calculator to perform addition, subtraction, multiplication, and division, as shown in Figure 33.14.



**FIGURE 33.14** This JSF application enables you to perform addition, subtraction, multiplication, and division.

Here are the steps to develop this project:

Step 1. Create a new managed bean named **calculator** with the request scope as create managed bean

shown in Listing 33.7, CalculatorJSFBean.java.

Step 2. Create a JSF facelet in Listing 33.8, Calculator.xhtml. create JSF facelet

### LISTING 33.7 CalculatorJSFBean.java

```

1 package jsf2demo;
2
3 import javax.inject.Named;
4 import javax.enterprise.context.RequestScoped;
5
6 @Named(value = "calculator")
7 @RequestScoped
8 public class CalculatorJSFBean {
9 private Double number1;
10 private Double number2;
11 private Double result;
12
13 public CalculatorJSFBean() {
14 }
15
16 public Double getNumber1() {
17 return number1;
18 }
19
20 public Double getNumber2() {
21 return number2;
22 }
23
24 public Double getResult() {
25 return result;
26 }
27
28 public void setNumber1(Double number1) {
29 this.number1 = number1;
30 }
31
32 public void setNumber2(Double number2) {
33 this.number2 = number2;
34 }
35
36 public void setResult(Double result) {
37 this.result = result;
38 }
39

```

property number1  
property number2  
property result

```

add 40 public void add() {
41 result = number1 + number2;
42 }
43
subtract 44 public void subtract() {
45 result = number1 - number2;
46 }
47
divide 48 public void divide() {
49 result = number1 / number2;
50 }
51
multiply 52 public void multiply() {
53 result = number1 * number2;
54 }
55 }
```

The managed bean has three properties `number1`, `number2`, and `result` (lines 9–38). The methods `add()`, `subtract()`, `divide()`, and `multiply()` add, subtract, multiply, and divide `number1` with `number2` and assigns the result to `result` (lines 40–54).

### LISTING 33.8 Calculator.xhtml

```

1 <?xml version='1.0' encoding='UTF-8' ?>
2 <!DOCTYPE html PUBLIC "-//W3C//DTD XHTML 1.0 Transitional//EN"
3 "http://www.w3.org/TR/xhtml1/DTD/xhtml1-transitional.dtd">
4 <html xmlns="http://www.w3.org/1999/xhtml"
5 xmlns:h="http://xmlns.jcp.org/jsf/html">
6 <h:head>
7 <title>Calculator</title>
8 </h:head>
9 <h:body>
10 <h:form>
11 <h:panelGrid columns="6">
12 <h:outputLabel value="Number 1"/>
13 <h:inputText id="number1InputText" size ="4"
14 style="text-align: right"
15 value="#{calculator.number1}" />
16 <h:outputLabel value="Number 2" />
17 <h:inputText id="number2InputText" size ="4"
18 style="text-align: right"
19 value="#{calculator.number2}" />
20 <h:outputLabel value="Result" />
21 <h:inputText id="resultInputText" size ="4"
22 style="text-align: right"
23 value="#{calculator.result}" />
24 </h:panelGrid>
25
26 <h:panelGrid columns="4">
27 <h:commandButton value="Add"
28 action ="#{calculator.add}" />
29 <h:commandButton value="Subtract"
30 action ="#{calculator.subtract}" />
31 <h:commandButton value="Multiply"
32 action ="#{calculator.multiply}" />
33 <h:commandButton value="Divide"
34 action ="#{calculator.divide}" />
35 </h:panelGrid>
36 </h:form>
37 </h:body>
38 </html>
```

right align  
bind text input

action

Three text input components along with their labels are placed in the grid panel (lines 11–24). Four button components are placed in the grid panel (lines 26–35).

The bean property `number1` is bound to the text input for Number 1 (line 15). The CSS style `text-align: right` (line 14) specifies that the text is right-aligned in the input box.

The `action` attribute for the *Add* button is set to the `add` method in the calculator bean (line 28). When the *Add* button is clicked, the `add` method in the bean is invoked to add `number1` with `number2` and assign the result to `result`. Since the `result` property is bound to the Result input text (line 23), the new result is now displayed in the text input field.

## 33.6 Session Tracking

*You can create a managed bean at the application scope, session scope, view scope, or request scope.*



JSF supports session tracking using JavaBeans at the application scope, session scope, view scope, and request scope. The *scope* is the lifetime of a bean. A *request*-scoped bean is alive in a single HTTP request. After the request is processed, the bean is no longer alive. A *view*-scoped bean lives as long as you are in the same JSF page. A *session*-scoped bean is alive for the entire Web session between a client and the server. An *application*-scoped bean lives as long as the Web application runs. In essence, a request-scoped bean is created once for a request; a view-scoped bean is created once for the view; a session-scoped bean is created once for the entire session; and an application-scoped bean is created once for the entire application.

Consider the following example that prompts the user to guess a number. When the page starts, the program randomly generates a number between `0` and `99`. This number is stored in a bean. When the user enters a guess, the program checks the guess with the random number in the bean and tells the user whether the guess is too high, too low, or just right, as shown in Figure 33.15.

Here are the steps to develop this project:

Step 1. Create a new managed bean named `guessNumber` with the view scope as shown in Listing 33.9, GuessNumberJSFBean.java.

create managed bean

Step 2. Create a JSF facelet in Listing 33.10, GuessNumber.xhtml.

create JSF facelet

### LISTING 33.9 GuessNumberJSFBean.java

```

1 package jsf2demo;
2
3 import javax.inject.Named;
4 import javax.faces.view.ViewScoped;
5
6 @Named(value = "guessNumber")
7 @ViewScoped
8 public class GuessNumberJSFBean {
9 private int number;
10 private String guessString;
11
12 public GuessNumberJSFBean() {
13 number = (int)(Math.random() * 100);
14 }
15
16 public String getGuessString() {
17 return guessString;
18 }
19
20 public void setGuessString(String guessString) {
21 this.guessString = guessString;
22 }

```

view scope

random number  
guess by user

create random number

getter method

setter method



FIGURE 33.15 The user enters a guess and the program displays the result.

```

23
get response
24 public String getResponse() {
25 if (guessString == null)
26 return ""; // No user input yet
27
check guess
28 int guess = Integer.parseInt(guessString);
29 if (guess < number)
30 return "Too low";
31 else if (guess == number)
32 return "You got it";
33 else
34 return "Too high";
35 }
36 }
```

The managed bean uses the `@ViewScope` annotation (line 7) to set up the view scope for the bean. The view scope is most appropriate for this project. The bean is alive as long as the view is not changed. The bean is created when the page is displayed for the first time. A random number between 0 and 99 is assigned to `number` (line 13) when the bean is created. This number will not change as long as the bean is alive in the same view.

The `getResponse` method converts `guessString` from the user input to an integer (line 28) and determines if the guess is too low (line 30), too high (line 34), and just right (line 32).

### LISTING 33.10 GuessNumber.xhtml

```

1 <?xml version='1.0' encoding='UTF-8' ?>
2 <!DOCTYPE html PUBLIC "-//W3C//DTD XHTML 1.0 Transitional//EN"
3 "http://www.w3.org/TR/xhtml1/DTD/xhtml1-transitional.dtd">
4 <html xmlns="http://www.w3.org/1999/xhtml">
5 xmlns:h="http://xmlns.jcp.org/jsf/html">
6 <h:head>
7 <title>Guess a number</title>
8 </h:head>
9 <h:body>
10 <h:form>
11 <h:outputLabel value="Enter your guess: "/>
12 <h:inputText style="text-align: right; width: 50px"
13 id="guessInputText"
14 value="#{guessNumber.guessString}"/>bind text input
15 <h:commandButton style="margin-left: 60px" value="Guess" />
16

17 <h:outputText style="color: red"
18 value="#{guessNumber.response}" />bind text output
19 </h:form>
20 </h:body>
21 </html>
```

The bean property `guessString` is bound to the text input (line 14). The CSS style `text-align: right` (line 13) specifies that the text is right-aligned in the input box.

The CSS style `margin-left: 60px` (line 15) specifies that the command button has a left margin of 60 pixels.

The bean property `response` is bound to the text output (line 18). The CSS style `color: red` (line 17) specifies that the text is displayed in red in the output box.

The project uses the `view` scope. What happens if the scope is changed to the request scope? Every time the page is refreshed, JSF creates a new bean with a new random number. What happens if the scope is changed to the `session` scope? The bean will be alive as long as the browser is alive. What happens if the scope is changed to the `application` scope? The bean will be created once when the application is launched from the server. So every client will use the same random number.

**33.13** What is a scope? What are the available scopes in JSF? Explain request scope, view scope, session scope, and application scope. How do you set a request scope, view scope, session scope, and application scope in a managed bean?



**33.14** What happens if the bean scope in Listing 33.9 `GuessNumberJSFBean.java` is changed to request?

**33.15** What happens if the bean scope in Listing 33.9 `GuessNumberJSFBean.java` is changed to session?

**33.16** What happens if the bean scope in Listing 33.9 `GuessNumberJSFBean.java` is changed to application?

## 33.7 Validating Input

*JSF provides tools for validating user input.*

In the preceding `GuessNumber` page, an error would occur if you entered a noninteger in the input box before clicking the *Guess* button. One way to fix the problem is to check the text field before processing any event. But a better way is to use the validators. You can use the



standard validator tags in the JSF Core Tag Library or create custom validators. Table 33.2 lists some JSF input validator tags.

**TABLE 33.2 JSF Input Validator Tags**

| JSF Tag               | Description                                                                     |
|-----------------------|---------------------------------------------------------------------------------|
| f:validateLength      | validates the length of the input.                                              |
| f:validateDoubleRange | validates whether numeric input falls within acceptable range of double values. |
| f:validateLongRange   | validates whether numeric input falls within acceptable range of long values.   |
| f:validateRequired    | validates whether a field is not empty.                                         |
| f:validateRegex       | validates whether the input matches a regular expression.                       |
| f:validateBean        | invokes a custom method in a bean to perform custom validation.                 |

Consider the following example that displays a form for collecting user input as shown in Figure 33.16. All text fields in the form must be filled. If not, error messages are displayed. The SSN must be formatted correctly. If not, an error is displayed. If all input are correct, clicking *Submit* displays the result in an output text, as shown in Figure 33.17.

(a) The required messages are displayed if input is required, but empty.

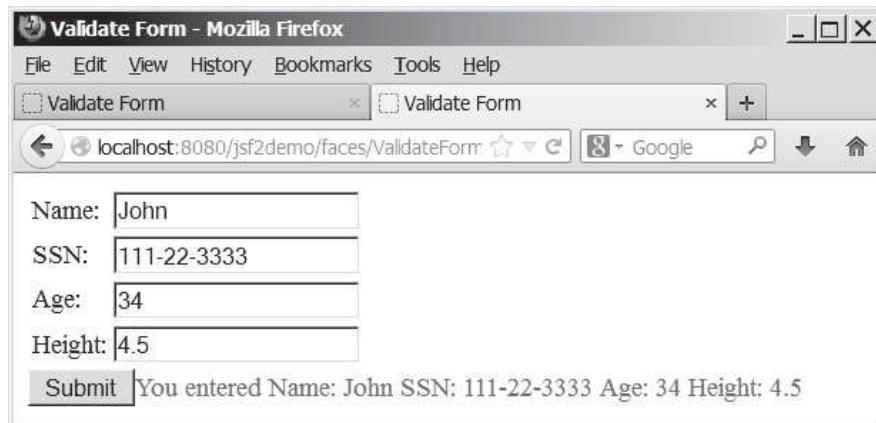
(b) Error messages are displayed if input is incorrect.

**FIGURE 33.16** The input fields are validated.

Here are the steps to create this project.

Step 1. Create a new page in Listing 33.11, ValidateForm.xhtml.

Step 2. Create a new managed bean named `validateForm`, as shown in Listing 33.12.



**FIGURE 33.17** The correct input values are displayed.

### LISTING 33.11 ValidateForm.xhtml

```

1 <?xml version='1.0' encoding='UTF-8' ?>
2 <!DOCTYPE html PUBLIC "-//W3C//DTD XHTML 1.0 Transitional//EN"
3 "http://www.w3.org/TR/xhtml1/DTD/xhtml1-transitional.dtd">
4 <html xmlns="http://www.w3.org/1999/xhtml"
5 xmlns:h="http://xmlns.jcp.org/jsf/html"
6 xmlns:f="http://xmlns.jcp.org/jsf/core">
7 <h:head>
8 <title>Validate Form</title>
9 </h:head>
10 <h:body>
11 <h:form>
12 <h:panelGrid columns="3">
13 <h:outputLabel value="Name:" />
14 <h:inputText id="nameInputText" required="true"
15 requiredMessage="Name is required"
16 validatorMessage="Name must have 1 to 10 chars"
17 value="#{validateForm.name}">
18 <f:validateLength minimum="1" maximum="10" />
19 </h:inputText>
20 <h:message for="nameInputText" style="color:red"/>
21
22 <h:outputLabel value="SSN:" />
23 <h:inputText id="ssnInputText" required="true"
24 requiredMessage="SSN is required"
25 validatorMessage="Invalid SSN"
26 value="#{validateForm.ssn}">
27 <f:validateRegex pattern="[\d]{3}-[\d]{2}-[\d]{4}" />
28 </h:inputText>
29 <h:message for="ssnInputText" style="color:red"/>
30
31 <h:outputLabel value="Age:" />
32 <h:inputText id="ageInputText" required="true"
33 requiredMessage="Age is required"
34 validatorMessage="Age must be between 16 and 120"
35 value="#{validateForm.ageString}">
36 <f:validateLongRange minimum="16" maximum="120"/>
37 </h:inputText>
38 <h:message for="ageInputText" style="color:red"/>
39
40 <h:outputLabel value="Height:" />

```

required input  
required message  
validator message  
validate length  
message element  
validate regex  
validate integer range

```

41 <h:inputText id="heightInputText" required="true"
42 requiredMessage="Height is required"
43 validatorMessage="Height must be between 3.5 and 9.5"
44 value="#{validateForm.heightString}">
45 <f:validateDoubleRange minimum="3.5" maximum="9.5"/>
46 </h:inputText>
47 <h:message for="heightInputText" style="color:red"/>
48 </h:panelGrid>
49
50 <h:commandButton value="Submit" />
51
52 <h:outputText style="color:red"
53 value="#{validateForm.response}" />
54 </h:form>
55 </h:body>
56 </html>
```

required attribute  
requiredMessage

validatorMessage  
f:validateLength

h:message

f:validateRegex

f:validateLongRange

f:validateDoubleRange

For each input text field, set its **required** attribute **true** (lines 14, 23, 32, 41) to indicate that an input value is required for the field. When a required input field is empty, the **requiredMessage** is displayed (lines 15, 24, 33, 42).

The **validatorMessage** attribute specifies a message to be displayed if the input field is invalid (line 16). The **f:validateLength** tag specifies the minimum or maximum length of the input (line 18). JSF will determine whether the input length is valid.

The **h:message** element displays the **validatorMessage** if the input is invalid. The element's **for** attribute specifies the **id** of the element for which the message will be displayed (line 20).

The **f:validateRegex** tag specifies a regular expression for validating the input (line 27). For information on regular expression, see Appendix H.

The **f:validateLongRange** tag specifies a range for an integer input using the **minimum** and **maximum** attribute (line 36). In this project, a valid age value is between **16** and **120**.

The **f:validateDoubleRange** tag specifies a range for a double input using the **minimum** and **maximum** attribute (line 45). In this project, a valid height value is between **3.5** and **9.5**.

### LISTING 33.12 ValidateFormJSFBean.java

```

1 package jsf2demo;
2
3 import javax.enterprise.context.RequestScoped;
4 import javax.inject.Named;
5
6 @Named(value = "validateForm")
7 @RequestScoped
8 public class ValidateFormJSFBean {
9 private String name;
10 private String ssn;
11 private String ageString;
12 private String heightString;
13
14 public String getName() {
15 return name;
16 }
17
18 public void setName(String name) {
19 this.name = name;
20 }
21
22 public String getSSN() {
23 return ssn;
```

```

24 }
25
26 public void setSsn(String ssn) {
27 this.ssn = ssn;
28 }
29
30 public String getAgeString() {
31 return ageString;
32 }
33
34 public void setAgeString(String ageString) {
35 this.ageString = ageString;
36 }
37
38 public String getHeightString() {
39 return heightString;
40 }
41
42 public void setHeightString(String heightString) {
43 this.heightString = heightString;
44 }
45
46 public String getResponse() {
47 if (name == null || ssn == null || ageString == null
48 || heightString == null) {
49 return "";
50 }
51 else {
52 return "You entered " +
53 " Name: " + name +
54 " SSN: " + ssn +
55 " Age: " + ageString +
56 " Height: " + heightString;
57 }
58 }
59 }

```

If an input is invalid, its value is not set to the bean. So only when all input are correct, the `getResponse()` method will return all input values (lines 46–58)

some input not set

- 33.17** Write a tag that validates an input text with minimal length of **2** and maximum **12**.
- 33.18** Write a tag that validates an input text for SSN using a regular expression.
- 33.19** Write a tag that validates an input text for a double value with minimal **4.5** and maximum **19.9**.
- 33.20** Write a tag that validates an input text for an integer value with minimal **4** and maximum **20**.
- 33.21** Write a tag that makes an input text required.



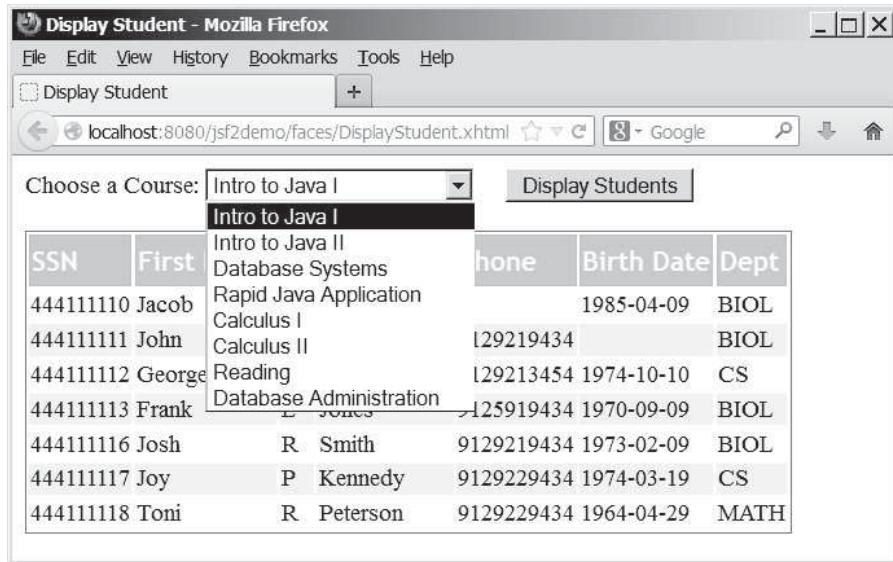
## 33.8 Binding Database with Facelets

*You can bind a database in JSF applications.*



Often you need to access a database from a Web page. This section gives examples of building Web applications using databases.

Consider the following example that lets the user choose a course, as shown in Figure 33.18. After a course is selected in the combo box, the students enrolled in the course are displayed in the table, as shown in Figure 33.19. In this example, all the course titles in the `Course` table



**FIGURE 33.18** You need to choose a course and display the students enrolled in the course.

| SSN      | First Name | MI | Last Name | Phone      | Birth Date | Dept |
|----------|------------|----|-----------|------------|------------|------|
| 44411110 | Jacob      | R  | Smith     | 9129219434 | 1985-04-09 | BIOL |
| 44411111 | John       | K  | Stevenson | 9129219434 |            | BIOL |
| 44411113 | Frank      | E  | Jones     | 9125919434 | 1970-09-09 | BIOL |
| 44411118 | Toni       | R  | Peterson  | 9129229434 | 1964-04-29 | MATH |

**FIGURE 33.19** The table displays the students enrolled in the course.

are bound to the combo box and the query result for the students enrolled in the course is bound to the table.

Here are the steps to create this project:

Managed bean

Step 1. Create a managed bean named **courseName** with application scope, as shown in Listing 33.13.

JSF page

Step 2. Create a JSF page in Listing 33.14, **DisplayStudent.xhtml**.

style sheet

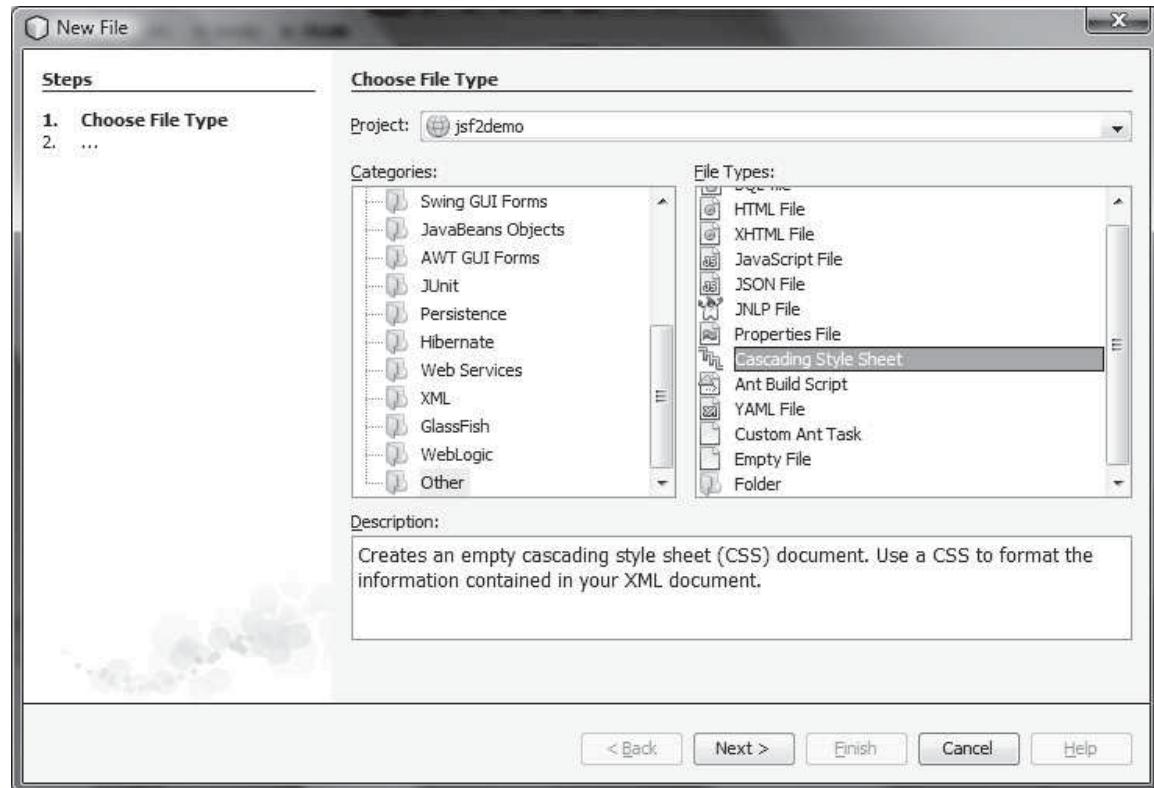
Step 3. Create a cascading style sheet for formatting the table as follows:

Step 3.1. Right-click the **resources** node to choose *New, Others* to display the New File dialog box, as shown in Figure 33.20.

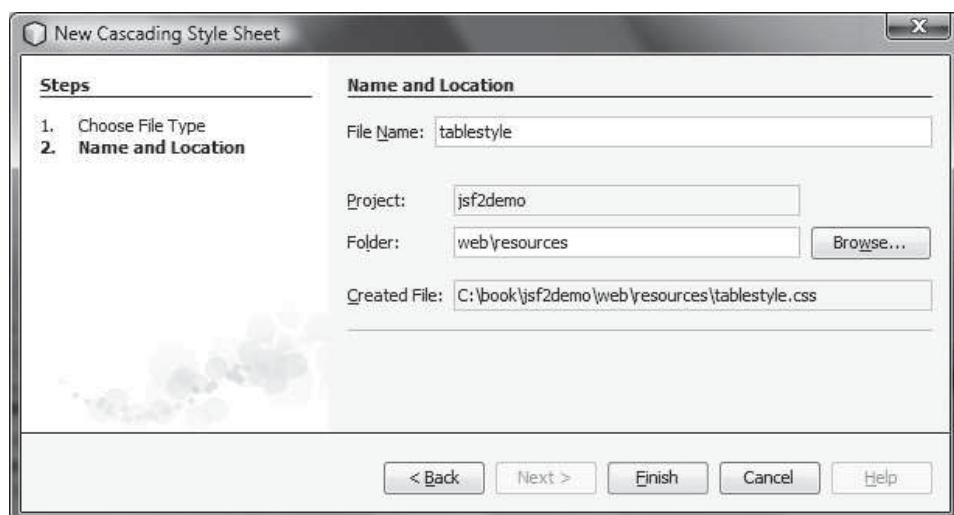
Step 3.2. Choose **Other** in the Categories section and **Cascading Style Sheet** in the File Types section to display the New Cascading Style Sheet dialog box, as shown in Figure 33.21.

Step 3.3. Enter **tablestyle** as the File Name and click *Finish* to create tablestyle.css under the resources node.

Step 3.4. Define the CSS style as shown in Listing 33.15.



**FIGURE 33.20** You can create CSS files for Web project in NetBenas.



**FIGURE 33.21** The New Cascading Style Sheet dialog box creates a new style sheet file.

**LISTING 33.13 CourseNameJSFBean.java**

```

1 package jsf2demo;
2
3 import java.sql.*;
4 import java.util.ArrayList;
5 import javax.enterprise.context.ApplicationScoped;
6 import javax.inject.Named;
7
8 @Named(value = "courseName")
9 @ApplicationScoped
10 public class CourseNameJSFBean {
11 private PreparedStatement studentStatement = null;
12 private String choice; // Selected course
13 private String[] titles; // Course titles
14
15 /** Creates a new instance of CourseName */
16 public CourseNameJSFBean() {
17 initializeJdbc();
18 }
19
20 /** Initialize database connection */
21 private void initializeJdbc() {
22 try {
23 Class.forName("com.mysql.jdbc.Driver");
24 System.out.println("Driver Loaded");
25
26 // Connect to the sample database
27 Connection connection = DriverManager.getConnection(
28 "jdbc:mysql://localhost/javabook", "scott", "tiger");
29
30 // Get course titles
31 PreparedStatement statement = connection.prepareStatement(
32 "select title from course");
33
34 ResultSet resultSet = statement.executeQuery();
35
36 // Store resultSet into array titles
37 ArrayList<String> list = new ArrayList<>();
38 while (resultSet.next()) {
39 list.add(resultSet.getString(1));
40 }
41 titles = new String[list.size()]; // Array for titles
42 list.toArray(titles); // Copy strings from list to array
43
44 // Define a SQL statement for getting students
45 studentStatement = connection.prepareStatement(
46 "select Student.ssn, "
47 + "student.firstName, Student.mi, Student.lastName, "
48 + "Student.phone, Student.birthDate, Student.street, "
49 + "Student.zipCode, Student.deptId "
50 + "from Student, Enrollment, Course "
51 + "where Course.title = ? "
52 + "and Student.ssn = Enrollment.ssn "
53 + "and Enrollment.courseId = Course.courseId;");
54 }
55 catch (Exception ex) {
56 ex.printStackTrace();
57 }
58 }

```

application scope

initialize JDBC

connect to database

get course titles

execute SQL

titles array

```

59
60 public String[] getTitles() {
61 return titles;
62 }
63
64 public String getChoice() {
65 return choice;
66 }
67
68 public void setChoice(String choice) {
69 this.choice = choice;
70 }
71
72 public ResultSet getStudents() throws SQLException { get students
73 if (choice == null) {
74 if (titles.length == 0)
75 return null;
76 else
77 studentStatement.setString(1, titles[0]); set a default course
78 }
79 else {
80 studentStatement.setString(1, choice); // Set course title set a course
81 }
82
83 // Get students for the specified course
84 return studentStatement.executeQuery(); return students
85 }
86 }
```

We use the same MySQL database **javabook** created in Chapter 32, “Java Database Programming.” The scope for this managed bean is **application**. The bean is created when the project is launched from the server. The **initializeJdbc** method loads the JDBC driver for MySQL (lines 23–24), connects to the MySQL database (lines 27–28), creates statement for obtaining course titles (lines 31–32), and creates a statement for obtaining the student information for the specified course (lines 45–53). Lines 31–42 execute the statement for obtaining course titles and store them in array **titles**.

The **getStudents()** method returns a **ResultSet** that consists of all students enrolled in the specified course (lines 72–85). The choice for the title is set in the statement to obtain the student for the specified title (line 80). If choice is **null**, the first title in the titles array is set in the statement (line 77). If no titles in the course, **getStudents()** returns **null** (line 75).



### TIP

In order to use the MySQL database from this project, you have to add the MySQL JDBC driver from the Libraries node in the Project pane in NetBeans.

add MySQL in the Libraries node

### LISTING 33.14 DisplayStudent.xhtml

```

1 <?xml version='1.0' encoding='UTF-8' ?>
2 <!DOCTYPE html PUBLIC "-//W3C//DTD XHTML 1.0 Transitional//EN"
3 "http://www.w3.org/TR/xhtml1/DTD/xhtml1-transitional.dtd">
4 <html xmlns="http://www.w3.org/1999/xhtml"
5 xmlns:h="http://xmlns.jcp.org/jsf/html"
6 xmlns:f="http://xmlns.jcp.org/jsf/core">
7 <h:head>
8 <title>Display Student</title>
9 <h:outputstylesheet name="tablestyle.css" /> style sheet
10 </h:head>
11 <h:body>
```

```

12 <h:form>
13 <h:outputLabel value="Choose a Course: " />
14 <h:selectOneMenu value="#{courseName.choice}">
15 <f:selectItems value="#{courseName.titles}" />
16 </h:selectOneMenu>
17
18 <h:commandButton style="margin-left: 20px"
19 value="Display Students" />
20
21

22 <h:dataTable value="#{courseName.students}" var="student"
23 rowClasses="oddTableRow, evenTableRow"
24 headerClass="tableHeader"
25 styleClass="table">
26 <h:column>
27 <f:facet name="header">SSN</f:facet>
28 #{student.ssn}
29 </h:column>
30
31 <h:column>
32 <f:facet name="header">First Name</f:facet>
33 #{student.firstName}
34 </h:column>
35
36 <h:column>
37 <f:facet name="header">MI</f:facet>
38 #{student.mi}
39 </h:column>
40
41 <h:column>
42 <f:facet name="header">Last Name</f:facet>
43 #{student.lastName}
44 </h:column>
45
46 <h:column>
47 <f:facet name="header">Phone</f:facet>
48 #{student.phone}
49 </h:column>
50
51 <h:column>
52 <f:facet name="header">Birth Date</f:facet>
53 #{student.birthDate}
54 </h:column>
55
56 <h:column>
57 <f:facet name="header">Dept</f:facet>
58 #{student.deptId}
59 </h:column>
60 </h:dataTable>
61 </h:form>
62 </h:body>
63 </html>

```

Line 9 specifies that the style sheet `tablestyle.css` created in Step 3 is used in this XMTHL file. The `rowClasses = "oddTableRow, evenTableRow"` attribute specifies the style applied to the rows alternately using `oddTableRow` and `evenTableRow` (line 23). The `headerClasses = "tableHeader"` attribute specifies that the `tableHeader` class is used for header style (line 24). The `styleClasses = "table"` attribute specifies that the `table` class is used for the style of all other elements in the table (line 25).

Line 14 binds the `choice` property in the `courseName` bean with the combo box. The selection values in the combo box are bound with the `titles` array property (line 15).

Line 22 binds the table value with a database result set using the attribute `value="#{courseName.students}"`. The `var="student"` attribute associates a row in the result set with `student`. Lines 26–59 specify the column values using `student.ssn` (line 28), `student.firstName` (line 33), `student.mi` (line 38), `student.lastName` (line 33), `student.phone` (line 48), `student.birthDate` (line 53), and `student.deptId` (line 58).

### LISTING 33.15 tablestyle.css

```

1 /* Style for table */
2 .tableHeader { tableHeader
3 font-family:"Trebuchet MS", Arial, Helvetica, sans-serif;
4 border-collapse:collapse;
5 font-size:1.1em;
6 text-align:left;
7 padding-top:5px;
8 padding-bottom:4px;
9 background-color:#A7C942;
10 color:white;
11 border:1px solid #98bf21;
12 }
13
14 .oddTableRow { oddTableRow
15 border:1px solid #98bf21;
16 }
17
18 .evenTableRow { evenTableRow
19 background-color: #eeeeee;
20 font-size:1em;
21
22 padding:3px 7px 2px 7px;
23
24 color:#000000;
25 background-color:#EAF2D3;
26 }
27
28 .table { table
29 border:1px solid green;
30 }
```

The style sheet file defines the style classes `tableHeader` (line 2) for table header style, `oddTableRow` for odd table rows (line 14), `evenTableRow` for even table rows (line 18), and `table` for all other table elements (line 28).

## 33.9 Opening New JSF Pages

*You can open new JSF pages from the current JSF pages.*

All the examples you have seen so far use only one JSF page in a project. Suppose you want to register student information to the database. The application first displays the page as shown in Figure 33.22 to collect student information. After the user enters the information and clicks the *Submit* button, a new page is displayed to ask the user to confirm the input, as shown in Figure 33.23. If the user clicks the *Confirm* button, the data are stored into the database and the status page is displayed, as shown in Figure 33.24. If the user clicks the *Go Back* button, it goes back to the first page.



**Student Registration Form**

Please register to your instructor's student address book.

Last Name  First Name  MI

Telephone  Email

Street

City  State  Zip

Last Name and First Name are required

**FIGURE 33.22** This page lets the user enter input.

You entered

Last Name: Smith  
First Name: John  
MI: C  
Telephone: 213549989  
Email: smith@gmail.com  
Street: 100 Main Street  
City: Atlanta  
Street: 100 Main Street  
City: Atlanta  
State: GA  
Zip: 34313

**FIGURE 33.23** This page lets the user confirm the input.

**Address Stored?**

John Smith is now registered in the database.

**FIGURE 33.24** This page displays the status of the user input.

For this project, you need to create three JSF pages named AddressRegistration.xhtml, ConfirmAddress.xhtml, AddressStoredStatus.xhtml in Listings 33.16–33.18. The project starts with AddressRegistration.xhtml. When clicking the *Submit* button, the action for the button returns "ConfirmAddress" if the last name and first name are not empty, which causes ConfirmAddress.xhtml to be displayed. When clicking the *Confirm* button, the status page AddressStoredStatus is displayed. When clicking the *Go Back* button, the first page AddressRegistration is now displayed.

### LISTING 33.16 AddressRegistration.xhtml

```

1 <?xml version='1.0' encoding='UTF-8' ?>
2 <!DOCTYPE html PUBLIC "-//W3C//DTD XHTML 1.0 Transitional//EN"
3 "http://www.w3.org/TR/xhtml1/DTD/xhtml1-transitional.dtd">
4 <html xmlns="http://www.w3.org/1999/xhtml"
5 xmlns:h="http://xmlns.jcp.org/jsf/html"
6 xmlns:f="http://xmlns.jcp.org/jsf/core"> jsf core namespace
7 <h:head>
8 <title>Student Registration Form</title>
9 </h:head>
10 <h:body>
11 <h:form>
12 <!-- Use h:graphicImage -->
13 <h3>Student Registration Form
14 <h:graphicImage name="usIcon.gif" library="image"/>
15 </h3>
16
17 Please register to your instructor's student address book.
18 <!-- Use h:panelGrid -->
19 <h:panelGrid columns="6">
20 <h:outputLabel value="Last Name" style="color:red"/>
21 <h:inputText id="lastNameInputText"
22 value="#{addressRegistration.lastName}"> bind lastName
23 <h:outputLabel value="First Name" style="color:red"/>
24 <h:inputText id="firstNameInputText"
25 value="#{addressRegistration.firstName}"> bind firstName
26 <h:outputLabel value="MI" />
27 <h:inputText id="miInputText" size="1"
28 value="#{addressRegistration.mi}"> bind mi
29 </h:panelGrid>
30
31 <h:panelGrid columns="4">
32 <h:outputLabel value="Telephone"/>
33 <h:inputText id="telephoneInputText"
34 value="#{addressRegistration.telephone}"> bind telephone
35 <h:outputLabel value="Email"/>
36 <h:inputText id="emailInputText"
37 value="#{addressRegistration.email}"> bind email
38 </h:panelGrid>
39
40 <h:panelGrid columns="4">
41 <h:outputLabel value="Street"/>
42 <h:inputText id="streetInputText"
43 value="#{addressRegistration.street}"> bind street
44 </h:panelGrid>
45
46 <h:panelGrid columns="6">
47 <h:outputLabel value="City"/>
48 <h:inputText id="cityInputText"
49 value="#{addressRegistration.city}"> bind city

```

```

50 <h:outputLabel value="State"/>
51 <h:selectOneMenu id="stateSelectOneMenu"
bind state value="#{addressRegistration.state}">
52 <f:selectItem itemLabel="Georgia-GA" itemValue="GA" />
53 <f:selectItem itemLabel="Oklahoma-OK" itemValue="OK" />
54 <f:selectItem itemLabel="Indiana-IN" itemValue="IN"/>
55 </h:selectOneMenu>
56 <h:outputLabel value="Zip"/>
57 <h:inputText id="zipInputText"
bind zip value="#{addressRegistration.zip}" />
58 </h:panelGrid>
59
60 <!-- Use command button -->
61 <h:commandButton value="Register"
process register action="#{addressRegistration.processSubmit()}" />
62

63 <h:outputText escape="false" style="color:red"
64 value="#{addressRegistration.requiredFields}" />
65 </h:form>
66 </h:body>
67 </html>

```

**LISTING 33.17 ConfirmAddress.xhtml**

```

1 <?xml version='1.0' encoding='UTF-8' ?>
2 <!DOCTYPE html PUBLIC "-//W3C//DTD XHTML 1.0 Transitional//EN"
3 "http://www.w3.org/TR/xhtml1/DTD/xhtml1-transitional.dtd">
4 <html xmlns="http://www.w3.org/1999/xhtml"
5 xmlns:h="http://xmlns.jcp.org/jsf/html">
6 <h:head>
7 <title>Confirm Student Registration</title>
8 </h:head>
9 <h:body>
10 <h:form>
11 <h:outputText escape="false" style="color:red"
12 value="#{registration1.input}" />
13 <h:panelGrid columns="2">
14 <h:commandButton value="Confirm"
15 action = "#{registration1.storeStudent()}" />
16 <h:commandButton value="Go Back"
17 action = "AddressRegistration" />
18 </h:panelGrid>
19 </h:form>
20 </h:body>
21 </html>

```

**LISTING 33.18 AddressStoredStatus.xhtml**

```

1 <?xml version='1.0' encoding='UTF-8' ?>
2 <!DOCTYPE html PUBLIC "-//W3C//DTD XHTML 1.0 Transitional//EN"
3 "http://www.w3.org/TR/xhtml1/DTD/xhtml1-transitional.dtd">
4 <html xmlns="http://www.w3.org/1999/xhtml"
5 xmlns:h="http://xmlns.jcp.org/jsf/html">
6 <h:head>
7 <title>Address Stored?</title>
8 </h:head>
9 <h:body>
10 <h:form>
11 <h:outputText escape="false" style="color:green"
12 value="#{registration1.status}" />

```

display status

```

13 </h:form>
14 </h:body>
15 </html>
```

**LISTING 33.19 AddressRegistrationJSFBean.java**

```

1 package jsf2demo;
2
3 import javax.inject.Named;
4 import javax.enterprise.context.SessionScoped;
5 import java.sql.*;
6 import java.io.Serializable;
7
8 @Named(value = "addressRegistration")
9 @SessionScoped
10 public class AddressRegistrationJSFBean implements Serializable {
11 private String lastName;
12 private String firstName;
13 private String mi;
14 private String telephone;
15 private String email;
16 private String street;
17 private String city;
18 private String state;
19 private String zip;
20 private String status = "Nothing stored";
21 // Use a prepared statement to store a student into the database
22 private PreparedStatement pstmt;
23
24 public AddressRegistrationJSFBean() {
25 initializeJdbc();
26 }
27
28 public String getLastName() {
29 return lastName;
30 }
31
32 public void setLastName(String lastName) {
33 this.lastName = lastName;
34 }
35
36 public String getFirstName() {
37 return firstName;
38 }
39
40 public void setFirstName(String firstName) {
41 this.firstName = firstName;
42 }
43
44 public String getMi() {
45 return mi;
46 }
47
48 public void setMi(String mi) {
49 this.mi = mi;
50 }
51
52 public String getTelephone() {
53 return telephone;
54 }
```

managed bean  
session scope  
property lastName  
initialize database

```

55
56 public void setTelephone(String telephone) {
57 this.telephone = telephone;
58 }
59
60 public String getEmail() {
61 return email;
62 }
63
64 public void setEmail(String email) {
65 this.email = email;
66 }
67
68 public String getStreet() {
69 return street;
70 }
71
72 public void setStreet(String street) {
73 this.street = street;
74 }
75
76 public String getCity() {
77 return city;
78 }
79
80 public void setCity(String city) {
81 this.city = city;
82 }
83
84 public String getState() {
85 return state;
86 }
87
88 public void setState(String state) {
89 this.state = state;
90 }
91
92 public String getZip() {
93 return zip;
94 }
95
96 public void setZip(String zip) {
97 this.zip = zip;
98 }
99
100 private boolean isRequiredFieldsFilled() {
101 return !(lastName == null || firstName == null
102 || lastName.trim().length() == 0
103 || firstName.trim().length() == 0);
104 }
105
106 public String processSubmit() {
107 if (isRequiredFieldsFilled())
108 return "ConfirmAddress";
109 else
110 return "";
111 }
112
113 public String getRequiredFields() {
114 if (isRequiredFieldsFilled())

```

go to a new page

check required fields

```

115 return "";
116 else
117 return "Last Name and First Name are required";
118 }
119
120 public String getInput() { get input
121 return "<p style=\"color:red\">You entered
" +
122 + "Last Name: " + lastName + "
" +
123 + "First Name: " + firstName + "
" +
124 + "MI: " + mi + "
" +
125 + "Telephone: " + telephone + "
" +
126 + "Email: " + email + "
" +
127 + "Street: " + street + "
" +
128 + "City: " + city + "
" +
129 + "Street: " + street + "
" +
130 + "City: " + city + "
" +
131 + "State: " + state + "
" +
132 + "Zip: " + zip + "</p>";
133 }
134
135 /** Initialize database connection */
136 private void initializeJdbc() {
137 try {
138 // Explicitly load a MySQL driver
139 Class.forName("com.mysql.jdbc.Driver");
140 System.out.println("Driver loaded");
141
142 // Establish a connection
143 Connection conn = DriverManager.getConnection(
144 "jdbc:mysql://localhost/javabook", "scott", "tiger");
145
146 // Create a Statement
147 pstmt = conn.prepareStatement("insert into Address (lastName,"
148 + " firstName, mi, telephone, email, street, city, "
149 + "state, zip) values (?, ?, ?, ?, ?, ?, ?, ?, ?, ?)");
150 }
151 catch (Exception ex) {
152 System.out.println(ex);
153 }
154 }
155
156 /** Store an address to the database */
157 public String storeStudent() { store address
158 try {
159 pstmt.setString(1, lastName);
160 pstmt.setString(2, firstName);
161 pstmt.setString(3, mi);
162 pstmt.setString(4, telephone);
163 pstmt.setString(5, email);
164 pstmt.setString(6, street);
165 pstmt.setString(7, city);
166 pstmt.setString(8, state);
167 pstmt.setString(9, zip);
168 pstmt.executeUpdate();
169 status = firstName + " " + lastName update status
170 + " is now registered in the database.";
171 }
172 catch (Exception ex) {
173 status = ex.getMessage();
174 }

```

```

175
176 return "AddressStoredStatus";
177 }
178
179 public String getStatus() {
180 return status;
181 }
182 }
```

A session-scoped managed bean must implement the `java.io.Serializable` interface. So, the `AddressRegistration` class is defined as a subtype of `java.io.Serializable`.

The action for the *Register* button in the `AddressRegistration` JSF page is `processSubmit()` (line 64 in `AddressRegistration.xhtml`). This method checks if last name and first name are not empty (lines 106–111 in `AddressRegistrationJSFBean.java`). If so, it returns a string "`ConfirmAddress`", which causes the `ConfirmAddress` JSF page to be displayed.

The `ConfirmAddress` JSF page displays the data entered from the user (line 12 in `ConfirmAddress.xhtml`). The `getInput()` method (lines 120–133 in `AddressRegistrationJSFBean.java`) collects the input.

The action for the *Confirm* button in the `ConfirmAddress` JSF page is `storeStudent()` (line 15 in `ConfirmAddress.xhtml`). This method stores the address in the database (lines 157–177 in `AddressRegistrationJSFBean.java`) and returns a string "`AddressStoredStatus`", which causes the `AddressStoredStatus` page to be displayed. The status message is displayed in this page (line 12 in `AddressStoredStatus.xhtml`).

The action for the *Go Back* button in the `ConfirmAddress` page is "`AddressRegistration`" (line 17 in `ConfirmAddress.xhtml`). This causes the `AddressRegistration` page to be displayed for the user to reenter the input.

The scope of the managed bean is session (line 9 `AddressRegistrationJSFBean.java`) so the multiple pages can share the same bean.

Note that this program loads the database driver explicitly (line 139 `AddressRegistrationJSFBean.java`). Sometimes, an IDE such as NetBeans is not able to find a suitable driver. Loading a driver explicitly can avoid this problem.

## KEY TERMS

---

application scope 1233  
JavaBean 1217  
request scope 1233

scope 1233  
session scope 1233  
view scope 1233

## CHAPTER SUMMARY

---

1. JSF enables you to completely separate Java code from HTML.
2. A **facelet** is an XHTML page that mixes JSF tags with XHTML tags.
3. JSF applications are developed using the Model-View-Controller (MVC) architecture, which separates the application's data (contained in the model) from the graphical presentation (the view).
4. The controller is the JSF framework that is responsible for coordinating interactions between view and the model.

5. In JSF, the facelets are the view for presenting data. Data are obtained from Java objects. Objects are defined using Java classes.
6. In JSF, the objects that are accessed from a facelet are JavaBeans objects.
7. The JSF expression can either use the property name or invoke the method to obtain the current time.
8. JSF provides many elements for displaying GUI components. The tags with the **h** prefix are in the JSF HTML Tag library. The tags with the **f** prefix are in the JSF Core Tag library.
9. You can specify the JavaBeans objects at the application scope, session scope, view scope, or request scope.
10. The view scope keeps the bean alive as long as you stay on the view. The view scope is between session and request scopes.
11. JSF provides several convenient and powerful ways for input validation. You can use the standard validator tags in the JSF Core Tag Library or create custom validators.

## Quiz

---

Answer the quiz for this chapter online at [www.cs.armstrong.edu/liang/intro10e/quiz.html](http://www.cs.armstrong.edu/liang/intro10e/quiz.html).

## PROGRAMMING EXERCISES

---

MyProgrammingLab™

- \*33.1 (*Factorial table in JSF*) Write a JSF page that displays a factorial page as shown in Figure 33.25. Display the table in an **h:outputText** component. Set its **escape** property to **false** to display it as HTML contents.
- \*33.2 (*Multiplication table*) Write a JSF page that displays a multiplication table as shown in Figure 33.26.
- \*33.3 (*Calculate tax*) Write a JSF page to let the user enter taxable income and filing status, as shown in Figure 33.27a. Clicking the *Compute Tax* button computes and displays the tax, as shown in Figure 33.27b. Use the **computeTax** method introduced in Listing 3.5, ComputeTax.java, to compute tax.
- \*33.4 (*Calculate loan*) Write a JSF page that lets the user enter loan amount, interest rate, and number of years, as shown in Figure 33.28a. Click the *Compute Loan Payment* button to compute and display the monthly and total loan payments, as shown in Figure 33.28b. Use the **Loan** class given in Listing 10.2, Loan.java, to compute the monthly and total payments.
- \*33.5 (*Addition quiz*) Write a JSF program that generates addition quizzes randomly, as shown in Figure 33.29a. After the user answers all questions, it displays the result, as shown in Figure 33.29b.
- \*33.6 (*Large factorial*) Rewrite Exercise 33.1 to handle large factorial. Use the **BigInteger** class introduced in Section 10.9.
- \*33.7 (*Guess birthday*) Listing 4.3, GuessBirthday.java, gives a program for guessing a birthday. Write a JSF program that displays five sets of numbers, as shown in Figure 33.30a. After the user checks the appropriate boxes and clicks the *Guess Birthday* button, the program displays the birthday, as shown in Figure 33.30b.

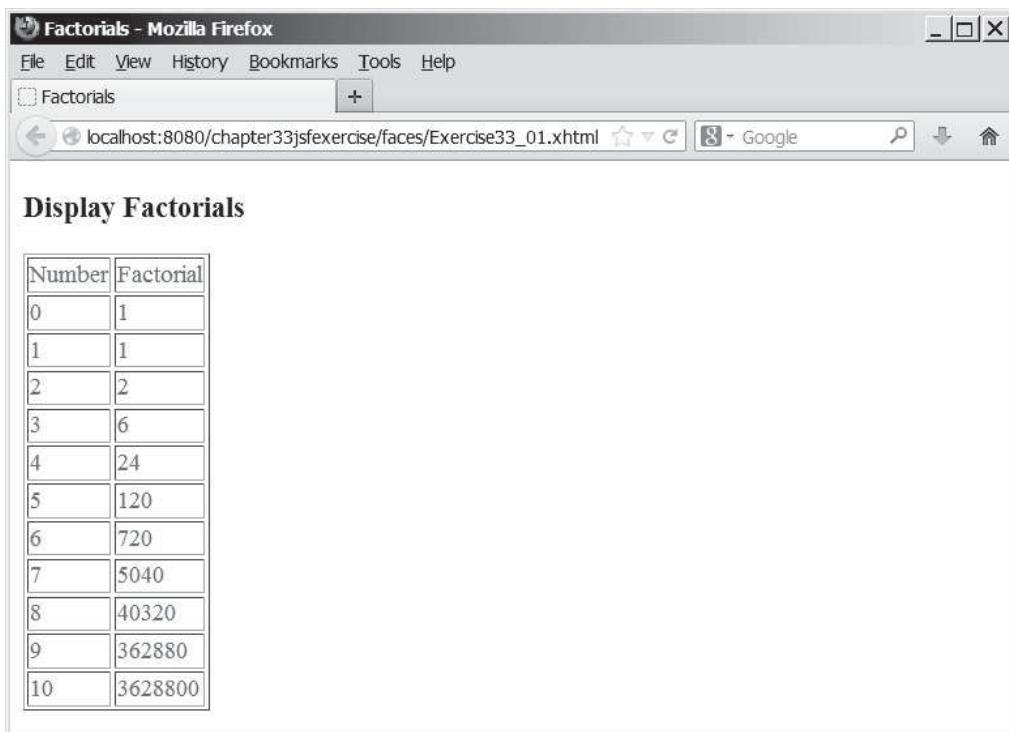
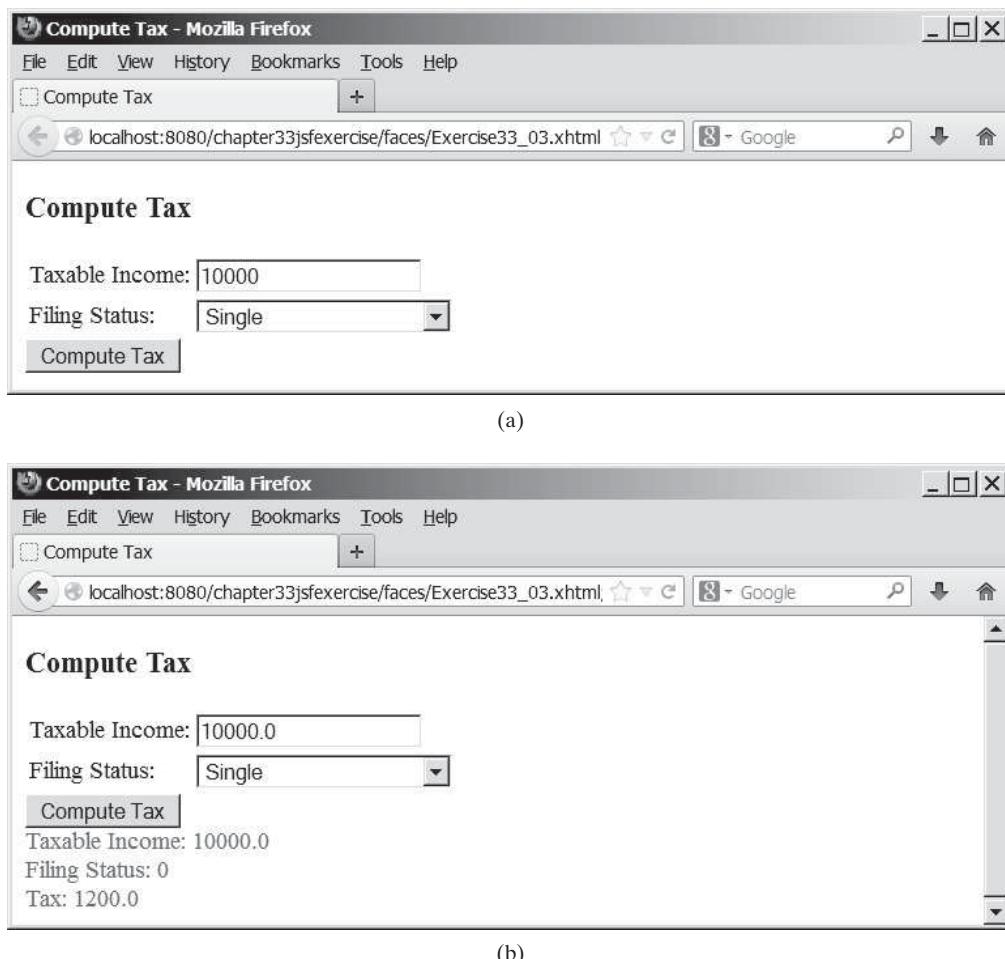


FIGURE 33.25 The JSF page displays factorials for the numbers from 0 to 10 in a table.



FIGURE 33.26 The JSF page displays the multiplication table.



The figure consists of two screenshots of a Mozilla Firefox browser window. Both windows show a JSF page titled "Compute Tax". The page contains two input fields: "Taxable Income" with the value "10000" and "Filing Status" set to "Single". Below these fields is a "Compute Tax" button. In the first screenshot (a), the button is a standard grey color. In the second screenshot (b), the button is highlighted in blue, indicating it has been clicked. The browser's menu bar, toolbar, and address bar are visible at the top of both windows.

**FIGURE 33.27** The JSF page computes the tax.

**\*33.8** (*Guess capitals*) Write a JSF that prompts the user to enter a capital for a state, as shown in Figure 33.31a. Upon receiving the user input, the program reports whether the answer is correct, as shown in Figure 33.31b. You can click the *Next* button to display another question. You can use a two-dimensional array to store the states and capitals, as proposed in Exercise 8.37. Create a list from the array and apply the **shuffle** method to reorder the list so the questions will appear in random order.

**\*33.9** (*Access and update a Staff table*) Write a JSF program that views, inserts, and updates staff information stored in a database, as shown in Figure 33.32. The view button displays a record with a specified ID. The **Staff** table is created as follows:

```
create table Staff (
 id char(9) not null,
 lastName varchar(15),
 firstName varchar(15),
 mi char(1),
 address varchar(20),
 city varchar(20),
```

```

state char(2),
telephone char(10),
email varchar(40),
primary key (id)
);

```

- \*33.10** (*Random cards*) Write a JSF that displays four random cards from a deck of 52 cards, as shown in Figure 33.33. When the user clicks the *Refresh* button, four new random cards are displayed.
- \*\*\*33.11** (*Game: the 24-point card game*) Rewrite Exercise 20.13 using JSF, as shown in Figure 33.34. Upon clicking the *Refresh* button, the program displays four random cards and displays an expression if a 24-point solution exists. Otherwise, it displays **No solution**.
- \*\*\*33.12** (*Game: the 24-point card game*) Rewrite Exercise 20.17 using JSF, as shown in Figure 33.35. The program lets the user enter four card values and finds a solution upon clicking the *Find a Solution* button.

Exercise33\_04 - Mozilla Firefox

File Edit View History Bookmarks Tools Help

Exercise33\_04

localhost:8080/chapter33jsfexercise/faces/Exercise33\_04.xhtml

Compute Loan Payment

Loan Amount:

Annual Interest Rate:

Number of Years:

Compute Loan Payment | Reset |

(a)

Exercise33\_04 Result - Mozilla Firefox

File Edit View History Bookmarks Tools Help

Exercise33\_04 Result

localhost:8080/chapter33jsfexercise/faces/Exercise33\_04.xhtml

Loan Amount: 10000.0  
Annual Interest Rate: 5.0  
Number of Years: 15  
Monthly Payment: 79.07936267415464  
Monthly Payment: 14234.285281347835

(b)

**FIGURE 33.28** The JSF page computes the loan payment.

**Exercise33\_05 - Mozilla Firefox**

File Edit View History Bookmarks Tools Help

Exercise33\_05 +

localhost:8080/chapter33jsfexercise/faces/Exercise33\_05.xhtml Google

20 + 3 = 23  
 17 + 3 = 20  
 16 + 5 = 21  
 14 + 7 = 21  
 22 + 5 = 27  
 26 + 5 = 5  
 11 + 1 = 5  
 21 + 0 = 5  
 14 + 8 = 5  
 12 + 2 = 5

Submit Generate New Questions

(a)

**Addition Quiz - Mozilla Firefox**

File Edit View History Bookmarks Tools Help

Addition Quiz +

localhost:8080/chapter33jsfexercise/faces/Exercise33\_05.xhtml Google

20 + 3 = 23 Correct  
 17 + 3 = 20 Correct  
 16 + 5 = 21 Correct  
 14 + 7 = 21 Correct  
 22 + 5 = 27 Correct  
 26 + 5 = 5 Wrong  
 11 + 1 = 5 Wrong  
 21 + 0 = 5 Wrong  
 14 + 8 = 5 Wrong  
 12 + 2 = 5 Wrong

There are 5 correct guesses

(b)

**FIGURE 33.29** The program displays addition questions in (a) and answers in (b).

**\*33.13** (*Day of week*) Write a program that displays the day of the week for a given day, month, and year, as shown in Figure 33.36. The program lets the user select a day, month, and year, and click the *Get Day of Week* button to display the day of week. The Time field displays Future if it is a future day or Past otherwise. Use the Zeller's congruence to find the day of the week (See Programming Exercise 3.21).

**Guess Birthday - Mozilla Firefox**

File Edit View History Bookmarks Tools Help

Guess Birthday

localhost:8080/chapter33jsfexercise/faces/Exercise33\_07.xhtml

Check the boxes if your birthday is in these sets

|                          |                                     |                          |                                     |                          |
|--------------------------|-------------------------------------|--------------------------|-------------------------------------|--------------------------|
| 01 03 05 07              | 02 03 06 07                         | 04 05 06 07              | 08 09 10 11                         | 16 17 18 19              |
| 09 11 13 15              | 10 11 14 15                         | 12 13 14 15              | 12 13 14 15                         | 20 21 22 23              |
| 17 19 21 23              | 18 19 22 23                         | 20 21 22 23              | 24 25 26 27                         | 24 25 26 27              |
| 25 27 29 31              | 26 27 30 31                         | 28 29 30 31              | 28 29 30 31                         | 28 29 30 31              |
| <input type="checkbox"/> | <input checked="" type="checkbox"/> | <input type="checkbox"/> | <input checked="" type="checkbox"/> | <input type="checkbox"/> |

Guess Birthday

(a)

**Guess Birthday - Mozilla Firefox**

File Edit View History Bookmarks Tools Help

Guess Birthday

localhost:8080/chapter33jsfexercise/faces/Exercise33\_07.xhtml

Check the boxes if your birthday is in these sets

|                          |                                     |                          |                                     |                          |
|--------------------------|-------------------------------------|--------------------------|-------------------------------------|--------------------------|
| 01 03 05 07              | 02 03 06 07                         | 04 05 06 07              | 08 09 10 11                         | 16 17 18 19              |
| 09 11 13 15              | 10 11 14 15                         | 12 13 14 15              | 12 13 14 15                         | 20 21 22 23              |
| 17 19 21 23              | 18 19 22 23                         | 20 21 22 23              | 24 25 26 27                         | 24 25 26 27              |
| 25 27 29 31              | 26 27 30 31                         | 28 29 30 31              | 28 29 30 31                         | 28 29 30 31              |
| <input type="checkbox"/> | <input checked="" type="checkbox"/> | <input type="checkbox"/> | <input checked="" type="checkbox"/> | <input type="checkbox"/> |

Guess Birthday 10

(b)

**FIGURE 33.30** (a) The program displays five sets of numbers for the user to check the boxes. (b) The program displays the date.

**Exercise 33.8- Guess the State Capitals - Mozilla Firefox**

File Edit View History Bookmarks Tools Help

Exercise 33.8- Guess the State Ca...

localhost:8080/chapter33jsfexercise/faces/Exercise33\_08.xhtml

What is the capital of Delaware?  Submit

(a)

**Exercise 33.8- Guess the State Capitals - Mozilla Firefox**

File Edit View History Bookmarks Tools Help

Exercise 33.8- Guess the State Ca...

localhost:8080/chapter33jsfexercise/faces/Exercise33\_08.xhtml

No. The capital of Delaware is Dover.

[Next](#)

(b)

**FIGURE 33.31** (a) The program displays a question. (b) The program displays the answer to the question.

**Staff Information**

ID:

Last Name  First Name  MI

Address

City  State

Telephone

**Staff Information**

ID:

Last Name  First Name  MI

Address

City  State

Telephone

FIGURE 33.32 The web page lets you view, insert, and update staff information.

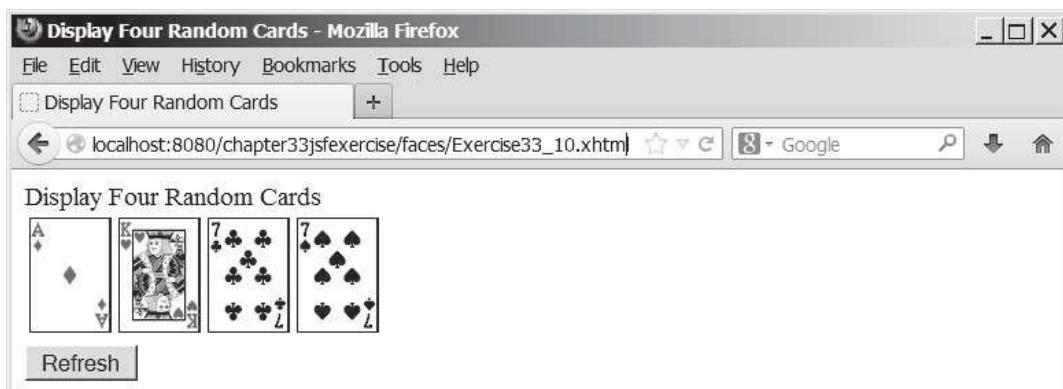
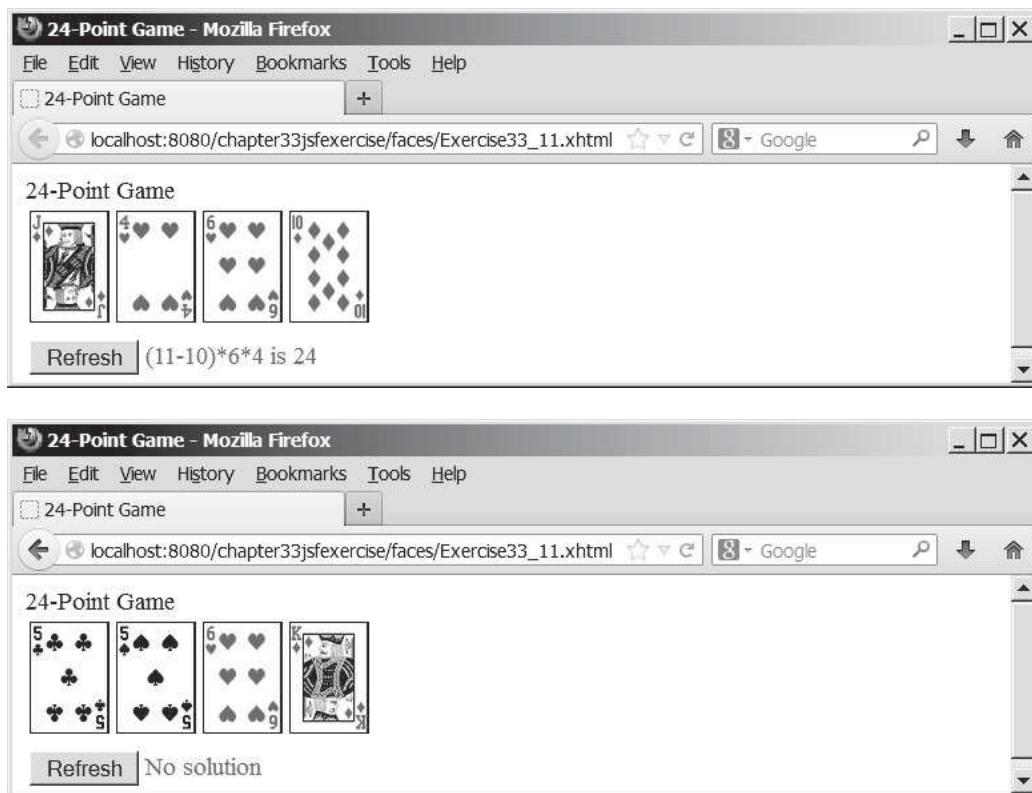
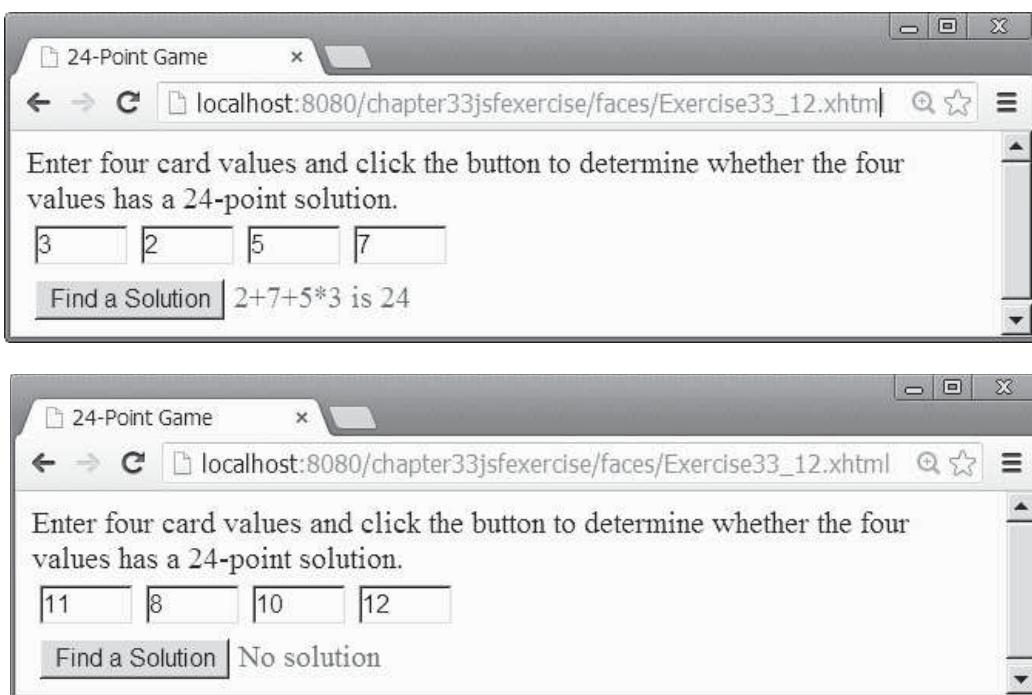


FIGURE 33.33 This JSF application displays four random cards.



**FIGURE 33.34** The JSF application solves a 24-Point card game.



**FIGURE 33.35** The user enters four numbers and the program finds a solution.



**FIGURE 33.36** The user enters a day, month, and year and the program finds the day of the week.

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# APPENDIXES

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## **Appendix A**

Java Keywords

## **Appendix B**

The ASCII Character Set

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## **Appendix I**

Enumerated Types

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# APPENDIX A

## Java Keywords

The following fifty keywords are reserved for use by the Java language:

|                       |                         |                        |                           |
|-----------------------|-------------------------|------------------------|---------------------------|
| <code>abstract</code> | <code>double</code>     | <code>int</code>       | <code>super</code>        |
| <code>assert</code>   | <code>else</code>       | <code>interface</code> | <code>switch</code>       |
| <code>boolean</code>  | <code>enum</code>       | <code>long</code>      | <code>synchronized</code> |
| <code>break</code>    | <code>extends</code>    | <code>native</code>    | <code>this</code>         |
| <code>byte</code>     | <code>final</code>      | <code>new</code>       | <code>throw</code>        |
| <code>case</code>     | <code>finally</code>    | <code>package</code>   | <code>throws</code>       |
| <code>catch</code>    | <code>float</code>      | <code>private</code>   | <code>transient</code>    |
| <code>char</code>     | <code>for</code>        | <code>protected</code> | <code>try</code>          |
| <code>class</code>    | <code>goto</code>       | <code>public</code>    | <code>void</code>         |
| <code>const</code>    | <code>if</code>         | <code>return</code>    | <code>volatile</code>     |
| <code>continue</code> | <code>implements</code> | <code>short</code>     | <code>while</code>        |
| <code>default</code>  | <code>import</code>     | <code>static</code>    |                           |
| <code>do</code>       | <code>instanceof</code> | <code>strictfp*</code> |                           |

The keywords `goto` and `const` are C++ keywords reserved, but not currently used in Java. This enables Java compilers to identify them and to produce better error messages if they appear in Java programs.

The literal values `true`, `false`, and `null` are not keywords, just like literal value `100`. However, you cannot use them as identifiers, just as you cannot use `100` as an identifier.

In the code listing, we use the keyword color for `true`, `false`, and `null` to be consistent with their coloring in Java IDEs.

---

\*The `strictfp` keyword is a modifier for a method or class that enables it to use strict floating-point calculations. Floating-point arithmetic can be executed in one of two modes: *strict* or *nonstrict*. The strict mode guarantees that the evaluation result is the same on all Java Virtual Machine implementations. The nonstrict mode allows intermediate results from calculations to be stored in an extended format different from the standard IEEE floating-point number format. The extended format is machine-dependent and enables code to be executed faster. However, when you execute the code using the nonstrict mode on different JVMs, you may not always get precisely the same results. By default, the nonstrict mode is used for floating-point calculations. To use the strict mode in a method or a class, add the `strictfp` keyword in the method or the class declaration. Strict floating-point may give you slightly better precision than nonstrict floating-point, but the distinction will only affect some applications. Strictness is not inherited; that is, the presence of `strictfp` on a class or interface declaration does not cause extended classes or interfaces to be strict.

# APPENDIX B

---

## The ASCII Character Set

Tables B.1 and B.2 show ASCII characters and their respective decimal and hexadecimal codes. The decimal or hexadecimal code of a character is a combination of its row index and column index. For example, in Table B.1, the letter **A** is at row 6 and column 5, so its decimal equivalent is 65; in Table B.2, letter **A** is at row 4 and column 1, so its hexadecimal equivalent is 41.

**TABLE B.1** ASCII Character Set in the Decimal Index

|    | <i>0</i> | <i>1</i> | <i>2</i> | <i>3</i> | <i>4</i> | <i>5</i> | <i>6</i> | <i>7</i> | <i>8</i> | <i>9</i> |
|----|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| 0  | nul      | soh      | stx      | etx      | eot      | enq      | ack      | bel      | bs       | ht       |
| 1  | nl       | vt       | ff       | cr       | so       | si       | dle      | dcl      | dc2      | dc3      |
| 2  | dc4      | nak      | syn      | etb      | can      | em       | sub      | esc      | fs       | gs       |
| 3  | rs       | us       | sp       | !        | "        | #        | \$       | %        | &        | ,        |
| 4  | (        | )        | *        | +        | ,        | -        | .        | /        | 0        | 1        |
| 5  | 2        | 3        | 4        | 5        | 6        | 7        | 8        | 9        | :        | ;        |
| 6  | <        | =        | >        | ?        | @        | A        | B        | C        | D        | E        |
| 7  | F        | G        | H        | I        | J        | K        | L        | M        | N        | O        |
| 8  | P        | Q        | R        | S        | T        | U        | V        | W        | X        | Y        |
| 9  | Z        | [        | \        | ]        | ^        | -        | ,        | a        | b        | c        |
| 10 | d        | e        | f        | g        | h        | i        | j        | k        | l        | m        |
| 11 | n        | o        | p        | q        | r        | s        | t        | u        | v        | w        |
| 12 | x        | y        | z        | {        |          | }        | ~        | del      |          |          |

**TABLE B.2** ASCII Character Set in the Hexadecimal Index

|   | <i>0</i> | <i>1</i> | <i>2</i> | <i>3</i> | <i>4</i> | <i>5</i> | <i>6</i> | <i>7</i> | <i>8</i> | <i>9</i> | <i>A</i> | <i>B</i> | <i>C</i> | <i>D</i> | <i>E</i> | <i>F</i> |
|---|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| 0 | nul      | soh      | stx      | etx      | eot      | enq      | ack      | bel      | bs       | ht       | nl       | vt       | ff       | cr       | so       | si       |
| 1 | dle      | dcl      | dc2      | dc3      | dc4      | nak      | syn      | etb      | can      | em       | sub      | esc      | fs       | gs       | rs       | us       |
| 2 | sp       | !        | "        | #        | \$       | %        | &        | '        | (        | )        | *        | +        | ,        | -        | .        | /        |
| 3 | 0        | 1        | 2        | 3        | 4        | 5        | 6        | 7        | 8        | 9        | :        | ;        | <        | =        | >        | ?        |
| 4 | @        | A        | B        | C        | D        | E        | F        | G        | H        | I        | J        | K        | L        | M        | N        | O        |
| 5 | P        | Q        | R        | S        | T        | U        | V        | W        | X        | Y        | Z        | [        | \        | ]        | ^        | -        |
| 6 | ,        | a        | b        | c        | d        | e        | f        | g        | h        | i        | j        | k        | l        | m        | n        | o        |
| 7 | p        | q        | r        | s        | t        | u        | v        | w        | x        | y        | z        | {        |          | }        | ~        | del      |

# APPENDIX C

## Operator Precedence Chart

The operators are shown in decreasing order of precedence from top to bottom. Operators in the same group have the same precedence, and their associativity is shown in the table.

| Operator   | Name                            | Associativity |
|------------|---------------------------------|---------------|
| ( )        | Parentheses                     | Left to right |
| ( )        | Function call                   | Left to right |
| [ ]        | Array subscript                 | Left to right |
| .          | Object member access            | Left to right |
| ++         | Postincrement                   | Left to right |
| --         | Postdecrement                   | Left to right |
| ++         | Preincrement                    | Right to left |
| --         | Predecrement                    | Right to left |
| +          | Unary plus                      | Right to left |
| -          | Unary minus                     | Right to left |
| !          | Unary logical negation          | Right to left |
| (type)     | Unary casting                   | Right to left |
| new        | Creating object                 | Right to left |
| *          | Multiplication                  | Left to right |
| /          | Division                        | Left to right |
| %          | Remainder                       | Left to right |
| +          | Addition                        | Left to right |
| -          | Subtraction                     | Left to right |
| <<         | Left shift                      | Left to right |
| >>         | Right shift with sign extension | Left to right |
| >>>        | Right shift with zero extension | Left to right |
| <          | Less than                       | Left to right |
| <=         | Less than or equal to           | Left to right |
| >          | Greater than                    | Left to right |
| >=         | Greater than or equal to        | Left to right |
| instanceof | Checking object type            | Left to right |

| <i>Operator</i>         | <i>Name</i>               | <i>Associativity</i> |
|-------------------------|---------------------------|----------------------|
| <code>==</code>         | Equal comparison          | Left to right        |
| <code>!=</code>         | Not equal                 | Left to right        |
| <code>&amp;</code>      | (Unconditional AND)       | Left to right        |
| <code>^</code>          | (Exclusive OR)            | Left to right        |
| <code> </code>          | (Unconditional OR)        | Left to right        |
| <code>&amp;&amp;</code> | Conditional AND           | Left to right        |
| <code>  </code>         | Conditional OR            | Left to right        |
| <code>?:</code>         | Ternary condition         | Right to left        |
| <code>=</code>          | Assignment                | Right to left        |
| <code>+=</code>         | Addition assignment       | Right to left        |
| <code>-=</code>         | Subtraction assignment    | Right to left        |
| <code>*=</code>         | Multiplication assignment | Right to left        |
| <code>/=</code>         | Division assignment       | Right to left        |
| <code>%=</code>         | Remainder assignment      | Right to left        |

# APPENDIX D

## Java Modifiers

Modifiers are used on classes and class members (constructors, methods, data, and class-level blocks), but the `final` modifier can also be used on local variables in a method. A modifier that can be applied to a class is called a *class modifier*. A modifier that can be applied to a method is called a *method modifier*. A modifier that can be applied to a data field is called a *data modifier*. A modifier that can be applied to a class-level block is called a *block modifier*. The following table gives a summary of the Java modifiers.

| Modifier                | Class | Constructor | Method | Data | Block | Explanation                                                                                                             |
|-------------------------|-------|-------------|--------|------|-------|-------------------------------------------------------------------------------------------------------------------------|
| <code>(default)*</code> | ✓     | ✓           | ✓      | ✓    | ✓     | A class, constructor, method, or data field is visible in this package.                                                 |
| <code>public</code>     | ✓     | ✓           | ✓      | ✓    |       | A class, constructor, method, or data field is visible to all the programs in any package.                              |
| <code>private</code>    |       | ✓           | ✓      | ✓    |       | A constructor, method, or data field is only visible in this class.                                                     |
| <code>protected</code>  |       | ✓           | ✓      | ✓    |       | A constructor, method, or data field is visible in this package and in subclasses of this class in any package.         |
| <code>static</code>     |       |             | ✓      | ✓    | ✓     | Define a class method, a class data field, or a static initialization block.                                            |
| <code>final</code>      | ✓     |             | ✓      | ✓    |       | A final class cannot be extended. A final method cannot be modified in a subclass.<br>A final data field is a constant. |
| <code>abstract</code>   | ✓     |             |        | ✓    |       | An abstract class must be extended. An abstract method must be implemented in a concrete subclass.                      |
| <code>native</code>     |       |             |        | ✓    |       | A native method indicates that the method is implemented using a language other than Java.                              |

\*Default access doesn't have a modifier associated with it. For example: `class Test {}`

| <i>Modifier</i>     | <i>Class</i> | <i>Constructor</i> | <i>Method</i> | <i>Data</i> | <i>Block</i> | <i>Explanation</i>                                                                                      |
|---------------------|--------------|--------------------|---------------|-------------|--------------|---------------------------------------------------------------------------------------------------------|
| <b>synchronized</b> |              |                    | √             |             | √            | Only one thread at a time can execute this method.                                                      |
| <b>strictfp</b>     |              | √                  |               | √           |              | Use strict floating-point calculations to guarantee that the evaluation result is the same on all JVMs. |
| <b>transient</b>    |              |                    |               | √           |              | Mark a nonserializable instance data field.                                                             |

The modifiers default (no modifier), **public**, **private**, and **protected** are known as *visibility* or *accessibility modifiers* because they specify how classes and class members are accessed.

The modifiers **public**, **private**, **protected**, **static**, **final**, and **abstract** can also be applied to inner classes.

# APPENDIX E

## Special Floating-Point Values

Dividing an integer by zero is invalid and throws `ArithmeticException`, but dividing a floating-point value by zero does not cause an exception. Floating-point arithmetic can overflow to infinity if the result of the operation is too large for a `double` or a `float`, or underflow to zero if the result is too small for a `double` or a `float`. Java provides the special floating-point values `POSITIVE_INFINITY`, `NEGATIVE_INFINITY`, and `NaN` (Not a Number) to denote these results. These values are defined as special constants in the `Float` class and the `Double` class.

If a positive floating-point number is divided by zero, the result is `POSITIVE_INFINITY`. If a negative floating-point number is divided by zero, the result is `NEGATIVE_INFINITY`. If a floating-point zero is divided by zero, the result is `NaN`, which means that the result is undefined mathematically. The string representations of these three values are `Infinity`, `-Infinity`, and `NaN`. For example,

```
System.out.print(1.0 / 0); // Print Infinity
System.out.print(-1.0 / 0); // Print -Infinity
System.out.print(0.0 / 0); // Print NaN
```

These special values can also be used as operands in computations. For example, a number divided by `POSITIVE_INFINITY` yields a positive zero. Table E.1 summarizes various combinations of the `/`, `*`, `%`, `+`, and `-` operators.

**TABLE E.1** Special Floating-Point Values

| <i>x</i>               | <i>y</i>              | <i>x/y</i>             | <i>x*y</i>       | <i>x%y</i>       | <i>x + y</i>           | <i>x - y</i>           |
|------------------------|-----------------------|------------------------|------------------|------------------|------------------------|------------------------|
| Finite                 | $\pm\ 0.0$            | $\pm\ \text{infinity}$ | $\pm\ 0.0$       | <code>NaN</code> | Finite                 | Finite                 |
| Finite                 | <code>infinity</code> | $\pm\ 0.0$             | $\pm\ 0.0$       | <code>x</code>   | $\pm\ \text{infinity}$ | <code>infinity</code>  |
| $\pm\ 0.0$             | $\pm\ 0.0$            | <code>NaN</code>       | $\pm\ 0.0$       | <code>NaN</code> | $\pm\ 0.0$             | $\pm\ 0.0$             |
| $\pm\ \text{infinity}$ | Finite                | $\pm\ \text{infinity}$ | $\pm\ 0.0$       | <code>NaN</code> | $\pm\ \text{infinity}$ | $\pm\ \text{infinity}$ |
| $\pm\ \text{infinity}$ | <code>infinity</code> | <code>NaN</code>       | $\pm\ 0.0$       | <code>NaN</code> | $\pm\ \text{infinity}$ | <code>infinity</code>  |
| $\pm\ 0.0$             | <code>infinity</code> | $\pm\ 0.0$             | <code>NaN</code> | $\pm\ 0.0$       | $\pm\ \text{infinity}$ | $\pm\ 0.0$             |
| NaN                    | Any                   | <code>NaN</code>       | <code>NaN</code> | <code>NaN</code> | NaN                    | NaN                    |
| Any                    | NaN                   | <code>NaN</code>       | <code>NaN</code> | <code>NaN</code> | NaN                    | NaN                    |



### Note

If one of the operands is `NaN`, the result is `NaN`.

# APPENDIX F

## Number Systems

### F.1 Introduction

Computers use binary numbers internally, because computers are made naturally to store and process 0s and 1s. The binary number system has two digits, 0 and 1. A number or character is stored as a sequence of 0s and 1s. Each 0 or 1 is called a *bit* (binary digit).

In our daily life we use decimal numbers. When we write a number such as 20 in a program, it is assumed to be a decimal number. Internally, computer software is used to convert decimal numbers into binary numbers, and vice versa.

We write computer programs using decimal numbers. However, to deal with an operating system, we need to reach down to the “machine level” by using binary numbers. Binary numbers tend to be very long and cumbersome. Often hexadecimal numbers are used to abbreviate them, with each hexadecimal digit representing four binary digits. The hexadecimal number system has 16 digits: 0–9 and A–F. The letters A, B, C, D, E, and F correspond to the decimal numbers 10, 11, 12, 13, 14, and 15.

The digits in the decimal number system are 0, 1, 2, 3, 4, 5, 6, 7, 8, and 9. A decimal number is represented by a sequence of one or more of these digits. The value that each digit represents depends on its position, which denotes an integral power of 10. For example, the digits 7, 4, 2, and 3 in decimal number 7423 represent 7000, 400, 20, and 3, respectively, as shown below:

$$\boxed{7 \ 4 \ 2 \ 3} = 7 \times 10^3 + 4 \times 10^2 + 2 \times 10^1 + 3 \times 10^0$$

$$10^3 \ 10^2 \ 10^1 \ 10^0 = 7000 + 400 + 20 + 3 = 7423$$

The decimal number system has ten digits, and the position values are integral powers of 10. We say that 10 is the *base* or *radix* of the decimal number system. Similarly, since the binary number system has two digits, its base is 2, and since the hex number system has 16 digits, its base is 16.

If 1101 is a binary number, the digits 1, 1, 0, and 1 represent  $1 \times 2^3$ ,  $1 \times 2^2$ ,  $0 \times 2^1$ , and  $1 \times 2^0$ , respectively:

$$\boxed{1 \ 1 \ 0 \ 1} = 1 \times 2^3 + 1 \times 2^2 + 0 \times 2^1 + 1 \times 2^0$$

$$2^3 \ 2^2 \ 2^1 \ 2^0 = 8 + 4 + 0 + 1 = 13$$

If 7423 is a hex number, the digits 7, 4, 2, and 3 represent  $7 \times 16^3$ ,  $4 \times 16^2$ ,  $2 \times 16^1$ , and  $3 \times 16^0$ , respectively:

$$\boxed{7 \ 4 \ 2 \ 3} = 7 \times 16^3 + 4 \times 16^2 + 2 \times 16^1 + 3 \times 16^0$$

$$16^3 \ 16^2 \ 16^1 \ 16^0 = 28672 + 1024 + 32 + 3 = 29731$$

binary numbers

decimal numbers

hexadecimal number

base  
radix

## F.2 Conversions Between Binary and Decimal Numbers

binary to decimal

Given a binary number  $b_n b_{n-1} b_{n-2} \dots b_2 b_1 b_0$ , the equivalent decimal value is

$$b_n \times 2^n + b_{n-1} \times 2^{n-1} + b_{n-2} \times 2^{n-2} + \dots + b_2 \times 2^2 + b_1 \times 2^1 + b_0 \times 2^0$$

Here are some examples of converting binary numbers to decimals:

| Binary   | Conversion Formula                                                                                                      | Decimal |
|----------|-------------------------------------------------------------------------------------------------------------------------|---------|
| 10       | $1 \times 2^1 + 0 \times 2^0$                                                                                           | 2       |
| 1000     | $1 \times 2^3 + 0 \times 2^2 + 0 \times 2^1 + 0 \times 2^0$                                                             | 8       |
| 10101011 | $1 \times 2^7 + 0 \times 2^6 + 1 \times 2^5 + 0 \times 2^4 + 1 \times 2^3 + 0 \times 2^2 + 1 \times 2^1 + 1 \times 2^0$ | 171     |

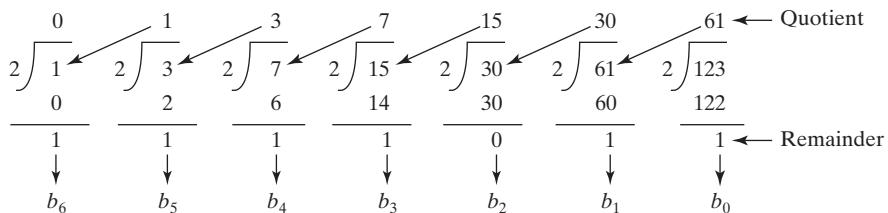
decimal to binary

To convert a decimal number  $d$  to a binary number is to find the bits  $b_n, b_{n-1}, b_{n-2}, \dots, b_2, b_1$  and  $b_0$  such that

$$d = b_n \times 2^n + b_{n-1} \times 2^{n-1} + b_{n-2} \times 2^{n-2} + \dots + b_2 \times 2^2 + b_1 \times 2^1 + b_0 \times 2^0$$

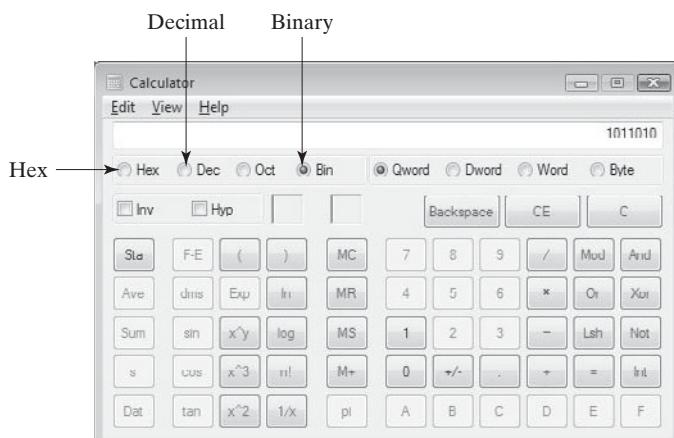
These bits can be found by successively dividing  $d$  by 2 until the quotient is 0. The remainders are  $b_0, b_1, b_2, \dots, b_{n-2}, b_{n-1}$ , and  $b_n$ .

For example, the decimal number 123 is 1111011 in binary. The conversion is done as follows:



### Tip

The Windows Calculator, as shown in Figure F.1, is a useful tool for performing number conversions. To run it, search for *Calculator* from the *Start* button and launch Calculator, then under *View* select *Scientific*.



**FIGURE F.1** You can perform number conversions using the Windows Calculator.

### F.3 Conversions Between Hexadecimal and Decimal Numbers

Given a hexadecimal number  $h_nh_{n-1}h_{n-2}\dots h_2h_1h_0$ , the equivalent decimal value is

hex to decimal

$$h_n \times 16^n + h_{n-1} \times 16^{n-1} + h_{n-2} \times 16^{n-2} + \dots + h_2 \times 16^2 + h_1 \times 16^1 + h_0 \times 16^0$$

Here are some examples of converting hexadecimal numbers to decimals:

| Hexadecimal | Conversion Formula                                                  | Decimal |
|-------------|---------------------------------------------------------------------|---------|
| 7F          | $7 \times 16^1 + 15 \times 16^0$                                    | 127     |
| FFFF        | $15 \times 16^3 + 15 \times 16^2 + 15 \times 16^1 + 15 \times 16^0$ | 65535   |
| 431         | $4 \times 16^2 + 3 \times 16^1 + 1 \times 16^0$                     | 1073    |

To convert a decimal number  $d$  to a hexadecimal number is to find the hexadecimal digits  $h_n, h_{n-1}, h_{n-2}, \dots, h_2, h_1$ , and  $h_0$  such that

decimal to hex

$$\begin{aligned} d = h_n \times 16^n + h_{n-1} \times 16^{n-1} + h_{n-2} \times 16^{n-2} + \dots + h_2 \times 16^2 \\ + h_1 \times 16^1 + h_0 \times 16^0 \end{aligned}$$

These numbers can be found by successively dividing  $d$  by 16 until the quotient is 0. The remainders are  $h_0, h_1, h_2, \dots, h_{n-2}, h_{n-1}$ , and  $h_n$ .

For example, the decimal number 123 is 7B in hexadecimal. The conversion is done as follows:

$$\begin{array}{r} & 0 & & 7 & \leftarrow \text{Quotient} \\ 16 \sqrt{7} & \swarrow & 16 \sqrt{123} & & \\ & 0 & & 112 & \\ \hline & 7 & & 11 & \leftarrow \text{Remainder} \\ & \downarrow & & \downarrow & \\ & h_1 & & h_0 & \end{array}$$

### F.4 Conversions Between Binary and Hexadecimal Numbers

To convert a hexadecimal to a binary number, simply convert each digit in the hexadecimal number into a four-digit binary number, using Table F.1.

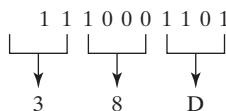
hex to binary

For example, the hexadecimal number 7B is 1111011, where 7 is 111 in binary, and B is 1011 in binary.

To convert a binary number to a hexadecimal, convert every four binary digits from right to left in the binary number into a hexadecimal number.

binary to hex

For example, the binary number 1110001101 is 38D, since 1101 is D, 1000 is 8, and 11 is 3, as shown below.



**TABLE F.1** Converting Hexadecimal to Binary

| <i>Hexadecimal</i> | <i>Binary</i> | <i>Decimal</i> |
|--------------------|---------------|----------------|
| 0                  | 0000          | 0              |
| 1                  | 0001          | 1              |
| 2                  | 0010          | 2              |
| 3                  | 0011          | 3              |
| 4                  | 0100          | 4              |
| 5                  | 0101          | 5              |
| 6                  | 0110          | 6              |
| 7                  | 0111          | 7              |
| 8                  | 1000          | 8              |
| 9                  | 1001          | 9              |
| A                  | 1010          | 10             |
| B                  | 1011          | 11             |
| C                  | 1100          | 12             |
| D                  | 1101          | 13             |
| E                  | 1110          | 14             |
| F                  | 1111          | 15             |

**Note**

Octal numbers are also useful. The octal number system has eight digits, 0 to 7. A decimal number 8 is represented in the octal system as 10.

Here are some good online resources for practicing number conversions:

- [http://forums.cisco.com/CertCom/game/binary\\_game\\_page.htm](http://forums.cisco.com/CertCom/game/binary_game_page.htm)
- <http://people.sinclair.edu/nickreeder/Flash/binDec.htm>
- <http://people.sinclair.edu/nickreeder/Flash/binHex.htm>



- F.1** Convert the following decimal numbers into hexadecimal and binary numbers:  
100; 4340; 2000
- F.2** Convert the following binary numbers into hexadecimal and decimal numbers:  
1000011001; 100000000; 100111
- F.3** Convert the following hexadecimal numbers into binary and decimal numbers:  
FEFA9; 93; 2000

# APPENDIX G

## Bitwise Operations

To write programs at the machine-level, often you need to deal with binary numbers directly and perform operations at the bit-level. Java provides the bitwise operators and shift operators defined in Table G.1.

The bit operators apply only to integer types (`byte`, `short`, `int`, and `long`). A character involved in a bit operation is converted to an integer. All bitwise operators can form bitwise assignment operators, such as `=`, `|=`, `<<=`, `>>=`, and `>>>=`.

TABLE G.1

| Operator                  | Name                                     | Example<br>(using bytes in the example)                                | Description                                                                                                                                                |
|---------------------------|------------------------------------------|------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <code>&amp;</code>        | Bitwise AND                              | 10101110 & 10010010<br>yields 10000010                                 | The AND of two corresponding bits yields a 1 if both bits are 1.                                                                                           |
| <code> </code>            | Bitwise inclusive OR                     | 10101110   10010010<br>yields 10111110                                 | The OR of two corresponding bits yields a 1 if either bit is 1.                                                                                            |
| <code>^</code>            | Bitwise exclusive OR                     | 10101110 ^ 10010010<br>yields 00111100                                 | The XOR of two corresponding bits yields a 1 only if two bits are different.                                                                               |
| <code>~</code>            | One's complement                         | <code>~</code> 10101110 yields<br>01010001                             | The operator toggles each bit from 0 to 1 and from 1 to 0.                                                                                                 |
| <code>&lt;&lt;</code>     | Left shift                               | 10101110 << 2 yields<br>10111000                                       | The operator shifts bits in the first operand left by the number of bits specified in the second operand, filling with 0s on the right.                    |
| <code>&gt;&gt;</code>     | Right shift with sign extension          | 10101110 >> 2 yields<br>11101011<br>00101110 >> 2 yields<br>00001011   | The operator shifts bit in the first operand right by the number of bits specified in the second operand, filling with the highest (sign) bit on the left. |
| <code>&gt;&gt;&gt;</code> | Unsigned right shift with zero extension | 10101110 >>> 2 yields<br>00101011<br>00101110 >>> 2 yields<br>00001011 | The operator shifts bit in the first operand right by the number of bits specified in the second operand, filling with 0s on the left.                     |

# APPENDIX H

---

## Regular Expressions

Often you need to write the code to validate user input such as to check whether the input is a number, a string with all lowercase letters, or a social security number. How do you write this type of code? A simple and effective way to accomplish this task is to use the regular expression.

regular expression

A *regular expression* (abbreviated *regex*) is a string that describes a pattern for matching a set of strings. Regular expression is a powerful tool for string manipulations. You can use regular expressions for matching, replacing, and splitting strings.

### H.1 Matching Strings

matches

Let us begin with the `matches` method in the `String` class. At first glance, the `matches` method is very similar to the `equals` method. For example, the following two statements both evaluate to `true`.

```
"Java".matches("Java");
"Java".equals("Java");
```

However, the `matches` method is more powerful. It can match not only a fixed string, but also a set of strings that follow a pattern. For example, the following statements all evaluate to `true`.

```
"Java is fun".matches("Java.*")
"Java is cool".matches("Java.*")
"Java is powerful".matches("Java.*")
```

`"Java.*"` in the preceding statements is a regular expression. It describes a string pattern that begins with Java followed by any zero or more characters. Here, the substring `.*` matches any zero or more characters.

### H.2 Regular Expression Syntax

A regular expression consists of literal characters and special symbols. Table H.1 lists some frequently used syntax for regular expressions.



#### Note

Backslash is a special character that starts an escape sequence in a string. So you need to use `\d` in Java to represent `\d`.



#### Note

Recall that a *whitespace character* is `' '`, `'\t'`, `'\n'`, `'\r'`, or `'\f'`. So `\s` is the same as `[ \t\n\r\f]`, and `\S` is the same as `[^ \t\n\r\f]`.

**TABLE H.1** Frequently Used Regular Expressions

| Regular Expression | Matches                                 | Example                                                |
|--------------------|-----------------------------------------|--------------------------------------------------------|
| x                  | a specified character x                 | Java matches Java                                      |
| .                  | any single character                    | Java matches J..a                                      |
| (ab cd)            | ab or cd                                | ten matches t(en im)                                   |
| [abc]              | a, b, or c                              | Java matches Ja[uvwxyz]a                               |
| [^abc]             | any character except a, b, or c         | Java matches Ja[^ars]a                                 |
| [a-z]              | a through z                             | Java matches [A-M]av[a-d]                              |
| [^a-z]             | any character except a through z        | Java matches Jav[^b-d]                                 |
| [a-e[m-p]]         | a through e or m through p              | Java matches [A-G[I-M]]av[a-d]                         |
| [a-e&&[c-p]]       | intersection of a-e with c-p            | Java matches [A-P&&[I-M]]av[a-d]                       |
| \d                 | a digit, same as [0-9]                  | Java2 matches "Java[\d]"                               |
| \D                 | a non-digit                             | \$Java matches "[\D][\D]ava"                           |
| \w                 | a word character                        | Java1 matches "[\w]ava[\w]"                            |
| \W                 | a non-word character                    | \$Java matches "[\W][\w]ava"                           |
| \s                 | a whitespace character                  | "Java 2" matches "Java\s2"                             |
| \S                 | a non-whitespace char                   | Java matches "[\S]ava"                                 |
| p*                 | zero or more occurrences of pattern p   | aaaabb matches "a*bb"<br>ababab matches "(ab)*"        |
| p+                 | one or more occurrences of pattern p    | a matches "a+b*"<br>able matches "(ab)+.*"             |
| p?                 | zero or one occurrence of pattern p     | Java matches "J?Java"<br>Java matches "J?ava"          |
| p{n}               | exactly n occurrences of pattern p      | Java matches "Ja{1}.*"<br>Java does not match ".{2}"   |
| p{n,}              | at least n occurrences of pattern p     | aaaa matches "a{1,}"<br>a does not match "a{2,}"       |
| p{n,m}             | between n and m occurrences (inclusive) | aaaa matches "a{1,9}"<br>abb does not match "a{2,9}bb" |



### Note

A word character is any letter, digit, or the underscore character. So \w is the same as [a-z[A-Z][0-9]\_] or simply [a-zA-Z0-9\_], and \W is the same as [^a-zA-Z0-9\_].



### Note

The last six entries \*, +, ?, {n}, {n,}, and {n, m} in Table H.1 are called *quantifiers* that specify how many times the pattern before a quantifier may repeat. For example, A\* matches zero or more A's, A+ matches one or more A's, A? matches zero or one A's, A{3} matches exactly AAA, A{3,} matches at least three A's, and A{3,6} matches between 3 and 6 A's. \* is the same as {0,}, + is the same as {1,}, and ? is the same as {0,1}.

quantifier

**Caution**

Do not use spaces in the repeat quantifiers. For example, `A{3,6}` cannot be written as `A{3, }6` with a space after the comma.

**Note**

You may use parentheses to group patterns. For example, `(ab){3}` matches `ababab`, but `ab{3}` matches `abbb`.

Let us use several examples to demonstrate how to construct regular expressions.

**Example 1**

The pattern for social security numbers is `xxx-xx-xxxx`, where `x` is a digit. A regular expression for social security numbers can be described as

`[\\d]{3}-[\\d]{2}-[\\d]{4}`

For example,

`"111-22-3333".matches("[\\d]{3}-[\\d]{2}-[\\d]{4}")` returns `true`.  
`"11-22-3333".matches("[\\d]{3}-[\\d]{2}-[\\d]{4}")` returns `false`.

**Example 2**

An even number ends with digits `0, 2, 4, 6, or 8`. The pattern for even numbers can be described as

`[\\d]*[02468]`

For example,

`"123".matches("[\\d]*[02468]")` returns `false`.  
`"122".matches("[\\d]*[02468]")` returns `true`.

**Example 3**

The pattern for telephone numbers is `(xxx) xxx-xxxx`, where `x` is a digit and the first digit cannot be zero. A regular expression for telephone numbers can be described as

`\\(([1-9][\\d]{2})\\) [\\d]{3}-[\\d]{4}`

Note that the parentheses symbols `(` and `)` are special characters in a regular expression for grouping patterns. To represent a literal `(` or `)` in a regular expression, you have to use `\\\(` and `\\\)`.

For example,

`"(912) 921-2728".matches("\\(([1-9][\\d]{2})\\) [\\d]{3}-[\\d]{4}")`  
 returns `true`.  
`"921-2728".matches("\\(([1-9][\\d]{2})\\) [\\d]{3}-[\\d]{4}")`  
 returns `false`.

**Example 4**

Suppose the last name consists of at most 25 letters and the first letter is in uppercase. The pattern for a last name can be described as

`[A-Z] [a-zA-Z]{1,24}`

Note that you cannot have arbitrary whitespace in a regular expression. For example, `[A-Z] [a-zA-Z]{1, 24}` would be wrong.

For example,

```
"Smith".matches("[A-Z][a-zA-Z]{1,24}") returns true.
"Jones123".matches("[A-Z][a-zA-Z]{1,24}") returns false.
```

### Example 5

Java identifiers are defined in Section 2.4, “Identifiers.”

- An identifier must start with a letter, an underscore (\_), or a dollar sign (\$). It cannot start with a digit.
- An identifier is a sequence of characters that consists of letters, digits, underscores (\_), and dollar signs (\$).

The pattern for identifiers can be described as

$$[a-zA-Z_\$][\w\$\ast]$$

### Example 6

What strings are matched by the regular expression "Welcome to (Java|HTML)"? The answer is **Welcome to Java** or **Welcome to HTML**.

### Example 7

What strings are matched by the regular expression "A.\*"? The answer is any string that starts with letter A.

## H.3 Replacing and Splitting Strings

The **matches** method in the **String** class returns **true** if the string matches the regular expression. The **String** class also contains the **replaceAll**, **replaceFirst**, and **split** methods for replacing and splitting strings, as shown in Figure H.1.

| java.lang.String                                          |                                                                                                                         |
|-----------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------|
| +matches(regex: String): boolean                          | Returns true if this string matches the pattern.                                                                        |
| +replaceAll(regex: String, replacement: String): String   | Returns a new string that replaces all matching substrings with the replacement.                                        |
| +replaceFirst(regex: String, replacement: String): String | Returns a new string that replaces the first matching substring with the replacement.                                   |
| +split(regex: String): String[]                           | Returns an array of strings consisting of the substrings split by the matches.                                          |
| +split(regex: String, limit: int): String[]               | Same as the preceding split method except that the limit parameter controls the number of times the pattern is applied. |

**FIGURE H.1** The **String** class contains the methods for matching, replacing, and splitting strings using regular expressions.

The **replaceAll** method replaces all matching substring and the **replaceFirst** method replaces the first matching substring. For example, the following code

```
System.out.println("Java Java Java".replaceAll("v\\w", "wi"));
```

displays

Jawi Jawi Jawi

The following code

```
System.out.println("Java Java Java".replaceFirst("v\\w", "wi"));
```

displays

```
Jawi Java Java
```

There are two overloaded **split** methods. The **split(regex)** method splits a string into substrings delimited by the matches. For example, the following statement

```
String[] tokens = "Java1HTML2Perl".split("\\d");
```

splits string "Java1HTML2Perl" into **Java**, **HTML**, and **Perl** and saved in **tokens[0]**, **tokens[1]**, and **tokens[2]**.

In the **split(regex, limit)** method, the **limit** parameter determines how many times the pattern is matched. If **limit <= 0**, **split(regex, limit)** is same as **split(regex)**. If **limit > 0**, the pattern is matched at most **limit - 1** times. Here are some examples:

```
"Java1HTML2Perl".split("\\d", 0); splits into Java, HTML, Perl

"Java1HTML2Perl".split("\\d", 1); splits into Java1HTML2Perl

"Java1HTML2Perl".split("\\d", 2); splits into Java, HTML2Perl

"Java1HTML2Perl".split("\\d", 3); splits into Java, HTML, Perl

"Java1HTML2Perl".split("\\d", 4); splits into Java, HTML, Perl

"Java1HTML2Perl".split("\\d", 5); splits into Java, HTML, Perl
```



### Note

By default, all the quantifiers are *greedy*. This means that they will match as many occurrences as possible. For example, the following statement displays **JRvaa**, since the first match is **aaa**.

```
System.out.println("Jaaavaa".replaceFirst("a+", "R"));
```

You can change a qualifier's default behavior by appending a question mark (?) after it. The quantifier becomes *reluctant*, which means that it will match as few occurrences as possible. For example, the following statement displays **JRaavaa**, since the first match is **a**.

```
System.out.println("Jaaavaa".replaceFirst("a+?", "R"));
```

# APPENDIX I

---

## Enumerated Types

### I.1 Simple Enumerated Types

An enumerated type defines a list of enumerated values. Each value is an identifier. For example, the following statement declares a type, named **MyFavoriteColor**, with values **RED**, **BLUE**, **GREEN**, and **YELLOW** in this order.

```
enum MyFavoriteColor {RED, BLUE, GREEN, YELLOW};
```

A value of an enumerated type is like a constant and so, by convention, is spelled with all uppercase letters. So, the preceding declaration uses **RED**, not **red**. By convention, an enumerated type is named like a class with first letter of each word capitalized.

Once a type is defined, you can declare a variable of that type:

```
MyFavoriteColor color;
```

The variable **color** can hold one of the values defined in the enumerated type **MyFavoriteColor** or **null**, but nothing else. Java enumerated type is *type-safe*, meaning that an attempt to assign a value other than one of the enumerated values or **null** will result in a compile error.

The enumerated values can be accessed using the syntax

```
EnumName.valueName
```

For example, the following statement assigns enumerated value **BLUE** to variable **color**:

```
color = MyFavoriteColor.BLUE;
```

Note that you have to use the enumerated type name as a qualifier to reference a value such as **BLUE**.

As with any other type, you can declare and initialize a variable in one statement:

```
MyFavoriteColor color = MyFavoriteColor.BLUE;
```

An enumerated type is treated as a special class. An enumerated type variable is therefore a reference variable. An enumerated type is a subtype of the **Object** class and the **Comparable** interface. Therefore, an enumerated type inherits all the methods in the **Object** class and the **compraeTo** method in the **Comparable** interface. Additionally, you can use the following methods on an enumerated object:

- **public String name();**

Returns a name of the value for the object.

- **public int ordinal();**

Returns the ordinal value associated with the enumerated value. The first value in an enumerated type has an ordinal value of 0, the second has an ordinal value of 1, the third one 3, and so on.

Listing I.1 gives a program that demonstrates the use of enumerated types.

### LISTING I.1 EnumeratedTypeDemo.java

```

1 public class EnumeratedTypeDemo {
2 static enum Day {SUNDAY, MONDAY, TUESDAY, WEDNESDAY, THURSDAY,
3 FRIDAY, SATURDAY};
4
5 public static void main(String[] args) {
6 Day day1 = Day.FRIDAY;
7 Day day2 = Day.THURSDAY;
8
9 System.out.println("day1's name is " + day1.name());
10 System.out.println("day2's name is " + day2.name());
11 System.out.println("day1's ordinal is " + day1.ordinal());
12 System.out.println("day2's ordinal is " + day2.ordinal());
13
14 System.out.println("day1.equals(day2) returns " +
15 day1.equals(day2));
16 System.out.println("day1.toString() returns " +
17 day1.toString());
18 System.out.println("day1.compareTo(day2) returns " +
19 day1.compareTo(day2));
20 }
21 }
```



```

day1's name is FRIDAY
day2's name is THURSDAY
day1's ordinal is 5
day2's ordinal is 4
day1.equals(day2) returns false
day1.toString() returns FRIDAY
day1.compareTo(day2) returns 1

```

An enumerated type **Day** is defined in lines 2–3. Variables **day1** and **day2** are declared as the **Day** type and assigned enumerated values in lines 6–7. Since **day1**'s value is **FRIDAY**, its ordinal value is 5 (line 11). Since **day2**'s value is **THURSDAY**, its ordinal value is 4 (line 12).

Since an enumerated type is a subclass of the **Object** class and the **Comparable** interface, you can invoke the methods **equals**, **toString**, and **compareTo** from an enumerated object reference variable (lines 14–19). **day1.equals(day2)** returns true if **day1** and **day2** have the same ordinal value. **day1.compareTo(day2)** returns the difference between **day1**'s ordinal value to **day2**'s.

Alternatively, you can rewrite the code in Listing I.1 into Listing I.2.

### LISTING I.2 StandaloneEnumTypeDemo.java

```

1 public class StandaloneEnumTypeDemo {
2 public static void main(String[] args) {
3 Day day1 = Day.FRIDAY;
4 Day day2 = Day.THURSDAY;
5
6 System.out.println("day1's name is " + day1.name());
7 System.out.println("day2's name is " + day2.name());
8 System.out.println("day1's ordinal is " + day1.ordinal());
```

```

9 System.out.println("day2's ordinal is " + day2.ordinal());
10 System.out.println("day1.equals(day2) returns " +
11 day1.equals(day2));
12 System.out.println("day1.toString() returns " +
13 day1.toString());
14 System.out.println("day1.compareTo(day2) returns " +
15 day1.compareTo(day2));
16 }
17 }
18 }
19
20 enum Day {SUNDAY, MONDAY, TUESDAY, WEDNESDAY, THURSDAY,
21 FRIDAY, SATURDAY}

```

An enumerated type can be defined inside a class, as shown in lines 2–3 in Listing I.1, or standalone as shown in lines 20–21 Listing I.2. In the former case, the type is treated as an inner class. After the program is compiled, a class named `EnumeratedTypeDemo$Day.class` is created. In the latter case, the type is treated as a standalone class. After the program is compiled, a class named `Day.class` is created.



### Note

When an enumerated type is declared inside a class, the type must be declared as a member of the class and cannot be declared inside a method. Furthermore, the type is always **static**. For this reason, the **static** keyword in line 2 in Listing I.1 may be omitted. The visibility modifiers on inner class can be also be applied to enumerated types defined inside a class.



### Tip

Using enumerated values (e.g., `Day.MONDAY`, `Day.TUESDAY`, and so on) rather than literal integer values (e.g., 0, 1, and so on) can make program easier to read and maintain.

## I.2 Using **if** or **switch** Statements with an Enumerated Variable

An enumerated variable holds a value. Often your program needs to perform a specific action depending on the value. For example, if the value is `Day.MONDAY`, play soccer; if the value is `Day.TUESDAY`, take piano lesson, and so on. You can use an **if** statement or a **switch** statement to test the value in the variable, as shown in (a) and (b)

```

if (day.equals(Day.MONDAY)) {
 // process Monday
}
else if (day.equals(Day.TUESDAY)) {
 // process Tuesday
}
else
 ...

```

Equivalent

```

switch (day) {
 case MONDAY:
 // process Monday
 break;
 case TUESDAY:
 // process Tuesday
 break;
 ...
}

```

(a)

(b)

In the **switch** statement in (b), the case label is an unqualified enumerated value (e.g., `MONDAY`, but not `Day.MONDAY`).

## I.3 Processing Enumerated Values Using a Foreach Loop

Each enumerated type has a static method `values()` that returns all enumerated values for the type in an array. For example,

```
Day[] days = Day.values();
```

You can use a regular for loop in (a) or a foreach loop in (b) to process all the values in the array.

|                                                                                      |            |                                                             |
|--------------------------------------------------------------------------------------|------------|-------------------------------------------------------------|
| <pre>for (int i = 0; i &lt; days.length; i++)     System.out.println(days[i]);</pre> | Equivalent | <pre>for (Day day: days)     System.out.println(day);</pre> |
| (a)                                                                                  | (b)        |                                                             |

## I.4 Enumerated Types with Data Fields, Constructors, and Methods

The simple enumerated types introduced in the preceding section define a type with a list of enumerated values. You can also define an enum type with data fields, constructors, and methods, as shown in Listing I.3.

### LISTING I.3 TrafficLight.java

```

1 public enum TrafficLight {
2 RED ("Please stop"), GREEN ("Please go"),
3 YELLOW ("Please caution");
4
5 private String description;
6
7 private TrafficLight(String description) {
8 this.description = description;
9 }
10
11 public String getDescription() {
12 return description;
13 }
14 }
```

The enumerated values are defined in lines 2–3. The value declaration must be the first statement in the type declaration. A data field named `description` is declared in line 5 to describe an enumerated value. The constructor `TrafficLight` is declared in lines 7–9. The constructor is invoked whenever an enumerated value is accessed. The enumerated value's argument is passed to the constructor, which is then assigned to `description`.

Listing I.4 gives a test program to use `TrafficLight`.

### LISTING I.4 TestTrafficLight.java

```

1 public class TestTrafficLight {
2 public static void main(String[] args) {
3 TrafficLight light = TrafficLight.RED;
4 System.out.println(light.getDescription());
5 }
6 }
```

An enumerated value `TrafficLight.red` is assigned to variable `light` (line 3). Accessing `TrafficLight.RED` causes the JVM to invoke the constructor with argument “please stop”. The methods in enumerated type are invoked in the same way as the methods in a class. `light.getDescription()` returns the description for the enumerated value (line 4).



### Note

The Java syntax requires that the constructor for enumerated types be private to prevent it from being invoked directly. The private modifier may be omitted. In this case, it is considered private by default.

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## Java Quick Reference

### Console Input

```
Scanner input = new Scanner(System.in);
int intValue = input.nextInt();
long longValue = input.nextLong();
double doubleValue = input.nextDouble();
float floatValue = input.nextFloat();
String string = input.next();
String line = input.nextLine();
```

### Console Output

```
System.out.println(anyValue);
```

### Conditional Expression

```
boolean-expression ? expression1 :
expression2
y = (x > 0) ? 1 : -1
System.out.println(number % 2 == 0 ?
"number is even" : "number is odd");
```

### Primitive Data Types

|                |            |
|----------------|------------|
| <b>byte</b>    | 8 bits     |
| <b>short</b>   | 16 bits    |
| <b>int</b>     | 32 bits    |
| <b>long</b>    | 64 bits    |
| <b>float</b>   | 32 bits    |
| <b>double</b>  | 64 bits    |
| <b>char</b>    | 16 bits    |
| <b>boolean</b> | true/false |

### Arithmetic Operators

|              |                |
|--------------|----------------|
| <b>+</b>     | addition       |
| <b>-</b>     | subtraction    |
| <b>*</b>     | multiplication |
| <b>/</b>     | division       |
| <b>%</b>     | remainder      |
| <b>++var</b> | preincrement   |
| <b>--var</b> | predecrement   |
| <b>var++</b> | postincrement  |
| <b>var--</b> | postdecrement  |

### Assignment Operators

|           |                           |
|-----------|---------------------------|
| <b>=</b>  | assignment                |
| <b>+=</b> | addition assignment       |
| <b>-=</b> | subtraction assignment    |
| <b>*=</b> | multiplication assignment |
| <b>/=</b> | division assignment       |
| <b>%=</b> | remainder assignment      |

### Relational Operators

|              |                          |
|--------------|--------------------------|
| <b>&lt;</b>  | less than                |
| <b>&lt;=</b> | less than or equal to    |
| <b>&gt;</b>  | greater than             |
| <b>&gt;=</b> | greater than or equal to |
| <b>==</b>    | equal to                 |
| <b>!=</b>    | not equal                |

### Logical Operators

|                   |                   |
|-------------------|-------------------|
| <b>&amp;&amp;</b> | short circuit AND |
| <b>  </b>         | short circuit OR  |
| <b>!</b>          | NOT               |
| <b>^</b>          | exclusive OR      |

### if Statements

```
if (condition) {
 statements;
}

if (condition) {
 statements;
}
else {
 statements;
}

if (condition1) {
 statements;
}
else if (condition2) {
 statements;
}
else {
 statements;
}
```

### switch Statements

```
switch (intExpression) {
 case value1:
 statements;
 break;
 ...
 case valueN:
 statements;
 break;
 default:
 statements;
}
```

### Loop Statements

```
while (condition) {
 statements;
}

do {
 statements;
} while (condition);

for (init; condition;
adjustment) {
 statements;
}
```

## Java Quick Reference

### Frequently Used Static Constants/Methods

```
Math.PI
Math.random()
Math.pow(a, b)
Math.abs(a)
Math.max(a, b)
Math.min(a, b)
Math.sqrt(a)
Math.sin(radians)
Math.asin(a)
Math.toRadians(degrees)
Math.toDegrees(radians)
System.currentTimeMillis()
Integer.parseInt(string)
Integer.parseInt(string, radix)
Double.parseDouble(string)
Arrays.sort(type[] list)
Arrays.binarySearch(type[] list, type key)
```

### Array/Length/Initializer

```
int[] list = new int[10];
list.length;
int[] list = {1, 2, 3, 4};
```

### Multidimensional Array/Length/Initializer

```
int[][] list = new int[10][10];
list.length;
list[0].length;
int[][] list = {{1, 2}, {3, 4}};
```

### Ragged Array

```
int[][] m = {{1, 2, 3, 4},
 {1, 2, 3},
 {1, 2},
 {1}};
```

### Text File Output

```
PrintWriter output =
 new PrintWriter(filename);
output.print(...);
output.println(...);
output.printf(...);
```

### Text File Input

```
Scanner input = new Scanner(
 new File(filename));
```

### File Class

```
File file =
 new File(filename);
file.exists()
file.renameTo(File)
file.delete()
```

### Object Class

```
Object o = new Object();
o.toString();
o.equals(o1);
```

### Comparable Interface

```
c.compareTo(Comparable)
c is a Comparable object
```

### String Class

```
String s = "Welcome";
String s = new String(char[]);
int length = s.length();
char ch = s.charAt(index);
int d = s.compareTo(s1);
boolean b = s.equals(s1);
boolean b = s.startsWith(s1);
boolean b = s.endsWith(s1);
boolean b = s.contains(s1);
String s1 = s.trim();
String s1 = s.toUpperCase();
String s1 = s.toLowerCase();
int index = s.indexOf(ch);
int index = s.lastIndexOf(ch);
String s1 = s.substring(ch);
String s1 = s.substring(i,j);
char[] chs = s.toCharArray();
boolean b = s.matches(regex);
String s1 = s.replaceAll(regex,repl);
String[] tokens = s.split(regex);
```

### ArrayList Class

```
ArrayList<E> list = new ArrayList<E>();
list.add(object);
list.add(index, object);
list.clear();
Object o = list.get(index);
boolean b = list.isEmpty();
boolean b = list.contains(object);
int i = list.size();
list.remove(index);
list.set(index, object);
int i = list.indexOf(object);
int i = list.lastIndexOf(object);
```

### printf Method

```
System.out.printf("%b %c %d %f %e %s",
 true, 'A', 45, 45.5, 45.5, "Welcome");
System.out.printf("%-5d %10.2f %10.2e %8s",
 45, 45.5, 45.5, "Welcome");
```