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Covers Java 17

# Java in a Nutshell

## A Desktop Quick Reference

Compliments of
Red Hat Developer

Benjamin J. Evans,
Jason Clark &
David Flanagan

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# Java in a Nutshell

The updated edition of this Nutshell guide helps experienced Java programmers get the most out of versions through Java 17 and serves as a learning path for new developers. Chock-full of examples that demonstrate how to take complete advantage of modern Java APIs and development best practices, this thoroughly revised book includes new material on recent enhancements to the Java object model that every developer should know.

The first section provides a fast-paced, no-fluff introduction to the Java programming language and the core runtime aspects of the Java platform. The second section is a core concept and API reference that explains how to perform real programming work with Java.

- **Get up to speed on language and core library details through Java 17**
- **Learn Java's syntax and model for object-oriented programming**
- **Explore generics, enumerations, annotations, and lambda expressions**
- **Examine how concurrency and memory are intertwined**
- **Delve into Java's latest I/O APIs, including asynchronous channels**
- **Become familiar with development tools in OpenJDK**

"This is a must-have book for developers to get a clear picture of how Java works and how it has evolved over the years."

**—Achyut Madhusudan**
Software Developer at RedHat

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JAVA

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# JAVA IN A NUTSHELL

## A Desktop Quick Reference

**Eighth Edition**

*Benjamin J. Evans, Jason Clark, and David Flanagan*

Beijing • Boston • Farnham • Sebastopol • Tokyo

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by Benjamin J. Evans, Jason Clark, and David Flanagan



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[LSI]

*This book is dedicated to all who teach peace and resist violence.*

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# Foreword

A lot can happen in four years.

This is as true of programming languages as it is of anything else.

Java 11, the first post-8 Java release with long-term support, arrived in September 2018 and the seventh edition of *Java in a Nutshell* came out a few months later.

Since then, both the wider world and the Java ecosystem have seen major upheavals that were largely unpredictable at that time.

The new release cadence, of a LTS release every three years (now changed to every two years), has found favor with the Java ecosystem—very few companies have chosen to adopt the interim, feature releases, and instead everyone prefers to stay on an upgrade path where only the LTS releases are productionized.

Java 11 has proved to be an excellent release and a worthy successor to the now-legacy Java 8.

With the release of Java 17, the language has moved forward yet again, with new features such as switch expressions and the introduction of Java's version of *algebraic data types*, in the form of records and sealed types.

Java performance continues to improve, and Java 17 is the fastest release yet.

In all, this is a great time to be joining (or returning to) application development in Java. Looking forward, the future holds some major changes that will alter the character of Java development in fundamental ways.

The next year or two will start to see these changes arrive and become part of the Java developer's everyday experience.

Once again, in working on this new edition of a classic text, if we have preserved the feel of *Java in a Nutshell*, while updating it to bring it to the attention of a new generation of developers, then we shall be well satisfied.

*—Ben Evans,*
*Barcelona, Spain, 2022*
*Jason Clark, Portland, Oregon*
*(& Barcelona, Spain), 2022*

# Preface

This book is a desktop Java reference, designed to sit faithfully by your keyboard while you program. Part I, "Introducing Java" is a fast-paced, "no-fluff" introduction to the Java programming language and the core runtime aspects of the Java platform. Part II, "Working with the Java Platform" is a reference section that blends elucidation of core concepts with examples of important core APIs. The book covers Java 17, but we recognize that some shops may not have adopted it yet—so where possible we call out if a feature was introduced after Java 8. We use Java 17 syntax throughout, including `var` and lambda expressions.

## Changes in the Eighth Edition

The seventh edition of this book covers Java 11, whereas this edition covers Java 17. However, the release process of Java changed significantly with the arrival of Java 9, and certain releases of Java are now badged as *long-term support* (LTS) releases. So, Java 17 is the next LTS release of Java after Java 11.

With the eighth edition we have tried to update the concept of what it means to be a "Nutshell" guide. The modern Java developer needs to know more than just syntax and APIs. As the Java environment has matured, such topics as concurrency, object-oriented design, memory, and the Java type system have all grown in importance for all developers.

In this edition, we have taken the approach that only the most recent versions of Java are likely to be of interest to the majority of Java developers, so we usually only call out when new features arrived after Java 8.

For example, the module system (that arrived with Java 9) is still likely to be new for at least some developers, and it represents a major change. However, it is also something of an advanced topic and is in someways separate from the rest of the language, so we have restricted our treatment of it to a single chapter.

## Contents of This Book

The first six chapters document the Java language and the Java platform—they should all be considered essential reading. The book is biased toward the Oracle/OpenJDK (Open Java Development Kit) implementation of Java but not greatly so. Developers working with other Java environments will still find plenty to occupy them. Part I includes:

*Chapter 1, "Introduction to the Java Environment"*
: This chapter is an overview of the Java language and the Java platform. It explains the important features and benefits of Java, including the lifecycle of a Java program. We also touch on Java security and answer some criticisms of Java.

*Chapter 2, "Java Syntax from the Ground Up"*
: This chapter explains the details of the Java programming language, including the Java 8 language changes. It is a long and detailed chapter that does not assume substantial programming experience. Experienced Java programmers can use it as a language reference. Programmers with substantial experience with languages such as C and C++ should be able to pick up Java syntax quickly by reading this chapter; beginning programmers with only a modest amount of experience should be able to learn Java programming by studying this chapter carefully, although it is best read in conjunction with an introductory text (such as O'Reilly's *Head First Java* by Kathy Sierra, Bert Bates, and Trisha Gee).

*Chapter 3, "Object-Oriented Programming in Java"*
: This chapter describes how the basic Java syntax documented in Chapter 2 is used to write simple object-oriented programs using classes and objects in Java. The chapter assumes no prior experience with object-oriented programming. It can be used as a tutorial by new programmers or as a reference by experienced Java programmers.

*Chapter 4, "The Java Type System"*
: This chapter builds on the basic description of object-oriented programming in Java and introduces the other aspects of Java's type system, such as generic types, enumerated types, and annotations. With this more complete picture, we can discuss the biggest change in Java 8—the arrival of lambda expressions.

*Chapter 5, "Introduction to Object-Oriented Design in Java"*
: This chapter is an overview of some basic techniques used in the design of sound object-oriented programs, and it briefly touches on the topic of design patterns and their use in software engineering.

*Chapter 6, "Java's Approach to Memory and Concurrency"*
: This chapter explains how the Java Virtual Machine manages memory on behalf of the programmer, and how memory and visibility are intimately entwined with Java's support for concurrent programming and threads.

These first six chapters teach you the Java language and get you up and running with the most important concepts of the Java platform. Part II is all about how to get real programming work done in the Java environment. It contains plenty of examples and is designed to complement the cookbook approach found in some other texts. This part includes:

*Chapter 7, "Programming and Documentation Conventions"*
: This chapter documents important and widely adopted Java programming conventions. It also explains how you can make your Java code self-documenting by including specially formatted documentation comments.

*Chapter 8, "Working with Java Collections"*
: This chapter introduces Java's standard collections libraries. These contain data structures that are vital to the functioning of virtually every Java program—such as `List`, `Map`, and `Set`. The new `Stream` abstraction and the relationship between lambda expressions and the collections are explained in detail.

*Chapter 9, "Handling Common Data Formats"*
: This chapter discusses how to use Java to work effectively with very common data formats, such as text, numbers, and temporal (date and time) information.

*Chapter 10, "File Handling and I/O"*
: This chapter covers several different approaches to file access—from the more classic approach found in older versions of Java, to more modern and even asynchronous styles. The chapter concludes with a short introduction to networking with the core Java platform APIs.

*Chapter 11, "Classloading, Reflection, and Method Handles"*
: This chapter introduces the subtle art of metaprogramming in Java—first introducing the concept of metadata about Java types, then turning to the subject of classloading and how Java's security model is linked to the dynamic loading of types. The chapter concludes with some applications of classloading and the relatively new feature of method handles.

*Chapter 12, "Java Platform Modules"*
: This chapter describes Java Platform Module System (JPMS), the major feature that was introduced as part of Java 9, and provides an introduction to the wide-ranging changes that it brings.

*Chapter 13, "Platform Tools"*
: Oracle's JDK (as well as OpenJDK) includes a number of useful Java development tools, most notably the Java interpreter and the Java compiler. This chapter documents those tools, as well as the `jshell` interactive environment and new tools for working with modular Java.

*Appendix*
: This appendix covers Java beyond version 17, including the releases Java 18 and 19 as well as ongoing research and development projects to enhance the language and JVM.

## Related Books

O'Reilly publishes an entire series of books on Java programming, including several companion books to this one:

*Learning Java* by Patrick Niemeyer and Daniel Leuck
: This book is a comprehensive tutorial introduction to Java and includes topics such as XML and client-side Java programming.

*Java 8 Lambdas* by Richard Warburton
: This book documents the new Java 8 feature of lambda expressions in detail and introduces concepts of functional programming that may be unfamiliar to Java developers coming from earlier versions.

*Head First Java* by Kathy Sierra, Bert Bates, and Trisha Gee
: This book uses a unique approach to teaching Java. Developers who think visually often find it a great accompaniment to a traditional Java book.

You can find a complete list of Java books from O'Reilly at *http://java.oreilly.com*.

## Conventions Used in This Book

The following typographical conventions are used in this book:

*Italic*
: Indicates new terms, URLs, email addresses, filenames, and file extensions.

`Constant width`
: Used for program listings, as well as within paragraphs to refer to program elements such as variable or function names, databases, data types, environment variables, statements, and keywords.

**`Constant width bold`**
: Shows commands or other text that should be typed literally by the user.

*`Constant width italic`*
: Shows text that should be replaced with user-supplied values or by values determined by context.

This element signifies a tip or suggestion.

This element signifies a general note.

This element indicates a warning or caution.

## Using Code Examples

Supplemental material (code examples, exercises, etc.) is available for download at *https://github.com/kittylyst/javanut8*.

If you have a technical question or a problem using the code examples, please send an email to *bookquestions@oreilly.com*.

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# I

# Introducing Java

Part I is an introduction to the Java language and the Java platform. These chapters provide enough information for you to get started using Java right away:

# 1

# Introduction to the Java Environment

Welcome to Java in 2023.

You may be coming to the Java world from another tradition, or maybe this is your first taste of computer programming. Whatever road you may have traveled to get here, welcome—we're glad you've arrived.

Java is a powerful, general-purpose programming environment. It is one of the most widely used programming environments in the world and has been exceptionally successful in business and enterprise computing for over 25 years.

In this chapter, we'll set the scene by describing the Java *language* (which programmers write their applications in), the Java *execution environment* (known as the "Java Virtual Machine," which actually runs those applications), and the Java *ecosystem* (which provides a lot of the value of the programming environment to development teams).

All three of these concepts (language, execution environment, and ecosystem) are habitually referred to just as "Java," with the precise usage inferred from context. In practice, they are such connected ideas that this isn't as confusing as it might first seem.

We'll briefly cover the history of the Java language and virtual machine, move on to discuss the lifecycle of a Java program, and then clear up some common questions about the differences between Java and other environments.

## The Language, the JVM, and the Ecosystem

The base Java programming environment has been around since the late 1990s. It is composed of the Java language and the supporting runtime, the Java Virtual

Machine (JVM). The third leg—the Java ecosystem beyond the standard library that ships with Java—is provided by third parties, such as open-source projects and Java technology vendors.

At the time that Java was initially developed, this split was considered novel, but trends in software development in the intervening years have made it more commonplace. Notably, Microsoft's .NET environment, announced a few years after Java, adopted a very similar approach to platform architecture.

One important difference between Microsoft's .NET platform and Java is that Java was always conceived as a relatively open ecosystem of multiple vendors, albeit led by a steward who owns the technology. Throughout Java's history, these vendors have both cooperated and competed on aspects of Java technology.

One of the main reasons for Java's success is that this ecosystem is a standardized environment. This means there are specifications for the technologies that comprise the environment. These standards give the developer and consumer confidence that the technology will be compatible with other components, even if they come from a different technology vendor.

The current steward of Java is Oracle Corporation (which acquired Sun Microsystems, the originator of Java). Other corporations, such as Red Hat, IBM, Amazon, Microsoft, AliBaba, SAP, Azul Systems, and Bellsoft, are also involved in producing implementations of standardized Java technologies.

> From Java 7 onwards, the reference implementation of Java is the open source OpenJDK (Java Development Kit), which many of these companies collaborate on and base their shipping products upon.

Java was originally composed of several different, but related, environments and specifications, such as Java Mobile Edition (Java ME),[1] Java Standard Edition (Java SE), and Java Enterprise Edition (Java EE).[2] In this book, we'll only cover Java SE, version 17, with some historical notes related to when certain features were introduced into the platform. Generally speaking, if someone says "Java" without any further clarification, they usually mean Java SE.

We will have more to say about standardization later, so let's move on to discuss the Java language and JVM as separate but related concepts.

1 Java ME was an older standard for feature phones and first-generation smartphones. Android and iOS dominate the market on phones today, and Java ME is no longer being updated.

2 Java EE has now been transferred to the Eclipse Foundation, where it continues its life as the Jakarta EE project.

## What Is the Java Language?

Java programs are written as source code in the Java language. This is a human-readable programming language, which is strictly class based and object-oriented. The language syntax is deliberately modeled on that of C and C++, and it was explicitly intended to be familiar to programmers coming from those languages, which were very dominant languages at the time Java was created.

> Although the source code is similar to C++, in practice Java includes features and a managed runtime that has much more in common with dynamic languages such as Smalltalk.

Java is considered to be relatively easy to read and write (if occasionally a bit verbose). It has a rigid grammar and simple program structure and is intended to be easy to learn and to teach. It is built on industry experience with languages like C++ and tries to remove complex features as well as preserving "what works" from previous programming languages.

The Java language is governed by the Java Language Specification (JLS), which defines how a conforming implementation must behave.

Overall, Java is intended to provide a stable, solid base for companies to develop business-critical applications. As a programming language, it has a relatively conservative design and a slow rate of change. These properties are a conscious attempt to serve the goal of protecting the investment that organizations have made in Java technology.

The language has undergone gradual revision (but no complete rewrites) since its inception in 1996. This does mean that some of Java's original design choices, which were expedient in the late 1990s, are still affecting the language today—see Chapters 2 and 3 for more details.

On the other hand, in the last 10 or so years, Java has modernized its language syntax somewhat, to address concerns about verbosity and provide features more familiar to programmers coming from other popular languages.

For example, in 2014, Java 8 added the most radical changes seen in the language for almost a decade. Features like lambda expressions and the introduction of the Streams API were enormously popular and changed forever the way that Java developers write code.

As we'll discuss later in this chapter, the Java project has transitioned to a new release model. In this new model Java versions are released every 6 months but only certain versions (8, 11, and 17) are considered eligible for LTS. All other versions are supported for only 6 months and have not seen widespread adoption by development teams.

## What Is the JVM?

The JVM is a program that provides the runtime environment necessary for Java programs to execute. Java programs cannot run unless there is a JVM available for the appropriate hardware and OS platform we wish to execute on.

Fortunately, the JVM has been ported to run on a large number of hardware environments—anything from a set-top box or Blu-ray player to a huge mainframe will probably have a JVM available for it. The JVM has its own specification, the Java Virtual Machine Specification, and every implementation must conform to the rules of the specification. When new hardware types arrive in the mainstream market then it is likely that companies or individuals interested in the hardware will start a project to port OpenJDK to the new chip. A recent example of this was the new Apple M1 chip—Red Hat ported the JVM to the AArch64 architecture and then Microsoft ported the build changes needed to build on Apple's silicon.

Java programs can be started in several ways, but the simplest (and oldest) method is to start from a command line:

```
java <arguments> <program name>
```

This brings up the JVM as an operating system process that provides the Java runtime environment and then executes our program in the context of the freshly started (and empty) virtual machine.

It is important to understand that when the JVM takes in a Java program for execution, the program is not provided as Java language source code. Instead, the Java language source must be compiled into a form known as Java bytecode. Java bytecode is then supplied to the JVM in a format called class files (which always have a *.class* extension). The Java platform has always emphasized backward compatibility, and code written for Java 1.0 will still run on today's JVMs without modification or recompilation.

The JVM provides an *execution environment* for the program. It starts an interpreter for the bytecode form of the program that steps through one bytecode instruction at a time. However, production-quality JVMs also provide a special compiler that operates while the Java program is running. This compiler (known as a "JIT" or just-in-time) will accelerate the important parts of the program by replacing them with equivalent compiled (and heavily optimized) machine code.

You should also be aware that both the JVM and the user program are capable of spawning additional threads of execution, so that a user program may have many different functions running simultaneously.

The original design of the JVM was built on many years of experience with earlier programming environments, notably C and C++, so we can think of it as having several different goals—all intended to make life easier for the programmer:

- Comprise a standard execution environment for application code to run inside
- Facilitate secure and reliable code execution (as compared to C/C++)

- Take low-level memory management out of the hands of developers
- Provide a cross-platform execution environment

These objectives are often mentioned together in discussions of the platform.

We've already mentioned the first of these goals, when we discussed the JVM and its bytecode interpreter—it functions as the container for application code.

We'll discuss the second and third goals in Chapter 6, when we talk about how the Java environment deals with memory management.

The fourth goal, sometimes called "write once, run anywhere" (WORA), is the property that Java class files can be moved from one execution platform to another, and they will run unaltered provided a JVM is available.

This means that a Java program can be developed (and converted to class files) on a machine running macOS on an M1 chip, and then the class files can be moved to Linux or Microsoft Windows on Intel hardware (or other platforms) and the Java program will run without any further work needed.

> The Java environment has been very widely ported, including to platforms that are very different from mainstream platforms like Linux, macOS, and Windows. In this book, we use the phrase "most implementations" to indicate those platforms that the majority of developers are likely to encounter; macOS, Windows, Linux, BSD Unix, and the like are all considered "mainstream platforms" and count within "most implementations."

In addition to these four primary goals, there is another aspect of the JVM's design that is not always recognized or discussed—it uses runtime information to self-manage.

Software research in the 1970s and 1980s revealed that the runtime behavior of programs has a large number of interesting and useful patterns that cannot be deduced at compile time. The JVM was the first truly mainstream programming environment to use the results of this research.

It collects runtime information to make better decisions about how to execute code. That means that the JVM can monitor and optimize a program running on it in a manner not possible for platforms without this capability.

A key example is the runtime fact that not all parts of a Java program are equally likely to be called during the lifetime of the program—some portions will be called far, far more often than others. The Java platform takes advantage of this fact with a technology called just-in-time (JIT) compilation.

In the HotSpot JVM (which was the JVM that Sun first shipped as part of Java 1.3, and is still in use today), the JVM first identifies which parts of the program are called most often—the “hot methods.” Then the JVM compiles these hot methods directly into machine code, bypassing the JVM interpreter.

The JVM uses the available runtime information to deliver higher performance than would be possible from purely interpreted execution. In fact, the optimizations that the JVM uses now in many cases produce performance that surpasses compiled C and C++ code.

The standard that describes how a properly functioning JVM must behave is called the JVM Specification.

## What Is the Java Ecosystem?

The Java language is easy to learn and contains relatively few abstractions, compared to other programming languages. The JVM provides a solid, portable, high-performance base for Java (or other languages) to execute on. Taken together, these two connected technologies provide a foundation that businesses can feel confident about when choosing where to base their development efforts.

The benefits of Java do not end there, however. Since Java’s inception, an extremely large ecosystem of third-party libraries and components has grown up. This means that a development team can benefit hugely from the existence of connectors and drivers for practically every technology imaginable—both proprietary and open source.

In the modern technology ecosystem, it is now rare indeed to find a technology component that does *not* offer a Java connector. From traditional relational databases, to NoSQL, to every type of enterprise monitoring system, to messaging systems, to Internet of Things (IoT)—everything integrates with Java.

It is this fact that has been a major driver of adoption of Java technologies by enterprises and larger companies. Development teams have been able to unlock their potential by making use of preexisting libraries and components. This has promoted developer choice and encouraged open, best-of-breed architectures with Java technology cores.

> Google’s Android environment is sometimes thought of as being “based on Java.” However, the picture is actually rather more complicated. Android code is written in Java (or the Kotlin language) but originally used a different implementation of Java’s class libraries along with a cross compiler to convert to a different file format for a non-Java virtual machine.

The combination of a rich ecosystem and a first-rate virtual machine with an open standard for program binaries makes the Java platform a very attractive execution target. In fact, there are a large number of non-Java languages that target the JVM and also interoperate with Java (which allows them to piggyback off the platform’s success). These languages include Kotlin, JRuby, Scala, Clojure, and many others.

While all of them are small compared to Java, they have distinct niches within the Java world and provide a source of innovation and healthy competition to Java.



## The Lifecycle of a Java Program

To better understand how Java code is compiled and executed, and the difference between Java and other types of programming environments, consider the pipeline in Figure 1-1.

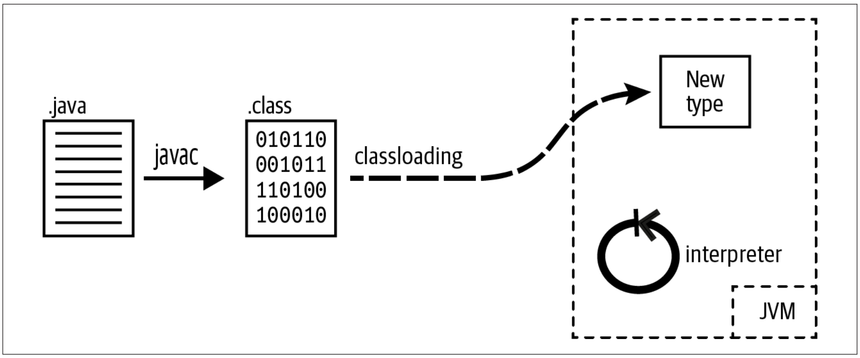


*Figure 1-1. How Java code is compiled and loaded*

This starts wth Java source and passes it through the `javac` program to produce class files—which contain the source code compiled to Java bytecode. The class file is the smallest unit of functionality the platform will deal with and the only way to get new code into a running program.

New class files are onboarded via the classloading mechanism (see Chapter 10 for a lot more detail on how classloading works). This makes the new code (represented as a type) available to the interpreter for execution, and execution begins in the `main()` method.

The performance analysis and optimization of Java program is a major topic, and interested readers should consult a specialist text, such as *Optimizing Java* (O'Reilly).

## Frequently Asked Questions

In this section, we'll discuss some of the most frequently asked questions about Java and the lifecycle of programs written in the Java environment.

### What is a virtual machine?

When developers are first introduced to the concept of a virtual machine, they sometimes think of it as "a computer inside a computer" or "a computer simulated in software." It's then easy to imagine bytecode as "machine code for the CPU of the internal computer" or "machine code for a made-up processor." However, this simple intuition can be misleading.

### What is bytecode?

In fact, JVM bytecode is actually not very similar to machine code that would run on a real hardware processor. Instead, computer scientists would call bytecode a type of *intermediate representation*—a halfway house between source code and machine code.

### Is javac a compiler?

Compilers usually produce machine code, but `javac` produces bytecode, which is not that similar to machine code. However, class files are a bit like object files (like Windows *.dll* files, or Unix *.so* files)—and they are certainly not human readable.

In theoretical computer science terms, `javac` is most similar to the *front half* of a compiler—it creates the intermediate representation that can then be used later to produce (emit) machine code.

However, because creation of class files is a separate build-time step that resembles compilation in C/C++, many developers consider running `javac` to be compilation. In this book, we will use the terms "source code compiler" or "`javac` compiler" to mean the production of class files by `javac`.

We will reserve "compilation" as a standalone term to mean JIT compilation—as it's JIT compilation that actually produces machine code.

### Why is it called "bytecode"?

The instruction code (opcode) is just a single byte (some operations also have parameters that follow them in the bytestream), so there are only 256 possible instructions. In practice, some are unused—about 200 are in use, but some of them aren't emitted by recent versions of `javac`.

### Is bytecode optimized?

In the early days of the platform, `javac` produced heavily optimized bytecode. This turned out to be a mistake.

With the advent of JIT compilation, the important methods are going to be compiled to very fast machine code. It's therefore very important to make the job of the JIT compiler easier—as there are much bigger gains available from JIT compilation than there are from optimizing bytecode, which will still have to be interpreted.

### Is bytecode really machine independent? What about things like endianness?

The format of bytecode is always the same, regardless of what type of machine it was created on. This includes the byte ordering (sometimes called "endianness") of the machine. For readers who are interested in the details, bytecode is always big-endian.

### Is Java an interpreted language?

The JVM is basically an interpreter (with JIT compilation to give it a big performance boost). However, most interpreted languages directly interpret programs from source form (usually by constructing an abstract syntax tree from the input source file). The JVM interpreter, on the other hand, requires class files—which, of course, require a separate source code compilation step with `javac`.

In fact, the modern version of many languages that were traditionally interpreted (such as PHP, Ruby, and Python) now also have JIT compilers, so the divide between "interpreted" and "compiled" languages is increasingly blurred. Once again, Java's design decisions have been validated by their adoption in other programming environments.

### Can other languages run on the JVM?

Yes. The JVM can run any valid class file, so this means that non-Java languages can run on the JVM in several ways. First, they could have a source code compiler (similar to `javac`) that produces class files, which would run on the JVM just like Java code (this is the approach taken by languages like Kotlin and Scala).

Alternatively, a non-Java language could implement an interpreter and runtime in Java and then interpret the source form of their language directly. This second option is the approach taken by languages like JRuby (but JRuby has a very sophisticated runtime that is capable of *secondary JIT compilation* in some circumstances).

# Comparing Java to Other Languages

In this section, we'll briefly highlight some differences between the Java platform and other programming environments you may be familiar with.

## Java Compared to JavaScript

- Java is statically typed; JavaScript is dynamically typed.
- Java uses class-based objects; JavaScript is prototype based (the JS keyword `class` is syntactic sugar).
- Java provides good object encapsulation; JavaScript does not.
- Java has namespaces; JavaScript does not.
- Java is multithreaded; JavaScript is not.

## Java Compared to Python

- Java is statically typed; Python is dynamically typed (with optional, *gradual* typing).

- Java is an OO language with functional programming (FP) features; Python is a hybrid OO / procedural language with some FP support.
- Java and Python both have a bytecode format—Java uses JVM class files; Python uses Python bytecode.
- Java's bytecode has extensive static checks; Python's bytecode does not.
- Java is multithreaded; Python allows only one thread to execute Python bytecode at once (the Global Interpreter Lock).

### Java Compared to C

- Java is object-oriented; C is procedural.
- Java is portable as class files; C needs to be recompiled.
- Java provides extensive instrumentation as part of the runtime.
- Java has no pointers and no equivalent of pointer arithmetic.
- Java provides automatic memory management via garbage collection.
- Java currently has no ability to lay out memory at a low level (no structs).
- Java has no preprocessor.

### Java Compared to C++

- Java has a simplified object model compared to C++.
- Java's method dispatch is virtual by default.
- Java is always pass-by-value (but one of the only possibilities for Java values is object references).
- Java does not support full multiple inheritance.
- Java's generics are less powerful (but also less dangerous) than C++ templates.
- Java has no operator overloading.

## Answering Some Criticisms of Java

Java has had a long history in the public eye and, as a result, has attracted its fair share of criticism over the years. Some of this negative press can be attributed to some technical shortcomings combined with rather overzealous marketing in the first versions of Java.

Some criticisms have, however, entered technical folklore despite no longer being very accurate. In this section, we'll look at some common grumbles and the extent to which they're true for modern versions of the platform.

## Overly Verbose

The Java core language has sometimes been criticized as overly verbose. Even simple Java statements such as `Object o = new Object();` seem to be repetitious—the type `Object` appears on both the left and right side of the assignment. Critics point out that this is essentially redundant, that other languages do not need this duplication of type information, and that many languages support features (e.g., type inference) that remove it.

The counterpoint to this argument is that Java was designed from the start to be easy to read (code is read more often than written) and that many programmers, especially novices, find the extra type information helpful when reading code.

Java is widely used in enterprise environments, which often have separate dev and ops teams. The extra verbosity can often be a blessing when you are responding to an outage call, or when you need to maintain and patch code that was written by developers who have long since moved on.

In recent versions of Java, the language designers have attempted to respond to some of these points by finding places where the syntax can become less verbose and by making better use of type information. For example:

```
// Files helper methods
byte[] contents =
  Files.readAllBytes(Paths.get("/home/ben/myFile.bin"));

// Diamond syntax for repeated type information
List<String> l = new ArrayList<>();

// Local variables can be type inferred
var threadPool = Executors.newScheduledThreadPool(2);

// Lambda expressions simplify Runnables
threadPool.submit(() -> { System.out.println("On Threadpool"); });
```

However, Java's overall philosophy is to make changes to the language only very slowly and carefully, so the pace of these changes may not satisfy detractors completely.

## Slow to Change

The original Java language is now well over 20 years old and has not undergone a complete revision in that time. Many other languages (e.g., Microsoft's C#) have released backward-incompatible versions in the same period, and some developers criticize Java for not doing likewise.

Furthermore, in recent years, the Java language has come under fire for being slow to adopt language features that are now commonplace in other languages.

The conservative approach to language design that Sun (and now Oracle) has taken is an attempt to avoid imposing the costs and externalities of misfeatures on a very large user base. Many Java shops have made major investments in the technology, and the language designers have taken seriously the responsibility of not disrupting the existing user and install base.

Each new language feature needs to be very carefully thought about—not only in isolation but in terms of how it will interact with all the existing features of the language. New features can sometimes have impacts beyond their immediate scope—and Java is widely used in very large codebases, where there are more potential places for an unexpected interaction to manifest.

It is almost impossible to remove a feature that turns out to be incorrect after it has shipped. Java has a couple of misfeatures (such as the serialization mechanism) that have been all-but-impossible to remove safely without impacting the install base. The language designers have taken the view that extreme caution is required when evolving the language.

Having said that, the new language features that have arrived in recent versions are a significant step toward addressing the most common complaints about missing features, and they should cover many of the idioms that developers have been asking for.

## Performance Problems

The Java platform is still sometimes criticized for being slow—but of all the criticisms that are leveled at the platform, this is probably the one that is least justified. It is a genuine myth about the platform.

Release 1.3 of Java brought in the HotSpot Virtual Machine and its JIT compiler. Since then, there have been over 15 years of continual innovation and improvement in the virtual machine and its performance. The Java platform is now blazingly fast, regularly winning performance benchmarks on popular frameworks, and even beating native-compiled C and C++.

Criticism in this area appears to be largely caused by a folk memory that Java was slow at some point in the past. Some of the larger, more sprawling architectures that Java has been used within may also have contributed to this impression.

The truth is that any large architecture will require benchmarking, analysis, and performance tuning to get the best out of it—and Java is no exception.

The core of the platform—language and JVM—was and remains one of the fastest general-use environments available to the developer.

## Insecure

Some people have historically criticized Java's record of security vulnerabilities.

Many of these vulnerabilities involved the desktop and GUI components of the Java system and wouldn't affect websites or other server-side code written in Java.

The truth is that Java has been designed from the ground up with security in mind; this gives it a great advantage over many other existing systems and platforms. The Java security architecture was designed by security experts and has been studied and probed by many other security experts since the platform's inception. The consensus is that the architecture itself is strong and robust, without any security holes in the design (at least none that have been discovered yet).

Fundamental to the design of the security model is that bytecode is heavily restricted in what it can express—there is no way, for example, to directly address memory. This cuts out entire classes of security problems that have plagued languages like C and C++. Furthermore, the VM goes through a process known as *bytecode verification* whenever it loads an untrusted class, which removes a further large class of problems (see Chapter 10 for more about bytecode verification).

Despite all this, however, no system can guarantee 100% security, and Java is no exception.

While the design is still theoretically robust, the implementation of the security architecture is another matter, and there is a long history of security flaws being found and patched in particular implementations of Java. In all likelihood, security flaws will continue to be discovered (and patched) in Java VM implementations.

All programming platforms have security issues at times, and many other languages have a comparable history of security vulnerabilities that have been significantly less well publicized. For practical server-side coding, Java remains perhaps the most secure general-purpose platform currently available, especially when kept patched up to date.

## Too Corporate

Java is a platform that is extensively used by corporate and enterprise developers. The perception that it is too corporate is therefore not surprising—Java has often been perceived as lacking the "freewheeling" style of languages that are deemed to be more community oriented.

In truth, Java has always been, and remains, a very widely used language for community and free or open source software development. It is one of the most popular languages for projects hosted on GitHub and other project-hosting sites. Not only that, but the Java community is regularly held up as one of the real strengths of the ecosystem—with user groups, conferences, journals, and all of the most visible signs of an active and healthy user community.

Finally, the most widely used implementation of the language itself is based on OpenJDK—which is itself an open-source project with a vibrant and growing community.

## A Brief History of Java and the JVM

*Java 1.0 (1996)*
: This was the first public version of Java. It contained just 212 classes organized in eight packages.

*Java 1.1 (1997)*
: This release of Java more than doubled the size of the Java platform. This release introduced "inner classes" and the first version of the Reflection API.

*Java 1.2 (1998)*
: This was a very significant release of Java; it tripled the size of the Java platform. This release marked the first appearance of the Java Collections API (with sets, maps, and lists). The many new features in the 1.2 release led Sun to rebrand the platform as "the Java 2 Platform." The term "Java 2" was simply a trademark, however, and not an actual version number for the release.

*Java 1.3 (2000)*
: This was primarily a maintenance release, focused on bug fixes, stability, and performance improvements. This release also brought in the HotSpot Java Virtual Machine, which is still in use today (although heavily modified and improved since then).

*Java 1.4 (2002)*
: This was another fairly big release, adding important new functionality such as a higher-performance, low-level I/O API; regular expressions for text handling; XML and XSLT libraries; SSL support; a logging API; and cryptography support.

*Java 5 (2004)*
: This large release of Java introduced a number of changes to the core language itself, including generic types, enumerated types (enums), annotations, varargs methods, autoboxing, and a new `for` loop. These changes were considered significant enough to change the major version number and to start numbering as major releases. This release included 3,562 classes and interfaces in 166 packages. Notable additions included utilities for concurrent programming, a remote management framework, and classes for the remote management and instrumentation of the Java VM itself.

*Java 6 (2006)*
: This release was also largely a maintenance and performance release. It introduced the Compiler API, expanded the usage and scope of annotations, and provided bindings to allow scripting languages to interoperate with Java. There were also a large number of internal bug fixes and improvements to the JVM and the Swing GUI technology.

*Java 7 (2011)*
: The first release of Java under Oracle's stewardship included a number of major upgrades to the language and platform, as well as being the first release

to be based on the Open Source reference implementation. The introduction of `try`-with-resources and the NIO.2 API enabled developers to write much safer and less error-prone code for handling resources and I/O. The Method Handles API provided a simpler and safer alternative to reflection; in addition, it opened the door for `invokedynamic` (the first new bytecode since version 1.0 of Java).

*Java 8 (2014) (LTS)*
: This was a huge release—potentially the most significant changes to the language since Java 5 (or possibly ever). The introduction of lambda expressions provided the ability to significantly enhance the productivity of developers, the Collections were updated to make use of lambdas, and the machinery required to achieve this marked a fundamental change in Java's approach to object orientation. Other major updates include a new date and time API and major updates to the concurrency libraries.

*Java 9 (2017)*
: Significantly delayed, this release introduced the new platform modularity feature, which allows Java applications to be packaged into deployment units and modularize the platform runtime. Other changes include a new default garbage collection algorithm, a new API for handling processes, and some changes to the way that frameworks can access the internals. This release also changed the release cycle itself, so that new versions arrive every 6 months, but only the LTS releases have gained traction. Accordingly, we only record the LTS releases beyond this point.

*Java 11 (September 2018) (LTS)*
: This release was the first modular Java to be considered as a long-term support (LTS) release. It adds a few new features that are directly visible to the developer—primarily improved support for type inference (`var`), JDK Flight Recorder (JFR), and the new HTTP/2 API. There were some additional internal changes and substantial performance improvements, but this LTS release was primarily intended for stabilization after Java 9.

*Java 17 (September 2021) (LTS)*
: The current version LTS release. Includes important changes to Java's OO model (Sealed classes, Records, and Nestmates) as well as Switch Expressions, Text Blocks, and a first version of language Pattern Matching. The JVM had additional performance improvements and better support for running in containers. The internal upgrades continued, and two new garbage collectors were added.

As it stands, the only current production versions are the LTS releases, 11 and 17. Due to the highly significant changes that are introduced by modules, Java 8 was retrospectively declared to be an LTS release to provide extra time for teams and applications to migrate to a supported modular Java. It is now considered a "classic" release, and teams are strongly encouraged to migrate to one of the modern LTS versions.

## Summary

In this introductory chapter, we've placed Java in context within the overall landscape and history of programming languages. We've compared the language to other popular alternatives, taken a first look at the basic anatomy of how a Java program is compiled and executed, and tried to dispel some of the popular myths about Java.

The next chapter covers Java's language syntax—primarily from a *bottom-up* perspective, focusing on the individual basic units of lexical syntax and building upwards. If you are already familiar with the syntax of a language similar to Java (such as JavaScript, C or C++), you may choose to skim or skip this chapter and refer to it when you encounter any syntax that is unfamiliar to you.

# 2
# Java Syntax from the Ground Up

This chapter is fairly dense but should provide a comprehensive introduction to Java syntax. It is written primarily for readers who are new to the language but have some previous programming experience. Determined novices with no prior programming experience may also find it useful. If you already know Java, you should find it a useful language reference. The chapter includes some comparisons of Java to JavaScript, C, and C++ for the benefit of programmers coming from those languages.

This chapter documents the syntax of Java programs by starting at the very lowest level of Java syntax and building from there, moving on to increasingly higher orders of structure. It covers:

- The characters used to write Java programs and the encoding of those characters.
- Literal values, identifiers, and other tokens that comprise a Java program.
- The data types that Java can manipulate.
- The operators used in Java to group individual tokens into larger expressions.
- Statements, which group expressions and other statements to form logical chunks of Java code.
- Methods, which are named collections of Java statements that can be invoked by other Java code.
- Classes, which are collections of methods and fields. Classes are the central program element in Java and form the basis for object-oriented programming. Chapter 3 is devoted entirely to a discussion of classes and objects.

- Packages, which are collections of related classes.
- Java programs, which consist of one or more interacting classes that may be drawn from one or more packages.

The syntax of most programming languages is complex, and Java is no exception. In general, it is not possible to document all elements of a language without referring to other elements that have not yet been discussed. For example, it is not really possible to explain in a meaningful way the operators and statements supported by Java without referring to objects. But it is also not possible to document objects thoroughly without referring to the operators and statements of the language. The process of learning Java, or any language, is therefore an iterative one.

# Java Programs from the Top Down

Before we begin our bottom-up exploration of Java syntax, let's take a moment for a top-down overview of a Java program. Java programs consist of one or more files, or *compilation units*, of Java source code. Near the end of the chapter, we describe the structure of a Java file and explain how to compile and run a Java program. Each compilation unit begins with an optional `package` declaration followed by zero or more `import` declarations. These declarations specify the namespace within which the compilation unit will define names and the namespaces from which the compilation unit imports names. We'll see `package` and `import` again later in this chapter in "Packages and the Java Namespace" on page 98.

The optional `package` and `import` declarations are followed by zero or more reference type definitions. We will meet the full variety of possible reference types in Chapters 3 and 4, but for now, we should note that these are most often either `class` or `interface` definitions.

Within the definition of a reference type, we will encounter *members* such as *fields*, *methods*, and *constructors*. Methods are the most important kind of member. Methods are blocks of Java code composed of *statements*.

With these basic terms defined, let's start by approaching a Java program from the bottom up by examining the basic units of syntax—often referred to as *lexical tokens*.

# Lexical Structure

This section explains the lexical structure of a Java program. It starts with a discussion of the Unicode character set in which Java programs are written. It then covers the tokens that comprise a Java program, explaining comments, identifiers, reserved words, literals, and so on.

## The Unicode Character Set

Java programs are written using Unicode. You can use Unicode characters anywhere in a Java program, including comments and identifiers such as variable names. Unlike the 7-bit ASCII character set, which is useful only for English, and the 8-bit ISO Latin-1 character set, which is useful only for major Western European languages, the Unicode character set can represent virtually every written language in common use on the planet.

> If you do not use a Unicode-enabled text editor, or if you do not want to force other programmers who view or edit your code to use a Unicode-enabled editor, you can embed Unicode characters into your Java programs using the special Unicode escape sequence `\u`*xxxx*—that is, a backslash and a lowercase u, followed by four hexadecimal characters. For example, `\u0020` is the space character, and `\u03c0` is the character π.

Java has invested a large amount of time and engineering effort in ensuring that its Unicode support is first class. If your business application needs to deal with global users, especially in non-Western markets, then the Java platform is a great choice. Java also has support for multiple encodings and character sets, in case applications need to interact with non-Java applications that do not speak Unicode.

## Case Sensitivity and Whitespace

Java is a case-sensitive language. Its keywords are written in lowercase and must always be used that way. That is, `While` and `WHILE` are not the same as the `while` keyword. Similarly, if you declare a variable named `i` in your program, you may not refer to it as `I`.

> In general, relying on case sensitivity to distinguish identifiers is a terrible idea. The more similar identifiers there are, the more difficult the code is to read and understand. Do not use it in your own code, and in particular never give an identifier the same name as a keyword but differently cased.

Java ignores spaces, tabs, newlines, and other whitespace, except when they appear within quoted characters and string literals. Programmers typically use whitespace to format and indent their code for easy readability, but it has no influence on the program's behavior as indents do in Python. You will see common indentation conventions in this book's code examples.

## Comments

Comments are natural-language text intended for human readers of a program. They are ignored by the Java compiler. Java supports three types of comments.

The first type is a single-line comment, which begins with the characters `//` and continues until the end of the current line. For example:

```
int i = 0;   // Initialize the loop variable
```

The second kind of comment is a multiline comment. It begins with the characters `/*` and continues, over any number of lines, until the characters `*/`. Any text between the `/*` and the `*/` is ignored by `javac`. Although this style of comment is typically used for multiline comments, it also can be used for single-line comments. This type of comment cannot be nested (i.e., one `/* */` comment cannot appear within another). When writing multiline comments, programmers often use extra `*` characters to make the comments stand out. Here is a typical multiline comment:

```
/*
 * First, establish a connection to the server.
 * If the connection attempt fails, quit right away.
 */
```

The third type of comment is a special case of the second. If a comment begins with `/**`, it is regarded as a special *doc comment*. Like regular multiline comments, doc comments end with `*/` and cannot be nested. When you write a Java class you expect other programmers to use, provide doc comments to embed documentation about the class and each of its methods directly into the source code. A program named `javadoc` extracts these comments and processes them to create online documentation for your class. A doc comment can contain HTML tags and can use additional syntax understood by `javadoc`. For example:

```
/**
 * Upload a file to a web server.
 *
 * @param file The file to upload.
 * @return <tt>true</tt> on success,
 *         <tt>false</tt> on failure.
 * @author David Flanagan
 */
```

See Chapter 7 for more information on the doc comment syntax and Chapter 13 for more information on the `javadoc` program.

Comments may appear between any tokens of a Java program but may not appear within a token. In particular, comments may not appear within double-quoted string literals. A comment within a string literal simply becomes a literal part of that string.

## Reserved Words

The following words are reserved in Java (they are part of the syntax of the language and may not be used to name variables, classes, and so forth):

```
abstract   const      final      int        public      throw
assert     continue   finally    interface  return      throws
boolean    default    float      long       short       transient
```

```
break      do        for          native     static        true
byte       double    goto         new        strictfp      try
case       else      if           null       super         void
catch      enum      implements   package    switch        volatile
char       extends   import       private    synchronized  while
class      false     instanceof   protected  this
_ (underscore)
```

Of these, `true`, `false`, and `null` are technically literals.

Note that `const` and `goto` are reserved but aren't actually used in the language and that `interface` has an additional variant form—`@interface`, which is used when defining types known as annotations. Some of the reserved words (notably `final` and `default`) have a variety of meanings depending on context.

Other keywords exist that are not reserved in general and are known as *contextual keywords*.

```
exports      opens      requires     uses
module       permits    sealed       var
non-sealed   provides   to           with
open         record     transitive   yield
```

`var` indicates a local variable that should be type-inferred. `sealed`, `non-sealed`, and `record` are used when defining classes, which we'll meet in Chapter 3. `yield` appears within `switch` expressions we'll meet later in this chapter, while the remaining contextual keywords deal with modules, the syntax and use of which are covered in Chapter 12.

Using contextual keywords as variable names, while allowed for compatibility, is discouraged. `var var = "var";` may be a valid statement, but it is a valid statement that ought to be viewed with suspicion.

## Identifiers

An *identifier* is simply a name given to some part of a Java program, such as a class, a method within a class, or a variable declared within a method. Identifiers may be of any length and may contain letters and digits drawn from the entire Unicode character set. An identifier may not begin with a digit.

In general, identifiers may not contain punctuation characters. Exceptions include the dollar sign (`$`) as well as other Unicode currency symbols such as `£` and `¥`.

Currency symbols are intended for use in automatically generated source code, such as code produced by `javac`. By avoiding the use of currency symbols in your own identifiers, you don't have to worry about collisions with automatically generated identifiers.

The ASCII underscore (_) also deserves special mention. Originally, the underscore could be freely used as an identifier or part of one. However, in recent versions of Java, including Java 17, the underscore may not be used as an identifier.

The underscore character can still appear in a Java identifier, but it is no longer legal as a complete identifier by itself. This is to support an expected forthcoming language feature whereby the underscore will acquire a special new syntactic meaning.

The usual Java convention is to name variables using *camel case*. This means that the first letter of a variable should be lowercase but that the first letter of any other words in the identifier should be uppercase.

Formally, the characters allowed at the beginning of and within an identifier are defined by the methods `isJavaIdentifierStart()` and `isJavaIdentifierPart()` of the class `java.lang.Character`.

The following are examples of legal identifiers:

```
i    x1    theCurrentTime    current    獺
```

Note in particular the example of a UTF-8 identifier, 獺. This is the Kanji character for "otter" and is perfectly legal as a Java identifier. The use of non-ASCII identifiers is unusual in programs predominantly written by Westerners, but it is sometimes seen.

## Literals

Literals are sequences of source characters that directly represent constant values that appear as is in Java source code. They include integer and floating-point numbers, single characters within single quotes, strings of characters within double quotes, and the reserved words `true`, `false`, and `null`. For example, the following are all literals:

```
1    1.0    '1'    1L    "one"    true    false    null
```

The syntax for expressing numeric, character, and string literals is detailed in "Primitive Data Types" on page 25.

## Punctuation

Java also uses a number of punctuation characters as tokens. The Java Language Specification divides these characters (somewhat arbitrarily) into two categories, separators and operators. The 12 separators are:

```
(   )   {   }   [   ]

...     @       ::

;       ,       .
```

The operators are:

```
+    —    *    /    %    &    |    ^    <<    >>    >>>
+=   -=   *=   /=   %=   &=   |=   ^=   <<=   >>=   >>>=
=    ==   !=   <    <=   >    >=
!    ~    &&   ||   ++   --   ?    :    ->
```

We'll see separators throughout the book and will cover each operator individually in "Expressions and Operators" on page 34.

# Primitive Data Types

Java supports eight basic data types known as *primitive types* as described in Table 2-1. The primitive types include a boolean type, a character type, four integer types, and two floating-point types. The four integer types and the two floating-point types differ in the number of bits that represent them and therefore in the range of numbers they can represent. Note that the size of these types is the notional size in the Java language. Different JVM implementations may use more actual space to hold these values due to padding, alignment, and the like.

*Table 2-1. Java primitive data types*

| Type | Contains | Default | Size | Range |
|---|---|---|---|---|
| `boolean` | `true` or `false` | `false` | 1 bit | NA |
| `char` | Unicode character | `\u0000` | 16 bits | `\u0000` to `\uFFFF` |
| `byte` | Signed integer | 0 | 8 bits | –128 to 127 |
| `short` | Signed integer | 0 | 16 bits | –32768 to 32767 |
| `int` | Signed integer | 0 | 32 bits | –2147483648 to 2147483647 |
| `long` | Signed integer | 0 | 64 bits | –9223372036854775808 to 9223372036854775807 |
| `float` | IEEE 754 floating point | 0.0 | 32 bits | 1.4E–45 to 3.4028235E+38 |
| `double` | IEEE 754 floating point | 0.0 | 64 bits | 4.9E–324 to 1.7976931348623157E+308 |

The next section summarizes these primitive data types. In addition to these primitive types, Java supports nonprimitive data types known as reference types, which are introduced in "Reference Types" on page 94.

## The boolean Type

The `boolean` type represents truth values. This type has only two possible values, representing the two Boolean states: on or off, yes or no, true or false. Java reserves the words `true` and `false` to represent these two Boolean values.

Programmers coming to Java from other languages (especially JavaScript, Python, or C) should note that Java is much stricter about its Boolean values than other languages; in particular, a `boolean` is neither an integral nor an object type, and incompatible values cannot be used in place of a `boolean`. In other words, you cannot take shortcuts such as the following in Java:

```
Object o = new Object();
int i = 1;

if (o) {     // Invalid!
  while(i) {
    //...
  }
}
```

Instead, Java forces you to write cleaner code by explicitly stating the comparisons you want:

```
if (o != null) {
  while(i != 0) {
    // ...
  }
}
```

## The char Type

The `char` type represents Unicode characters. Java has a slightly unique approach to representing characters—`javac` accepts identifiers and literals as UTF-8 (a variable-width encoding) in input. However, internally, Java represents chars in a fixed-width encoding—either a 16-bit encoding (before Java 9) or as ISO-8859-1 (an 8-bit encoding, used for Western European languages, also called Latin-1) if possible (Java 9 and later).

This distinction between external and internal representation does not normally need to concern the developer. In most cases, all that is required is to remember the rule that to include a character literal in a Java program, simply place it between single quotes (apostrophes):

```
char c = 'A';
```

You can, of course, use Unicode characters as character literals with the `\u` Unicode escape sequence. In addition, Java supports a number of other escape sequences that make it easy both to represent commonly used nonprinting ASCII characters, such as `newline`, and to escape certain punctuation characters that have special meaning in Java. For example:

```
char tab = '\t', nul = '\000', aleph = '\u05D0', backslash = '\\';
```

Table 2-2 lists the escape characters that can be used in `char` literals. These characters can also be used in string literals, which are covered in the next section.



*Table 2-2. Java escape characters*

| Escape sequence | Character value |
|---|---|
| `\b` | Backspace |
| `\t` | Horizontal tab |
| `\n` | Newline |
| `\f` | Form feed |
| `\r` | Carriage return |
| `\"` | Double quote |
| `\'` | Single quote |
| `\\` | Backslash |
| `\`*`xxx`* | The Latin-1 character with the encoding *`xxx`*, where *`xxx`* is an octal (base 8) number between 000 and 377. The forms `\`*`x`* and `\`*`xx`* are also legal, as in `\`*`0`*, but are not recommended because they can cause difficulties in string constants where the escape sequence is followed by a regular digit. This form is generally discouraged in favor of the `\uXXXX` form. |
| `\u`*`xxxx`* | The Unicode character with encoding *`xxxx`*, where *`xxxx`* is four hexadecimal digits. Unicode escapes can appear anywhere in a Java program, not only in character and string literals. |

`char` values can be converted to and from the various integral types, and the `char` data type is a 16-bit integral type. Unlike `byte`, `short`, `int`, and `long`, however, `char` is an unsigned type and may receive values only in the range 0 to 65535. The `Character` class defines a number of useful `static` methods for working with characters, including `isDigit()`, `isJavaLetter()`, `isLowerCase()`, and `toUpperCase()`.

The Java language and its `char` type were designed with Unicode in mind. The Unicode standard is evolving, however, and each new version of Java adopts a new version of Unicode. Java 11 uses Unicode 10.0.0 and Java 17 uses Unicode 13.0.

A complication in recent Unicode releases is the introduction of characters whose encodings, or *codepoints*, do not fit in 16 bits. These supplementary characters, which are mostly infrequently used Han (Chinese) ideographs, occupy 21 bits and cannot be represented in a single `char` value. Instead, you must use an `int` value to hold the codepoint of a supplementary character, or you must encode it into a so-called "surrogate pair" of two `char` values.

Unless you commonly write programs that use Asian languages, you are unlikely to encounter any supplementary characters. If you do anticipate having to process characters that do not fit into a `char`, methods have been added to the `Character`, `String`, and related classes for working with text using `int` codepoints.

### String literals

In addition to the `char` type, Java also has a data type for working with strings of text (usually simply called *strings*). The `String` type is a class, however, and is not one of the primitive types of the language. Because strings are so commonly used, though, Java does have syntax for including string values literally in a program. A `String` literal consists of arbitrary text within double quotes (as opposed to the single quotes for `char` literals). For example:

```
"Hello World"
"'This' is a string!"
```

Recent versions of Java also introduced a multiline string literal syntax called *text blocks*. A text block begins with a `"""` and a newline and ends when another sequence of `"""` is seen. These are handled entirely by the `javac` compiler and result in identical string literals to normal `"` strings in bytecode.

```
"""
Multi-line text blocks
Can use "double quotes" without escaping
"""
```

String literals can contain any of the escape sequences that can appear as `char` literals (see Table 2-2). Use the `\"` sequence to include a double quote within a standard `String` literal. Text blocks allow such escape sequences but do not require them for newlines or double quotes.

Because `String` is a reference type, string literals are described in more detail later in this chapter in "String literals" on page 84. Chapter 9 contains more details on some of the ways you can work with `String` objects in Java.

## Integer Types

The integer types in Java are `byte`, `short`, `int`, and `long`. As shown in Table 2-1, these four types differ only in the number of bits and, therefore, in the range of numbers each type can represent. All integral types represent signed numbers; there is no `unsigned` keyword as there is in C and C++.

Literals for each of these types are written exactly as you would expect: as a sequence of decimal digits, optionally preceded by a minus sign.[1] Digits in any of these literals may be separated by an underscore (_) for better readability. Here are some legal integer literals:

```
0
1
123
9_000
-42000
```

Integer literals are 32-bit values (and so are taken to be the Java type `int`) unless they end with the character `L` or `l`, in which case they are 64-bit values (and are understood to be the Java type `long`):

```
1234        // An int value
1234L       // A long value
0xffL       // Another long value
```

Integer literals can also be expressed in hexadecimal, binary, or octal notation. A literal that begins with `0x` or `0X` is taken as a hexadecimal number, using the letters `A` to `F` (or `a` to `f`) as the additional digits required for base-16 numbers.

Integer binary literals start with `0b` and may, of course, feature only the digits 1 or 0. Use of the underscore separator in binary literals is very common, as binary literals can be very long.

Java also supports octal (base-8) integer literals. These literals begin with a leading `0` and cannot include the digits 8 or 9. They are not often used and should be avoided unless needed. Legal hexadecimal, binary, and octal literals include:

```
0xff              // Decimal 255, expressed in hexadecimal
0377              // The same number, expressed in octal (base 8)
0b0010_1111       // Decimal 47, expressed in binary
0xCAFEBABE        // A magic number used to identify Java class files
```

Integer arithmetic in Java never produces an overflow or an underflow when you exceed the range of a given integer type. Instead, numbers just wrap around. For example, let's look at an overflow:

```
byte b1 = 127, b2 = 1;        // Largest byte is 127
byte sum = (byte)(b1 + b2);   // Sum wraps to -128, the smallest byte
```

and the corresponding underflow behavior:

```
byte b3 = -128, b4 = 5;        // Smallest byte is -128
byte sum2 = (byte)(b3 - b4);   // Sum wraps to a large byte value, 123
```

1 Technically, the minus sign is an operator that operates on the literal and not part of the literal itself.

Neither the Java compiler nor the Java interpreter warns you in any way when this occurs. When doing integer arithmetic, you simply must ensure that the type you are using has a sufficient range for the purposes you intend. Integer division by zero and modulo by zero are illegal and cause an `ArithmeticException` to be thrown. (We'll see more about exceptions soon in "Checked and Unchecked Exceptions" on page 79).

Each integer type has a corresponding wrapper class: `Byte`, `Short`, `Integer`, and `Long`. Each of these classes defines `MIN_VALUE` and `MAX_VALUE` constants that describe the range of the type. Each class also provides a static `valueOf()` method that is strongly preferred for creating an instance of the wrapper class from a primitive value. While the wrapper classes have plain constructors that take the primitives, they are deprecated and should be avoided. The wrapper classes also define useful static methods, such as `Byte.parseByte()` and `Integer.parseInt()`, for converting strings to integer values.

## Floating-Point Types

Real numbers in Java are represented by the `float` and `double` data types. As shown in Table 2-1, `float` is a 32-bit, single-precision, floating-point value, and `double` is a 64-bit, double-precision, floating-point value. Both types adhere to the IEEE 754-1985 standard, which specifies both the format of the numbers and the behavior of arithmetic for the numbers.

Floating-point values can be included literally in a Java program as an optional string of digits, followed by a decimal point and another string of digits. Here are some examples:

```
123.45
0.0
.01
```

Floating-point literals can also use exponential, or scientific, notation, in which a number is followed by the letter `e` or `E` (for exponent) and another number. This second number represents the power of 10 by which the first number is multiplied. For example:

```
1.2345E02    // 1.2345 * 10^2 or 123.45
1e-6         // 1 * 10^-6 or 0.000001
6.02e23      // Avogadro's Number: 6.02 * 10^23
```

Floating-point literals are `double` values by default. To include a `float` value literally in a program, follow the number with `f` or `F`:

```
double d = 6.02E23;
float f = 6.02e23f;
```

Floating-point literals cannot be expressed in hexadecimal, binary, or octal notation.

## Floating-Point Representations

Most real numbers, by their very nature, cannot be represented exactly in any finite number of bits. Thus, it is important to remember that `float` and `double` values are only approximations of the numbers they are meant to represent. A `float` is a 32-bit approximation, which results in at least six significant decimal digits, and a `double` is a 64-bit approximation, which results in at least 15 significant digits. In Chapter 9, we will cover floating-point representations in more detail.

In addition to representing ordinary numbers, the `float` and `double` types can also represent four special values: positive and negative infinity, zero, and NaN. The infinity values result when a floating-point computation produces a value that overflows the representable range of a `float` or `double`.

When a floating-point computation underflows the representable range of a `float` or a `double`, a zero value results.

> We can imagine repeatedly dividing the double value `1.0` by `2.0` (e.g., in a `while` loop). In mathematics, no matter how often we perform the division, the result will never become equal to zero. However, in a floating-point representation, after enough divisions, the result will eventually be so small as to be indistinguishable from zero.

The Java floating-point types make a distinction between positive zero and negative zero, depending on the direction from which the underflow occurred. In practice, positive and negative zero behave pretty much the same. Finally, the last special floating-point value is NaN, which stands for "Not a Number." The NaN value results when an illegal floating-point operation, such as 0.0/0.0, is performed. Here are examples of statements that result in these special values:

```
double inf = 1.0/0.0;             // Infinity
double neginf = -1.0/0.0;         // Negative infinity
double negzero = -1.0/inf;        // Negative zero
double NaN = 0.0/0.0;             // Not a Number
```

The `float` and `double` primitive types have corresponding classes, named `Float` and `Double`. Each of these classes defines the following useful constants: `MIN_VALUE`, `MAX_VALUE`, `NEGATIVE_INFINITY`, `POSITIVE_INFINITY`, and `NaN`. Much like the integer wrapper classes, the floating-point wrappers also have a static `valueOf()` for constructing instances.

Java floating-point types can handle overflow to infinity and underflow to zero and have a special NaN value. This means floating-point arithmetic never throws exceptions, even when performing illegal operations, like dividing zero by zero or taking the square root of a negative number.

The infinite floating-point values behave as you would expect. Adding or subtracting any finite value to or from infinity, for example, yields infinity. Negative zero behaves almost identically to positive zero, and, in fact, the `==` equality operator reports that negative zero is equal to positive zero. One way to distinguish negative zero from positive, or regular, zero is to divide by it: `1.0/0.0` yields positive infinity, but `1.0` divided by negative zero yields negative infinity. Finally, because NaN is Not a Number, the `==` operator says that it is not equal to any other number, including itself!

```
double NaN = 0.0/0.0;              // Not a Number
NaN == NaN;                        // false
Double.isNaN(NaN);                 // true
```

To check whether a `float` or `double` value is NaN, you must use the `Float.isNaN()` and `Double.isNaN()` methods.

## Primitive Type Conversions

Java allows conversions between integer values and floating-point values. In addition, because every character corresponds to a number in the Unicode encoding, `char` values can be converted to and from the integer and floating-point types. In fact, `boolean` is the only primitive type that cannot be converted to or from another primitive type in Java.

There are two basic types of conversions. A *widening conversion* occurs when a value of one type is converted to a wider type—one that has a larger range of legal values. For example, Java performs widening conversions automatically when you assign an `int` literal to a `double` variable or a `char` literal to an `int` variable.

Narrowing conversions are another matter, however. A *narrowing conversion* occurs when a value is converted to a type that is not wider than it is. Narrowing conversions are not always safe: it is reasonable to convert the integer value 13 to a `byte`, for example, but it is not reasonable to convert 13,000 to a `byte`, because `byte` can hold only numbers between –128 and 127. Because you can lose data in a narrowing conversion, `javac` complains when you attempt any narrowing conversion, even if the value being converted would in fact fit in the narrower range of the specified type:

```
int i = 13;
// byte b = i;    // Incompatible types: possible lossy conversion
                  // from int to byte
```

The one exception to this rule is that you can assign an integer literal (an `int` value) to a `byte` or `short` variable if the literal falls within the range of the variable.

```
byte b = 13;
```

If you need to perform a narrowing conversion and are confident you can do so without losing data or precision, you can force Java to perform the conversion using a language construct known as a *cast*. Perform a cast by placing the name of the desired type in parentheses before the value to be converted. For example:

```
int i = 13;
byte b = (byte) i;    // Force the int to be converted to a byte
i = (int) 13.456;     // Force this double literal to the int 13
```

Casts of primitive types are most often used to convert floating-point values to integers. When you do this, the fractional part of the floating-point value is simply truncated (i.e., the floating-point value is rounded toward zero, not toward the nearest integer). The static methods `Math.round()`, `Math.floor()`, and `Math.ceil()` perform other types of rounding.

The `char` type acts like an integer type in most ways, so a `char` value can be used anywhere an `int` or `long` value is required. Recall, however, that the `char` type is *unsigned*, so it behaves differently than the `short` type, even though both are 16 bits wide:

```
short s = (short) 0xffff; // These bits represent the number -1
char c = '\uffff';        // The same bits, as a Unicode character
int i1 = s;               // Converting the short to an int yields -1
int i2 = c;               // Converting the char to an int yields 65535
```

Table 2-3 shows which primitive types can be converted to which other types and how the conversion is performed. The letter N in the table means that the conversion cannot be performed. The letter Y means that the conversion is a widening conversion and is therefore performed automatically and implicitly by Java. The letter C means that the conversion is a narrowing conversion and requires an explicit cast.

Finally, the notation Y* means that the conversion is an automatic widening conversion, but some of the least significant digits of the value may be lost in the conversion. This can happen when you are converting an `int` or `long` to a floating-point type—see the table for details. The floating-point types have a larger range than the integer types, so any `int` or `long` can be represented by a `float` or `double`. However, the floating-point types are approximations of numbers and cannot always hold as many significant digits as the integer types (see Chapter 9 for some more detail about floating-point numbers).

*Table 2-3. Java primitive type conversions*

| | Convert to: | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Convert from:** | **boolean** | **byte** | **short** | **char** | **int** | **long** | **float** | **double** |
| boolean | - | N | N | N | N | N | N | N |
| byte | N | - | Y | C | Y | Y | Y | Y |
| short | N | C | - | C | Y | Y | Y | Y |
| char | N | C | C | - | Y | Y | Y | Y |
| int | N | C | C | C | - | Y | Y* | Y |
| long | N | C | C | C | C | - | Y* | Y* |
| float | N | C | C | C | C | C | - | Y |
| double | N | C | C | C | C | C | C | - |

## Expressions and Operators

So far in this chapter, we've learned about the primitive types that Java programs can manipulate and seen how to include primitive values as *literals* in a Java program. We've also used *variables* as symbolic names that represent, or hold, values. These literals and variables are the tokens out of which Java programs are built.

An *expression* is the next higher level of structure in a Java program. The Java interpreter *evaluates* an expression to compute its value. The very simplest expressions are called *primary expressions* and consist of literals and variables. So, for example, the following are all expressions:

```
1.7         // A floating-point literal
true        // A Boolean literal
sum         // A variable
```

When the Java interpreter evaluates a literal expression, the resulting value is the literal itself. When the interpreter evaluates a variable expression, the resulting value is the value stored in the variable.

Primary expressions are not very interesting. More complex expressions are made by using *operators* to combine primary expressions. For example, the following expression uses the assignment operator to combine two primary expressions—a variable and a floating-point literal—into an assignment expression:

```
sum = 1.7
```

But operators are used not just with primary expressions; they also can be used with expressions at any level of complexity. The following are all legal expressions:

```
sum = 1 + 2 + 3 * 1.2 + (4 + 8)/3.0
sum/Math.sqrt(3.0 * 1.234)
(int)(sum + 33)
```

## Operator Summary



The kinds of expressions you can write in a programming language depend entirely on the set of operators available to you. Java has a wealth of operators, but to work effectively with them, you must understand two important concepts: *precedence* and *associativity*. These concepts—and the operators themselves—are explained in more detail in the following sections.

### Precedence

The P column of Table 2-4 specifies the *precedence* of each operator. Precedence specifies the order in which operations are performed. Operations that have higher precedence are performed before those with lower precedence. For example, consider this expression:

```
a + b * c
```

The multiplication operator has higher precedence than the addition operator, so `a` is added to the product of `b` and `c`, just as we expect from elementary mathematics. Operator precedence can be thought of as a measure of how tightly operators bind to their operands. The higher the number, the more tightly they bind.

Default operator precedence can be overridden through the use of parentheses that explicitly specify the order of operations. The previous expression can be rewritten to specify that the addition should be performed before the multiplication:

```
(a + b) * c
```

The default operator precedence in Java was chosen for compatibility with C; the designers of C chose this precedence so that most expressions can be written naturally without parentheses. Only a few common Java idioms require parentheses. Examples include:

```
// Class cast combined with member access
((Integer) o).intValue();

// Assignment combined with comparison
while((line = in.readLine()) != null) { ... }

// Bitwise operators combined with comparison
if ((flags & (PUBLIC | PROTECTED)) != 0) { ... }
```

## Associativity

Associativity is a property of operators that defines how to evaluate expressions that would otherwise be ambiguous. This is particularly important when an expression involves several operators that have the same precedence.

Most operators are left-to-right associative, which means that the operations are performed from left to right. The assignment and unary operators, however, have right-to-left associativity. The A column of Table 2-4 specifies the associativity of each operator or group of operators. The value L means left to right, and R means right to left.

The additive operators are all left-to-right associative, so the expression `a+b-c` is evaluated from left to right: `(a+b)-c`. Unary operators and assignment operators are evaluated from right to left. Consider this complex expression:

```
a = b += c = -~d
```

This is evaluated as follows:

```
a = (b += (c = -(~d)))
```

As with operator precedence, operator associativity establishes a default order of evaluation for an expression. This default order can be overridden through the use of parentheses. However, the default operator associativity in Java has been chosen to yield a natural expression syntax.

## Operator summary table

Table 2-4 summarizes the operators available in Java. The P and A columns of the table specify the precedence and associativity of each group of related operators, respectively. The table is ordered from highest precedence to lowest. Use this table as a quick reference for operators (especially their precedence) when required.

*Table 2-4. Java operators*

| P | A | Operator | Operand type(s) | Operation performed |
|---|---|---|---|---|
| 16 | L | . | object, member | Object member access |
| | | [ ] | array, int | Array element access |
| | | ( *args* ) | method, arglist | Method invocation |
| | | ++, -- | variable | Post-increment, post-decrement |
| 15 | R | ++, -- | variable | Pre-increment, pre-decrement |
| | | +, - | number | Unary plus, unary minus |

| P | A | Operator | Operand type(s) | Operation performed |
|---|---|---|---|---|
| | | `~` | integer | Bitwise complement |
| | | `!` | boolean | Boolean NOT |
| 14 | R | `new` | class, arglist | Object creation |
| | | `(` *`type`* `)` | type, any | Cast (type conversion) |
| 13 | L | `*`, `/`, `%` | number, number | Multiplication, division, remainder |
| 12 | L | `+`, `-` | number, number | Addition, subtraction |
| | | `+` | string, any | String concatenation |
| 11 | L | `<<` | integer, integer | Left shift |
| | | `>>` | integer, integer | Right shift with sign extension |
| | | `>>>` | integer, integer | Right shift with zero extension |
| 10 | L | `<`, `<=` | number, number | Less than, less than or equal |
| | | `>`, `>=` | number, number | Greater than, greater than or equal |
| | | `instanceof` | reference, type | Type comparison |
| 9 | L | `==` | primitive, primitive | Equal (have identical values) |
| | | `!=` | primitive, primitive | Not equal (have different values) |
| | | `==` | reference, reference | Equal (refer to same object) |
| | | `!=` | reference, reference | Not equal (refer to different objects) |
| 8 | L | `&` | integer, integer | Bitwise AND |
| | | `&` | boolean, boolean | Boolean AND |
| 7 | L | `^` | integer, integer | Bitwise XOR |
| | | `^` | boolean, boolean | Boolean XOR |
| 6 | L | `\|` | integer, integer | Bitwise OR |

<table>
<tr><th>P</th><th>A</th><th>Operator</th><th>Operand type(s)</th><th>Operation performed</th></tr>
<tr><td></td><td></td><td>|</td><td>boolean, boolean</td><td>Boolean OR</td></tr>
<tr><td>5</td><td>L</td><td>&&</td><td>boolean, boolean</td><td>Conditional AND</td></tr>
<tr><td>4</td><td>L</td><td>||</td><td>boolean, boolean</td><td>Conditional OR</td></tr>
<tr><td>3</td><td>R</td><td>? :</td><td>boolean, any</td><td>Conditional (ternary) operator</td></tr>
<tr><td>2</td><td>R</td><td>=</td><td>variable, any</td><td>Assignment</td></tr>
<tr><td></td><td></td><td>*=, /=, %=,<br>+=, -=, <<=,<br>>>=, >>>=,<br>&=, ^=, |=</td><td>variable, any</td><td>Assignment with operation</td></tr>
<tr><td>1</td><td>R</td><td>→</td><td>arglist, method body</td><td>lambda expression</td></tr>
</table>

### Operand number and type

The fourth column of Table 2-4 specifies the number and type of the operands expected by each operator. Some operators operate on only one operand; these are called unary operators. For example, the unary minus operator changes the sign of a single number:

```
-n              // The unary minus operator
```

Most operators, however, are binary operators that operate on two operand values. The – operator actually comes in both forms:

```
a - b           // The subtraction operator is a binary operator
```

Java also defines one ternary operator, often called the conditional operator. It is like an `if` statement inside an expression. Its three operands are separated by a question mark and a colon; the second and third operands must be convertible to the same type:

```
x > y ? x : y   // Ternary expression; evaluates to larger of x and y
```

In addition to expecting a certain number of operands, each operator also expects particular types of operands. The fourth column of the table lists the operand types. Some of the codes used in that column require further explanation:

*Number*
: An integer, floating-point value, or character (i.e., any primitive type except `boolean`). Auto-unboxing (see "Boxing and Unboxing Conversions" on page

98) means that the wrapper classes (such as `Character`, `Integer`, and `Double`) for these types can be used in this context as well.

*Integer*
: A `byte`, `short`, `int`, `long`, or `char` value (`long` values are not allowed for the array access operator `[ ]`). With auto-unboxing, `Byte`, `Short`, `Integer`, `Long`, and `Character` values are also allowed.

*Reference*
: An object or array.

*Variable*
: A variable or anything else, such as an array element, to which a value can be assigned.



### Return type

Just as every operator expects its operands to be of specific types, each operator produces a value of a specific type. The arithmetic, increment and decrement, bitwise, and shift operators return a `double` if at least one of the operands is a `double`. They return a `float` if at least one of the operands is a `float`. They return a `long` if at least one of the operands is a `long`. Otherwise, they return an `int`, even if both operands are `byte`, `short`, or `char` types that are narrower than `int`.

The comparison, equality, and Boolean operators always return `boolean` values. Each assignment operator returns whatever value it assigned, which is of a type compatible with the variable on the left side of the expression. The conditional operator returns the value of its second or third argument (which must both be convertible to the same type).

### Side effects

Every operator computes a value based on one or more operand values. Some operators, however, have *side effects* in addition to their basic evaluation. If an expression contains side effects, evaluating it changes the state of a Java program in such a way that evaluating the expression again may yield a different result.

For example, the `++` increment operator has the side effect of incrementing a variable. The expression `++a` increments the variable `a` and returns the newly incremented value. If this expression is evaluated again, the value will be different. The various assignment operators also have side effects. For example, the expression `a*=2` can also be written as `a=a*2`. The value of the expression is the value of `a` multiplied by 2, but the expression has the side effect of storing that value back into `a`.

The method invocation operator `()` has side effects if the invoked method has side effects. Some methods, such as `Math.sqrt()`, simply compute and return a value without side effects of any kind. Typically, however, methods do have side effects. Finally, the `new` operator has the profound side effect of creating a new object.

### Order of evaluation

When the Java interpreter evaluates an expression, it performs the various operations in an order specified by the parentheses in the expression, the precedence of the operators, and the associativity of the operators. Before any operation is performed, however, the interpreter first evaluates the operands of the operator. (The exceptions are the `&&`, `||`, and `?:` operators, which do not always evaluate all their operands.) The interpreter always evaluates operands in order from left to right. This matters if any of the operands are expressions that contain side effects. Consider this code, for example:

```
int a = 2;
int v = ++a + ++a * ++a;
```

Although the multiplication is performed before the addition, the operands of the `+` operator are evaluated first. As the operand of `++` are both `++a`, these are evaluated to `3` and `4`, and so the expression evaluates to `3 + 4 * 5`, or `23`.

## Arithmetic Operators

The arithmetic operators can be used with integers, floating-point numbers, and even characters (i.e., they can be used with any primitive type other than `boolean`). If either of the operands is a floating-point number, floating-point arithmetic is used; otherwise, integer arithmetic is used. This matters because integer arithmetic and floating-point arithmetic differ in the way division is performed and in the way underflows and overflows are handled, for example. The arithmetic operators are:

*Addition (+)*
: The `+` operator adds two numbers. As we'll see shortly, the `+` operator can also be used to concatenate strings. If either operand of `+` is a string, the other one is converted to a string as well. Be sure to use parentheses when you want to combine addition with concatenation. For example:

```
System.out.println("Total: " + 3 + 4);   // Prints "Total: 34", not 7!
```

The `+` operator can also be used in unary form to express a positive number, such as `+42`.

*Subtraction (-)*
: When the `-` operator is used as a binary operator, it subtracts its second operand from its first. For example, `7-3` evaluates to `4`. The `-` operator can also perform unary negation.

*Multiplication (*)*
: The `*` operator multiplies its two operands. For example, `7*3` evaluates to `21`.

*Division (/)*
: The `/` operator divides its first operand by its second. If both operands are integers, the result is an integer, and any remainder is lost. If either operand is a floating-point value, however, the result is a floating-point value. When

you divide two integers, division by zero throws an `ArithmeticException`. For floating-point calculations, however, division by zero simply yields an infinite result or `NaN`:

```
7/3          // Evaluates to 2
7/3.0f       // Evaluates to 2.333333f
7/0          // Throws an ArithmeticException
7/0.0        // Evaluates to positive infinity
0.0/0.0      // Evaluates to NaN
```

*Modulo (`%`)*

The `%` operator computes the first operand modulo the second operand (i.e., it returns the remainder when the first operand is divided by the second operand an integral number of times). For example, `7%3` is `1`. The sign of the result is the same as the sign of the first operand. While the modulo operator is typically used with integer operands, it also works for floating-point values. For example, `4.3%2.1` evaluates to `0.1`. When you are operating with integers, trying to compute a value modulo zero causes an `ArithmeticException`. When you are working with floating-point values, anything modulo `0.0` evaluates to `NaN`, as does infinity modulo anything.

*Unary minus (`-`)*

When the `-` operator is used as a unary operator—that is, before a single operand—it performs unary negation. In other words, it converts a positive value to an equivalently negative value, and vice versa.

## String Concatenation Operator

In addition to adding numbers, the `+` operator (and the related `+=` operator) also concatenates, or joins, strings. If either of the operands to `+` is a string, the operator converts the other operand to a string. For example:

```
// Prints "Quotient: 2.3333333"
System.out.println("Quotient: " + 7/3.0f);
```

As a result, you must be careful to put any addition expressions in parentheses when combining them with string concatenation. If you do not, the addition operator is interpreted as a concatenation operator.

Java has built-in string conversions for all primitive types. An object is converted to a string by invoking its `toString()` method. Some classes define custom `toString()` methods so that objects of that class can easily be converted to strings in this way. Sadly not all classes return friendly results when converted to strings. For example, the built-in `toString()` for an array doesn't return a useful string representation of its contents, only information about the array object itself.

## Increment and Decrement Operators

The `++` operator increments its single operand, which must be a variable, an element of an array, or a field of an object, by 1. The behavior of this operator depends on its position relative to the operand. When used before the operand, where it is known as the *pre-increment* operator, it increments the operand and evaluates to the incremented value of that operand. When used after the operand, where it is known as the *post-increment* operator, it increments its operand but evaluates to the value of that operand before it was incremented.

For example, the following code sets both `i` and `j` to 2:

```
i = 1;
j = ++i;
```

But these lines set `i` to 2 and `j` to 1:

```
i = 1;
j = i++;
```

Similarly, the `--` operator decrements its single numeric operand, which must be a variable, an element of an array, or a field of an object, by one. Like the `++` operator, the behavior of `--` depends on its position relative to the operand. When used before the operand, it decrements the operand and returns the decremented value. When used after the operand, it decrements the operand but returns the *undecremented* value.

The expressions `x++` and `x--` are equivalent to `x = x + 1` and `x = x - 1`, respectively, except that when you are using the increment and decrement operators, `x` is evaluated only once. If `x` is itself an expression with side effects, this makes a big difference. For example, these two expressions are not equivalent, as the second form increments `i` twice:

```
a[i++]++;             // Increments an element of an array

// Adds 1 to an array element and stores new value in another element
a[i++] = a[i++] + 1;
```

These operators, in both prefix and postfix forms, are most commonly used to increment or decrement the counter that controls a loop. However, an increasing number of programmers prefer to avoid using the increment and decrement operators altogether, preferring to use explicit code. This view is motivated by the large number of bugs that have, historically, been caused by incorrect usage of the operators.

## Comparison Operators

The comparison operators consist of the equality operators that test values for equality or inequality and the relational operators used with ordered types (numbers and characters) to test for greater than and less than relationships. Both types of operators yield a `boolean` result, so they are typically used with `if` statements, the ternary conditional operator, or `while` and `for` loops to make branching and looping decisions. For example:

```
if (o != null) ...;           // The not equals operator
while(i < a.length) ...;      // The less than operator
```

Java provides the following equality operators:

*Equals (==)*
: The == operator evaluates to `true` if its two operands are equal and `false` otherwise. With primitive operands, it tests whether the operand values themselves are identical. For operands of reference types, however, it tests whether the operands refer to the same object or array. In other words, it does not test the equality of two distinct objects or arrays. In particular, note that you cannot test two distinct strings for equality with this operator.



> If you experiment comparing strings via == you may see results that suggest it works properly. This is a side effect of Java's internal caching of strings, known as *interning*. The only reliable way to compare strings (or any other reference type for that matter) for equality is the `equals()` method.
>
> The same applies with primitive wrapper classes, so `new Integer(1) != new Integer(1)`, while the preferred `Integer.valueOf(1) == Integer.valueOf(1)` does. The lesson is clearly that looking at equality on any nonprimitive type should be done with `equals()`. More discussion of object equality can be found in "equals()" on page 209.

If == is used to compare two numeric or character operands that are not of the same type, the narrower operand is converted to the type of the wider operand before the comparison is done. For example, when you are comparing a `short` to a `float`, the `short` is first converted to a `float` before the comparison is performed. For floating-point numbers, the special negative zero value tests equal to the regular, positive zero value. Also, the special `NaN` (Not a Number) value is not equal to any other number, including itself. To test whether a floating-point value is `NaN`, use the `Float.isNan()` or `Double.isNan()` method.

*Not equals (`!=`)*
: The `!=` operator is exactly the opposite of the == operator. It evaluates to `true` if its two primitive operands have different values or if its two reference operands refer to different objects or arrays. Otherwise, it evaluates to `false`.

The relational operators can be used with numbers and characters but not with `boolean` values, objects, or arrays because those types are not ordered.

Java provides the following relational operators:

*Less than (<)*
: Evaluates to `true` if the first operand is less than the second.

*Less than or equal* (`<=`)
: Evaluates to `true` if the first operand is less than or equal to the second.

*Greater than* (`>`)
: Evaluates to `true` if the first operand is greater than the second.

*Greater than or equal* (`>=`)
: Evaluates to `true` if the first operand is greater than or equal to the second.

## Boolean Operators

As we've just seen, the comparison operators compare their operands and yield a `boolean` result, which is often used in branching and looping statements. In order to make branching and looping decisions based on conditions more interesting than a single comparison, you can use the Boolean (or logical) operators to combine multiple comparison expressions into a single, more complex expression. The Boolean operators require their operands to be `boolean` values and they evaluate to `boolean` values. The operators are:

*Conditional AND* (`&&`)
: This operator performs a Boolean AND operation on its operands. It evaluates to `true` if and only if both its operands are `true`. If either or both operands are `false`, it evaluates to `false`. For example:

```
if (x < 10 && y > 3) ... // If both comparisons are true
```

This operator (and all the Boolean operators except the unary `!` operator) have a lower precedence than the comparison operators. Thus, it is perfectly legal to write a line of code like the one just shown. However, some programmers prefer to use parentheses to make the order of evaluation explicit:

```
if ((x < 10) && (y > 3)) ...
```

You should use whichever style you find easier to read.

This operator is called a conditional AND because it conditionally evaluates its second operand. If the first operand evaluates to `false`, the value of the expression is `false`, regardless of the value of the second operand. Therefore, to increase efficiency, the Java interpreter takes a shortcut and skips the second operand. The second operand is not guaranteed to be evaluated, so you must use caution when using this operator with expressions that have side effects. On the other hand, the conditional nature of this operator allows us to write Java expressions such as the following:

```
if (data != null && i < data.length && data[i] != -1)
    ...
```

The second and third comparisons in this expression would cause errors if the first or second comparisons evaluated to `false`. Fortunately, we don't have to worry about this because of the conditional behavior of the `&&` operator.

*Conditional OR (`||`)*

This operator performs a Boolean OR operation on its two `boolean` operands. It evaluates to `true` if either or both of its operands are `true`. If both operands are `false`, it evaluates to `false`. Like the `&&` operator, `||` does not always evaluate its second operand. If the first operand evaluates to `true`, the value of the expression is `true`, regardless of the value of the second operand. Thus, the operator simply skips the second operand in that case.



*Boolean NOT (`!`)*

This unary operator changes the `boolean` value of its operand. If applied to a `true` value, it evaluates to `false`, and if applied to a `false` value, it evaluates to `true`. It is useful in expressions like these:

```
if (!found) ...          // found is a boolean declared somewhere
while (!c.isEmpty()) ... // The isEmpty() method returns a boolean
```

Because `!` is a unary operator, it has a high precedence and often must be used with parentheses:

```
if (!(x > y && y > z))
```

*Boolean AND (`&`)*

When used with `boolean` operands, the `&` operator behaves like the `&&` operator, except that it always evaluates both operands, regardless of the value of the first operand. This operator is almost always used as a bitwise operator with integer operands, however, and many Java programmers would not even recognize its use with `boolean` operands as legal Java code.

*Boolean OR (`|`)*

This operator performs a Boolean OR operation on its two `boolean` operands. It is like the `||` operator, except that it always evaluates both operands, even if the first one is `true`. The `|` operator is almost always used as a bitwise operator on integer operands; its use with `boolean` operands is very rare.

*Boolean XOR (`^`)*

When used with `boolean` operands, this operator computes the exclusive OR (XOR) of its operands. It evaluates to `true` if exactly one of the two operands is `true`. In other words, it evaluates to `false` if both operands are `false` or if both operands are `true`. Unlike the `&&` and `||` operators, this one must always evaluate both operands. The `^` operator is much more commonly used as a bitwise operator on integer operands. With `boolean` operands, this operator is equivalent to the `!=` operator.

## Bitwise and Shift Operators

The bitwise and shift operators are low-level operators that manipulate the individual bits that make up an integer value. The bitwise operators are not commonly used in modern Java except for low-level work (e.g., network programming). They are used for testing and setting individual flag bits in a value. To understand their behavior, you must understand binary (base-2) numbers and the two's complement format used to represent negative integers.

You cannot use these operators with floating-point, `boolean`, array, or object operands. When used with `boolean` operands, the `&`, `|`, and `^` operators perform a different operation, as described in the previous section.

If either of the arguments to a bitwise operator is a `long`, the result is a `long`. Otherwise, the result is an `int`. If the left operand of a shift operator is a `long`, the result is a `long`; otherwise, the result is an `int`. The operators are:

*Bitwise complement (~)*
: The unary `~` operator is known as the bitwise complement, or bitwise NOT, operator. It inverts each bit of its single operand, converting 1s to 0s and 0s to 1s. For example:

```
byte b = ~12;          // ~00001100 =  => 11110011 or -13 decimal
flags = flags & ~f;    // Clear flag f in a set of flags
```

*Bitwise AND (&)*
: This operator combines its two integer operands by performing a Boolean AND operation on their individual bits. The result has a bit set only if the corresponding bit is set in both operands. For example:

```
10 & 7                  // 00001010 & 00000111 =  => 00000010 or 2
if ((flags & f) != 0)   // Test whether flag f is set
```

When used with `boolean` operands, `&` is the infrequently used Boolean AND operator described earlier.

*Bitwise OR (|)*
: This operator combines its two integer operands by performing a Boolean OR operation on their individual bits. The result has a bit set if the corresponding bit is set in either or both of the operands. It has a zero bit only where both corresponding operand bits are zero. For example:

```
10 | 7                  // 00001010 | 00000111 =  => 00001111 or 15
flags = flags | f;      // Set flag f
```

When used with `boolean` operands, `|` is the infrequently used Boolean OR operator described earlier.

*Bitwise XOR (^)*
: This operator combines its two integer operands by performing a Boolean XOR (exclusive OR) operation on their individual bits. The result has a bit set if the corresponding bits in the two operands are different. If the corresponding operand bits are both 1s or both 0s, the result bit is a 0. For example:

```
10 ^ 7               // 00001010 ^ 00000111 =  => 00001101 or 13
```

When used with `boolean` operands, `^` is the seldom used Boolean XOR operator.

*Left shift (<<)*

The << operator shifts the bits of the left operand left by the number of places specified by the right operand. High-order bits of the left operand are lost, and zero bits are shifted in from the right. Shifting an integer left by *n* places is equivalent to multiplying that number by $2^n$. For example:

```
10 << 1    // 0b00001010 << 1 = 00010100 = 20 = 10*2
7 << 3     // 0b00000111 << 3 = 00111000 = 56 = 7*8
-1 << 2    // 0xFFFFFFFF << 2 = 0xFFFFFFFC = -4 = -1*4
           // 0xFFFF_FFFC == 0b1111_1111_1111_1111_1111_1111_1111_1100
```

If the left operand is a `long`, the right operand should be between 0 and 63. Otherwise, the left operand is taken to be an `int`, and the right operand should be between 0 and 31. If either of these ranges is exceeded, you may see unintuitive wrapping behavior from these operators.

*Signed right shift (>>)*

The >> operator shifts the bits of the left operand to the right by the number of places specified by the right operand. The low-order bits of the left operand are shifted away and are lost. The high-order bits shifted in are the same as the original high-order bit of the left operand. In other words, if the left operand is positive, 0s are shifted into the high-order bits. If the left operand is negative, 1s are shifted in instead. This technique is known as *sign extension*; it is used to preserve the sign of the left operand. For example:

```
10 >> 1      // 00001010 >> 1 = 00000101 = 5 = 10/2
27 >> 3      // 00011011 >> 3 = 00000011 = 3 = 27/8
-50 >> 2     // 11001110 >> 2 = 11110011 = -13 != -50/4
```

If the left operand is positive and the right operand is *n*, the >> operator is the same as integer division by $2^n$.

*Unsigned right shift (>>>)*

This operator is like the >> operator, except that it always shifts zeros into the high-order bits of the result, regardless of the sign of the lefthand operand. This technique is called *zero extension*; it is appropriate when the left operand is being treated as an unsigned value (despite the fact that Java integer types are all signed). These are examples:

```
0xff >>> 4    // 11111111 >>> 4 = 00001111 = 15  = 255/16
-50 >>> 2     // 0xFFFFFFCE >>> 2 = 0x3FFFFFF3 = 1073741811
```

## Assignment Operators

The assignment operators store, or assign, a value into a piece of the computer's memory--often referred to as a *storage location*. The left operand must evaluate to an appropriate local variable, array element, or object field.

The lefthand side of an assignment expression is sometimes called an *lvalue*. In Java it must refer to some assignable storage (i.e., memory that can be written to).

The righthand side (the *rvalue*) can be any value of a type compatible with the variable. An assignment expression evaluates to the value that is assigned to the variable. More importantly, however, the expression has the side effect of actually performing the assignment—storing the `rvalue` in the `lvalue`.

Unlike all other binary operators, the assignment operators are right-associative, which means that the assignments in `a=b=c` are performed right to left, as follows: `a=(b=c)`.

The basic assignment operator is `=`. Do not confuse it with the equality operator, `==`. To keep these two operators distinct, we recommend that you read `=` as "is assigned the value."

In addition to this simple assignment operator, Java also defines 11 other operators that combine assignment with the 5 arithmetic operators and the 6 bitwise and shift operators. For example, the `+=` operator reads the value of the left variable, adds the value of the right operand to it, stores the sum back into the left variable as a side effect, and returns the sum as the value of the expression. Thus, the expression `x+=2` is almost the same as `x=x+2`. The difference between these two expressions is that when you use the `+=` operator, the left operand is evaluated only once. This makes a difference when that operand has a side effect. Consider the following two expressions, which are not equivalent:

```
a[i++] += 2;
a[i++] = a[i++] + 2;
```

The general form of these combination assignment operators is:

```
lvalue op= rvalue
```

This is equivalent (unless there are side effects in `lvalue`) to:

```
lvalue = lvalue op rvalue
```

The available operators are:

```
+=    -=    *=    /=    %=    // Arithmetic operators plus assignment

&=    |=    ^=                // Bitwise operators plus assignment

<<=   >>=   >>>=              // Shift operators plus assignment
```

The most commonly used operators are += and -=, although &= and |= can also be useful when you are working with boolean or bitwise flags. For example:

```
i += 2;          // Increment a loop counter by 2
c -= 5;          // Decrement a counter by 5
flags |= f;      // Set a flag f in an integer set of flags
flags &= ~f;     // Clear a flag f in an integer set of flags
```



## The Conditional Operator

The conditional operator ?: is a somewhat obscure ternary (three-operand) operator inherited from C. It allows you to embed a conditional within an expression. You can think of it as the operator version of the if/else statement. The first and second operands of the conditional operator are separated by a question mark (?), while the second and third operands are separated by a colon (:). The first operand must evaluate to a boolean value. The second and third operands can be of any type, but they must be convertible to the same type.

The conditional operator starts by evaluating its first operand. If it is true, the operator evaluates its second operand and uses that as the value of the expression. On the other hand, if the first operand is false, the conditional operator evaluates and returns its third operand. The conditional operator never evaluates both its second and third operand, so be careful when using expressions with side effects with this operator. Examples of this operator are:

```
int max = (x > y) ? x : y;
String name = (value != null) ? value : "unknown";
```

Note that the ?: operator has lower precedence than all other operators except the assignment operators, so parentheses are not usually necessary around the operands of this operator. Many programmers find conditional expressions easier to read if the first operand is placed within parentheses, however. This is especially true because the conditional if statement always has its conditional expression written within parentheses.

## The instanceof Operator

The instanceof operator is intimately bound up with objects and the operation of the Java type system. If this is your first look at Java, it may be preferable to skim this definition and return to this section after you have a decent grasp of Java's objects.

instanceof requires an object or array value as its left operand and the name of a reference type as its right operand. In its basic form, it evaluates to true if the object or array is an *instance* of the specified type; it returns false otherwise. If the left operand is null, instanceof always evaluates to false. If an instanceof expression evaluates to true, it means that you can safely cast and assign the left operand to a variable of the type of the right operand.

The `instanceof` operator can be used only with reference types and objects, not primitive types and values. Examples of `instanceof` are:

```
// True: all strings are instances of String
"string" instanceof String
// True: strings are also instances of Object
"" instanceof Object
// False: null is never an instance of anything
null instanceof String

Object o = new int[] {1,2,3};
o instanceof int[]   // True: the array value is an int array
o instanceof byte[]  // False: the array value is not a byte array
o instanceof Object  // True: all arrays are instances of Object

// Use instanceof to make sure that it is safe to cast an object
if (object instanceof Account) {
   Account a = (Account) object;
}
```

In Java 17 `instanceof` has an extended form known as *pattern matching*. The final example above demonstrates a common pattern-checking `instanceof` and then casting to the type within a conditional. With pattern matching we can express this all at once by including a variable after the reference type. If `instanceof` sees the type is compatible, the variable is assigned the casted object.

```
if (object instanceof Account a) {
   // variable a is available in this scope
}
```

This sort of pattern matching is a recent addition in Java. Upcoming releases are expected to provide more of these sorts of convenience throughout the language.

Historically using `instanceof` was discouraged in favor of other more object-oriented solutions we'll see in Chapter 5. Java's increasing adoption of pattern matching, though, is changing attitudes about this operator. `instanceof` is especially well suited to the common scenarios around receiving data in unpredictable formats through an API and is often a pragmatic option these days rather than a last resort.

## Special Operators

Java has six language constructs that are sometimes considered operators and sometimes considered simply part of the basic language syntax. These "operators" were included in Table 2-4 to show their precedence relative to the other true operators. The use of these language constructs is detailed elsewhere in this book, but it is described briefly here so that you can recognize them in code examples:

*Member access* (`.`)
: An *object* is a collection of data and methods that operate on that data; the data fields and methods of an object are called its members. The dot (.) operator

accesses these members. If `o` is an expression that evaluates to an object reference (or a class name), and `f` is the name of a field of the class, `o.f` evaluates to the value contained in that field. If `m` is the name of a method, `o.m` refers to that method and allows it to be invoked using the `()` operator shown later.

*Array element access (`[]`)*
An *array* is a numbered list of values. Each element of an array can be referred to by its number, or *index*. The `[ ]` operator allows you to refer to the individual elements of an array. If `a` is an array, and `i` is an expression that evaluates to an `int`, `a[i]` refers to one of the elements of `a`. Unlike other operators that work with integer values, this operator restricts array index values to be of type `int` or narrower.

*Method invocation (`()`)*
A *method* is a named collection of Java code that can be run, or *invoked*, by following the name of the method with zero or more comma-separated expressions contained within parentheses. The values of these expressions are the *arguments* to the method. The method processes the arguments and optionally returns a value that becomes the value of the method invocation expression. If `o.m` is a method that expects no arguments, the method can be invoked with `o.m()`. If the method expects three arguments, for example, it can be invoked with an expression such as `o.m(x,y,z)`. `o` is referred to as the *receiver* of the method—if `o` is an object, then it is said to be the *receiver object*. Before the Java interpreter invokes a method, it evaluates each of the arguments to be passed to the method. These expressions are guaranteed to be evaluated in order from left to right (which matters if any of the arguments have side effects).

*Lambda expression (`->`)*
A *lambda expression* is an anonymous collection of executable Java code, essentially a method body. It consists of a method argument list (zero or more comma-separated expressions contained within parentheses) followed by the lambda *arrow* operator followed by a block of Java code. If the block of code comprises just a single statement, then the usual curly braces to denote block boundaries can be omitted. If the lambda takes only a single argument, the parentheses around the argument can be omitted.

*Object creation (`new`)*
In Java, objects are created with the `new` operator, which is followed by the type of the object to be created and a parenthesized list of arguments to be passed to the object *constructor*. A constructor is a special block of code that initializes a newly created object, so the object creation syntax is similar to the Java method invocation syntax. For example:

```
new ArrayList<String>();
new Account("Jason", 0.0, 42);
```

*Array creation* (`new`)
: Arrays are a special case of objects and they too are created with the `new` operator, with a slightly different syntax. The keyword is followed by the type of the array to be created and the size of the array encased in square brackets—for example, as `new int[5]`. In some circumstances, arrays can also be created using the *array literal* syntax.

*Type conversion or casting* (`()`)
: As we've already seen, parentheses can also be used as an operator to perform narrowing type conversions, or casts. The first operand of this operator is the type to be converted to; it is placed between the parentheses. The second operand is the value to be converted; it follows the parentheses. For example:

```
(byte) 28          // An integer literal cast to a byte type
(int) (x + 3.14f)  // A floating-point sum value cast to an integer
(String)h.get(k)   // A generic object cast to a string
```

# Statements

A *statement* is a basic unit of execution in the Java language—it expresses a single piece of intent by the programmer. Unlike expressions, Java statements do not have a value. Statements also typically contain expressions and operators (especially assignment operators) and are frequently executed for the side effects that they cause.

Many of the statements defined by Java are flow-control statements, such as conditionals and loops, that can alter the default, linear order of execution in well-defined ways. Table 2-5 summarizes the statements defined by Java.

*Table 2-5. Table 2-5. Java statements*

| Statement | Purpose | Syntax |
|---|---|---|
| *expression* | side effects | *`variable`* `=` *`expr`* `;` *`expr`* `++;` *`method`* `();` `new` *`Type`* `( );` |
| *compound* | group statements | `{` *`statements`* `}` |
| *empty* | do nothing | `;` |
| *labeled* | name a statement | *`label`* `:` *`statement`* |
| *variable* | declare a variable | `[final]` *`type name`* `[=` *`value`* `] [,` *`name`* `[=` *`value`* `]] …;` |
| `if` | conditional | `if (` *`expr`* `)` *`statement`* `[ else` *`statement`* `]` |
| `switch` | conditional | `switch (` *`expr`* `) { [ case` *`expr`* `:` *`statements`* `] …`<br>`[ default:` *`statements`* `] }` |

| Statement | Purpose | Syntax |
| --- | --- | --- |
| `switch` | conditional expression | `switch (` *expr* `) {[ case` *expr* `, [` *expr* `…] ->` *expr* `;] …[ default ->` *expr* `;] }` |
| `while` | loop | `while (` *expr* `)` *statement* |
| `do` | loop | `do` *statement* `while (` *expr* `);` |
| `for` | simplified loop | `for (` *init* `;` *test* `;` *increment* `)` *statement* |
| *foreach* | collection iteration | `for (` *variable* `:` *iterable* `)` *statement* |
| `break` | exit block | `break [` *label* `] ;` |
| `continue` | restart loop | `continue [` *label* `] ;` |
| `return` | end method | `return [` *expr* `] ;` |
| `synchronized` | critical section | `synchronized (` *expr* `) {` *statements* `}` |
| `throw` | throw exception | `throw` *expr* `;` |
| `try` | handle exception | `try {` *statements* `} [ catch (` *type name* `) {` *statements* `} ] …[ finally {` *statements* `} ]` |
| `try` | handle exception, closing resources | `try ([` *variable* `=` *expr* `]) {` *statements* `} [ catch (` *type name* `) {` *statements* `} ] …[ finally {` *statements* `} ]` |
| `assert` | verify invariant | `assert` *invariant* `[` *error* `];` |

## Expression Statements

As we saw earlier in the chapter, certain types of Java expressions have side effects. In other words, they do not simply evaluate to some value; they also change the program state in some way. You can use any expression with side effects as a statement simply by following it with a semicolon. The legal types of expression statements are assignments, increments and decrements, method calls, and object creation. For example:

```
a = 1;                              // Assignment
x *= 2;                             // Assignment with operation
i++;                                // Post-increment
--c;                                // Pre-decrement
System.out.println("statement");    // Method invocation
```

## Compound Statements

A *compound statement* is any number and kind of statements grouped together within curly braces. You can use a compound statement anywhere a statement is required by Java syntax:

```
for(int i = 0; i < 10; i++) {
   a[i]++;           // Body of this loop is a compound statement.
   b[i]--;           // It consists of two expression statements
}                    // within curly braces.
```

## The Empty Statement

An *empty statement* in Java is written as a single semicolon. The empty statement doesn't do anything, but the syntax is occasionally useful. For example, you can use it to indicate an empty loop body in a `for` loop:

```
for(int i = 0; i < 10; a[i++]++)  // Increment array elements
     /* empty */;                 // Loop body is empty statement
```

## Labeled Statements

A *labeled statement* is simply a statement that you have given a name by prepending an identifier and a colon to it. Labels are used by the `break` and `continue` statements. For example:

```
rowLoop: for(int r = 0; r < rows.length; r++) {        // Labeled loop
   colLoop: for(int c = 0; c < columns.length; c++) {  // Another one
     break rowLoop;                                    // Use a label
   }
}
```

## Local Variable Declaration Statements

A *local variable*, often simply called a variable, is a symbolic name for a location to store a value that is defined within a method or compound statement. All variables must be declared before they can be used; this is done with a variable declaration statement. Because Java is a statically typed language, a variable declaration specifies the type of the variable, and only values of that type can be stored in the variable.

In its simplest form, a variable declaration specifies a variable's type and name:

```
int counter;
String s;
```

A variable declaration can also include an *initializer*, an expression that specifies an initial value for the variable. For example:

```
int i = 0;
String s = readLine();
int[] data = {x+1, x+2, x+3}; // Array initializers are discussed later
```

The Java compiler does not allow you to use a local variable that has not been initialized, so it is usually convenient to combine variable declaration and initialization into a single statement. The initializer expression need not be a literal value or a constant expression that can be evaluated by the compiler; it can be an arbitrarily complex expression whose value is computed when the program is run.

If a variable has an initializer, then the programmer can use a special syntax to ask the compiler to automatically work out the type, if it is possible to do so:

```
var i = 0;          // type of i inferred as int
var s = readLine(); // type of s inferred as String
```

This can be a useful syntax, but it is potentially harder to read. Our second example, for instance, requires that you know that the return type of `readLine()` is `String` to know what type will be inferred for `s`. For this reason, throughout the text we only use `var` in examples when the initializer makes the type completely redundant. As you learn the Java language, this may be a reasonable policy to follow while you become familiar with the Java type system.

A single variable declaration statement can declare and initialize more than one variable, but all variables must be of the same explicitly declared type. Variable names and optional initializers are separated from each other with commas:

```
int i, j, k;
float x = 1.0f, y = 1.0f;
String question = "Really Quit?", response;
```

Variable declaration statements can begin with the `final` keyword. This modifier specifies that once an initial value is defined for the variable, that value is never allowed to change:

```
final String greeting = getLocalLanguageGreeting();
```

We will have more to say about the `final` keyword later on, especially when talking about the design of classes and the immutable style of programming.

Java variable declaration statements can appear anywhere in Java code; they are not restricted to the beginning of a method or block of code. Local variable declarations can also be integrated with the *initialize* portion of a `for` loop, as we'll discuss shortly.

Local variables can be used only within the method or block of code in which they are defined. This is called their *scope* or *lexical scope*:

```
void method() {            // A method definition
   int i = 0;              // Declare variable i
   while (i < 10) {        // i is in scope here
     int j = 0;            // Declare j; the scope of j begins here
     i++;                  // i is in scope here; increment it
   }                       // j is no longer in scope;
   System.out.println(i);  // i is still in scope here
}                          // The scope of i ends here
```

## The if/else Statement

The `if` statement is a fundamental control statement that allows Java to make decisions or, more precisely, to execute statements conditionally. The `if` statement has an associated expression and statement. If the expression evaluates to `true`, the interpreter executes the statement. If the expression evaluates to `false`, the interpreter skips the statement.

> Java allows the expression to be of the wrapper type `Boolean` instead of the primitive type `boolean`. In this case, the wrapper object is automatically unboxed.

Here is an example `if` statement:

```
if (username == null)         // If username is null,
   username = "John Doe";     // use a default value
```

Although they look extraneous, the parentheses around the expression are a required part of the syntax for the `if` statement. As we already saw, a block of statements enclosed in curly braces is itself a statement, so we can write `if` statements that look like this as well:

```
if ((address == null) || (address.equals(""))) {
   address = "[undefined]";
   System.out.println("WARNING: no address specified.");
}
```

An `if` statement can include an optional `else` keyword that is followed by a second statement. In this form of the statement, the expression is evaluated, and, if it is `true`, the first statement is executed. Otherwise, the second statement is executed. For example:

```
if (username != null)
   System.out.println("Hello " + username);
else {
   username = askQuestion("What is your name?");
   System.out.println("Hello " + username + ". Welcome!");
}
```

When you use nested `if/else` statements, some caution is required to ensure that the `else` clause goes with the appropriate `if` statement. Consider the following lines:

```
if (i == j)
   if (j == k)
     System.out.println("i equals k");
else
   System.out.println("i doesn't equal j");    // WRONG!!
```

In this example, the inner `if` statement forms the single statement allowed by the syntax of the outer `if` statement. Unfortunately, it is not clear (except from the hint given by the indentation) which `if` the `else` goes with. And in this example, the indentation hint is wrong. The rule is that an `else` clause like this is associated with the nearest `if` statement. Properly indented, this code looks like this:

```
if (i == j)
   if (j == k)
     System.out.println("i equals k");
   else
     System.out.println("i doesn't equal j");    // WRONG!!
```

This is legal code, but it is clearly not what the programmer had in mind. When working with nested `if` statements, you should use curly braces to make your code easier to read. Here is a better way to write the code:

```
if (i == j) {
   if (j == k)
     System.out.println("i equals k");
}
else {
   System.out.println("i doesn't equal j");
}
```

### The else if clause

The `if/else` statement is useful for testing a condition and choosing between two statements or blocks of code to execute. But what about when you need to choose between several blocks of code? This is typically done with an `else if` clause, which is not really new syntax but a common idiomatic usage of the standard `if/else` statement. It looks like this:

```
if (n == 1) {
    // Execute code block #1
}
else if (n == 2) {
    // Execute code block #2
}
else if (n == 3) {
    // Execute code block #3
}
else {
    // If all else fails, execute block #4
}
```

There is nothing special about this code. It is just a series of `if` statements, where each `if` is part of the `else` clause of the previous statement. Using the `else if` idiom is preferable to, and more legible than, writing these statements out in their fully nested form:

```java
if (n == 1) {
   // Execute code block #1
}
else {
   if (n == 2) {
     // Execute code block #2
   }
   else {
     if (n == 3) {
       // Execute code block #3
     }
     else {
       // If all else fails, execute block #4
     }
   }
}
```

## The switch Statement

An `if` statement causes a branch in the flow of a program's execution. You can use multiple `if` statements, as shown in the previous section, to perform a multiway branch. This is not always the best solution, however, especially when all of the branches depend on the value of a single variable.

In this case, the repeated `if` statements may seriously hamper readability, especially if the code has been refactored over time or features multiple levels of nested `if`.

A better solution is to use a `switch` statement, which is inherited from the C programming language. Note, however, that the syntax of this statement is not nearly as elegant as other parts of Java. The failure to revisit the design of the feature is widely regarded as a mistake, one that has been partially addressed in recent versions with an expression form of `switch` we'll examine in a moment. However, that alternative format won't erase the long history of `switch` statements in the language, so it's good to come to grips with it.

> A `switch` statement starts with an expression whose type is an `int`, `short`, `char`, `byte` (or their wrapper type), `String`, or an enum (see Chapter 4 for more on enumerated types).

This expression is followed by a block of code in curly braces that contains various entry points that correspond to possible values for the expression. For example, the following `switch` statement is equivalent to the repeated `if` and `else/if` statements shown in the previous section:

```java
switch(n) {
   case 1:                      // Start here if n == 1
     // Execute code block #1
     break;                     // Stop here
```

```
    case 2:                         // Start here if n == 2
      // Execute code block #2
      break;                        // Stop here
    case 3:                         // Start here if n == 3
      // Execute code block #3
      break;                        // Stop here
    default:                        // If all else fails...
      // Execute code block #4
      break;                        // Stop here
}
```



As you can see from the example, the various entry points into a `switch` statement are labeled either with the keyword `case`, followed by an integer value and a colon, or with the special `default` keyword, followed by a colon. When a `switch` statement executes, the interpreter computes the value of the expression in parentheses and then looks for a `case` label that matches that value. If it finds one, the interpreter starts executing the block of code at the first statement following the `case` label. If it does not find a `case` label with a matching value, the interpreter starts execution at the first statement following a special-case `default`: label. Or, if there is no `default`: label, the interpreter skips the body of the `switch` statement altogether.

Note the use of the `break` keyword at the end of each `case` in the previous code. The `break` statement is described later in this chapter, but, in this example, it causes the interpreter to exit the body of the `switch` statement. The `case` clauses in a `switch` statement specify only the starting point of the desired code. The individual `case`s are not independent blocks of code, and they do not have any implicit ending point.

> You must explicitly specify the end of each `case` with a `break` or related statement. In the absence of `break` statements, a `switch` statement begins executing code at the first statement after the matching `case` label and continues executing statements until it reaches the end of the block. The control flow will *fall through* into the next `case` label and continue executing, rather than exit the block.

On rare occasions, it is useful to write code like this that falls through from one `case` label to the next, but 99% of the time you should be careful to end every `case` and `default` section with a statement that causes the `switch` statement to stop executing. Normally you use a `break` statement, but `return` and `throw` also work.

As a consequence of this default fall-through, a `switch` statement can have more than one `case` clause labeling the same statement. Consider the `switch` statement in the following method:

```
boolean parseYesOrNoResponse(char response) {
    switch(response) {
      case 'y':
      case 'Y': return true;
      case 'n':
```

```
        case 'N': return false;
        default:
          throw new IllegalArgumentException("Response must be Y or N");
      }
    }
```

The `switch` statement and its `case` labels have some important restrictions. First, the expression associated with a `switch` statement must have an appropriate type—either `byte`, `char`, `short`, `int` (or their wrappers), or an enum type or a `String`. The floating-point and `boolean` types are not supported, and neither is `long`, even though `long` is an integer type. Second, the value associated with each `case` label must be a constant value or a constant expression the compiler can evaluate. A `case` label cannot contain a runtime expression involving variables or method calls, for example. Third, the `case` label values must be within the range of the data type used for the `switch` expression. And finally, it is not legal to have two or more `case` labels with the same value or more than one `default` label.

With all those caveats, let's look at how the new `switch` expression makes for a cleaner experience.

## The switch Expression

A frequent problem with the classic `switch` statement arises when capturing a variable value.

```
Boolean yesOrNo = null;
switch(input) {
    case "y":
    case "Y":
        yesOrNo = true;
        break;
    case "n":
    case "N":
        yesOrNo = false;
        break;
    default:
        throw new IllegalArgumentException("Response must be Y or N");
}
```

For the variable to be available after the `switch`, it must be declared outside the statement and provided an initial value. Then each `case` must be certain to set the variable. However, we have no guarantees, and in code with more branches than this simple example, it's an easy thing to miss and introduce a bug.

The `switch` expression is explicitly designed to address these and other faults. As the name calls out, it's an *expression*—one of the more syntactically complex ones in the language—and as such results in a value.

```
boolean yesOrNo = switch(input) {
    case "y" -> true;
    case "Y" -> true;
```

```
        case "N" -> false;
        case "n" -> false;
        default -> throw new IllegalArgumentException("Y or N");
    };
```

Much like the `switch` statement, each `case` here evaluates the input against its value. After an `->` you provide the resulting value for the switch expression as a whole. In this example, we're assigning that to our variable `yesOrNo`, which no longer needs to be the nullable wrapper type.

Our code as written here hides one of the protections that the `switch` expressions is giving us. If we remove the `default` clause, the compiler will give us an error because the expression cannot always be evaluated fully.

```
    boolean yesOrNo = switch(input) {
        case "y" -> true;
        case "Y" -> true;
        case "N" -> false;
        case "n" -> false;
    };

    // Compiler error:
    //   the switch expression does not cover all possible input values
```

Switch expressions do not fall through like the statement form. To support multiple values evaluating to the same result, each `case` can take a comma-separated list of values instead of just a single value.

```
    boolean yesOrNo = switch(input) {
        case "y", "Y" -> true;
        case "n", "N" -> false;
        default -> throw new IllegalArgumentException("Y or N");
    };
```

Our desired result can't always be expressed as a single value or method call. To support that, curly braces may introduce a statement. However, the statement must end with either `yield` to exit the switch with a value, or a `return` leaving the entire enclosing method.

```
    boolean yesOrNo = switch(input) {
        case "y", "Y" -> { System.out.println("Got it"); yield true; }
        case "n", "N" -> { System.out.println("Nope"); yield false; }
        default -> throw new IllegalArgumentException("Y or N");
    };
```

And in fact, if we don't make use of the `switch` expression result, we can even use this syntax, with its improved branch checking and safety, purely for side effects.

```
    switch(input) {
        case "y", "Y" -> System.out.println("Sure");
        case "n", "N" -> System.out.println("Nope");
        default -> throw new IllegalArgumentException("Y or N");
    }
```

## The while Statement

The `while` statement is a basic statement that allows Java to perform repetitive actions—or, to put it another way, it is one of Java's primary *looping constructs*. It has the following syntax:

```
while (expression)
  statement
```

The `while` statement works by first evaluating the *`expression`*, which must result in a `boolean` or `Boolean` value. If the value is `false`, the interpreter skips the *`statement`* associated with the loop and moves to the next statement in the program. If it is `true`, however, the *`statement`* that forms the body of the loop is executed, and the *`expression`* is reevaluated. Again, if the value of *`expression`* is `false`, the interpreter moves on to the next statement in the program; otherwise, it executes the *`statement`* again. This cycle continues while the *`expression`* remains `true` (i.e., until it evaluates to `false`), at which point the `while` statement ends, and the interpreter moves on to the next statement. You can create an infinite loop with the syntax `while(true)`.

Here is an example `while` loop that prints the numbers 0 to 9:

```
int count = 0;
while (count < 10) {
   System.out.println(count);
   count++;
}
```

As you can see, the variable `count` starts off at 0 in this example and is incremented each time the body of the loop runs. Once the loop has executed 10 times, the expression becomes `false` (i.e., `count` is no longer less than 10), the `while` statement finishes, and the Java interpreter can move to the next statement in the program. Most loops have a counter variable like `count`. The variable names `i`, `j`, and `k` are commonly used as loop counters, although you should use more descriptive names if it makes your code easier to understand.

## The do Statement

A `do` loop is much like a `while` loop, except that the loop expression is tested at the bottom of the loop rather than at the top. This means that the body of the loop is always executed at least once. The syntax is:

```
do
   statement
while (expression);
```

Notice a couple of differences between the `do` loop and the more ordinary `while` loop. First, the `do` loop requires both the `do` keyword to mark the beginning of the loop and the `while` keyword to mark the end and introduce the loop condition. Also, unlike the `while` loop, the `do` loop is terminated with a semicolon. This is because the `do` loop ends with the loop condition rather than simply ending with a curly brace that marks the end of the loop body. The following `do` loop prints the same output as the `while` loop just discussed:

```
int count = 0;
do {
   System.out.println(count);
   count++;
} while(count < 10);
```

The `do` loop is much less commonly used than its `while` cousin because, in practice, it is unusual to encounter a situation where you are sure you always want a loop to execute at least once.

## The for Statement

The `for` statement provides a looping construct that is often more convenient than the `while` and `do` loops. The `for` statement takes advantage of a common looping pattern. Most loops have a counter, or state variable of some kind, that is initialized before the loop starts, tested to determine whether to execute the loop body, and then incremented or updated somehow at the end of the loop body before the test expression is evaluated again. The *`initialize`*, *`test`*, and *`update`* steps are the three crucial manipulations of a loop variable, and the `for` statement makes these three steps an explicit part of the loop syntax:

```
for(initialize; test; update) {
    statement
}
```

This `for` loop is basically equivalent to the following `while` loop:

```
initialize;
while (test) {
   statement;
   update;
}
```

Placing the *`initialize`*, *`test`*, and *`update`* expressions at the top of a `for` loop makes it especially easy to understand what the loop is doing, and it prevents mistakes such as forgetting to initialize or update the loop variable. The interpreter discards the values of the *`initialize`* and *`update`* expressions, so to be useful, these expressions must have side effects. *`initialize`* is typically an assignment expression, while *`update`* is usually an increment, decrement, or some other assignment.

The following `for` loop prints the numbers 0 to 9, just as the previous `while` and `do` loops have done:

```
int count;
for(count = 0 ; count < 10 ; count++)
   System.out.println(count);
```

Notice how this syntax places all the important information about the loop variable on a single line, making it very clear how the loop executes. Placing the *`update`* expression in the `for` statement itself also simplifies the body of the loop to a single statement; we don't even need to use curly braces to produce a statement block.

The `for` loop supports some additional syntax that makes it even more convenient to use. Because many loops use their loop variables only within the loop, the `for` loop allows the *`initialize`* expression to be a full variable declaration, so that the variable is scoped to the body of the loop and is not visible outside of it. For example:

```
for(int count = 0 ; count < 10 ; count++)
   System.out.println(count);
```

Furthermore, the `for` loop syntax does not restrict you to writing loops that use only a single variable. Both the *`initialize`* and *`update`* expressions of a `for` loop can use a comma to separate multiple initializations and update expressions. For example:

```
for(int i = 0, j = 10 ; i < 10 ; i++, j--)
     sum += i * j;
```

Even though all the examples so far have counted numbers, `for` loops are not restricted to loops that count numbers. For example, you might use a `for` loop to iterate through the elements of a linked list:

```
for(Node n = listHead; n != null; n = n.nextNode())
   process(n);
```

The *`initialize`*, *`test`*, and *`update`* expressions of a `for` loop are all optional; only the semicolons that separate the expressions are required. If the *`test`* expression is omitted, it is assumed to be `true`. Thus, you can write an infinite loop as `for(;;)`.

## The foreach Statement

Java's `for` loop works well for primitive types, but it is needlessly clunky for handling collections of objects. Instead, an alternative syntax known as a *foreach* loop is used for handling collections of objects that need to be looped over.

The foreach loop uses the keyword `for` followed by an opening parenthesis, a variable declaration (without initializer), a colon, an expression, a closing parenthesis, and finally the statement (or block) that forms the body of the loop:

```
for( declaration : expression )
     statement
```

Despite its name, the foreach loop does not have a keyword `foreach`—instead, it is common to read the colon as "in"—as in "foreach name in studentNames."

For the `while`, `do`, and `for` loops, we've shown an example that prints 10 numbers. The foreach loop can do this too, but it needs a collection to iterate over. In order to loop 10 times (to print out 10 numbers), we need an array or other collection with 10 elements. Here's code we can use:

```
// These are the numbers we want to print
int[] primes = new int[] { 2, 3, 5, 7, 11, 13, 17, 19, 23, 29 };
// This is the loop that prints them
for(int n : primes)
    System.out.println(n);
```

### What foreach cannot do

The foreach is different from the `while`, `for`, or `do` loops, because it hides the loop counter or `Iterator` from you. This is a very powerful idea, as we'll see when we discuss lambda expressions, but there are some algorithms that cannot be expressed very naturally with a foreach loop.

For example, suppose you want to print the elements of an array as a comma-separated list. To do this, you need to print a comma after every element of the array except the last, or equivalently, before every element of the array except the first. With a traditional `for` loop, the code might look like this:

```
for(int i = 0; i < words.length; i++) {
    if (i > 0) System.out.print(", ");
    System.out.print(words[i]);
}
```

This is a very straightforward task, but you simply cannot do it with foreach without keeping track of additional state. The problem is that the foreach loop doesn't give you a loop counter or any other way to tell if you're on the first iteration, the last iteration, or somewhere in between.

> A similar issue exists when you're using foreach to iterate through the elements of a collection. Just as a foreach loop over an array has no way to obtain the array index of the current element, a foreach loop over a collection has no way to obtain the `Iterator` object that is being used to itemize the elements of the collection.

Here are some other things you cannot do with a foreach-style loop:

- Iterate backward through the elements of an array or `List`.
- Use a single loop counter to access the same-numbered elements of two distinct arrays.
- Iterate through the elements of a `List` using calls to its `get()` method rather than calls to its iterator.

## The break Statement

A `break` statement causes the Java interpreter to skip immediately to the end of a containing statement. We have already seen the `break` statement used with the `switch` statement. The `break` statement is most often written as simply the keyword `break` followed by a semicolon:

```
break;
```

When used in this form, it causes the Java interpreter to immediately exit the innermost containing `while`, `do`, `for`, or `switch` statement. For example:

```
for(int i = 0; i < data.length; i++) {
    if (data[i] == target) {  // When we find what we're looking for,
        index = i;              // remember where we found it
        break;                  // and stop looking!
    }
}   // The Java interpreter goes here after executing break
```

The `break` statement can also be followed by the name of a containing labeled statement. When used in this form, `break` causes the Java interpreter to immediately exit the named block, which can be any kind of statement, not just a loop or `switch`. For example:

```
TESTFORNULL: if (data != null) {
   for(int row = 0; row < numrows; row++) {
     for(int col = 0; col < numcols; col++) {
       if (data[row][col] == null)
         break TESTFORNULL;           // treat the array as undefined.
     }
   }
}  // Java interpreter goes here after executing break TESTFORNULL
```

## The continue Statement

While a `break` statement exits a loop, a `continue` statement quits the current iteration of a loop and starts the next one. `continue`, in both its unlabeled and labeled forms, can be used only within a `while`, `do`, or `for` loop. When used without a label, `continue` causes the innermost loop to start a new iteration. When used with a label that is the name of a containing loop, it causes the named loop to start a new iteration. For example:

```
for(int i = 0; i < data.length; i++) {  // Loop through data.
   if (data[i] == -1)                    // If a data value is missing,
     continue;                           // skip to the next iteration.
   process(data[i]);                     // Process the data value.
}
```

`while`, `do`, and `for` loops differ slightly in the way that `continue` starts a new iteration:

- With a `while` loop, the Java interpreter simply returns to the top of the loop, tests the loop condition again, and, if it evaluates to `true`, executes the body of the loop again.
- With a `do` loop, the interpreter jumps to the bottom of the loop, where it tests the loop condition to decide whether to perform another iteration of the loop.
- With a `for` loop, the interpreter jumps to the top of the loop, where it first evaluates the *`update`* expression and then evaluates the *`test`* expression to decide whether to loop again. As you can see from the examples, the behavior of a `for` loop with a `continue` statement is different from the behavior of the "basically equivalent" `while` loop presented earlier; *`update`* gets evaluated in the `for` loop but not in the equivalent `while` loop.



## The return Statement

A `return` statement tells the Java interpreter to stop executing the current method. If the method is declared to return a value, the `return` statement must be followed by an expression. The value of the expression becomes the return value of the method. For example, the following method computes and returns the square of a number:

```
double square(double x) {      // A method to compute x squared
   return x * x;               // Compute and return a value
}
```

Some methods are declared `void` to indicate that they do not return any value. The Java interpreter runs methods like this by executing their statements one by one until it reaches the end of the method. After executing the last statement, the interpreter returns implicitly. Sometimes, however, a `void` method has to return explicitly before reaching the last statement. In this case, it can use the `return` statement by itself, without any expression. For example, the following method prints, but does not return, the square root of its argument. If the argument is a negative number, it returns without printing anything:

```
// A method to print square root of x
void printSquareRoot(double x) {
   if (x < 0) return;               // If x is negative, return
   System.out.println(Math.sqrt(x)); // Print the square root of x
}                                   // Method end: return implicitly
```

## The synchronized Statement

Java has always provided support for multithreaded programming. We cover this in some detail later on (especially in "Java's Support for Concurrency" on page 249); however, be aware that concurrency is difficult to get right and has a number of subtleties.

In particular, when working with multiple threads, you must often take care to prevent multiple threads from modifying an object simultaneously in a way that might corrupt the object's state. Java provides the `synchronized` statement to help the programmer prevent corruption. The syntax is:

```
synchronized ( expression ) {
   statements
}
```

*`expression`* is an expression that must evaluate to an object (including arrays). *`statements`* constitute the code of the section that could cause damage and must be enclosed in curly braces.

> In Java, the protection of object state (i.e., data) is the primary concern of the concurrency primitives. This is unlike some other languages, where the exclusion of threads from *critical sections* (i.e., code) is the main focus.

Before executing the statement block, the Java interpreter first obtains an exclusive lock on the object or array specified by *`expression`*. It holds the lock until it is finished running the block, then releases it. While a thread holds the lock on an object, no other thread can obtain that lock.

As well as the block form, `synchronized` can also be used as a method modifier in Java. When applied to a method, the keyword indicates that the entire method is treated as `synchronized`.

For a `synchronized` instance method, Java obtains an exclusive lock on the class instance. (Class and instance methods are discussed in Chapter 3.) It can be thought of as a `synchronized (this) { ... }` block that covers the entire method.

A `static synchronized` method (a class method) causes Java to obtain an exclusive lock on the class (technically the class object corresponding to the type) before executing the method.

## The throw Statement

An *exception* is a signal that indicates some sort of exceptional condition or error has occurred. To *throw* an exception is to signal an exceptional condition. To *catch* an exception is to handle it—to take whatever actions are necessary to recover from it.

In Java, the `throw` statement is used to throw an exception:

```
throw expression;
```

The *`expression`* must evaluate to an exception object that describes the exception or error that has occurred. We'll talk more about types of exceptions shortly; for now, all you need to know is that an exception:

- Is represented by an object
- Has a type that is a subclass of `Exception`
- Has a slightly specialized role in Java's syntax
- Can be of two different types: *checked* or *unchecked*

Here is some example code that throws an exception:

```
public static double factorial(int x) {
   if (x < 0)
     throw new IllegalArgumentException("x must be >= 0");
   double fact;
   for(fact=1.0; x > 1; fact *= x, x--)
     /* empty */ ;          // Note use of the empty statement
   return fact;
}
```

When the Java interpreter executes a `throw` statement, it immediately stops normal program execution and starts looking for an exception handler that can catch, or handle, the exception. Exception handlers are written with the `try/catch/finally` statement, which is described in the next section. The Java interpreter first looks at the enclosing block of code to see if it has an associated exception handler. If so, it exits that block of code and starts running the exception-handling code associated with the block. After running the exception handler, the interpreter continues execution at the statement immediately following the handler code.

If the enclosing block of code does not have an appropriate exception handler, the interpreter checks the next higher enclosing block of code in the method. This continues until a handler is found. If the method does not contain an exception handler that can handle the exception thrown by the `throw` statement, the interpreter stops running the current method and returns to the caller. Now the interpreter starts looking for an exception handler in the blocks of code of the calling method. In this way, exceptions propagate up through the lexical structure of Java methods, up the call stack of the Java interpreter. If the exception is never caught, it propagates all the way up to the `main()` method of the program. If it is not handled in that method, the Java interpreter prints an error message, prints a stack trace to indicate where the exception occurred, and then exits.

## The try/catch/finally Statement

Java has two slightly different exception-handling mechanisms. The classic form is the `try/catch/finally` statement. The `try` clause of this statement establishes a block of code for exception handling. This `try` block is followed by zero or more `catch` clauses, each of which is a block of statements designed to handle specific exceptions. Each `catch` block can handle more than one different exception—to indicate that a `catch` block should handle multiple exceptions, we use the `|` symbol to separate the different exceptions a `catch` block should handle. The `catch` clauses are followed by an optional `finally` block that contains cleanup code guaranteed to be executed regardless of what happens in the `try` block.

### try Block Syntax

Both the `catch` and `finally` clauses are optional, but every `try` block must either declare some automatically managed resources (the *try-with-resources* construct we'll see in "The try-with-resources Statement" on page 72) or be accompanied by a `catch`, a `finally`, or both. The `try`, `catch`, and `finally` blocks all begin and end with curly braces. These are a required part of the syntax and cannot be omitted, even if the clause contains only a single statement.

The following code illustrates the syntax and purpose of the `try/catch/finally` statement:

```
try {
   // Normally this code runs from the top of the block to the bottom
   // without problems. But it can sometimes throw an exception,
   // either directly with a throw statement or indirectly by calling
   // a method that throws an exception.
}
catch (SomeException e1) {
   // This block contains statements that handle an exception object
   // of type SomeException or a subclass of that type. Statements in
   // this block can refer to that exception object by the name e1.
}
catch (AnotherException | YetAnotherException e2) {
   // This block contains statements that handle an exception of
   // type AnotherException or YetAnotherException, or a subclass of
   // either of those types. Statements in this block refer to the
   // exception object they receive by the name e2.
}
finally {
   // This block contains statements that are always executed
   // after we leave the try clause, regardless of whether we leave it:
   //   1) normally, after reaching the bottom of the block;
   //   2) because of a break, continue, or return statement;
   //   3) with an exception that is handled by a catch clause above;
   //   4) with an uncaught exception that has not been handled.
   // If the try clause calls System.exit(), however, the interpreter
   // exits before the finally clause can be run.
}
```

#### try

The `try` clause simply establishes a block of code that either has its exceptions handled or needs special cleanup code to be run when it terminates for any reason. The `try` clause by itself doesn't do anything interesting; it is the `catch` and `finally` clauses that do the exception-handling and cleanup operations.

### catch

A `try` block can be followed by zero or more `catch` clauses that specify code to handle various types of exceptions. Each `catch` clause is declared with a single argument that specifies the types of exceptions the clause can handle (possibly using the special `|` syntax to indicate that the `catch` block can handle more than one type of exception) and also provides a name the clause can use to refer to the exception object it is currently handling. Any type that a `catch` block wishes to handle must be some subclass of `Throwable`.

When an exception is thrown, the Java interpreter looks for a `catch` clause with an argument that matches the same type as the exception object or a superclass of that type. The interpreter invokes the first such `catch` clause it finds. The code within a `catch` block should take whatever action is necessary to cope with the exceptional condition. If the exception is a `java.io.FileNotFoundException`, for example, you might handle it by asking the user to check their spelling and try again.

It is not required to have a `catch` clause for every possible exception; in some cases, the correct response is to allow the exception to propagate up and be caught by the invoking method. In other cases, such as a programming error signaled by `NullPointerException`, the correct response is probably not to catch the exception at all but allow it to propagate and have the Java interpreter exit with a stack trace and an error message.

### finally

The `finally` clause is generally used to clean up after the code in the `try` clause (e.g., close files and shut down network connections). The `finally` clause is useful because it is guaranteed to be executed if any portion of the `try` block is executed, regardless of how the code in the `try` block completes. In fact, the only way a `try` clause can exit without allowing the `finally` clause to be executed is by invoking the `System.exit()` method, which causes the Java interpreter to stop running.

In the normal case, control reaches the end of the `try` block and then proceeds to the `finally` block, which performs any necessary cleanup. If control leaves the `try` block because of a `return`, `continue`, or `break` statement, the `finally` block is executed before control transfers to its new destination.

If an exception occurs in the `try` block and there is an associated `catch` block to handle the exception, control transfers first to the `catch` block and then to the `finally` block. If there is no local `catch` block to handle the exception, control transfers first to the `finally` block, and then propagates up to the nearest containing `catch` clause that can handle the exception.

If a `finally` block itself transfers control with a `return`, `continue`, `break`, or `throw` statement or by calling a method that throws an exception, the pending control transfer is abandoned, and this new transfer is processed. For example, if a `finally` clause throws an exception, that exception replaces any exception that was in the process of being thrown. If a `finally` clause issues a `return` statement, the method returns normally, even if an exception has been thrown and has not yet been handled.

`try` and `finally` can be used together without exceptions or any `catch` clauses. In this case, the `finally` block is simply cleanup code that is guaranteed to be executed, regardless of any `break`, `continue`, or `return` statements within the `try` clause.

## The try-with-resources Statement

The standard form of a `try` block is very general, but there is a common set of circumstances that require developers to be very careful when writing `catch` and `finally` blocks. These circumstances are when operating with resources that need to be cleaned up or closed when they are no longer needed.

Java provides a very useful mechanism for automatically closing resources that require cleanup. This is known as *try-with-resources*, or TWR. We discuss TWR in detail in "Classic Java I/O" on page 343, but for completeness, let's introduce the syntax now. The following example shows how to open a file using the `FileInputStream` class (which results in an object that will require cleanup):

```
try (InputStream is = new FileInputStream("/Users/ben/details.txt")) {
  // ... process the file
}
```

This new form of `try` takes parameters that are all objects that require cleanup.[2] These objects are scoped to this `try` block and are then cleaned up automatically no matter how this block is exited. The developer does not need to write any `catch` or `finally` blocks—the Java compiler automatically inserts correct cleanup code.

All new code that deals with resources should be written in the TWR style—it is considerably less error prone than manually writing `catch` blocks and does not suffer from the problems that plague techniques such as finalization (see "Finalization" on page 248 for details).

## The assert Statement

An `assert` statement is an attempt to provide a capability to verify design assumptions in Java code. An *assertion* consists of the `assert` keyword followed by a boolean expression that the programmer believes should always evaluate to `true`. By default, assertions are not enabled, and the `assert` statement does not actually do anything.

It is possible to enable assertions as a debugging tool, however; when this is done, the `assert` statement evaluates the expression. If it is indeed `true`, `assert` does

2 Technically, they must all implement the `AutoCloseable` interface.

nothing. On the other hand, if the expression evaluates to `false`, the assertion fails, and the `assert` statement throws a `java.lang.AssertionError`.

> Outside of the core JDK libraries, the `assert` statement is *extremely* rarely used. It turns out to be too inflexible for testing most applications and is not often used by ordinary developers. Instead, developers use ordinary testing libraries, such as JUnit.



The `assert` statement may include an optional second expression, separated from the first by a colon. When assertions are enabled and the first expression evaluates to `false`, the value of the second expression is taken as an error code or error message and is passed to the `AssertionError()` constructor. The full syntax of the statement is:

```
assert assertion;
```

or:

```
assert assertion : errorcode;
```

To use assertions effectively, you must also be aware of a couple of fine points. First, remember that your programs will normally run with assertions disabled and only sometimes with assertions enabled. This means that you should be careful not to write assertion expressions that contain side effects.

> You should never throw `AssertionError` from your own code, as it may have unexpected results in future versions of the platform.

If an `AssertionError` is thrown, it indicates that one of the programmer's assumptions has not held up. This means that the code is being used outside of the parameters for which it was designed, and it cannot be expected to work correctly. In short, there is no plausible way to recover from an `AssertionError`, and you should not attempt to catch it (unless you catch it at the top level simply so that you can display the error in a more user-friendly fashion).

### Enabling assertions

For efficiency, it does not make sense to test assertions each time code is executed —`assert` statements encode assumptions that should always be true. Thus, by default, assertions are disabled, and `assert` statements have no effect. The assertion code remains compiled in the class files, however, so it can always be enabled for diagnostic or debugging purposes. You can enable assertions, either across the board or selectively, with command-line arguments to the Java interpreter.

To enable assertions in all classes except for system classes, use the `-ea` argument. To enable assertions in system classes, use `-esa`. To enable assertions within a specific class, use `-ea` followed by a colon and the class name:

```
java -ea:com.example.sorters.MergeSort com.example.sorters.Test
```

To enable assertions for all classes in a package and in all of its subpackages, follow the `-ea` argument with a colon, the package name, and three dots:

```
java -ea:com.example.sorters... com.example.sorters.Test
```

You can disable assertions in the same way, using the `-da` argument. For example, to enable assertions throughout a package and then disable them in a specific class or subpackage, use:

```
java -ea:com.example.sorters... -da:com.example.sorters.QuickSort
java -ea:com.example.sorters... -da:com.example.sorters.plugins..
```

Finally, it is possible to control whether or not assertions are enabled or disabled at classloading time. If you use a custom classloader (see Chapter 11 for details on custom classloading) in your program and want to turn on assertions, you may be interested in these methods.

# Methods

A *method* is a named sequence of Java statements that can be invoked by other Java code. When a method is invoked, it is passed zero or more values known as *arguments*. The method performs some computations and, optionally, returns a value. As described earlier in "Expressions and Operators" on page 34, a method invocation is an expression that is evaluated by the Java interpreter. Because method invocations can have side effects, however, they also can be used as expression statements. This section does not discuss method invocation but instead describes how to define methods.

## Defining Methods

You already know how to define the body of a method; it is simply an arbitrary sequence of statements enclosed within curly braces. What is more interesting about a method is its *signature*.[3] The signature specifies:

- The name of the method
- The number, order, type, and name of the parameters used by the method
- The type of the value returned by the method
- The checked exceptions that the method can throw (the signature may also list unchecked exceptions, but these are not required)

3 In the Java Language Specification, the term "signature" has a technical meaning that is slightly different than that used here. This book uses a less formal definition of method signature.

- Various method modifiers that provide additional information about the method

A method signature defines everything you need to know about a method before calling it. It is the method *specification* and defines the API for the method. To use the Java platform's online API reference, you need to know how to read a method signature. And, to write Java programs, you need to know how to define your own methods, each of which begins with a method signature.

A method signature looks like this:

```
modifiers type name (paramlist) [ throws exceptions ]
```

The signature (the method specification) is followed by the method body (the method implementation), which is simply a sequence of Java statements enclosed in curly braces. If the method is *abstract* (see Chapter 3), the implementation is omitted, and the method body is replaced with a single semicolon.

The signature of a method may also include type variable declarations—such methods are known as *generic methods*. Generic methods and type variables are discussed in Chapter 4.

Here are some example method definitions, which begin with the signature and are followed by the method body:

```
// This method is passed an array of strings and has no return value.
// All Java programs have an entry point with this name and signature.
public static void main(String[] args) {
     if (args.length > 0) System.out.println("Hello " + args[0]);
     else System.out.println("Hello world");
}

// This method is passed two double arguments and returns a double.
static double distanceFromOrigin(double x, double y) {
     return Math.sqrt(x*x + y*y);
}

// This method is abstract which means it has no body.
// Note that it may throw exceptions when invoked.
protected abstract String readText(File f, String encoding)
    throws FileNotFoundException, UnsupportedEncodingException;
```

`modifiers` are zero or more special modifier keywords, separated from each other by spaces. A method might be declared with the `public` and `static` modifiers, for example. The allowed modifiers and their meanings are described in the next section.

The `type` in a method signature specifies the return type of the method. If the method does not return a value, `type` must be `void`. If a method is declared with a non-`void` return type, it must include a `return` statement that returns a value of (or is convertible to) the declared type.

A *constructor* is a block of code, similar to a method, that is used to initialize newly created objects. As we'll see in Chapter 3, constructors are defined in a very similar way to methods, except that their signatures do not include this *`type`* specification and must be named the same as the class.

The *`name`* of a method follows the specification of its modifiers and type. Method names, like variable names, are Java identifiers and, like all Java identifiers, may contain letters in any language represented by the Unicode character set. It is legal, and often quite useful, to define more than one method with the same name, as long as each version of the method has a different parameter list. Defining multiple methods with the same name is called *method overloading*.

> Unlike some other languages, Java does not have anonymous methods. Instead, Java 8 introduces lambda expressions, which are similar to anonymous methods, but which the Java runtime automatically converts to a suitable named method—see "Lambda Expressions" on page 85 for more details.

For example, the `System.out.println()` method we've seen already is an overloaded method. One method by this name prints a string, and other methods by the same name print the values of the various primitive types. The Java compiler decides which method to call based on the type of the argument passed to the method.

When you are defining a method, the name of the method is always followed by the method's parameter list, which must be enclosed in parentheses. The parameter list defines zero or more arguments that are passed to the method. The parameter specifications, if there are any, each consist of a type and a name and the specifications are separated from each other by commas (if there are multiple parameters). When a method is invoked, the argument values it is passed must match the number, type, and order of the parameters specified in this method signature line. The values passed need not have exactly the same type as specified in the signature, but they must be convertible to those types without casting.

> When a Java method expects no arguments, its parameter list is simply `()`, not `(void)`. Java does not regard `void` as a type—C and C++ programmers in particular should pay heed.

Java allows the programmer to define and invoke methods that accept a variable number of arguments, using a syntax known colloquially as *varargs*. Varargs are covered in detail later in this chapter.

The final part of a method signature is the `throws` clause, which is used to list the *checked exceptions* that a method can throw. Checked exceptions are a category of exception classes that must be listed in the `throws` clauses of methods that can throw them.

If a method uses the `throw` statement to throw a checked exception, the method must declare that it can throw that exception. The method must also declare that it can throw in the case that it calls some other method that throws a checked exception, and the calling method does not explicitly catch that exception.

If a method can throw one or more checked exceptions, it specifies this by placing the `throws` keyword after the argument list and following it by the name of the exception class or classes it can throw. If a method does not throw any checked exceptions, it does not use the `throws` keyword. If a method throws more than one type of checked exception, separate the names of the exception classes from each other with commas. More on this in a bit.



## Method Modifiers

The modifiers of a method consist of zero or more modifier keywords such as `public`, `static`, or `abstract`. Here is a list of allowed modifiers and their meanings:

`abstract`
: An `abstract` method is a specification without an implementation. The curly braces and Java statements that would normally comprise the body of the method are replaced with a single semicolon. A class that includes an `abstract` method must itself be declared `abstract`. Such a class is incomplete and cannot be instantiated (see Chapter 3).

`default`
: A `default` method may be defined only on an interface. All classes implementing the interface receive the default method unless they override it directly. Implementing interfaces in classes is explored thoroughly in Chapter 3.

`final`
: A `final` method may not be overridden or hidden by a subclass, which makes it amenable to compiler optimizations that are not possible for regular methods. All `private` methods are implicitly `final`, as are all methods of any class that is declared `final`.

`native`
: The `native` modifier specifies that the method implementation is written in some "native" language such as C and is provided externally to the Java program. Like `abstract` methods, `native` methods have no body: the curly braces are replaced with a semicolon.

## Implementing native Methods

When Java was first released, `native` methods were sometimes used for efficiency reasons. That is almost never necessary today. Instead, `native` methods are used to interface Java code to existing libraries written in C or C++. `native` methods are implicitly platform-dependent, and the procedure for linking the implementation with the Java class that declares the method is dependent on the implementation of the Java virtual machine. `native` methods are not covered in this book but more information can be found in the Java Native Interface Specification.

`public`, `protected`, `private`
: These access modifiers specify whether and where a method can be used outside of the class that defines it. These very important modifiers are explained in Chapter 3.

`static`
: A method declared `static` is a *class method* associated with the class itself rather than with an instance of the class (we cover this in more detail in Chapter 3).

`strictfp`
: The `fp` in this awkwardly named, rarely used modifier stands for "floating point." For performance reasons, in Java 1.2 the language allowed for subtle deviation from the strict IEEE-754 standard when using certain floating-point acceleration hardware. The `strictfp` keyword was added to force Java to strictly obey the standard. These hardware considerations haven't been relevant for many years, so Java 17 returns the default to the IEEE standard. Use of the `strictfp` keyword will emit a warning, as it is no longer necessary.

`synchronized`
: The `synchronized` modifier makes a method threadsafe. Before a thread can invoke a `synchronized` method, it must obtain a lock on the method's class (for `static` methods) or on the relevant instance of the class (for non-`static` methods). This prevents two threads from executing the method at the same time.

The `synchronized` modifier is an implementation detail (because methods can make themselves threadsafe in other ways) and is not formally part of the method specification or API. Good documentation specifies explicitly whether a method is threadsafe; you should not rely on the presence or absence of the `synchronized` keyword when working with multithreaded programs.

> Annotations are an interesting special case (see Chapter 4 for more on annotations)—they can be thought of as a halfway house between a method modifier and additional supplementary type information.

## Checked and Unchecked Exceptions

The Java exception-handling scheme distinguishes between two types of exceptions, known as *checked* and *unchecked* exceptions.

The distinction between checked and unchecked exceptions has to do with the circumstances under which the exceptions could be thrown. Checked exceptions arise in specific, well-defined circumstances, and very often are conditions from which the application may be able to partially or fully recover.

For example, consider some code that might find its configuration file in one of several possible directories. If we attempt to open the file from a directory it isn't present in, then a `FileNotFoundException` will be thrown. In our example, we want to catch this exception and move on to try the next possible location for the file. In other words, although the file not being present is an exceptional condition, it is one from which we can recover, and it is an understood and anticipated failure.

On the other hand, in the Java environment there are a set of failures that cannot easily be predicted or anticipated, due to such things as runtime conditions or abuse of library code. There is no good way to predict an `OutOfMemoryError`, for example, and any method that uses objects or arrays can throw a `NullPointerException` if it is passed an invalid `null` argument.

These are the unchecked exceptions—and practically any method can throw an unchecked exception at essentially any time. They are the Java environment's version of Murphy's law: "Anything that can go wrong, will go wrong." Recovery from an unchecked exception is usually very difficult, if not impossible—simply due to their sheer unpredictability.

To figure out whether an exception is checked or unchecked, remember that exceptions are `Throwable` objects and that these fall into two main categories, specified by the `Error` and `Exception` subclasses. Any exception object that is an `Error` is unchecked. There is also a subclass of `Exception` called `RuntimeException`—and any subclass of `RuntimeException` is also an unchecked exception. All other exceptions are checked exceptions.

### Working with checked exceptions

Java has different rules for working with checked and unchecked exceptions. If you write a method that throws a checked exception, you must use a `throws` clause to declare the exception in the method signature. The Java compiler checks to make sure you have declared them in method signatures and produces a compilation error if you have not (that's why they're called "checked exceptions").

Even if you never throw a checked exception yourself, sometimes you must use a `throws` clause to declare a checked exception. If your method calls a method that can throw a checked exception, you must either include exception-handling code to handle that exception or use `throws` to declare that your method can also throw that exception.

For example, the following method tries to estimate the size of a web page—it uses the standard `java.net` libraries and the class `URL` (we'll meet these in Chapter 10) to contact the web page. It uses methods and constructors that can throw various types of `java.io.IOException` objects, so it declares this fact with a `throws` clause:

```
public static estimateHomepageSize(String host) throws IOException {
    URL url = new URL("htp://"+ host +"/");
    try (InputStream in = url.openStream()) {
        return in.available();
    }
}
```

In fact, the preceding code has a bug: we've misspelled the protocol specifier—there's no such protocol as *htp://*. So, the `estimateHomepageSize()` method will always fail with a `MalformedURLException`.

How do you know if the method you are calling can throw a checked exception? You can look at its method signature to find out. Or, failing that, the Java compiler will tell you (by reporting a compilation error) if you've called a method whose exceptions you must handle or declare.

## Variable-Length Argument Lists

Methods may be declared to accept, and may be invoked with, variable numbers of arguments. Such methods are commonly known as *varargs* methods. The "print formatted" method `System.out.printf()` as well as the related `format()` methods of `String` use varargs, as do a number of important methods from the Reflection API of `java.lang.reflect`.

To declare a variable-length argument list, follow the type of the last argument to the method with an ellipsis (`...`), indicating that this last argument can be repeated zero or more times. For example:

```
public static int max(int first, int... rest) {
    /* body omitted for now */
}
```

Varargs methods are handled purely by the compiler. They operate by converting the variable number of arguments into an array. To the Java runtime, the `max()` method is indistinguishable from this one:

```
public static int max(int first, int[] rest) {
    /* body omitted for now */
}
```

To convert a varargs signature to the "real" signature, simply replace `...` with `[ ]`. Remember that only one ellipsis can appear in a parameter list, and it may only appear on the last parameter in the list.

Let's flesh out the `max()` example a little:

```
public static int max(int first, int... rest) {
    int max = first;
    for(int i : rest) { // legal because rest is actually an array
        if (i > max) max = i;
    }
    return max;
}
```

This `max()` method is declared with two arguments. The first is just a regular `int` value. The second, however, may be repeated zero or more times. All of the following are legal invocations of `max()`:

```
max(0)
max(1, 2)
max(16, 8, 4, 2, 1)
```

Because varargs methods are compiled into methods that expect an array of arguments, invocations of those methods are compiled to include code that creates and initializes such an array. So the call `max(1,2,3)` is compiled to this:

```
max(1, new int[] { 2, 3 })
```

In fact, if you already have method arguments stored in an array, it is perfectly legal for you to pass them to the method that way, instead of writing them out individually. You can treat any `...` argument as if it were declared as an array. The converse is not true, however: you can use varargs method invocation syntax only when the method is actually declared as a varargs method using an ellipsis.

## Introduction to Classes and Objects

Now that we have introduced operators, expressions, statements, and methods, we can finally talk about classes. A *class* is a named collection of fields that holds data values and methods that operate on those values. Classes are just one of five reference types supported by Java, but they are the most important type. Classes are thoroughly documented in a chapter of their own (Chapter 3). We introduce them here, however, because they are the next higher level of syntax after methods, and because the rest of this chapter requires a basic familiarity with the concept of a class and the basic syntax for defining a class, instantiating it, and using the resulting *object*.

The most important thing about classes is that they define new data types. For example, you might define a class named `Account` to represent a bank account that holds a balance. The class would define fields to hold data items such as the balance (perhaps represented as a `double`), account holder's name and address (as `String` instances) and methods to manipulate and operate on the account. The `Account` class is a new data type.

When discussing data types, it is important to distinguish between the data type itself and the values the data type represents. `char` is a data type: it represents Unicode characters. But a `char` value represents a single specific character. A class is a data type; a class value is called an *object*. We use the name class because each class defines a type (or kind, or species, or class) of objects. The `Account` class is a data type that represents bank accounts, while an `Account` object represents a single specific account. As you might imagine, classes and their objects are closely linked. In the sections that follow, we will discuss both.

## Defining a Class

Here is a possible definition of the `Account` class we have been discussing:

```
/** Represents a customer bank account */
public class Account {
     public String name;
     public double balance;
     public int accountId;

     // A constructor that initializes the fields
     public Account(String name, double openingBalance, int id) {
         this.name = name;
         this.balance = openingBalance;
         this.accountId = id;
     }
}
```

This class definition is stored in a file named *Account.java* and compiled to a file named *Account.class*, where it is available for use by Java programs and other classes. This class definition is provided here for completeness and to provide context, but don't expect to understand all the details just yet; most of Chapter 3 is devoted to the topic of defining classes.

Keep in mind that you don't have to define every class you want to use in a Java program. The Java platform includes thousands of predefined classes that are guaranteed to be available on every computer that runs that given version of Java.

## Creating an Object

Now that we have defined the `Account` class as a new data type, we can use the following line to declare a variable that holds an `Account` object:

```
Account a;
```

Declaring a variable to hold an `Account` object does not create the object itself, however. To actually create an object, you must use the `new` operator. This keyword is followed by the object's class (i.e., its type) and an optional argument list in parentheses. These arguments are passed to the constructor for the class, which initializes internal fields in the new object:

```
// Declare variable a and store a reference to new Account object
Account a = new Account("Jason Clark", 0.0, 42);

// Create some other objects as well
// An object that represents the current time
LocalDateTime d = new LocalDateTime();

// A HashSet object to hold a set of strings
Set<String> words = new HashSet<>();
```

The `new` keyword is by far the most common way to create objects in Java. A few other ways are also worth mentioning. First, classes that meet certain criteria are so important that Java defines special literal syntax for creating objects of those types (as we discuss later in this section). Second, Java supports a mechanism that allows programs to load classes and create instances of those classes dynamically. See Chapter 11 for more details. Finally, objects can also be created by deserializing them. An object that has had its state saved, or serialized, usually to a file, can be recreated using the `java.io.ObjectInputStream` class.

## Using an Object

Now that we've seen how to define classes and instantiate them by creating objects, we need to look at the Java syntax that allows us to use those objects. Recall that a class defines a collection of fields and methods. Each object has its own copies of those fields and has access to those methods. We use the dot character (.) to access the named fields and methods of an object. For example:

```
Account a = new Account("Jason", 0.0, 42);  // Create an object

double b  = a.balance;                     // Read a field of the object
a.balance = a.balance + 10.0;              // Set the value of a field

String s  = a.toString();                  // Access a method of the object
```

This syntax is very common when programming in object-oriented languages, and Java is no exception. Note, in particular, the expression `a.toString()`. This tells the Java compiler to look up a method named `toString` (which is defined by the parent `Object` class of `Account`) and use that method to perform a computation on the object `a`. We'll cover the details of this operation in Chapter 3.

## Object Literals

In our discussion of primitive types, we saw that each primitive type has a literal syntax for including values of the type literally into the text of a program. Java also defines a literal syntax for a few special reference types, as described next.

### String literals

The `String` class represents text as a string of characters. Because programs usually communicate with their users through the written word, the ability to manipulate strings of text is quite important in any programming language. In Java, strings are objects; the data type used to represent text is the `String` class. Modern Java programs usually use more string data than anything else.

Accordingly, because strings are such a fundamental data type, Java allows you to include text literally in programs in one of two formats. Traditional strings are placed between double-quote (`"`) characters, or a newer text block form may be used between sequences of three double-quote characters (`"""`).

A traditional double-quoted string looks like this:

```
String name = "David";
System.out.println("Hello, " + name);
```

Don't confuse the double-quote characters that surround string literals with the single-quote (or apostrophe) characters that surround `char` literals.

String literals of either form can contain any of the escape sequences `char` literals can (see Table 2-2). Traditional double-quoted strings require escape sequences to embed double-quote characters or newlines. They also must consist of a single line in our Java code. For example:

```
String story = "\t\"How can you stand it?\" he asked sarcastically.\n";
```

The primary use for text blocks instead of traditional strings is representing multiline strings. Text blocks start with `"""`, followed by a newline, and end when a concluding `"""` is reached.

Along with their support for multiline strings, text blocks also allow us to use double quotes without escaping. This often makes text blocks much easier to read, particularly when expressing another programming language (such as SQL or HTML) in our Java code.

```
String html = """
              <html>
                <body class="main-body">
                  ...
                </body>
              </html>""";
System.out.println(html);
```

Examining the output from this code reveals one more interesting fact about text blocks regarding indentation. The above prints with `<html>` in the first column of the output with no leading spaces.

The compiler finds the smallest indentation across the lines of our text block and strips that many leading spaces from each line. If this is not desired, the placement of the closing `"""` also participates in choosing the indent. We could retain the full white space with:

```
String html = """
              <html>
                <body class="main-body">
                  ...
                </body>
              </html>
""";  // As smallest indent (0), this leaves the text block as written

System.out.println(html);
```



Before text blocks were introduced in Java, it was common to break up string literals for easier reading using + to concatenate them. Along with existing in many code bases, this remains a valid technique if your string shouldn't include newlines.

```
// This is illegal
// Traditional string literals cannot break across lines.
String x = "This is a test of the
            emergency broadcast system";

// Common before text blocks
// Still useful if avoiding newlines in the text
String s = "This is a test of the " +
           "emergency broadcast system";
```

Literals, whether traditional or text blocks, are concatenated when your program is compiled, not when it is run, so you do not need to worry about any kind of performance penalty.

### Type literals

The second type that supports its own special object literal syntax is the class named `Class`. Instances of the `Class` class represent a Java data type and contain metadata about the type that is referred to. To include a `Class` object literally in a Java program, follow the name of any data type with `.class`. For example:

```
Class<?> typeInt = int.class;
Class<?> typeIntArray = int[].class;
Class<?> typeAccount = Account.class;
```

### The null reference

The `null` keyword is a special literal value that is a reference to nothing, or an absence of a reference. The `null` value is unique because it is a member of every reference type. You can assign `null` to variables of any reference type. For example:

```
String s = null;
Account a = null;
```

## Lambda Expressions

Java 8 introduced a major new feature—*lambda expressions*. These are a very common programming language construct and in particular are extremely widely used in the family of languages known as *functional programming languages* (e.g., Lisp, Haskell, and OCaml). The power and flexibility of lambdas goes far beyond just functional languages, and they can be found in almost all modern programming languages.

### Definition of a Lambda Expression

A lambda expression is essentially a function that does not have a name and can be treated as a value in the language (e.g., assigned to a variable). As Java does not allow code to run around on its own outside of classes, in Java this means that a lambda is an anonymous method defined on some class (that is possibly unknown to the developer).

The syntax for a lambda expression looks like this:

```
( paramlist ) -> { statements }
```

One simple, very traditional example:

```
Runnable r = () -> System.out.println("Hello World");
```

When a lambda expression is used as a value, it is automatically converted to a new object of the correct type for the variable it is being placed into. This autoconversion and *type inference* is essential to Java's approach to lambda expressions. Unfortunately, it relies on a proper understanding of Java's type system as a whole. "Nested Types" on page 187 provides a more detailed explanation of lambda expressions—so for now, it suffices to simply recognize the syntax for lambdas.

A slightly more complex example:

```
ActionListener listener = (e) -> {
  System.out.println("Event fired at: "+ e.getWhen());
  System.out.println("Event command: "+ e.getActionCommand());
};
```

## Arrays

An *array* is a special kind of object that holds zero or more primitive values or references. These values are held in the *elements* of the array, which are unnamed variables referred to by their position or *index*. The type of an array is characterized by its *element type*, and all elements of the array must be of that type.

Array elements are numbered starting with zero, and valid indexes range from zero to the number of elements minus one. The array element with index 1, for example, is the *second* element in the array. The number of elements in an array is its *length*. The length of an array is specified when the array is created, and it never changes (unlike Java collections, which we'll see in Chapter 8).

The element type of an array may be any valid Java type, including array types. This means that Java supports arrays of arrays, which provide a kind of multidimensional array capability. Java does not support the matrix-style multidimensional arrays found in some languages.

While Java's Collection API, covered thoroughly in Chapter 8, is often more flexible and feature-rich than basic arrays, arrays remain common throughout the platform and it's worth understanding the details of using them.



## Array Types

Array types are reference types, just as classes are. Instances of arrays are objects, just as the instances of a class are.[4] Unlike classes, array types do not have to be defined. Simply place square brackets after the element type. For example, the following code declares three variables of array type:

```
byte b;                        // byte is a primitive type
byte[] arrayOfBytes;           // byte[] is an array of byte values
byte[][] arrayOfArrayOfBytes;  // byte[][] is an array of byte[]
String[] strings;              // String[] is an array of strings
```

The length of an array is not part of the array type. It is not possible, for example, to declare a method that expects an array of exactly four `int` values. If a method parameter is of type `int[]`, a caller can pass an array with any number (including zero) of elements.

Array types are not classes, but array instances are objects. This means that arrays inherit the methods of `java.lang.Object`. Arrays implement the `Cloneable` interface and override the `clone()` method to guarantee that an array can always be cloned and that `clone()` never throws a `CloneNotSupportedException`. Arrays also implement `Serializable` so that any array can be serialized if its element type can be serialized. Finally, all arrays have a `public final int` field named `length` that specifies the number of elements in the array.

### Array type widening conversions

Because arrays extend `Object` and implement the `Cloneable` and `Serializable` interfaces, any array type can be widened to any of these three types. But certain array types can also be widened to other array types. If the element type of an array is a reference type `T`, and `T` is assignable to a type `S`, the array type `T[]` is assignable to the array type `S[]`. Note that there are no widening conversions of this sort for arrays of a given primitive type. As examples, the following lines of code show legal array widening conversions:

```
String[] arrayOfStrings;      // Created elsewhere
int[][] arrayOfArraysOfInt;   // Created elsewhere
```

4 There is a terminology difficulty in discussions of arrays. Unlike with classes and their instances, we use the term "array" for both the array type and the array instance. In practice, it is usually clear from context whether a type or a value is being discussed.

```java
// String is assignable to Object,
// so String[] is assignable to Object[]
Object[] oa = arrayOfStrings;

// String implements Comparable, so a String[] can
// be considered a Comparable[]
Comparable[] ca = arrayOfStrings;

// An int[] is an Object, so int[][] is assignable to Object[]
Object[] oa2 = arrayOfArraysOfInt;

// All arrays are cloneable, serializable Objects
Object o = arrayOfStrings;
Cloneable c = arrayOfArraysOfInt;
Serializable s = arrayOfArraysOfInt[0];
```

This ability to widen an array type to another array type means that the compile-time type of an array is not always the same as its runtime type.

> This widening is known as *array covariance*, and as we shall see in "Bounded Type Parameters" on page 167, it is regarded by modern standards as a historical artifact and a misfeature, because of the mismatch between compile and runtime typing that it exposes.

The compiler must usually insert runtime checks before any operation that stores a reference value into an array element to ensure that the runtime type of the value matches the runtime type of the array element. An `ArrayStoreException` is thrown if the runtime check fails.

### C compatibility syntax

As we've seen, you write an array type simply by placing brackets after the element type. For compatibility with C and C++, however, Java supports an alternative syntax in variable declarations: brackets may be placed after the name of the variable instead of, or in addition to, the element type. This applies to local variables, fields, and method parameters. For example:

```java
// This line declares local variables of type int, int[] and int[][]
int justOne, arrayOfThem[], arrayOfArrays[][];

// These three lines declare fields of the same array type:
public String[][] aas1;   // Preferred Java syntax
public String aas2[][];   // C syntax
public String[] aas3[];   // Confusing hybrid syntax

// This method signature includes two parameters with the same type
public static double dotProduct(double[] x, double y[]) { ... }
```

This compatibility syntax is extremely uncommon, and you should not use it.



## Creating and Initializing Arrays

To create an array value in Java, you use the `new` keyword, just as you do to create an object. Array types don't have constructors, but you are required to specify a length whenever you create an array. Specify the desired size of your array as a nonnegative integer between square brackets:

```
// Create a new array to hold 1024 bytes
byte[] buffer = new byte[1024];
// Create an array of 50 references to strings
String[] lines = new String[50];
```

When you create an array with this syntax, each of the array elements is automatically initialized to the same default value that is used for the fields of a class: `false` for `boolean` elements, `\u0000` for `char` elements, `0` for integer elements, `0.0` for floating-point elements, and `null` for elements of reference type.

Array creation expressions can also be used to create and initialize a multidimensional array of arrays. This syntax is somewhat more complicated and is explained later in this section.

### Array initializers

To create an array and initialize its elements in a single expression, omit the array length and follow the square brackets with a comma-separated list of expressions within curly braces. The type of each expression must be assignable to the element type of the array, of course. The length of the array that is created is equal to the number of expressions. It is legal, but not necessary, to include a trailing comma following the last expression in the list. For example:

```
String[] greetings = new String[] { "Hello", "Hi", "Howdy" };
int[] smallPrimes = new int[] { 2, 3, 5, 7, 11, 13, 17, 19, };
```

Note that this syntax allows arrays to be created, initialized, and used without ever being assigned to a variable. In a sense, these array creation expressions are anonymous array literals. Here are examples:

```
// Call a method, passing an anonymous array literal that
// contains two strings
String response = askQuestion("Do you want to quit?",
                              new String[] {"Yes", "No"});

// Call another method with an anonymous array (of anonymous objects)
double d = sumAccounts(new Account[] { new Account("1st", 100.0, 1),
```

```
                                        new Account("2nd", 200.0, 2),
                                        new Account("3rd", 300.0, 3) });
```

When an array initializer is part of a variable declaration, you may omit the `new` keyword and element type and list the desired array elements within curly braces:

```
String[] greetings = { "Hello", "Hi", "Howdy" };
int[] powersOfTwo = {1, 2, 4, 8, 16, 32, 64, 128};
```

Array literals are created and initialized when the program is run, not when the program is compiled. Consider the following array literal:

```
int[] perfectNumbers = {6, 28};
```

This is compiled into Java bytecodes that are equivalent to:

```
int[] perfectNumbers = new int[2];
perfectNumbers[0] = 6;
perfectNumbers[1] = 28;
```

The fact that Java does all array initialization at runtime has an important corollary. It means that the expressions in an array initializer may be computed at runtime and need not be compile-time constants. For example:

```
Account[] accounts = { findAccountById(1), findAccountById(2) };
```

## Using Arrays

Once an array has been created, you are ready to start using it. The following sections explain basic access to the elements of an array and cover common idioms of array usage, such as iterating through the elements of an array and copying an array or part of an array.

### Accessing array elements

The elements of an array are variables. When an array element appears in an expression, it evaluates to the value held in the element. And when an array element appears on the lefthand side of an assignment operator, a new value is stored into that element. Unlike a normal variable, however, an array element has no name, only a number. Array elements are accessed using a square bracket notation. If `a` is an expression that evaluates to an array reference, you index that array and refer to a specific element with `a[i]`, where `i` is an integer literal or an expression that evaluates to an `int`. For example:

```
// Create an array of two strings
String[] responses = new String[2];
responses[0] = "Yes";  // Set the first element of the array
responses[1] = "No";   // Set the second element of the array

// Now read these array elements
System.out.println(question + " (" + responses[0] + "/" +
                   responses[1] + " ): ");
```

```
// Both the array reference and the array index may be more complex
double datum = data.getMatrix()[data.row() * data.numColumns() +
                   data.column()];
```

The array index expression must be of type `int`, or a type that can be widened to an `int`: `byte`, `short`, or even `char`. It is obviously not legal to index an array with a `boolean`, `float`, or `double` value. Remember that the `length` field of an array is an `int` and that arrays may not have more than `Integer.MAX_VALUE` elements. Indexing an array with an expression of type `long` generates a compile-time error, even if the value of that expression at runtime would be within the range of an `int`.



### Array bounds

Remember that the first element of an array `a` is `a[0]` , the second element is `a[1]`, and the last is `a[a.length-1]`.

A common bug involving arrays is use of an index that is too small (a negative index) or too large (greater than or equal to the array `length`). In languages like C or C++, accessing elements before the beginning or after the end of an array yields unpredictable behavior that can vary from invocation to invocation and platform to platform. Such bugs may not always be caught, and if a failure occurs, it may be at some later time. While it is just as easy to write faulty array indexing code in Java, Java guarantees predictable results by checking every array access at runtime. If an array index is too small or too large, Java immediately throws an `ArrayIndexOutOfBoundsException`.

### Iterating arrays

It is common to write loops that iterate through each of the elements of an array in order to perform some operation on it. This is typically done with a `for` loop. The following code, for example, computes the sum of an array of integers:

```
int[] primes = { 2, 3, 5, 7, 11, 13, 17, 19, 23 };
int sumOfPrimes = 0;
for(int i = 0; i < primes.length; i++)
    sumOfPrimes += primes[i];
```

The structure of this `for` loop is idiomatic, and you'll see it frequently. Java also has the foreach syntax that we've already met. The summing code could be rewritten succinctly as follows:

```
for(int p : primes) sumOfPrimes += p;
```

### Copying arrays

All array types implement the `Cloneable` interface, and any array can be copied by invoking its `clone()` method. Note that a cast is required to convert the return value to the appropriate array type, but the `clone()` method of arrays is guaranteed not to throw a `CloneNotSupportedException`:

```
int[] data = { 1, 2, 3 };
int[] copy = data.clone();
```

The `clone()` method makes a shallow copy. If the element type of the array is a reference type, only the references are copied, not the referenced objects themselves. Because the copy is shallow, any array can be cloned, even if the element type is not itself `Cloneable`.

Sometimes you simply want to copy elements from one existing array to another existing array. The `System.arraycopy()` method is designed to do this efficiently, and you can assume that Java VM implementations perform this method using high-speed block copy operations on the underlying hardware.

`arraycopy()` is a straightforward function that is difficult to use only because it has five arguments to remember. First, pass the source array from which elements are to be copied. Second, pass the index of the start element in that array. Pass the destination array and the destination index as the third and fourth arguments. Finally, as the fifth argument, specify the number of elements to be copied.

`arraycopy()` works correctly even for overlapping copies within the same array. For example, if you've "deleted" the element at index `0` from array `a` and want to shift the elements between indexes `1` and `n` down one so that they occupy indexes `0` through `n-1`, you could do this:

```
System.arraycopy(a, 1, a, 0, n);
```

### Array utilities

The `java.util.Arrays` class contains a number of static utility methods for working with arrays. Most of these methods are heavily overloaded, with versions for arrays of each primitive type and another version for arrays of objects.

The `sort()` and `binarySearch()` methods are particularly useful for sorting and searching arrays. The `equals()` method allows you to compare the content of two arrays. The `toString()` method is useful when you want to convert array content to a string, such as for debugging or logging output. `copyOf()` is a useful alternative to `arraycopy()` we've seen before if you're ok with a new array being allocated rather than copying into an existing one.

The `Arrays` class also includes `deepEquals()`, `deepHashCode()`, and `deepToString()` methods that work correctly for multidimensional arrays.

## Multidimensional Arrays

As we've seen, an array type is written as the element type followed by a pair of square brackets. An array of `char` is `char[]`, and an array of arrays of `char` is `char[][]`. When the elements of an array are themselves arrays, we say that the array is *multidimensional*. In order to work with multidimensional arrays, you need to understand a few additional details.

Imagine that you want to use a multidimensional array to represent a multiplication table:

```
int[][] products;      // A multiplication table
```

Each of the pairs of square brackets represents one dimension, so this is a two-dimensional array. To access a single `int` element of this two-dimensional array, you must specify two index values, one for each dimension. Assuming that this array was actually initialized as a multiplication table, the `int` value stored at any given element would be the product of the two indexes. That is, `products[2][4]` would be 8, and `products[3][7]` would be 21.



To create a new multidimensional array, use the `new` keyword and specify the size of both dimensions of the array. For example:

```
int[][] products = new int[10][10];
```

In some languages, an array like this would be created as a single block of 100 `int` values. Java does not work this way. This line of code does three things:

- Declares a variable named `products` to hold an array of arrays of `int`.
- Creates a 10-element array to hold 10 arrays of `int`.
- Creates 10 more arrays, each of which is a 10-element array of `int`. It assigns each of these 10 new arrays to the elements of the initial array. The default value of every `int` element of each of these 10 new arrays is 0.

To put this another way, the previous single line of code is equivalent to the following code:

```
int[][] products = new int[10][]; // An array to hold 10 int[] values
for(int i = 0; i < 10; i++)      // Loop 10 times...
    products[i] = new int[10];   // ...and create 10 arrays
```

The `new` keyword performs this additional initialization automatically for you. It works with arrays with more than two dimensions as well:

```
float[][][] globalTemperatureData = new float[360][180][100];
```

When using `new` with multidimensional arrays, you do not have to specify a size for all dimensions of the array, only the leftmost dimension or dimensions. For example, the following two lines are legal:

```
float[][][] globalTemperatureData = new float[360][][];
float[][][] globalTemperatureData = new float[360][180][];
```

The first line creates a single-dimensional array, where each element of the array can hold a `float[][]`. The second line creates a two-dimensional array, where each element of the array is a `float[]`. If you specify a size for only some of the dimensions of an array, however, those dimensions must be the leftmost ones. The following lines are not legal:

```
float[][][] globalTemperatureData = new float[360][][100];  // Error!
float[][][] globalTemperatureData = new float[][180][100];  // Error!
```

Like a one-dimensional array, a multidimensional array can be initialized using an array initializer. Simply use nested sets of curly braces to nest arrays within arrays. For example, we can declare, create, and initialize a 5 × 5 multiplication table like this:

```
int[][] products = { {0, 0, 0, 0, 0},
                     {0, 1, 2, 3, 4},
                     {0, 2, 4, 6, 8},
                     {0, 3, 6, 9, 12},
                     {0, 4, 8, 12, 16} };
```

Or, if you want to use a multidimensional array without declaring a variable, you can use the anonymous initializer syntax:

```
boolean response = bilingualQuestion(question, new String[][] {
                                                   { "Yes", "No" },
                                                   { "Oui", "Non" }});
```

When you create a multidimensional array using the `new` keyword, it is usually good practice to use only *rectangular* arrays: ones in which all the array values for a given dimension have the same size.

# Reference Types

Now that we've covered arrays and introduced classes and objects, we can turn to a more general description of *reference types*. Classes and arrays are two of Java's five kinds of reference types. Classes were introduced earlier and are covered in complete detail, along with *interfaces*, in Chapter 3. Enumerated types and annotation types are reference types introduced in Chapter 4.

This section does not cover specific syntax for any particular reference type but instead explains the general behavior of reference types and illustrates how they differ from Java's primitive types. In this section, the term *object* refers to a value or instance of any reference type, including arrays.

## Reference Versus Primitive Types

Reference types and objects differ substantially from primitive types and their primitive values:

*Eight primitive types are defined by the Java language, and the programmer cannot define new primitive types.*

Reference types are user-defined, so there is an unlimited number of them. For example, a program might define a class named `Account` and use objects of this newly defined type to store and track user bank accounts.

*Primitive types represent single values.*
: Reference types are aggregate types that hold zero or more primitive values or objects. Our hypothetical `Account` class, for example, might hold a numeric value for the balance, along with identifiers for the account owner. The `char[]` and `Account[]` array types are aggregate types because they hold a sequence of primitive `char` values or `Account` objects.

*Primitive types require between one and eight bytes of memory.*
: When a primitive value is stored in a variable or passed to a method, the computer makes a copy of the bytes that hold the value. Objects, on the other hand, may require substantially more memory. Memory to store an object is dynamically allocated on the heap when the object is created, and this memory is automatically "garbage collected" when the object is no longer needed.

> When an object is assigned to a variable or passed to a method, the memory that represents the object is not copied. Instead, only a reference to that memory is stored in the variable or passed to the method.

References are completely opaque in Java and the representation of a reference is an implementation detail of the Java runtime. If you are a C programmer, however, you can safely imagine a reference as a pointer or a memory address. Remember, though, that Java programs cannot manipulate references in any way.

Unlike pointers in C and C++, references cannot be converted to or from integers, and they cannot be incremented or decremented. C and C++ programmers should also note that Java does not support the `&` address-of operator or the `*` and `->` dereference operators.

## Manipulating Objects and Reference Copies

The following code manipulates a primitive `int` value:

```
int x = 42;
int y = x;
```

After these lines execute, the variable `y` contains a copy of the value held in the variable `x`. Inside the Java VM, there are two independent copies of the 32-bit integer 42.

Now think about what happens if we run the same basic code but use a reference type instead of a primitive type:

```
Account a = new Account("Jason", 0.0, 42);
Account b = a;
```

After this code runs, the variable `b` holds a copy of the reference held in the variable `a`. There is still only one copy of the `Account` object in the VM, but there are now two copies of the reference to that object. This has some important implications. Suppose the two previous lines of code are followed by this code:

```
System.out.println(a.balance);  // Print out balance of a: 0.0
b.balance = 13.0;               // Now change balance of b
System.out.println(a.balance);  // Print a's balance again: 13.0
```

Because the variables `a` and `b` hold references to the same object, either variable can be used to make changes to the object, and those changes are visible through the other variable as well. As arrays are a kind of object, the same thing happens with arrays, as illustrated by the following code:

```
// greet holds an array reference
char[] greet = { 'h','e','l','l','o' };
char[] cuss = greet;             // cuss holds the same reference
cuss[4] = '!';                   // Use reference to change an element
System.out.println(greet);       // Prints "hell!"
```

A similar difference in behavior between primitive types and reference types occurs when arguments are passed to methods. Consider the following method:

```
void changePrimitive(int x) {
    while(x > 0) {
        System.out.println(x--);
    }
}
```

When this method is invoked, the method is given a copy of the argument used to invoke the method in the parameter `x`. The code in the method uses `x` as a loop counter and decrements it to zero. Because `x` is a primitive type, the method has its own private copy of this value, so this is a perfectly reasonable thing to do.

On the other hand, consider what happens if we modify the method so that the parameter is a reference type:

```
void changeReference(Account b) {
    while (b.balance > 0) {
        System.out.println(b.balance--);
    }
}
```

When this method is invoked, it is passed a private copy of a reference to a `Account` object and can use this reference to change the `Account` object. For example, consider:

```
Account a = new Account("Jason", 3.0, 42);  // Account balance: 3.0
changeReference(a);             // Prints 3,2,1 and modifies the Account
System.out.println(a.balance);  // The balance of a is now 0!
```

When the `changeReference()` method is invoked, it is passed a copy of the reference held in variable `a`. Now both the variable `a` and the method parameter `b` hold references to the same object. The method can use its reference to change the contents of the object. Note, however, that it cannot change the contents of the variable a. In other words, the method can change the Account object beyond recognition, but it cannot change the fact that the variable a refers to that object.

## Comparing Objects

We've seen that primitive types and reference types differ significantly in the way they are assigned to variables, passed to methods, and copied. The types also differ in the way they are compared for equality. When used with primitive values, the equality operator (==) simply tests whether two values are identical (i.e., whether they have exactly the same bits). With reference types, however, == compares references, not actual objects. In other words, == tests whether two references refer to the same object; it does not test whether two objects have the same content. Here's an example:

```
String letter = "o";
String s = "hello";              // These two String objects
String t = "hell" + letter;      // contain exactly the same text.
if (s == t) System.out.println("equal"); // But they are not equal!

byte[] a = { 1, 2, 3 };
// A copy with identical content.
byte[] b = (byte[]) a.clone();
if (a == b) System.out.println("equal"); // But they are not equal!
```

When working with reference types, keep in mind there are two kinds of equality: equality of reference and equality of object. It is important to distinguish between these two kinds of equality. One way to do this is to use the word "identical" when talking about equality of references and the word "equal" when talking about two distinct objects that have the same content. To test two nonidentical objects for equality, pass one of them to the equals() method of the other:

```
String letter = "o";
String s = "hello";              // These two String objects
String t = "hell" + letter;      // contain exactly the same text.
if (s.equals(t)) {               // And the equals() method
    System.out.println("equal"); // tells us so.
}
```

All objects inherit an equals() method (from Object), but the default implementation simply uses == to test for identity of references, not equality of content. A class that wants to allow objects to be compared for equality can define its own version of the equals() method. Our Account class does not do this, but the String class does, as indicated in the code example. You can call the equals() method on an array, but it is the same as using the == operator, because arrays always inherit the default equals() method that compares references rather than array content. You can compare arrays for equality with the java.util.Arrays.equals() convenience method.

## Boxing and Unboxing Conversions

Primitive types and reference types behave quite differently. It is sometimes useful to treat primitive values as objects, and for this reason, the Java platform includes *wrapper classes* for each of the primitive types. `Boolean`, `Byte`, `Short`, `Character`, `Integer`, `Long`, `Float`, and `Double` are immutable, final classes whose instances each hold a single primitive value. These wrapper classes are usually used when you want to store primitive values in collections such as `java.util.List`:

```
// Create a List-of-Integer collection
List<Integer> numbers = new ArrayList<>();
// Store a wrapped primitive
numbers.add(Integer.valueOf(-1));
// Extract the primitive value
int i = numbers.get(0).intValue();
```

Java allows types of conversions known as boxing and unboxing conversions. Boxing conversions convert a primitive value to its corresponding wrapper object and unboxing conversions do the opposite. You may explicitly specify a boxing or unboxing conversion with a cast, but this is unnecessary, as these conversions are automatically performed when you assign a value to a variable or pass a value to a method. Furthermore, unboxing conversions are also automatic if you use a wrapper object when a Java operator or statement expects a primitive value. Because Java performs boxing and unboxing automatically, this language feature is often known as *autoboxing*.

Here are some examples of automatic boxing and unboxing conversions:

```
Integer i = 0;    // int literal 0 boxed to an Integer object
Number n = 0.0f; // float literal boxed to Float and widened to Number
Integer i = 1;    // this is a boxing conversion
int j = i;        // i is unboxed here
i++;              // i is unboxed, incremented, and then boxed up again
Integer k = i+2; // i is unboxed and the sum is boxed up again
i = null;
j = i;            // unboxing here throws a NullPointerException
```

Autoboxing makes dealing with collections much easier as well. Let's look at an example that uses Java's *generics* (a language feature we'll meet properly in "Java Generics" on page 162) that allows us to restrict what types can be put into lists and other collections:

```
List<Integer> numbers = new ArrayList<>(); // Create a List of Integer
numbers.add(-1);                           // Box int to Integer
int i = numbers.get(0);                    // Unbox Integer to int
```

# Packages and the Java Namespace

A *package* is a named collection of classes, interfaces, and other reference types. Packages serve to group related classes and define a namespace for the classes they contain.

The core classes of the Java platform are in packages whose names begin with `java`. For example, the most fundamental classes of the language are in the package `java.lang`. Various utility classes are in `java.util`. Classes for input and output are in `java.io`, and classes for networking are in `java.net`. Some of these packages contain subpackages, such as `java.lang.reflect` and `java.util.regex`. Extensions to the Java platform that have been standardized by Oracle (or originally Sun) typically have package names that begin with `javax`. Some of these extensions, such as `javax.swing` and its myriad subpackages, were later adopted into the core platform itself. Finally, the Java platform also includes several "endorsed standards," which have packages named after the standards body that created them, such as `org.w3c` and `org.omg`.



Every class has both a simple name, which is the name given to it in its definition, and a fully qualified name, which includes the name of the package of which it is a part. The `String` class, for example, is part of the `java.lang` package, so its fully qualified name is `java.lang.String`.

This section explains how to place your own classes and interfaces into a package and how to choose a package name that won't conflict with anyone else's package name. Next, it explains how to selectively import type names or static members into the namespace so that you don't have to type the package name of every class or interface you use.

## Package Declaration

To specify the package a class belongs to, you use a `package` declaration. The `package` keyword, if it appears, must be the first token of Java code (i.e., the first thing other than comments and space) in the Java file. The keyword should be followed by the name of the desired package and a semicolon. Consider a Java file that begins with this directive:

```
package org.apache.commons.net;
```

All classes defined by this file are part of the package `org.apache.commons.net`.

If no `package` directive appears in a Java file, all classes defined in that file are part of an unnamed default package. In this case, the qualified and unqualified names of a class are the same.

> The possibility of naming conflicts means that you should not use the default package. As your project grows more complicated, conflicts become almost inevitable—much better to create packages right from the start.

## Globally Unique Package Names

One of the important functions of packages is to partition the Java namespace and prevent name collisions between classes. It is only their package names that keep the `java.util.List` and `java.awt.List` classes distinct, for example. For this to work, however, package names must themselves be distinct. As the developer of Java, Oracle controls all package names that begin with `java`, `javax`, and `sun`.

One common scheme is to use your domain name, with its elements reversed, as the prefix for all your package names. For example, the Apache Project produces a networking library as part of the Apache Commons project. The Commons project can be found at *http://commons.apache.org* and accordingly, the package name used for the networking library is `org.apache.commons.net`.

Note that these package-naming rules apply primarily to API developers. If other programmers will be using classes that you develop along with unknown other classes, it is important that your package name be globally unique. On the other hand, if you are developing a Java application and will not be releasing any of the classes for reuse by others, you know the complete set of classes that your application will be deployed with and do not have to worry about unforeseen naming conflicts. In this case, you can choose a package-naming scheme for your own convenience rather than for global uniqueness. One common approach is to use the application name as the main package name (it may have subpackages beneath it).

## Importing Types

When referring to a class or interface in your Java code, you must, by default, use the fully qualified name of the type, including the package name. If you're writing code to manipulate a file and need to use the `File` class of the `java.io` package, you must type `java.io.File`. This rule has three exceptions:

- Types from the package `java.lang` are so important and so commonly used that they can always be referred to by their simple names.
- The code in a type `p.T` may refer to other types defined in the package `p` by their simple names.
- Types that have been *imported* into the namespace with an `import` declaration may be referred to by their simple names.

The first two exceptions are known as "automatic imports." The types from `java.lang` and the current package are "imported" into the namespace so that they can be used without their package name. Typing the package name of commonly used types that are not in `java.lang` or the current package quickly becomes tedious, and so it is also possible to explicitly import types from other packages into the namespace. This is done with the `import` declaration.

`import` declarations must appear at the start of a Java file, immediately after the `package` declaration, if there is one, and before any type definitions. You may use any number of `import` declarations in a file. An `import` declaration applies to all type definitions in the file (but not to any `import` declarations that follow it).

The `import` declaration has two forms. To import a single type into the namespace, follow the `import` keyword with the name of the type and a semicolon:

```
import java.io.File;    // Now we can type File instead of java.io.File
```

This is known as the "single type `import`" declaration.

The other form of `import` declaration is the "on-demand type `import`." In this form, you specify the name of a package followed by the characters `.*` to indicate that any type from that package may be used without its package name. Thus, if you want to use several other classes from the `java.io` package in addition to the `File` class, you can simply import the entire package:

```
import java.io.*;   // Use simple names for all classes in java.io
```

This on-demand `import` syntax does not apply to subpackages. If I import the `java.util` package, I must still refer to the `java.util.zip.ZipInputStream` class by its fully qualified name or import it.

Using an on-demand type `import` declaration is not the same as explicitly writing out a single type `import` declaration for every type in the package. It is more like an explicit single type `import` for every type in the package *that you actually use* in your code. This is the reason it's called "on demand"; types are imported as you use them.

### Naming conflicts and shadowing

`import` declarations are invaluable to Java programming. They do expose us to the possibility of naming conflicts, however. Consider the packages `java.util` and `java.awt`. Both contain types named `List`.

`java.util.List` is an important and commonly used interface. The `java.awt` package contains a number of important types that are commonly used in client-side applications, but `java.awt.List` has been superseded and is not one of these important types. It is illegal to import both `java.util.List` and `java.awt.List` in the same Java file. The following single type `import` declarations produce a compilation error:

```
import java.util.List;
import java.awt.List;
```

Using on-demand type imports for the two packages is legal:

```
import java.util.*;  // For collections and other utilities.
import java.awt.*;   // For fonts, colors, and graphics.
```

Difficulty arises, however, if you actually try to use the type `List`. This type can be imported "on demand" from either package, and any attempt to use `List` as an unqualified type name produces a compilation error. The workaround, in this case, is to explicitly specify the package name you want.

Because java.util.List is much more commonly used than java.awt.List, it is useful to combine the two on-demand type import declarations with a single type import declaration that serves to disambiguate what we mean when we say List:

```
import java.util.*;    // For collections and other utilities.
import java.awt.*;     // For fonts, colors, and graphics.
import java.util.List; // To disambiguate from java.awt.List
```

With these import declarations in place, we can use List to mean the java.util.List interface. If we actually need to use the java.awt.List class, we can still do so as long as we include its package name. There are no other naming conflicts between java.util and java.awt, and their types will be imported "on demand" when we use them without a package name.

## Importing Static Members

As well as types, you can import the static members of types using the keywords import static. (Static members are explained in Chapter 3. If you are not already familiar with them, you may want to come back to this section later.) Like type import declarations, these static import declarations come in two forms: single static member import and on-demand static member import. Suppose, for example, that you are writing a text-based program that sends a lot of output to System.out. In this case, you might use this single static member import to save yourself typing:

```
import static java.lang.System.out;
```

You can then use out.println() instead of System.out.println(). Or suppose you are writing a program that uses many of the trigonometric and other functions of the Math class. In a program that is clearly focused on numerical methods like this, having to repeatedly type the class name "Math" does not add clarity to your code; it just gets in the way. In this case, an on-demand static member import may be appropriate:

```
import static java.lang.Math.*
```

With this import declaration, you are free to write concise expressions like sqrt(abs(sin(x))) without having to prefix the name of each static method with the class name Math.

Another important use of import static declarations is to import the names of constants into your code. This works particularly well with enumerated types (see Chapter 4). Suppose, for example, that you want to use the values of this enumerated type in code you are writing:

```
package climate.temperate;
enum Seasons { WINTER, SPRING, SUMMER, AUTUMN };
```

You could import the type climate.temperate.Seasons and then prefix the constants with the type name: Seasons.SPRING. For more concise code, you could import the enumerated values themselves:

```
import static climate.temperate.Seasons.*;
```

Using static member `import` declarations for constants is generally a better technique than implementing an interface that defines the constants.

### Static member imports and overloaded methods

A static `import` declaration imports a *name*, not any one specific member with that name. Because Java allows method overloading and allows a type to have fields and methods with the same name, a single static member `import` declaration may actually import more than one member. Consider this code:

```
import static java.util.Arrays.sort;
```

This declaration imports the name "sort" into the namespace, not any one of the 19 `sort()` methods defined by `java.util.Arrays`. If you use the imported name `sort` to invoke a method, the compiler will look at the types of the method arguments to determine which method you mean.

It is even legal to import static methods with the same name from two or more different types as long as the methods all have different signatures. Here is one natural example:

```
import static java.util.Arrays.sort;
import static java.util.Collections.sort;
```

You might expect that this code would cause a syntax error. In fact, it does not because the `sort()` methods defined by the `Collections` class have different signatures than all of the `sort()` methods defined by the `Arrays` class. When you use the name "sort" in your code, the compiler looks at the types of the arguments to determine which of the 21 possible imported methods you mean.

## Java Source File Structure

This chapter has taken us from the smallest to the largest elements of Java syntax, from individual characters and tokens to operators, expressions, statements, and methods, and on up to classes and packages. From a practical standpoint, the unit of Java program structure you will be dealing with most often is the Java file. A Java file is the smallest unit of Java code that can be compiled by the Java compiler. A Java file consists of:

- An optional `package` directive
- Zero or more `import` or `import static` directives
- One or more type definitions

These elements can be interspersed with comments, of course, but they must appear in this order. This is all there is to a Java file. All Java statements (except the `package` and `import` directives, which are not true statements, and the specialized module descriptors we'll discuss in Chapter 12) must appear within methods, and all methods must appear within a type definition.

A special Java file named `module-info.java` is used only in declaring the structure and visibility of our packages in a modular Java application. These more advanced techniques and syntax are covered in detail in Chapter 12.

Java files have a couple of other important restrictions. First, each file can contain at most one top-level class that is declared `public`. A `public` class is one that is designed for use by other classes in other packages. A class can contain any number of nested or inner classes that are `public`. We'll see more about the `public` modifier and nested classes in Chapter 3.

The second restriction concerns the filename of a Java file. If a Java file contains a `public` class, the name of the file must be the same as the name of the class, with the extension *.java* appended. Therefore, if `Account` is defined as a `public` class, its source code must appear in a file named *Account.java*. Regardless of whether your classes are `public` or not, it is good programming practice to define only one per file and to give the file the same name as the class.

When a Java file is compiled, each of the classes it defines is compiled into a separate *class* file that contains Java bytecodes to be executed by the Java Virtual Machine. A class file has the same name as the class it defines, with the extension *.class* appended. Thus, if the file *Account.java* defines a class named `Account`, a Java compiler compiles it to a file named *Account.class*. On most systems, class files are stored in directories that correspond to their package names. For example, the class `com.davidflanagan.examples.Account` is defined by the class file *com/davidflanagan/examples/Account.class*.

The Java runtime knows where the class files for the standard system classes are located and can load them as needed. When the interpreter runs a program that wants to use a class named `com.davidflanagan.examples.Account`, it knows that the code for that class is located in a directory named *com/davidflanagan/examples/* and, by default, it "looks" in the current directory for a subdirectory of that name. In order to tell the interpreter to look in locations other than the current directory, you must use the `-classpath` option when invoking the interpreter or set the `CLASSPATH` environment variable. For details, see the documentation for the Java executable, *java*, in Chapter 13.

## Defining and Running Java Programs

A Java program consists of a set of interacting class definitions. But not every Java class or Java file defines a program. To create a program, you must define a class that has a special method with the following signature:

```
public static void main(String[] args)
```

This `main()` method is the main entry point for your program. It is where the Java interpreter starts running. This method is passed an array of strings and returns no value. When `main()` returns, the Java interpreter exits (unless `main()` has created separate threads, in which case the interpreter waits for all those threads to exit).

To run a Java program, you run the Java executable, *java*, specifying the fully qualified name of the class that contains the `main()` method. Note that you specify the name of the class, *not* the name of the class file that contains the class. Any additional arguments you specify on the command line are passed to the `main()` method as its `String[]` parameter. You may also need to specify the `-classpath` option (or `-cp`) to tell the interpreter where to look for the classes needed by the program. Consider the following command:

```
java -classpath /opt/Jude com.davidflanagan.jude.Jude datafile.jude
```

`java` is the command to run the Java interpreter. `-classpath /opt/Jude` tells the interpreter where to look for *.class* files. `com.davidflanagan.jude.Jude` is the name of the program to run (i.e., the name of the class that defines the `main()` method). Finally, `datafile.jude` is a string that is passed to that `main()` method as the single element of an array of `String` objects.

There is an easier way to run programs. If a program and all its auxiliary classes (except those that are part of the Java platform) have been properly bundled in a Java archive (JAR) file, you can run the program simply by specifying the name of the JAR file. In the next example, we show how to start up a log analyzer:

```
java -jar /usr/local/log-analyzer/log-analyzer.jar
```

Some operating systems make JAR files automatically executable. On those systems, you can simply say:

```
/usr/local/log-analyzer/log-analyzer.jar
```

Java 17 also introduced the ability to run `java` against a source file directly, similar to what's available in scripting languages such as Python. You still must define a class matching the name of the file and a `main()` method, but then you can execute the program with:

```
java MyClass.java
```

See Chapter 13 for more details on how to execute Java programs.

# Summary

In this chapter, we've introduced the basic syntax of the Java language. Due to the interlocking nature of the syntax of programming languages, it is perfectly fine if you don't feel at this point that you have completely grasped all of the syntax of the language. It is by practice that we acquire proficiency in any language, human or computer.

It is also worth observing that some parts of syntax are far more regularly used than others. For example, the `strictfp` and `assert` keywords are almost never used. Rather than trying to grasp every aspect of Java's syntax, it is far better to begin to acquire facility in the core aspects of Java and then return to any details of syntax that may still be troubling you. With this in mind, let's move to the next chapter and begin to discuss the classes and objects that are so central to Java and the basics of Java's approach to object-oriented programming.

# 3
# Object-Oriented Programming in Java

Now that we've covered fundamental Java syntax, we are ready to begin object-oriented programming in Java. All Java programs use objects, and the type of an object is defined by its *class* or *interface*. Every Java program is defined as a class, and nontrivial programs include a number of classes and interface definitions.

This chapter explains how to define new classes (and records) and how to do object-oriented programming with them. We also introduce the concept of an interface, but a full discussion of interfaces and Java's type system is deferred until Chapter 4.

> If you have experience with OO programming, however, be careful. The term "object-oriented" has different meanings in different languages. Don't assume that Java works the same way as your favorite OO language. (This is particularly true for JavaScript or Python programmers.)

This is a fairly lengthy chapter, so let's begin with an overview and some definitions.

## Overview of Classes and Records

Classes are the most fundamental structural element of all Java programs. You cannot write Java code without defining a class. All Java statements appear within classes, and all methods are implemented within classes.

## Basic OO Definitions

Here are some important definitions:

*Class*

A *class* is a collection of data fields that hold values, along with methods that operate on those values. A class defines a new reference type, such as the `Account` type defined in Chapter 2.

The `Account` class defines a type that represents customer accounts within a banking system.

From Java 17 onwards, the language also includes support for records—which are a special kind of class that have additional semantics.

*Object*

An *object* is an *instance* of a class.

An `Account` object is a value of that type: it represents a specific customer bank account.

Objects are often created by *instantiating* a class with the `new` keyword and a constructor invocation, as shown here:

```
Account a = new Account("John Smith", 100, 1144789);
```

Constructors are covered in detail later in this chapter in "Creating and Initializing Objects" on page 117.

A class definition consists of a *signature* and a *body*. The class signature defines the name of the class and may also specify other important information. The body of a class is a set of *members* enclosed in curly braces. The members of a class usually include fields and methods, and may also include constructors, initializers, and nested types.

Members can be *static* or nonstatic. A static member belongs to the class itself, while a nonstatic member is associated with the instances of a class (see "Fields and Methods" on page 111).

> There are four very common kinds of members—class fields, class methods, instance fields, and instance methods. The majority of work done with Java involves interacting with these kinds of members.

The signature of a class may declare that the class *extends* another class. The extended class is known as the *superclass* and the extension is known as the *subclass*. A subclass *inherits* the members of its superclass and may declare new members or *override* inherited methods with new implementations.

The members of a class may have *access modifiers* `public`, `protected`, or `private`.[1] These modifiers specify their visibility and accessibility to clients and to subclasses. This allows classes to control access to members that are not part of their public API. This ability to hide members enables an object-oriented design technique known as *data encapsulation*, which we discuss in "Data Hiding and Encapsulation" on page 135.

## Records

A *record* (or *record class*) is a special form of class that provides additional semantic guarantees that general classes do not.

Specifically, a record guarantees that the instance fields precisely define the only meaningful state of an object of that type. This can be expressed as the principle (or *pattern*) that the record class is a *data carrier* or "just holds fields." Agreeing to this principle imposes constraints on programmers, but it also frees them from needing to be explicit about some design details.



A record class is defined like this:

```
/** Represents a point in 2-dimensional space */
public record Point(double x, double y) {}
```

There is no need to explicitly declare a constructor, or accessor methods for the fields—for a record class the compiler automatically generates these members and adds them to the class definition. The accessor methods are named exactly the same as the underlying fields they provide access to. It is possible to add additional methods to a record, but it is not necessary to do so if all that is needed is the basic data carrier form.

Instances of record classes (or just records) are created and instantiated in the same way as for regular classes, and we can call the accessors on the objects we create:

```
// Create a Point object representing (2,-3.5).
// Declare a variable p and store a reference to the new Point object
Point p = new Point(2.0, -3.5);
double x = p.x();                    // Read a field of the object
```

One other aspect of records is that they are always immutable. Once created, the value of a record's fields cannot be altered. This means that there is no need for setter methods for the fields, as they cannot be modified.

The contract that Java records have is that the parameter name (as specified in the record declaration), the field name, and the method name are all identical: if there's a record parameter `x` of type `double` then the class has a field called `x` of type `double` and an instance method called `x()` that returns `double`.

1 There is also the default, aka package, visibility that we will meet later.

Records have certain other methods that are also automatically generated by the compiler. We will have more to say about them in Chapter 5 when we discuss how to use records as part of object-oriented design.

## Other Reference Types

The signature of a class may also declare that the class *implements* one or more interfaces. An *interface* is a reference type similar to a class that defines method signatures but does not usually include method bodies to implement the methods.

However, from Java 8 onward, interfaces may use the keyword `default` to indicate that a method specified in the interface is optional. If a method is optional, the interface file must include a default implementation (hence the choice of keyword), which will be used by all implementing classes that do not provide an implementation of the optional method.

A class that implements an interface is required to provide bodies for the interface's nondefault methods. Instances of a class that implement an interface are also instances of the interface type.

Classes and interfaces are the most important of the five fundamental reference types defined by Java. Arrays, enumerated types (or "enums"), and annotation types (usually just called "annotations") are the other three. Arrays are covered in Chapter 2. Enums are a specialized kind of class, and annotations are a specialized kind of interface—both are discussed later in Chapter 4, along with a full discussion of interfaces.

## Class Definition Syntax

At its simplest level, a class definition consists of the keyword `class` followed by the name of the class and a set of class members within curly braces. The `class` keyword may be preceded by modifier keywords and annotations. If the class extends another class, the class name is followed by the `extends` keyword and the name of the class being extended. If the class implements one or more interfaces, then the class name or the `extends` clause is followed by the `implements` keyword and a comma-separated list of interface names. For example, for the `Integer` class in `java.lang`

```
public class Integer extends Number
                     implements Serializable, Comparable {
    // class members go here
}
```

Java also includes the ability to declare *generic classes* that allow an entire family of types to be created from a single class declaration. We will meet this feature, along with its supporting mechanisms (such as *type parameters* and *wildcards*), in Chapter 4.

Class declarations may include modifier keywords. In addition to the access control modifiers (`public`, `protected`, etc.), these include:

`abstract`
: An `abstract` class is one whose implementation is incomplete and cannot be instantiated. Any class with one or more `abstract` methods must be declared `abstract`. Abstract classes are discussed in "Abstract Classes and Methods" on page 143.

`final`
: The `final` modifier specifies that the class may not be extended. A class cannot be declared to be both `abstract` and `final`.

`sealed`
: Sealed classes are those that may be extended only by a known set of subclasses. Sealed classes provide a halfway house between `final` classes and the default, open for extension classes. The use of sealed classes is discussed in more detail in Chapter 5. Sealed classes are available only in Java 17 and above.

`strictfp`
: A class can be declared `strictfp`; all its methods behave as if they were declared `strictfp`, and thus exactly follow the formal semantics of the floating-point standard. This modifier is *extremely* rarely used, and is in fact a no-op in Java 17, for the reasons discussed in Chapter 2.



## Fields and Methods

A class can be viewed as a collection of data (also referred to as *state*) and code to operate on that state. The data is stored in fields, and the code is organized into methods.

This section covers fields and methods, the two most important kinds of class members. Fields and methods come in two distinct types: class members (also known as static members) are associated with the class itself, while instance members are associated with individual instances of the class (i.e., with objects). This gives us four kinds of members:

- Class fields
- Class methods
- Instance fields
- Instance methods

The simple class definition for the class `Circle`, shown in Example 3-1, contains all four types of members.

*Example 3-1. A simple class and its members*

```
public class Circle {
  // A class field
  public static final double PI= 3.14159;     // A useful constant

  // A class method: just compute a value based on the arguments
  public static double radiansToDegrees(double radians) {
    return radians * 180 / PI;
  }

  // An instance field
  public double r;                  // The radius of the circle

  // Two instance methods: operate on an object's instance fields

  // Compute the area of the circle
  public double area() {
    return PI * r * r;
  }

  // Compute the circumference of the circle
  public double circumference() {
    return 2 * PI * r;
  }
}
```

> It is not good practice to have a public instance field such as `r` in our example. It would be much better to have a private field `r` and a method `radius()` (or `r()`) to provide access to it. The reason for this will be explained later, in "Data Hiding and Encapsulation" on page 135. For now, we use a public field simply to give examples of how to work with instance fields.

The following sections explain all four common kinds of members. First, we cover the declaration syntax for fields. (The syntax for declaring methods is covered later in this chapter in "Data Hiding and Encapsulation" on page 135.)

## Field Declaration Syntax

Field declaration syntax is much like the syntax for declaring local variables (see Chapter 2) except that field definitions may also include modifiers. The simplest field declaration consists of the field type followed by the field name.

The type may be preceded by zero or more modifier keywords or annotations, and the name may be followed by an equals sign and initializer expression that provides the initial value of the field. If two or more fields share the same type and modifiers, the type may be followed by a comma-separated list of field names and initializers. Here are some valid field declarations:

```
int x = 1;
private String name;
public static final int DAYS_PER_WEEK = 7;
String[] daynames = new String[DAYS_PER_WEEK];
private int a = 17, b = 37, c = 53;
```

Field modifier keywords comprise zero or more of the following keywords:

`public`, `protected`, `private`
: These access modifiers specify whether and where a field can be used outside of the class that defines it.

`static`
: If present, this modifier specifies that the field is associated with the defining class itself rather than with each instance of the class.

`final`
: This modifier specifies that once the field has been initialized, its value may never be changed. Fields that are both `static` and `final` are compile-time constants that `javac` may inline. `final` fields can also be used to create classes whose instances are immutable.

`transient`
: This modifier specifies that a field is not part of the persistent state of an object and that it need not be serialized along with the rest of the object. This modifier is very rarely seen.

`volatile`
: This modifier indicates that the field has extra semantics for concurrent use by two or more threads. The `volatile` modifier says that the value of a field must always be read from and flushed to main memory, and that it may not be cached by a thread (in a register or CPU cache). See Chapter 6 for more details.



## Class Fields

A *class field* is associated with the class in which it is defined rather than with an instance of the class. The following line declares a class field:

```
public static final double PI = 3.14159;
```

This line declares a field of type `double` named `PI` and assigns it a value of `3.14159`.

The `static` modifier says that the field is a class field. Class fields are sometimes called static fields because of this `static` modifier. The `final` modifier says that the value of the field cannot be reassigned directly. Because the field `PI` represents a constant, we declare it `final` so that it cannot be changed.

It is a convention in Java (and many other languages) that constants are named with capital letters, which is why our field is named `PI`, not `pi`. Defining constants like this is a common use for class fields, meaning that the `static` and `final` modifiers are often used together. Not all class fields are constants, however. In other words, a field can be declared `static` without being declared `final`.

> The use of public fields that are not `final` is a code smell—as multiple threads could update the field and cause behavior that is extremely hard to debug. Beginning Java programmers should not use public fields that are not final.

A public static field is essentially a global variable. The names of class fields are qualified by the unique names of the classes that contain them, however. Thus, Java does not suffer from the name collisions that can affect other languages when different modules of code define global variables with the same name.

The key point to understand about a static field is that there is only a single copy of it. This field is associated with the class itself, not with instances of the class. If you look at the various methods of the `Circle` class, you'll see that they use this field. From inside the `Circle` class, the field can be referred to simply as `PI`. Outside the class, however, both class and field names are required to uniquely specify the field. Methods that are not part of `Circle` access this field as `Circle.PI`.

## Class Methods

As with class fields, *class methods* are declared with the `static` modifier. They are also known as *static methods*:

```
public static double radiansToDegrees(double rads) {
  return rads * 180 / PI;
}
```

This line declares a class method named `radiansToDegrees()`. It has a single parameter of type `double` and returns a `double` value.

Like class fields, class methods are associated with a class, rather than with an object. When invoking a class method from code that exists outside the class, you must specify both the name of the class and the method. For example:

```
// How many degrees is 2.0 radians?
double d = Circle.radiansToDegrees(2.0);
```

If you want to invoke a class method from inside the class in which it is defined, you don't have to specify the class name. You can also shorten the amount of typing required via the use of a static import (as discussed in Chapter 2).

Note that the body of our `Circle.radiansToDegrees()` method uses the class field `PI`. A class method can use any class fields and class methods of its own class (or of any other class that is visible to it).

A class method cannot use any instance fields or instance methods because class methods are not associated with an instance of the class. In other words, although the `radiansToDegrees()` method is defined in the `Circle` class, it cannot use the instance part of any `Circle` objects.

> One way to think about this is that in any instance, we always have a reference—`this`—to the current object. The `this` reference is passed as an implicit parameter to any instance method. However, class methods are not associated with a specific instance, so they have no `this` reference and no access to instance fields.



As we discussed earlier, a class field is essentially a global variable. In a similar way, a class method is a global method, or global function. Although `radiansToDegrees()` does not operate on `Circle` objects, it is defined within the `Circle` class because it is a utility method that is sometimes useful when you're working with circles, and so it makes sense to package it along with the other functionality of the `Circle` class.

## Instance Fields

Any field declared without the `static` modifier is an *instance field*:

```
public double r;    // The radius of the circle
```

Instance fields are associated with instances of the class, so every `Circle` object we create has its own copy of the `double` field `r`. In our example, `r` represents the radius of a specific circle. Each `Circle` object can have a radius independent of all other `Circle` objects.

Inside a class definition, instance fields are referred to by name alone. You can see an example of this if you look at the method body of the `circumference()` instance method. In code outside the class, the name of an instance method must be prefixed with a reference to the object that contains it. For example, if the variable `c` holds a reference to a `Circle` object, we use the expression `c.r` to refer to the radius of that circle:

```
Circle c = new Circle(); // Create a Circle object; store a ref in c
c.r = 2.0;               // Assign a value to its instance field r
Circle d = new Circle(); // Create a different Circle object
d.r = c.r * 2;           // Make this one twice as big
```

Instance fields are key to object-oriented programming. Instance fields hold the state of an object; the values of those fields make one object distinct from another.

## Instance Methods

An *instance method* operates on a specific instance of a class (an object), and any method not declared with the `static` keyword is automatically an instance method.

Instance methods are the feature that makes object-oriented programming start to get interesting. The `Circle` class defined in Example 3-1 contains two instance methods, `area()` and `circumference()`, that compute and return the area and circumference of the circle represented by a given `Circle` object.

To use an instance method from outside the class in which it is defined, we must prefix it with a reference to the instance that is to be operated on. For example:

```
// Create a Circle object; store in variable c
Circle c = new Circle();
c.r = 2.0;                     // Set an instance field of the object
double a = c.area();           // Invoke an instance method of the object
```

This is why it is called object-oriented programming; the object is the focus here, not the method call.

From within an instance method, we naturally have access to all the instance fields that belong to the object the method was called on. Recall that an object is often best considered to be a bundle containing state (represented as the fields of the object), and behavior (the methods to act on that state).

All instance methods are implemented by using an implicit parameter not shown in the method signature. The implicit argument is named `this`; it holds a reference to the object through which the method is invoked. In our example, that object is a `Circle`.

The bodies of the `area()` and `circumference()` methods both use the class field `PI`. We saw earlier that class methods can use only class fields and class methods, not instance fields or methods. Instance methods are not restricted in this way: they can use any member of a class, whether it is declared `static` or not.

## How the this Reference Works

The implicit `this` parameter is not shown in method signatures because it is usually not needed; whenever a Java method accesses the instance fields in its class, it is implicit that it is accessing fields in the object referred to by the `this` parameter. The same is true when an instance method invokes another instance method in the same class—it's taken that this means "call the instance method on the current object."

However, you can use the `this` keyword explicitly when you want to make it clear that a method is accessing its own fields and/or methods. For example, we can rewrite the `area()` method to use `this` explicitly to refer to instance fields:

```
public double area() { return Circle.PI * this.r * this.r; }
```

This code also uses the class name explicitly to refer to class field `PI`. In a method this simple, it is not normally necessary to be quite so explicit. In more complicated cases, however, you may sometimes find that it increases the clarity of your code to use an explicit `this` even when it is not strictly required.

In some cases, the `this` keyword *is* required, however. For example, when a method parameter or local variable in a method has the same name as one of the fields of the class, you must use `this` to refer to the field. This is because the field name used alone refers to the method parameter or local variable, as discussed in "Lexical Scoping and Local Variables" on page 185.

For example, we can add the following method to the `Circle` class:

```
public void setRadius(double r) {
  this.r = r;      // Assign the argument (r) to the field (this.r)
                   // Note that writing r = r is a bug
}
```

Some developers will deliberately choose the names of their method arguments in such a way that they don't clash with field names, so the use of `this` can largely be avoided. However, accessor methods (setter) generated by any of the major Java IDEs will use the `this.x = x` style shown here.

Finally, note that while instance methods can use the `this` keyword, class methods cannot because class methods are not associated with individual objects.

## Creating and Initializing Objects

Now that we've covered fields and methods, let's move on to other important members of a class. In particular, we'll look at constructors—these are class members whose job is to initialize the fields of a class as new instances of the class are created.

Take another look at how we've been creating `Circle` objects:

```
Circle c = new Circle();
```

This can easily be read as creating a new instance of `Circle`, by calling something that looks a bit like a method. In fact, `Circle()` is an example of a *constructor*. This is a member of a class that has the same name as the class, and it has a body, like a method.

Here's how a constructor works. The `new` operator indicates that we need to create a new instance of the class. First of all, memory is allocated (in the Java heap) to hold the new object instance. Then, the constructor body is called, with any arguments that have been specified. The constructor uses these arguments to do whatever initialization of the new object is necessary.

Every class in Java has at least one *constructor*, and their purpose is to perform any necessary initialization for a new object. If the programmer does not explicitly define a constructor for a class, the `javac` compiler automatically creates a constructor (called the default constructor) that takes no arguments and performs no special initialization. The `Circle` class seen in Example 3-1 used this mechanism to automatically declare a constructor.

## Defining a Constructor

There is some obvious initialization we could do for our `Circle` objects, so let's define a constructor. Example 3-2 shows a new definition for `Circle` that contains a constructor that lets us specify the radius of a new `Circle` object. We've also taken the opportunity to make the field `r` protected (to prevent access to it from arbitary objects).

*Example 3-2. A constructor for the Circle class*

```
public class Circle {
    public static final double PI = 3.14159;  // A constant
    // An instance field that holds the radius of the circle
    protected double r;

    // The constructor: initialize the radius field
    public Circle(double r) { this.r = r; }

    // The instance methods: compute values based on the radius
    public double circumference() { return 2 * PI * r; }
    public double area() { return PI * r * r; }
    public double radius() { return r; }
}
```

When we relied on the default constructor supplied by the compiler, we had to write code like this to initialize the radius explicitly:

```
Circle c = new Circle();
c.r = 0.25;
```

With the new constructor, the initialization becomes part of the object creation step:

```
Circle c = new Circle(0.25);
```

Here are some basics regarding naming, declaring, and writing constructors:

- The constructor name is always the same as the class name.
- A constructor is declared without a return type (not even the `void` placeholder).
- The body of a constructor is the code that initializes the object. You can think of this as setting up the contents of the `this` reference.
- A constructor does not return `this` (or any other value).

## Defining Multiple Constructors

Sometimes you want to initialize an object in a number of different ways, depending on what is most convenient in a particular circumstance. For example, we might want to initialize the radius of a circle to a specified value or a reasonable default value. Here's how we can define two constructors for `Circle`:

```
public Circle() { r = 1.0; }
public Circle(double r) { this.r = r; }
```

Because our `Circle` class has only a single instance field, we can't initialize it in too many ways, of course. But in more complex classes, it is often convenient to define a variety of constructors.

It is perfectly legal to define multiple constructors for a class, as long as each constructor has a different parameter list. The compiler determines which constructor you wish to use based on the number and type of arguments you supply. This ability to define multiple constructors is analogous to method overloading.



## Invoking One Constructor from Another

A specialized use of the `this` keyword arises when a class has multiple constructors; it can be used from a constructor to invoke one of the other constructors of the same class. In other words, we can rewrite the two previous `Circle` constructors as follows:

```
// This is the basic constructor: initialize the radius
public Circle(double r) { this.r = r; }
// This constructor uses this() to invoke the constructor above
public Circle() { this(1.0); }
```

This is a useful technique when a number of constructors share a significant amount of initialization code, as it avoids repetition of that code. In more complex cases, where the constructors do a lot more initialization, this can be a very useful technique.

There is an important restriction on using `this()`: it can appear only as the first statement in a constructor, but the call may be followed by any additional initialization a particular constructor needs to perform. The reason for this restriction involves the automatic invocation of superclass constructors, which we'll explore later in this chapter.

## Field Defaults and Initializers

The fields of a class do not necessarily require initialization. If their initial values are not specified, the fields are automatically initialized to the default value `false`, `\u0000`, `0`, `0.0`, or `null`, depending on their type (see Table 2-1 for more details). These default values are specified by the Java language specification and apply to both instance fields and class fields.

> The default values are essentially the "natural" interpretation of the zero bit pattern for each type.

If the default field value is not appropriate for your field, you can instead explicitly provide a different initial value. For example:

```
public static final double PI = 3.14159;
public double r = 1.0;
```

Field declarations are not part of any method. Instead, the Java compiler generates initialization code for the field automatically and puts it into all the constructors for the class. The initialization code is inserted into a constructor in the order in which it appears in the source code, which means that a field initializer can use the initial values of any fields declared before it.

Consider the following code excerpt, which shows a constructor and two instance fields of a hypothetical class:

```
public class SampleClass {
  public int len = 10;
  public int[] table = new int[len];

  public SampleClass() {
    for(int i = 0; i < len; i = i + 1) {
        table[i] = i;
    }
  }

  // The rest of the class is omitted...
}
```

In this case, the code generated by `javac` for the constructor is actually equivalent to:

```
public SampleClass() {
  len = 10;
  table = new int[len];
  for(int i = 0; i < len; i = i + 1) {
      table[i] = i;
  }
}
```

If a constructor begins with a `this()` call to another constructor, the field initialization code does not appear in the first constructor. Instead, the initialization is handled in the constructor invoked by the `this()` call.

So, if instance fields are initialized in the constructor, where are class fields initialized? These fields are associated with the class, even if no instances of the class are ever created. Logically, this means they need to be initialized even before a constructor is called.

To support this, `javac` generates a class initialization method automatically for every class. Class fields are initialized in the body of this method, which is invoked exactly once before the class is first used (often when the class is first loaded by the Java VM).

As with instance field initialization, class field initialization expressions are inserted into the class initialization method in the order in which they appear in the source code. This means that the initialization expression for a class field can use the class fields declared before it.

The class initialization method is an internal method that is hidden from Java programmers. In the class file, it bears the name `<clinit>` (and you could see this method by, for example, examining the class file with `javap`—see Chapter 13 for more details on how to use `javap` to do this).

OO Programming

### Initializer blocks

So far, we've seen that objects can be initialized through the initialization expressions for their fields and by arbitrary code in their constructors. A class has a class initialization method (which is like a constructor), but we cannot explicitly define the body of this method in Java, although it is perfectly legal to do so in bytecode.

Java does however allow us to express class initialization with a construct known as a *static initializer*. A static initializer is simply the keyword `static` followed by a block of code in curly braces. A static initializer can appear in a class definition anywhere a field or method definition can appear. For example, consider the following code that performs some nontrivial initialization for two class fields:

```
// We can draw the outline of a circle using trigonometric functions
// Trigonometry is slow, though, so we precompute a bunch of values
public class TrigCircle {
  // Here are our static lookup tables and their own initializers
  private static final int NUMPTS = 500;
  private static double sines[] = new double[NUMPTS];
  private static double cosines[] = new double[NUMPTS];

  // Here's a static initializer that fills in the arrays
  static {
    double x = 0.0;
    double delta_x = (Circle.PI/2)/(NUMPTS - 1);
    for(int i = 0, x = 0.0; i < NUMPTS; i = i + 1, x += delta_x) {
      sines[i] = Math.sin(x);
      cosines[i] = Math.cos(x);
    }
  }
  // The rest of the class is omitted...
}
```

A class can have any number of static initializers. The body of each initializer block is incorporated into the class initialization method, along with any static field initialization expressions. A static initializer is like a class method in that it cannot use the `this` keyword or any instance fields or instance methods of the class.

## Record Constructors

Record classes, introduced as a standard feature in Java 16, implicitly define one constructor: the canonical constructor defined by the parameter list. There may be circumstances, however, when developers need to provide additional (aka auxiliary) constructors for record classes. For example, to provide default values for some of the record parameters, as in:

```
public record Point(double x, double y) {
    /** Constructor simulates default parameters */
    public Point(double x) {
        this(x, 0.0);
    }
}
```

Records also provide for another refinement to class constructors: the *compact constructor*. This is used when some sort of validation or other checking code is helpful for creating valid record objects. For example:

```
/** Represents a point in 2-dimensional space */
public record Point(double x, double y) {
    /** Compact constructor provides validation */
    public Point {
        if (Double.isNaN(x) || Double.isNaN(y)) {
            throw new IllegalArgumentException("Illegal NaN");
        }
    }
}
```

Note that in the compact constructor syntax, the parameter list does not need to be repeated (as it is inferred from the record declaration) and the parameters (in our example, `x` and `y`) are already in scope. Compact constructors, like the canonical constructor, also implicitly initialize the fields from the parameter values.

# Subclasses and Inheritance

The `Circle` defined earlier is a simple class that distinguishes circle objects only by their radii. Suppose, instead, that we want to represent circles that have both a size and a position. For example, a circle of radius 1.0 centered at point 0,0 in the Cartesian plane is different from the circle of radius 1.0 centered at point 1,2. To do this, we need a new class, which we'll call `PlaneCircle`.

We'd like to add the ability to represent the position of a circle without losing any of the existing functionality of the `Circle` class. We do this by defining `PlaneCircle` as a subclass of `Circle` so that `PlaneCircle` inherits the fields and methods of its superclass, `Circle`. The ability to add functionality to a class by subclassing, or extending, is central to the object-oriented programming paradigm.

## Extending a Class

In Example 3-3, we show how we can implement `PlaneCircle` as a subclass of the `Circle` class.

*Example 3-3. Extending the Circle class*

```
public class PlaneCircle extends Circle {
  // We automatically inherit the fields and methods of Circle,
  // so we only have to put the new stuff here.
  // New instance fields that store the center point of the circle
  private final double cx, cy;

  // A new constructor to initialize the new fields
  // It uses a special syntax to invoke the Circle() constructor
  public PlaneCircle(double r, double x, double y) {
    super(r);       // Invoke the constructor of the superclass, Circle()
    this.cx = x;    // Initialize the instance field cx
    this.cy = y;    // Initialize the instance field cy
  }

  public double getCenterX() {
    return cx;
  }

  public double getCenterY() {
    return cy;
  }

  // The area() and circumference() methods are inherited from Circle
  // A new instance method checks whether a point is inside the circle
  // Note that it uses the inherited instance field r
  public boolean isInside(double x, double y) {
    double dx = x - cx, dy = y - cy;             // Distance from center
    double distance = Math.sqrt(dx*dx + dy*dy);  // Pythagorean theorem
    return (distance < r);                       // Returns true or false
  }
}
```

Note the use of the keyword `extends` in the first line of Example 3-3. This keyword tells Java that `PlaneCircle` extends, or subclasses, `Circle`, meaning that it inherits the fields and methods of that class.

The definition of the `isInside()` method shows field inheritance; this method uses the field `r` (defined by the `Circle` class) as if it were defined right in `PlaneCircle` itself. `PlaneCircle` also inherits the methods of `Circle`. Therefore, if we have a `PlaneCircle` object referenced by variable `pc`, we can say:

```
double ratio = pc.circumference() / pc.area();
```

This works just as if the area() and circumference() methods were defined in PlaneCircle itself.

Another feature of subclassing is that every PlaneCircle object is also a perfectly legal Circle object. If pc refers to a PlaneCircle object, we can assign it to a Circle variable and forget all about its extra positioning capabilities:

```
// Unit circle at the origin
PlaneCircle pc = new PlaneCircle(1.0, 0.0, 0.0);
Circle c = pc;     // Assigned to a Circle variable without casting
```

This assignment of a PlaneCircle object to a Circle variable can be done without a cast. As we discussed in Chapter 2, a conversion like this is always legal. The value held in the Circle variable c is still a valid PlaneCircle object, but the compiler cannot know this for sure, so it doesn't allow us to do the opposite (narrowing) conversion without a cast:

```
// Narrowing conversions require a cast (and a runtime check by the VM)
PlaneCircle pc2 = (PlaneCircle) c;
boolean inside = ((PlaneCircle) c).isInside(0.0, 0.0);
```

This distinction is covered in more detail in "Nested Types" on page 187, where we talk about the distinction between the compile and runtime type of an object.

### Final classes

When a class is declared with the final modifier, it means that it cannot be extended or subclassed. java.lang.String is an example of a final class. Declaring a class final prevents unwanted extensions to the class: if you invoke a method on a String object, you know that the method is the one defined by the String class itself, even if the String is passed to you from some unknown outside source.

In general, many of the classes that Java developers create should be final. Think carefully about whether it will make sense to allow other (possibly unknown) code to extend your classes—if it doesn't, then disallow the mechanism by declaring your classes final.

## Superclasses, Object, and the Class Hierarchy

In our example, PlaneCircle is a subclass of Circle. We can also say that Circle is the superclass of PlaneCircle. The superclass of a class is specified in its extends clause, and a class may have only a single direct superclass:

```
public class PlaneCircle extends Circle { ... }
```

Every class the programmer defines has a superclass. If the superclass is not specified with an extends clause, then the superclass is taken to be the class java.lang.Object.

As a result, the Object class is special for a couple of reasons:

- It is the only class in Java that does not have a superclass.
- All Java classes inherit (directly or indirectly) the methods of `Object`.

Because every class (except `Object`) has a superclass, classes in Java form a class hierarchy, which can be represented as a tree with `Object` at its root.

> `Object` has no superclass, but every other class has exactly one superclass. A subclass cannot extend more than one superclass; see Chapter 4 for more information on how to achieve a similar result using interfaces.



Figure 3-1 shows a partial class hierarchy diagram that includes our `Circle` and `PlaneCircle` classes, as well as some of the standard classes from the Java API.

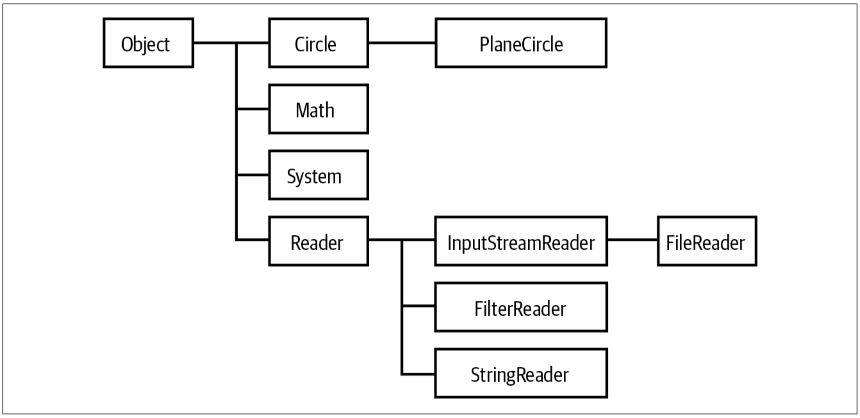


*Figure 3-1. A class hierarchy diagram*

## Subclass Constructors

Look again at the `PlaneCircle()` constructor from Example 3-3:

```
public PlaneCircle(double r, double x, double y) {
  super(r);       // Invoke the constructor of the superclass, Circle()
  this.cx = x;    // Initialize the instance field cx
  this.cy = y;    // Initialize the instance field cy
}
```

Although this constructor explicitly initializes the `cx` and `cy` fields newly defined by `PlaneCircle`, it relies on the superclass `Circle()` constructor to initialize the inherited fields of the class. To invoke the superclass constructor, our constructor calls `super()`.

`super` is a reserved word in Java. One of its main uses is to invoke the constructor of a superclass from within a subclass constructor. This use is analogous to the use of `this()` to invoke one constructor of a class from within another constructor of the same class. Invoking a constructor using `super()` is subject to the same restrictions as is using `this()`:

- `super()` can be used in this way only within a constructor.
- The call to the superclass constructor must appear as the first statement within the constructor, even before local variable declarations.

The arguments passed to `super()` must match the parameters of the superclass constructor. If the superclass defines more than one constructor, `super()` can be used to invoke any one of them, depending on the arguments passed.

## Constructor Chaining and the Default Constructor

Java guarantees that the constructor of a class is called whenever an instance of that class is created. It also guarantees that the constructor is called whenever an instance of any subclass is created. In order to guarantee this second point, Java must ensure that every constructor calls its superclass constructor.

Thus, if the first statement in a constructor does not explicitly invoke another constructor with `this()` or `super()`, the `javac` compiler inserts the call `super()` (i.e., it calls the superclass constructor with no arguments). If the superclass does not have a visible constructor that takes no arguments, this implicit invocation causes a compilation error.

Consider what happens when we create a new instance of the `PlaneCircle` class:

1. First, the `PlaneCircle` constructor is invoked.
2. This constructor explicitly calls `super(r)` to invoke a `Circle` constructor.
3. That `Circle()` constructor implicitly calls `super()` to invoke the constructor of its superclass, `Object` (`Object` only has one constructor).
4. At this point, we've reached the top of the hierarchy and constructors start to run.
5. The body of the `Object` constructor runs first.
6. When it returns, the body of the `Circle()` constructor runs.
7. Finally, when the call to `super(r)` returns, the remaining statements of the `PlaneCircle()` constructor are executed.

What all this means is that constructor calls are chained; any time an object is created, a sequence of constructors is invoked, from subclass to superclass on up to `Object` at the root of the class hierarchy.

Because a superclass constructor is always invoked as the first statement of its subclass constructor, the body of the `Object` constructor always runs first, followed by the constructor of its subclass and on down the class hierarchy to the class that is being instantiated.

Whenever a constructor is invoked, it can count on the fields of its superclass to be initialized by the time the constructor starts to run.

#### The default constructor

There is one missing piece in the previous description of constructor chaining. If a constructor does not invoke a superclass constructor, Java does so implicitly.

> If a class is declared without a constructor, Java implicitly adds a constructor to the class. This default constructor does nothing but invoke the superclass constructor.



For example, if we don't declare a constructor for the `PlaneCircle` class, Java implicitly inserts this constructor:

```
public PlaneCircle() { super(); }
```

Classes declared `public` are given `public` constructors. All other classes are given a default constructor that is declared without any visibility modifier; such a constructor has default visibility.

One very important point is that if a class declares constructors that take parameters but does not define a no-argument constructor, then all its subclasses must define constructors that explicitly invoke a constructor with the necessary arguments.

> If you are creating a `public` class that should not be publicly instantiated, declare at least one non-`public` constructor to prevent the insertion of a default `public` constructor.

Classes that should never be instantiated (such as `java.lang.Math` or `java.lang.System`) should define only a `private` constructor. Such a constructor can never be invoked from outside of the class, and it prevents the automatic insertion of the default constructor. The overall effect is that the class will never be instantiated, as it is not instantiated by the class itself and no other class has the correct access.

## Hiding Superclass Fields

For the sake of example, imagine that our `PlaneCircle` class needs to know the distance between the center of the circle and the origin (0,0). We can add another instance field to hold this value:

```
public double r;
```

Adding the following line to the constructor computes the value of the field:

```
this.r = Math.sqrt(cx*cx + cy*cy);  // Pythagorean theorem
```

But wait; this new field `r` has the same name as the radius field `r` in the `Circle` superclass. When this happens, we say that the field `r` of `PlaneCircle` *hides* the field `r` of `Circle`. (This is a contrived example, of course: the new field really should be called `distanceFromOrigin`.)

> In code that you write, you should avoid declaring fields with names that hide superclass fields. It is almost always a sign of bad code.

With this new definition of `PlaneCircle`, the expressions `r` and `this.r` both refer to the field of `PlaneCircle`. How, then, can we refer to the field `r` of `Circle` that holds the radius of the circle? A special syntax for this uses the `super` keyword:

```
r        // Refers to the PlaneCircle field
this.r   // Refers to the PlaneCircle field
super.r  // Refers to the Circle field
```

Another way to refer to a hidden field is to cast `this` (or any instance of the class) to the appropriate superclass and then access the field:

```
((Circle) this).r   // Refers to field r of the Circle class
```

This casting technique is particularly useful when you need to refer to a hidden field defined in a class that is not the immediate superclass. Suppose, for example, that classes `A`, `B`, and `C` all define a field named `x` and that `C` is a subclass of `B`, which is a subclass of `A`. Then, in the methods of class `C`, you can refer to these different fields as follows:

```
x              // Field x in class C
this.x         // Field x in class C
super.x        // Field x in class B
((B)this).x    // Field x in class B
((A)this).x    // Field x in class A
super.super.x  // Illegal; does not refer to x in class A
```

> You cannot refer to a hidden field `x` in the superclass of a superclass with `super.super.x`. This is not legal syntax.

Similarly, if you have an instance `c` of class `C`, you can refer to the three fields named `x` like this:

```
c.x               // Field x of class C
((B)c).x          // Field x of class B
((A)c).x          // Field x of class A
```

So far, we've been discussing instance fields. Class fields can also be hidden. You can use the same `super` syntax to refer to the hidden value of the field, but this is never necessary, as you can always refer to a class field by prepending the name of the desired class. Suppose, for example, that the implementer of `PlaneCircle` decides that the `Circle.PI` field does not declare to enough decimal places. She can define her own class field `PI`:

```
public static final double PI = 3.14159265358979323846;
```



Now code in `PlaneCircle` can use this more accurate value with the expressions `PI` or `PlaneCircle.PI`. It can also refer to the old, less accurate value with the expressions `super.PI` and `Circle.PI`. However, the `area()` and `circumference()` methods inherited by `PlaneCircle` are defined in the `Circle` class, so they use the value `Circle.PI`, even though that value is hidden now by `PlaneCircle.PI`.

## Overriding Superclass Methods

When a class defines an instance method using the same name, return type, and parameters as a method in its superclass, that method *overrides* the method of the superclass. When the method is invoked for an object of the class, it is the new definition of the method that is called, not the old definition from the superclass.

> The return type of the overriding method may be a subclass of the return type of the original method (instead of being exactly the same type). This is known as a *covariant return*.

Method overriding is an important and useful technique in object-oriented programming. `PlaneCircle` does not override either of the methods defined by `Circle`, and in fact it is difficult to think of a good example where any of the methods defined by `Circle` could have a well-defined override.

> Don't be tempted to consider subclassing `Circle` with a class like `Ellipse`—this would actually violate a core principle of object-oriented development (the Liskov principle, which we will meet later in this chapter).

Instead, let's look at a different example that does work with method overriding:

```
public class Car {
    public static final double LITRE_PER_100KM = 8.9;

    protected double topSpeed;
```

```
    protected double fuelTankCapacity;

    private int doors;

    public Car(double topSpeed, double fuelTankCapacity,
               int doors) {
        this.topSpeed = topSpeed;
        this.fuelTankCapacity = fuelTankCapacity;
        this.doors = doors;
    }

    public double getTopSpeed() {
        return topSpeed;
    }

    public int getDoors() {
        return doors;
    }

    public double getFuelTankCapacity() {
        return fuelTankCapacity;
    }

    public double range() {
        return 100 * fuelTankCapacity / LITRE_PER_100KM;
    }
}
```

This is a bit more complex, but it will illustrate the concepts behind overriding. Along with the `Car` class, we also have a specialized class, `SportsCar`. This has several differences: it has a fixed-size fuel tank and comes only in a two-door version. It may also have a much higher top speed than the regular form, but if the top speed rises above 200 km/h then the fuel efficiency of the car suffers, and as a result the overall range of the car starts to decrease:

```
public class SportsCar extends Car {

    private double efficiency;

    public SportsCar(double topSpeed) {
        super(topSpeed, 50.0, 2);
        if (topSpeed > 200.0) {
            efficiency = 200.0 / topSpeed;
        } else {
            efficiency = 1.0;
        }
    }

    public double getEfficiency() {
        return efficiency;
    }
```

```
    @Override
    public double range() {
        return 100 * fuelTankCapacity * efficiency / LITRE_PER_100KM;
    }

}
```

The upcoming discussion of method overriding considers only instance methods. Class (aka static) methods behave quite differently, and they cannot be overridden. Just like fields, class methods can be hidden by a subclass but not overridden. As noted earlier in this chapter, it is good programming style to always prefix a class method invocation with the name of the class in which it is defined. If you consider the class name part of the class method name, the two methods have different names, so nothing is actually hidden at all.



The code example for the `SportsCar` includes the syntax construct `@Override`. This is known as an *annotation*, and we shall meet this piece of Java syntax properly in Chapter 4.

Before we go any further with the discussion of method overriding, you should understand the difference between method overriding and method overloading. As we discussed in Chapter 2, method overloading refers to the practice of defining multiple methods (in the same class) that have the same name but different parameter lists.

On the other hand, a method overrides a method in its superclass when the instance method uses the same name, return type, and parameter list as a method in its superclass. These two features are very different from each other, so don't get them confused.

### Overriding is not hiding

Although Java treats the fields and methods of a class analogously in many ways, method overriding is not at all like field hiding. You can refer to hidden fields simply by casting an object to an instance of the appropriate superclass, but you cannot invoke overridden instance methods with this technique. The following code illustrates this crucial difference:

```
class A {                              // Define a class named A
  int i = 1;                           // An instance field
  int f() { return i; }                // An instance method
  static char g() { return 'A'; }      // A class method
}

class B extends A {                    // Define a subclass of A
  int i = 2;                           // Hides field i in class A
  int f() { return -i; }               // Overrides method f in class A
```

```
    static char g() { return 'B'; }  // Hides class method g() in class A
  }

  public class OverrideTest {
    public static void main(String args[]) {
      B b = new B();               // Creates a new object of type B
      System.out.println(b.i);     // Refers to B.i; prints 2
      System.out.println(b.f());   // Refers to B.f(); prints -2
      System.out.println(b.g());   // Refers to B.g(); prints B
      System.out.println(B.g());   // A better way to invoke B.g()

      A a = (A) b;                 // Casts b to an instance of class A
      System.out.println(a.i);     // Now refers to A.i; prints 1
      System.out.println(a.f());   // Still refers to B.f(); prints -2
      System.out.println(a.g());   // Refers to A.g(); prints A
      System.out.println(A.g());   // A better way to invoke A.g()
    }
  }
```

While this difference between method overriding and field hiding may seem surprising at first, a little thought makes the purpose clear.

Suppose we are manipulating a bunch of `Car` and `SportsCar` objects and store them in an array of type `Car[]`. We can do this because `SportsCar` is a subclass of `Car`, so all `SportsCar` objects are legal `Car` objects.

When we loop through the elements of this array, we don't have to know or care whether the element is actually a `Car` or a `SportsCar`. What we do care about very much, however, is that the correct value is computed when we invoke the `range()` method of any element of the array. In other words, we don't want to use the formula for the range of a car when the object is actually a sports car!

All we really want is for the objects we're computing the ranges of to "do the right thing"—the `Car` objects to use their definition of how to compute their own range, and the `SportsCar` objects to use the definition that is correct for them.

Seen in this context, it is not surprising that Java handles method overriding differently than field hiding.

### Virtual method lookup

If we have a `Car[]` array that holds `Car` and `SportsCar` objects, how does `javac` know whether to call the `range()` method of the `Car` class or the `SportsCar` class for any given item in the array? In fact, the source code compiler cannot know this at compilation time.

Instead, `javac` creates bytecode that uses *virtual* method lookup at runtime. When the interpreter runs the code, it looks up the appropriate `range()` method to call for each of the objects in the array. That is, when the interpreter interprets the expression `o.range()`, it checks the actual runtime type of the object referred to by the variable `o` and then finds the `range()` method that is appropriate for that type.

Some other languages (such as C# or C++) do not do virtual lookup by default and instead have a `virtual` keyword that programmers must explicitly use if they want subclasses to be able to override a method.

This is another way of approaching the concept of method overriding, which we discussed earlier. If the version of the `range()` method associated with the static type of `o` was used, without the runtime (aka virtual) lookup, then overriding would not work properly.

Virtual method lookup is the default for Java instance methods. See Chapter 4 for more details about compile-time and runtime types and how they affect virtual method lookup.



### Invoking an overridden method

We've seen the important differences between method overriding and field hiding. Nevertheless, the Java syntax for invoking an overridden method is quite similar to the syntax for accessing a hidden field: both use the `super` keyword. The following code illustrates:

```
class A {
  int i = 1;              // An instance field hidden by subclass B
  int f() { return i; } // An instance method overridden by subclass B
}

class B extends A {
  int i;                  // This field hides i in A
  int f() {               // This method overrides f() in A
    i = super.i + 1;      // It can retrieve A.i like this
    return super.f() + i; // It can invoke A.f() like this
  }
}
```

Recall that when you use `super` to refer to a hidden field, it is the same as casting `this` to the superclass type and accessing the field through it. Using `super` to invoke an overridden method, however, is not the same as casting the `this` reference. In other words, in the previous code, the expression `super.f()` is not the same as `((A)this).f()`.

When the interpreter invokes an instance method with the `super` syntax, a modified form of virtual method lookup is performed. The first step, as in regular virtual method lookup, is to determine the actual class of the object through which the method is invoked. Normally, the runtime search for an appropriate method definition would begin with this class. When a method is invoked with the `super` syntax, however, the search begins at the superclass of the class. If the superclass implements the method directly, that version of the method is invoked. If the superclass inherits the method, the inherited version of the method is invoked.

Note that the `super` keyword invokes the most immediately overridden version of a method. Suppose class `A` has a subclass `B` that has a subclass `C` and that all three classes define the same method `f()`. The method `C.f()` can invoke the method `B.f()`, which it overrides directly, with `super.f()`. But there is no way for `C.f()` to invoke `A.f()` directly: `super.super.f()` is not legal Java syntax. Of course, if `C.f()` invokes `B.f()`, it is reasonable to suppose that `B.f()` might also invoke `A.f()`.

This kind of chaining is relatively common with overridden methods: it is a way of augmenting the behavior of a method without replacing the method entirely.

> Don't confuse the use of `super` to invoke an overridden method with the `super()` method call used in a constructor to invoke a superclass constructor. Although they both use the same keyword, these are two entirely different syntaxes. In particular, you can use `super` to invoke an overridden method anywhere in the overriding class, while you can use `super()` only to invoke a superclass constructor as the very first statement of a constructor.

It is also important to remember that `super` can be used only to invoke an overridden method from within the class that overrides it. Given a reference to a `SportsCar` object `e`, there is no way for a program that uses `e` to invoke the `range()` method defined by the `Car` class on `e`.

## Sealed Classes

Until this point, we have only encountered two possibilities for class inheritance:

- Unrestricted ability to subclass (which is the default and has no keyword associated with it)
- Complete prevention of subclassing with the `final` keyword applied to a class

As of Java 17, there is a third possibility, which is controlled by the `sealed` keyword. A *sealed class* is one that can be subclassed but only by a specific list of known classes. This is done by using the `permits` keyword to enumerate the list of possible subclasses (which must all be in the same package as the base class) upfront, when the sealed class is declared. Like this:

```
// In Shape.java
public abstract sealed class Shape permits Circle, Triangle {
    // ...
}

// In Circle.java
public final class Circle extends Shape {
    // ...
}
```

```java
// In Triangle.java
public final class Triangle extends Shape {
    // ...
}
```

In this example, we have declared both `Circle` and `Triangle` as `final`, so they cannot be further subclassed. This is the usual approach, but it is also possible to declare a subtype of a sealed class as either `sealed` (with a further set of permitted subclasses), or as `non-sealed`, which restores the default Java behavior of unrestricted subclassing.

This last option (`non-sealed`) should not be used without a very good reason, as it undermines much of the semantic point of using class sealing in the first place. For this reason, it is a compile-time error to try to subclass a sealed class without providing one of the three sealing modifiers: there is no default behavior here.



> The introduction of `non-sealed` is the first example of a *hyphenated keyword* that's been seen in Java.

In this example we've used an abstract sealed base class (`Shape`). This is not always necessary but it is often a good practice, as it means that any instances of the type that we encounter are known to be one of the "leaf types," such as `Circle` or `Triangle`. We will meet abstract classes properly later in the chapter.

Although sealed classes are new with Java 17, we expect that many developers will adopt them quickly—along with records, they represent a "missing concept" that fits very naturally into Java's view of OO. We will have more to say about this in Chapter 5 when we discuss aspects of object-oriented design related to sealed types.

## Data Hiding and Encapsulation

We started this chapter by describing a class as a collection of data and methods. One of the most important object-oriented techniques we haven't discussed so far is hiding the data within the class and making it available only through the methods.

This technique is known as *encapsulation* because it contains the data (and internal methods) safely inside the "capsule" of the class, where it can be accessed only by trusted users (i.e., the methods of the class).

Why would you want to do this? The most important reason is to hide the internal implementation details of your class. If you prevent programmers from relying on those details, you can safely modify the implementation without worrying that you will break existing code that uses the class.

You should always encapsulate your code. It is almost always impossible to reason through and ensure the correctness of code that hasn't been well-encapsulated, especially in multi-threaded environments (and essentially all Java programs are multithreaded).

Another reason for encapsulation is to protect your class against accidental or willful stupidity. A class often contains a number of interdependent fields that must be in a consistent state. If you allow programmers (including yourself) to manipulate those fields directly, they may change one field without changing important related fields, leaving the class in an inconsistent state. If instead the programmer has to call a method to change the field, that method can be sure to do everything necessary to keep the state consistent. Similarly, if a class defines certain methods for internal use only, hiding these methods prevents users of the class from calling them.

Here's another way to think about encapsulation: when all the data for a class is hidden, the methods define the only possible operations that can be performed on objects of that class.

Once you have carefully tested and debugged your methods, you can be confident that the class will work as expected. On the other hand, if all the fields of the class can be directly manipulated, the number of possibilities you have to test becomes unmanageable.

This idea can be carried to a very powerful conclusion, as we will see in "Safe Java Programming" on page 234 when we discuss the *safety* of Java programs (which differs from the concept of *type safety* of the Java programming language).

Other, secondary, reasons to hide fields and methods of a class include:

- Internal fields and methods that are visible outside the class just clutter up the API. Keeping visible fields to a minimum keeps your class tidy and therefore easier to use and understand.
- If a method is visible to the users of your class, you have to document it. Save yourself time and effort by hiding it instead.

## Access Control

Java defines access control rules that can restrict members of a class from being used outside the class. In a number of examples in this chapter, you've seen the `public` modifier used in field and method declarations. This `public` keyword, along with `protected` and `private` (and one other, special one) are *access control modifiers*; they specify the access rules for the field or method.

### Access to modules

One of the biggest changes in Java 9 was the arrival of Java platform modules. These are a grouping of code that is larger than a single package and intended as the future way to deploy code for reuse. As Java is often used in large applications and environments, the arrival of modules should make it easier to build and manage enterprise codebases.

The modules technology is an advanced topic, and if Java is one of the first programming languages you have encountered, you should not try to learn it until you have gained some language proficiency. An introductory treatment of modules is provided in Chapter 12, and we defer discussing the access control impact of modules until then.



### Access to packages

Access control on a per-package basis is not directly part of the core Java language and instead is provided by the modules mechanism. In the normal course of programming, access control is usually done at the level of classes and members of classes.

> A package that has been loaded is always accessible to code defined within the same package. Whether it is accessible to code from other packages depends on the way the package is deployed on the host system. When the class files that comprise a package are stored in a directory, for example, a user must have read access to the directory and the files within it to have access to the package.

### Access to classes

By default, top-level classes are accessible within the package in which they are defined. However, if a top-level class is declared `public`, it is accessible everywhere.

> In Chapter 4, we'll meet nested classes. These are classes that can be defined as members of other classes. Because these inner classes are members of a class, they obey the member access-control rules.

### Access to members

The members of a class are always accessible within the body of the class. By default, members are also accessible throughout the package in which the class is defined. This default level of access is often called *package access*.

It is one of four possible levels of access. The other three levels are defined by the `public`, `protected`, and `private` modifiers. Here is some example code that uses these modifiers:

```java
public class Laundromat {    // People can use this class.
  private Laundry[] dirty;   // They cannot use this internal field,
  public void wash() { ... } // but they can use these public methods
  public void dry() { ... }  // to manipulate the internal field.
  // A subclass might want to tweak this field
  protected int temperature;
}
```

These access rules apply to members of a class:

- All the fields and methods of a class can always be used within the body of the class itself.
- If a member of a class is declared with the `public` modifier, it means that the member is accessible anywhere the containing class is accessible. This is the least restrictive type of access control.
- If a member of a class is declared `private`, the member is never accessible, except within the class itself. This is the most restrictive type of access control.
- If a member of a class is declared `protected`, it is accessible to all classes within the package (the same as the default package accessibility) and also accessible within the body of any subclass of the class, regardless of the package in which that subclass is defined.
- If a member of a class is not declared with any of these modifiers, it has *default* access (sometimes called *package* access), and it is accessible to code within all classes that are defined in the same package but inaccessible outside of the package.

Default access is *more* restrictive than `protected`—as default access does not allow access by subclasses outside the package.

`protected` access requires more elaboration. Suppose class `A` declares a `protected` field `x` and is extended by a class `B`, which is defined in a different package (this last point is important). Class `B` inherits the `protected` field `x`, and its code can access that field in the current instance of `B` or in any other instances of `B` that the code can refer to. This does not mean, however, that the code of class `B` can start reading the protected fields of arbitrary instances of `A`.

Let's look at this language detail in code. Here's the definition for `A`:

```java
package javanut8.ch03;

public class A {
    protected final String name;
```

```
    public A(String named) {
        name = named;
    }

    public String getName() {
        return name;
    }
}
```

Here's the definition for B:

```
package javanut8.ch03.different;

import javanut8.ch03.A;

public class B extends A {

    public B(String named) {
        super(named);
    }

    @Override
    public String getName() {
        return "B: " + name;
    }
}
```

> Java packages do not "nest," so `javanut8.ch03.different` is just a different package than `javanut8.ch03`; it is not contained inside it or related to it in any way.

However, if we try to add this new method to B, we will get a compilation error, because instances of B do not have access to arbitary instances of A:

```
    public String examine(A a) {
        return "B sees: " + a.name;
    }
```

If we change the method to this:

```
    public String examine(B b) {
        return "B sees another B: " + b.name;
    }
```

then the compiler is happy, because instances of the same exact type can always see each other's `protected` fields. Of course, if B was in the same package as A, then any instance of B could read any protected field of any instance of A because `protected` fields are visible to every class in the same package.

### Access control and inheritance

The Java specification states that:

- A subclass inherits all the instance fields and instance methods of its superclass accessible to it.
- If the subclass is defined in the same package as the superclass, it inherits all non-`private` instance fields and methods.
- If the subclass is defined in a different package, it inherits all `protected` and `public` instance fields and methods.
- `private` fields and methods are never inherited; neither are class fields or class methods.
- Constructors are not inherited (instead, they are chained, as described earlier in this chapter).

However, some programmers are confused by the statement that a subclass does not inherit the inaccessible fields and methods of its superclass. Let us be explicit: Every instance of a subclass includes a complete instance of the superclass within it, including all private fields and methods. When you create an instance of a subclass, memory is allocated for all `private` fields defined by the superclass; however, the subclass does not have access to these fields directly.

This existence of potentially inaccessible members seems to be in conflict with the statement that the members of a class are always accessible within the body of the class. To clear up this confusion, we define "inherited members" to mean those superclass members that are accessible.

Then the correct statement about member accessibility is: "All inherited members and all members defined in this class are accessible." An alternative way of saying this is:

- A class inherits *all* instance fields and instance methods (but not constructors) of its superclass.
- The body of a class can always access all the fields and methods it declares itself. It can also access the *accessible* fields and members it inherits from its superclass.

### Member access summary

We summarize the member access rules in Table 3-1.

*Table 3-1. Class member accessibility*

| Accessible to | Member visibility | | | |
|---|---|---|---|---|
| | Public | Protected | Default | Private |
| Defining class | Yes | Yes | Yes | Yes |
| Class in same package | Yes | Yes | Yes | No |
| Subclass in different package | Yes | Yes | No | No |
| Nonsubclass different package | Yes | No | No | No |



There are a few generally observed rules about what parts of a Java program should use each visibility modifier. It is important that even beginning Java programmers follow these rules:

- Use `public` only for methods and constants that form part of the public API of the class. The only acceptable usage of `public` fields is for constants or immutable objects, and they must be also declared `final`.
- Use `protected` for fields and methods that aren't required by most programmers using the class but that may be of interest to anyone creating a subclass as part of a different package.

> `protected` members are technically part of the exported API of a class. They must be documented and cannot be changed without potentially breaking code that relies on them.

- Use the default package visibility for fields and methods that are internal implementation details but are used by cooperating classes in the same package.
- Use `private` for fields and methods that are used only inside the class and should be hidden everywhere else.

If you are not sure whether to use `protected`, package, or `private` accessibility, start with `private`. If this is overly restrictive, you can always relax the access restrictions slightly (or provide accessor methods, in the case of fields).

This is especially important for designing APIs because increasing access restrictions is not a backward-compatible change and can break code that relies on access to those members.

## Data Accessor Methods

In the `Circle` example, we declared the circle radius to be a `public` field. The `Circle` class is one in which it may be reasonable to keep that field publicly accessible; it is a simple enough class, with no dependencies between its fields. On the other hand, our current implementation of the class allows a `Circle` object to have a negative radius, and circles with negative radii simply should not exist. As long as the radius is stored in a `public` field, however, any programmer can set the field to any value they want, no matter how unreasonable. The only solution is to restrict the programmer's direct access to the field and define `public` methods that provide indirect access to the field. Providing `public` methods to read and write a field is not the same as making the field itself `public`. The crucial difference is that methods can perform error checking.

We might, for example, want to prevent `Circle` objects with negative radii—these are obviously not sensible, but our current implementation does not prohibit this. In Example 3-4, we show how we might change the definition of `Circle` to prevent this.

This version of `Circle` declares the `r` field to be `protected` and defines accessor methods named `getRadius()` and `setRadius()` to read and write the field value while enforcing the restriction on negative radius values. Because the `r` field is `protected`, it is directly (and more efficiently) accessible to subclasses.

*Example 3-4. The Circle class using data hiding and encapsulation*

```
package javanut8.ch03.shapes; // Specify a package for the class

public class Circle {      // The class is still public
    // This is a generally useful constant, so we keep it public
    public static final double PI = 3.14159;

    protected double r;     // Radius is hidden but visible to subclasses

    // A method to enforce the restriction on the radius
    // Subclasses may be interested in this implementation detail
    protected void checkRadius(double radius) {
        if (radius < 0.0)
            throw new IllegalArgumentException("illegal negative radius");
    }

    // The non-default constructor
    public Circle(double r) {
        checkRadius(r);
        this.r = r;
    }

    // Public data accessor methods
    public double getRadius() { return r; }
```

```
    public void setRadius(double r) {
        checkRadius(r);
        this.r = r;
    }

    // Methods to operate on the instance field
    public double area() { return PI * r * r; }
    public double circumference() { return 2 * PI * r; }
}
```

We have defined the `Circle` class within a package named `javanut8.ch03.shapes`; `r` is `protected` so any other classes in the `javanut8.ch03.shapes` package have direct access to that field and can set it however they like. The assumption here is that all classes within the `javanut8.ch03.shapes` package were written by the same author or a closely cooperating group of authors, and that the classes all trust each other not to abuse their privileged level of access to each other's implementation details.



Finally, the code that enforces the restriction against negative radius values is itself placed within a `protected` method, `checkRadius()`. Although users of the `Circle` class cannot call this method, subclasses of the class can call it and even override it if they want to change the restrictions on the radius.

> One set of common (but older) conventions in Java—known as Java Beans conventions—is that data accessor methods begin with the prefixes "get" and "set." But if the field being accessed is of type `boolean`, the `get()` method may be replaced with an equivalent method that begins with "is"—the accessor method for a `boolean` field named `readable` is typically called `isReadable()` instead of `getReadable()`.

## Abstract Classes and Methods

In Example 3-4, we declared our `Circle` class to be part of a package named `shapes`. Suppose we plan to implement a number of shape classes: `Rectangle`, `Square`, `Hexagon`, `Triangle`, and so on. We can give these shape classes our two basic `area()` and `circumference()` methods. Now, to make it easy to work with an array of shapes, it would be helpful if all our shape classes had a common superclass, `Shape`. If we structure our class hierarchy this way, every shape object, regardless of the actual type of shape it represents, can be assigned to variables, fields, or array elements of type `Shape`. We want the `Shape` class to encapsulate whatever features all our shapes have in common (e.g., the `area()` and `circumference()` methods). But our generic `Shape` class doesn't represent any real kind of shape, so it cannot define useful implementations of the methods. Java handles this situation with *abstract methods*.

Java lets us define a method without implementing it by declaring the method with the `abstract` modifier. An `abstract` method has no body; it simply has a signature definition followed by a semicolon.[2] Here are the rules about `abstract` methods and the `abstract` classes that contain them:

- Any class with an `abstract` method is automatically `abstract` itself and must be declared as such. To fail to do so is a compilation error.
- An `abstract` class cannot be instantiated.
- A subclass of an `abstract` class can be instantiated only if it overrides each of the `abstract` methods of its superclass and provides an implementation (i.e., a method body) for all of them. Such a class is often called a *concrete* subclass, to emphasize the fact that it is not `abstract`.
- If a subclass of an `abstract` class does not implement all the `abstract` methods it inherits, that subclass is itself `abstract` and must be declared as such.
- `static`, `private`, and `final` methods cannot be `abstract`, because these types of methods cannot be overridden by a subclass. Similarly, a `final` class cannot contain any `abstract` methods.
- A class can be declared `abstract` even if it does not actually have any `abstract` methods. Declaring such a class `abstract` indicates that the implementation is somehow incomplete and is meant to serve as a superclass for one or more subclasses that complete the implementation. Such a class cannot be instantiated.

> The `ClassLoader` class that we will meet in Chapter 11 is a good example of an abstract class that does not have any abstract methods.

Let's look at an example of how these rules work. If we define the `Shape` class to have `abstract` `area()` and `circumference()` methods, any subclass of `Shape` is required to provide implementations of these methods so that it can be instantiated. In other words, every `Shape` object is guaranteed to have implementations of these methods defined. Example 3-5 shows how this might work. It defines an `abstract` `Shape` class and a concrete subclass of it. You should also imagine that the `Circle` class from Example 3-4 has been modified so that it `extends Shape`.

2 An `abstract` method in Java is something like a pure virtual function in C++ (i.e., a virtual function that is declared `= 0`). In C++, a class that contains a pure virtual function is called an abstract class and cannot be instantiated. The same is true of Java classes that contain `abstract` methods.

*Example 3-5. An abstract class and concrete subclass*

```
public abstract class Shape {
    public abstract double area();            // Abstract methods: note
    public abstract double circumference();   // semicolon instead of body.
}

public class Rectangle extends Shape {
    // Instance data
    protected double w, h;

    // Constructor
    public Rectangle(double w, double h) {
        this.w = w;  this.h = h;
    }

    // Accessor methods
    public double getWidth() { return w; }
    public double getHeight() { return h; }

    // Implementation of abstract methods
    public double area() { return w*h; }
    public double circumference() { return 2*(w + h); }
}
```

Each abstract method in Shape has a semicolon right after its parentheses. Method declarations of this sort have no curly braces, and no method body is defined.

Note that we could have declared the class Shape as a sealed class, but we have deliberately chosen not to. This is so other programmers can define their own shape classes as new subclasses of Shape, should they wish to.

Using the classes defined in Example 3-5, we can now write code such as:

```
Shape[] shapes = new Shape[3];          // Create an array to hold shapes
shapes[0] = new Circle(2.0);            // Fill in the array
shapes[1] = new Rectangle(1.0, 3.0);
shapes[2] = new Rectangle(4.0, 2.0);

double totalArea = 0;
for(int i = 0; i < shapes.length; i++) {
    totalArea += shapes[i].area();   // Compute the area of the shapes
}
```

Notice two important points here:

- Subclasses of Shape can be assigned to elements of an array of Shape. No cast is necessary. This is another example of a widening reference type conversion (discussed in Chapter 2).
- You can invoke the area() and circumference() methods for any Shape object, even though the Shape class does not define a body for these methods.

When you do this, the method to be invoked is found using virtual lookup, which we met earlier. In our case, this means that the area of a circle is computed using the method defined by `Circle`, and the area of a rectangle is computed using the method defined by `Rectangle`.

## Reference Type Conversions

Object references can be converted between different reference types. As with primitive types, reference type conversions can be widening conversions (allowed automatically by the compiler) or narrowing conversions that require a cast (and possibly a runtime check). In order to understand reference type conversions, you need to understand that reference types form a hierarchy, usually called the *class hierarchy*.

Every Java reference type *extends* some other type, known as its *superclass*. A type inherits the fields and methods of its superclass and then defines its own additional fields and methods. A special class named `Object` serves as the root of the class hierarchy in Java. All Java classes extend `Object` directly or indirectly. The `Object` class defines a number of special methods that are inherited (or overridden) by all objects.

The predefined `String` class and the `Account` class we discussed earlier in this chapter both extend `Object`. Thus, we can say that all `String` objects are also `Object` objects. We can also say that all `Account` objects are `Object` objects. The opposite is not true, however. We cannot say that every `Object` is a `String` because, as we've just seen, some `Object` objects are `Account` objects.

With this simple understanding of the class hierarchy, we can define the rules of reference type conversion:

- An object reference cannot be converted to an unrelated type. The Java compiler does not allow you to convert a `String` to a `Account`, for example, even if you use a cast operator.
- An object reference can be converted to the type of its superclass or of any ancestor class. This is a widening conversion, so no cast is required. For example, a `String` value can be assigned to a variable of type `Object` or passed to a method where an `Object` parameter is expected.

> No conversion is actually performed; the object is simply treated as if it were an instance of the superclass. This is a simple form of the Liskov substitution principle, after Barbara Liskov, the computer scientist who first explicitly formulated it.

- An object reference can be converted to the type of a subclass, but this is a narrowing conversion and requires a cast. The Java compiler provisionally allows this kind of conversion, but the Java interpreter checks at runtime to make sure it is valid. Only cast a reference to the type of a subclass if you are sure, based on the logic of your program, that the object is actually an instance of the subclass. If it is not, the interpreter throws a `ClassCastException`. For example, if we assign a `String` reference to a variable of type `Object`, we can later cast the value of that variable back to type `String`:

  ```
  Object o = "string";    // Widening conversion from String
                          // to Object later in the program...
  String s = (String) o;  // Narrowing conversion from Object
                          // to String
  ```



Arrays are objects and follow some conversion rules of their own. First, any array can be converted to an `Object` value through a widening conversion. A narrowing conversion with a cast can convert such an object value back to an array. Here's an example:

```
// Widening conversion from array to Object
Object o = new int[] {1,2,3};
// Later in the program...

int[] a = (int[]) o;      // Narrowing conversion back to array type
```

In addition to converting an array to an object, we can convert an array to another type of array if the "base types" of the two arrays are reference types that can themselves be converted. For example:

```
// Here is an array of strings.
String[] strings = new String[] { "hi", "there" };
// A widening conversion to CharSequence[] is allowed because String
// can be widened to CharSequence
CharSequence[] sequences = strings;
// The narrowing conversion back to String[] requires a cast.
strings = (String[]) sequences;

// This is an array of arrays of strings
String[][] s = new String[][] { strings };
// It cannot be converted to CharSequence[] because String[] cannot be
// converted to CharSequence: the number of dimensions don't match

sequences = s;  // This line will not compile
// s can be converted to Object or Object[], because all array types
// (including String[] and String[][]) can be converted to Object.
Object[] objects = s;
```

Note that these array conversion rules apply only to arrays of objects and arrays of arrays. An array of primitive type cannot be converted to any other array type, even if the primitive base types can be converted:

```
// Can't convert int[] to double[] even though
// int can be widened to double
// This line causes a compilation error
double[] data = new int[] {1,2,3};
// This line is legal, however,
// because int[] can be converted to Object
Object[] objects = new int[][] {{1,2},{3,4}};
```

## Modifier Summary

As we've seen, classes, interfaces, and their members can be declared with one or more *modifiers*—keywords such as `public`, `static`, and `final`. Let's conclude this chapter by listing the Java modifiers, explaining what types of Java constructs they can modify, and explaining what they do. Table 3-2 has the details; you can also refer to "Overview of Classes and Records" on page 107, "Field Declaration Syntax" on page 112, and "Method Modifiers" on page 77.

*Table 3-2. Java modifiers*

| Modifier | Used on | Meaning |
|---|---|---|
| `abstract` | Class | The class cannot be instantiated and may contain unimplemented methods. |
| | Interface | All interfaces are `abstract`. The modifier is optional in interface declarations. |
| | Method | No body is provided for the method; it is provided by a subclass. The signature is followed by a semicolon. The enclosing class must also be `abstract`. |
| `default` | Method | Implementation of this interface method is optional. The interface provides a default implementation for classes that elect not to implement it. See Chapter 4 for more details. |
| `final` | Class | The class cannot be subclassed. |
| | Method | The method cannot be overridden. |
| | Field | The field cannot have its value changed. `static final` fields are compile-time constants. |
| | Variable | A local variable, method parameter, or exception parameter cannot have its value changed. |

| Modifier | Used on | Meaning |
|---|---|---|
| `native` | Method | The method is implemented in some platform-dependent way (often in C). No body is provided; the signature is followed by a semicolon. |
| `non-sealed` | Class | The class inherits from a sealed type but itself has unrestricted open inheritance. |
| <None> (package) | Class | A non-`public` class is accessible only in its package. |
| | Interface | A non-`public` interface is accessible only in its package. |
| | Member | A member that is not `private`, `protected`, or `public` has package visibility and is accessible only within its package. |
| `private` | Member | The member is accessible only within the class that defines it. |
| `protected` | Member | The member is accessible only within the package in which it is defined and within subclasses. |
| `public` | Class | The class is accessible anywhere its package is. |
| | Interface | The interface is accessible anywhere its package is. |
| | Member | The member is accessible anywhere its class is. |
| `sealed` | Class | The class can be subclassed only by a known list of subclasses, as given by the `permits` clause. If the permits clause is missing, the class can be subclassed only by classes within the same compilation unit. |
| `static` | Class | An inner class declared `static` is a top-level class not associated with a member of the containing class. See Chapter 4 for more details. |
| | Method | A `static` method is a class method. It is not passed an implicit `this` object reference. It can be invoked through the class name. |
| | Field | A `static` field is a class field. There is only one instance of the field, regardless of the number of class instances created. It can be accessed through the class name. |
| | Initializer | The initializer is run when the class is loaded rather than when an instance is created. |
| `strictfp` | Class | All methods of the class are implicitly `strictfp`. |

| Modifier | Used on | Meaning |
|---|---|---|
| | Method | All floating-point computation done by the method must be performed in a way that strictly conforms to the IEEE 754 standard. In particular, all values, including intermediate results, must be expressed as IEEE `float` or `double` values and cannot take advantage of any extra precision or range offered by native platform floating-point formats or hardware. This modifier is extremely rarely used, and is a no-op in Java 17, as the language now always uses strict conformance to the standard. |
| `synchronized` | Method | The method makes nonatomic modifications to the class or instance, so care must be taken to ensure that two threads cannot modify the class or instance at the same time. For a `static` method, a lock for the class is acquired before executing the method. For a non-`static` method, a lock for the specific object instance is acquired. See Chapter 5 for more details. |
| `transient` | Field | The field is not part of the persistent state of the object and should not be serialized with the object. Used with object serialization; see `java.io.ObjectOutputStream`. |
| `volatile` | Field | The field can be accessed by unsynchronized threads, so certain optimizations must not be performed on it. This modifier can sometimes be used as an alternative to `synchronized`. See Chapter 5 for more details. |

# Summary

Java, like all object-oriented languages, has its own model of how OO should work. In this chapter we have met the basic concepts of this model: static typing, fields, methods, inheritance, access control, encapsulation, overloading, overriding, and sealing. To become a proficient Java programmer, you will need to gain proficiency in handling all of these concepts and understand the relationship between them and how they interact.

The next two chapters are devoted to exploring these features further and understanding how the basic aspects of object-oriented design in Java arise directly from this relatively small set of basic concepts.

# 4 The Java Type System

In this chapter, we move beyond basic object-oriented programming with classes and into the additional concepts required to work effectively with Java's type system.

> A *statically typed* language is one in which variables have definite types, and where it is a compile-time error to assign a value of an incompatible type to a variable. Languages that only check type compatibility at runtime are called *dynamically typed*.

Java is a fairly classic example of a statically typed language. JavaScript is an example of a dynamically typed language that allows any variable to store any type of value.

The Java type system involves not only classes and primitive types but also other kinds of reference type that are related to the basic concept of a class, but which differ in some way and are usually treated in a special way by `javac` or the JVM.

We have already met arrays and classes, two of Java's most widely used kinds of reference type. This chapter starts by discussing another very important kind of reference type—*interfaces*. We then move on to discuss Java's *generics*, which have a major role to play in Java's type system. With these topics under our belts, we can discuss the differences between compile-time and runtime types in Java.

To complete the full picture of Java's reference types, we look at specialized kinds of classes and interfaces—known as *enums* and *annotations*. We conclude the chapter by looking at *lambda expressions* and *nested types* and then reviewing how enhanced type inference has allowed Java's *nondenotable types* to become usable by programmers.

Let's get started by taking a look at interfaces—probably the most important of Java's reference types after classes and a key building block for the rest of Java's type system.

## Interfaces

In Chapter 3, we met the idea of inheritance. We also saw that a Java class can inherit only from a single class. This is quite a big restriction on the kinds of object-oriented programs that we want to build. The designers of Java knew this, but they also wanted to ensure that Java's approach to object-oriented programming was less complex and error-prone than, for example, that of C++.

The solution that they chose was to introduce the concept of an interface to Java. Like a class, an *interface* defines a new reference type. As its name implies, an interface is intended to represent only an API—so it provides a description of a type and the methods (and signatures) that classes that *implement* that API must provide.

In general, a Java interface does not provide any implementation code for the methods that it describes. These methods are considered *mandatory*—any class that wishes to implement the interface must provide an implementation of these methods.

However, an interface may wish to mark that some API methods are optional and that implementing classes do not need to implement them if they choose not to. This is done with the `default` keyword—and the interface must provide an implementation of these optional methods, which will be used by any implementing class that elects not to implement them.

> The ability to have optional methods in interfaces was new in Java 8. It is not available in any earlier version. See "Records and Interfaces" on page 156 for a full description of how optional (also called default) methods work.

It is not possible to directly instantiate an interface and create a member of the interface type. Instead, a class must *implement* the interface to provide the necessary method bodies.

Any instances of the implementing class are *compatible with* both the type defined by the class and the type defined by the interface. This means that the instances may be substituted at any point in the code that requires an instance of either the class type or the interface type. This extends the Liskov principle as seen in "Reference Type Conversions" on page 146.

Another way of saying this is that two objects that do not share the same class or superclass may still both be compatible with the same interface type if both objects are instances of classes that implement the interface.

## Defining an Interface

An interface definition is somewhat like a class definition in which all the (mandatory) methods are abstract and the keyword `class` has been replaced with `interface`. For example, this code shows the definition of an interface named `Centered` (a `Shape` class, such as those defined in Chapter 3, might implement this interface if it wants to allow the coordinates of its center to be set and queried):

```
interface Centered {
  void setCenter(double x, double y);
  double getCenterX();
  double getCenterY();
}
```

A number of restrictions apply to the members of an interface:

- All mandatory methods of an interface are implicitly `abstract` and must have a semicolon in place of a method body. The `abstract` modifier is allowed but by convention is usually omitted.
- An interface defines a public API. By convention, members of an interface are implicitly `public`, and it is conventional to omit the unnecessary `public` modifier.
- An interface may not define any instance fields. Fields are an implementation detail, and an interface is a specification, not an implementation. The only fields allowed in an interface definition are constants that are declared both `static` and `final`.
- An interface cannot be instantiated, so it does not define a constructor.
- Interfaces may contain nested types. Any such types are implicitly `public` and `static`. See "Nested Types" on page 187 for a full description of nested types.
- As of Java 8, an interface may contain static methods. Previous versions of Java did not allow this, which is widely believed to have been a flaw in the design of the Java language.
- As of Java 9, an interface may contain `private` methods. These have limited use cases, but with the other changes to the interface construct, it seems arbitrary to disallow them.
- It is a compile-time error to try to define a `protected` method in an interface.

## Extending Interfaces

Interfaces may extend other interfaces, and, like a class definition, an interface definition indicates this by including an `extends` clause. When one interface extends another, it inherits all the methods and constants of its superinterface and can define new methods and constants. Unlike classes, however, the `extends` clause of an interface definition may include more than one superinterface. For example, here are some interfaces that extend other interfaces:

```
interface Positionable extends Centered {
  void setUpperRightCorner(double x, double y);
  double getUpperRightX();
  double getUpperRightY();
}
interface Transformable extends Scalable, Translatable, Rotatable {}
interface SuperShape extends Positionable, Transformable {}
```

An interface that extends more than one interface inherits all the methods and constants from each of those interfaces and can define its own additional methods and constants. A class that implements such an interface must implement the abstract methods defined directly by the interface, as well as all the abstract methods inherited from all the superinterfaces.

## Implementing an Interface

Just as a class uses `extends` to specify its superclass, it can use `implements` to name one or more interfaces it supports. The `implements` keyword can appear in a class declaration following the `extends` clause. It should be followed by a comma-separated list of interfaces that the class implements.

When a class declares an interface in its `implements` clause, it is saying that it provides an implementation (i.e., a body) for each mandatory method of that interface. If a class implements an interface but does not provide an implementation for every mandatory interface method, it inherits those unimplemented `abstract` methods from the interface and must itself be declared `abstract`. If a class implements more than one interface, it must implement every mandatory method of each interface it implements (or be declared `abstract`).

The following code shows how to define a `CenteredRectangle` class that extends the `Rectangle` class from Chapter 3 and implements our `Centered` interface:

```
public class CenteredRectangle extends Rectangle implements Centered {
  // New instance fields
  private double cx, cy;

  // A constructor
  public CenteredRectangle(double cx, double cy, double w, double h) {
    super(w, h);
    this.cx = cx;
    this.cy = cy;
  }

  // We inherit all the methods of Rectangle but must
  // provide implementations of all the Centered methods.
  public void setCenter(double x, double y) { cx = x; cy = y; }
  public double getCenterX() { return cx; }
```

```
    public double getCenterY() { return cy; }
}
```

Suppose we implement `CenteredCircle` and `CenteredSquare` just as we have implemented this `CenteredRectangle` class. Each class extends `Shape`, so instances of the classes can be treated as instances of the `Shape` class, as we saw earlier. Because each class implements the `Centered` interface, instances can also be treated as instances of that type. The following code demonstrates how objects can be members of both a class type and an interface type:

```
Shape[] shapes = new Shape[3];      // Create an array to hold shapes

// Create some centered shapes, and store them in the Shape[]
// No cast necessary: these are all compatible assignments
shapes[0] = new CenteredCircle(1.0, 1.0, 1.0);
shapes[1] = new CenteredSquare(2.5, 2, 3);
shapes[2] = new CenteredRectangle(2.3, 4.5, 3, 4);

// Compute average area of the shapes and
// average distance from the origin
double totalArea = 0;
double totalDistance = 0;
for(int i = 0; i < shapes.length; i = i + 1) {
  totalArea += shapes[i].area();   // Compute the area of the shapes

  // Be careful, in general, the use of instanceof to determine the
  // runtime type of an object is quite often an indication of a
  // problem with the design
  if (shapes[i] instanceof Centered) { // The shape is a Centered shape
    // Note the required cast from Shape to Centered (no cast would
    // be required to go from CenteredSquare to Centered, however).
    Centered c = (Centered) shapes[i];

    double cx = c.getCenterX();    // Get coordinates of the center
    double cy = c.getCenterY();    // Compute distance from origin
    totalDistance += Math.sqrt(cx*cx + cy*cy);
  }
}
System.out.println("Average area: " + totalArea/shapes.length);
System.out.println("Average distance: " + totalDistance/shapes.length);
```

Interfaces are data types in Java, just like classes. When a class implements an interface, instances of that class can be assigned to variables of the interface type.

Don't interpret this example to imply that you must assign a `CenteredRectangle` object to a `Centered` variable before you can invoke the `setCenter()` method or to a `Shape` variable before invoking the `area()` method. Instead, because the

`CenteredRectangle` class defines `setCenter()` and inherits `area()` from its `Rectangle` superclass, you can always invoke these methods.

As we could see by examining the bytecode (e.g., by using the `javap` tool we will meet in Chapter 13), the JVM calls the `setCenter()` method slightly differently depending on whether the local variable holding the shape is of the type `CenteredRectangle` or `Centered`, but this is not a distinction that matters most of the time when you're writing Java code.

## Records and Interfaces

Records, being a special case of classes, can implement interfaces, just like any other class. The body of the record must contain implementation code for all of the mandatory methods of the interface, and it may contain overriding implementations for any of the default methods of the interface.

Let's look at an example as applied to the `Point` record we met in the last chapter. Given an interface defined like this:

```
interface Translatable {
    Translatable deltaX(double dx);
    Translatable deltaY(double dy);
    Translatable delta(double dx, double dy);
}
```

then we can update the `Point` type like this:

```
public record Point(double x, double y) implements Translatable {
    public Translatable deltaX(double dx) {
        return delta(dx, 0.0);
    }

    public Translatable deltaY(double dy) {
        return delta(0.0, dy);
    }

    public Translatable delta(double dx, double dy) {
        return new Point(x + dx, y + dy);
    }
}
```

Note that because records are immutable, it is not possible to mutate instances in-place and so, if we need a modified object, we have to create one and return it explicitly. This implies that not every interface will be suitable for implementation by a record type.

## Sealed Interfaces

We met the `sealed` keyword in the last chapter, as applied to classes. It can also be applied to interfaces, like this:

```java
sealed interface Rotate90 permits Circle, Rectangle {
    void clockwise();
    void antiClockwise();
}
```

This sealed interface represents the capability for a shape to be rotated by 90 degrees. Note that the declaration also contains a `permits` clause that specifies the only classes that are allowed to implement this interface—in this case just the `Circle` and `Rectangle` for simplicity. The `Circle` is modified like this:

```java
public final class Circle extends Shape implements Rotate90 {
    // ...

    @Override
    public void clockwise() {
        // No-op, circles are rotation-invariant
    }

    @Override
    public void antiClockwise() {
        // No-op, circles are rotation-invariant
    }

    // ...
}
```

whereas the `Rectangle` has been modified like this:

```java
public final class Rectangle extends Shape implements Rotate90 {
    // ...

    @Override
    public void clockwise() {
        // Swap width and height
        double tmp = w;
        w = h;
        h = tmp;
    }

    @Override
    public void antiClockwise() {
        // Swap width and height
        double tmp = w;
        w = h;
        h = tmp;
    }

    // ...
}
```

As it stands, we don't want to deal with the complexity of allowing other shapes to have rotational behavior, so we restrict the interface so that it can only be implemented by the two simplest cases: circles and rectangles.

There is also an interesting interplay between sealed interfaces and records, which we will discuss in Chapter 5.

## Default Methods

From Java 8 onward, it is possible to declare methods in interfaces that include an implementation. In this section, we'll discuss these methods, which should be understood as optional methods in the API the interfaces represent—they're usually called *default methods*. Let's start by looking at the reasons why we need the default mechanism in the first place.

### Backward compatibility

The Java platform has always been very concerned with backward compatibility. This means that code that was written (or even compiled) for an earlier version of the platform must continue to work with later releases of the platform. This principle allows development groups to have a high degree of confidence that an upgrade of their JDK or Java Runtime Environment (JRE) will not break currently working applications.

Backward compatibility is a great strength of the Java platform, but in order to achieve it, some constraints are placed on the platform. One of them is that interfaces may not have new mandatory methods added to them in a new release of the interface.

For example, let's suppose that we want to update the `Positionable` interface with the ability to add a bottom-left bounding point as well:

```
public interface Positionable extends Centered {
  void setUpperRightCorner(double x, double y);
  double getUpperRightX();
  double getUpperRightY();
  void setLowerLeftCorner(double x, double y);
  double getLowerLeftX();
  double getLowerLeftY();
}
```

With this new definition, if we try to use this new interface with code developed for the old, it just won't work, as the existing code is missing the mandatory methods `setLowerLeftCorner()`, `getLowerLeftX()`, and `getLowerLeftY()`.

> You can see this effect quite easily in your own code. Compile a class file that depends on an interface. Then add a new mandatory method to the interface and try to run the program with the new version of the interface, together with your old class file. You should see the program crash with a `NoClassDefError`.

This limitation was a concern for the designers of Java 8—as one of their goals was to be able to upgrade the core Java Collections libraries and introduce methods that used lambda expressions.

To solve this problem, a new mechanism was needed, essentially to allow interfaces to evolve by allowing new methods to be added without breaking backward compatibility.

### Implementation of default methods

Adding new methods to an interface without breaking backward compatibility requires providing some implementation for the older implementations of the interface so that they can continue to work. This mechanism is a `default` method, and it was first added to the platform in JDK 8.

> A default method (sometimes called an optional method) can be added to any interface. This must include an implementation, called the *default implementation*, which is written inline in the interface definition.



The basic behavior of a default method is:

- An implementing class may (but is not required to) implement the default method.
- If an implementing class implements the default method, then the implementation in the class is used.
- If no other implementation can be found, then the default implementation is used.

An example default method is the `sort()` method. It's been added to the interface `java.util.List` in JDK 8, and is defined as:

```
// The <E> syntax is Java's way of writing a generic type - see
// the next section for full details. If you aren't familiar with
// generics, just ignore that syntax for now.
interface List<E> {
  // Other members omitted

  public default void sort(Comparator<? super E> c) {
    Collections.<E>sort(this, c);
  }
}
```

Thus, from Java 8 upward, any object that implements `List` has an instance method `sort()` that can be used to sort the list using a suitable `Comparator`. As the return type is `void`, we might expect that this is an in-place sort, and this is indeed the case.

One consequence of default methods is that when implementing multiple interfaces, it's possible that two or more interfaces may contain a default method with a completely identical name and signature.

For example:

```
interface Vocal {
  default void call() {
    System.out.println("Hello!");
  }
}

interface Caller {
  default void call() {
    Switchboard.placeCall(this);
  }
}

public class Person implements Vocal, Caller {
  // ... which default is used?
}
```

These two interfaces have very different default semantics for `call()` and could cause a potential implementation clash—a *colliding default method*. In versions of Java prior to 8, this could not occur, as the language permitted only single inheritance of implementation. The introduction of default methods means that Java now permits a limited form of *multiple inheritance* (but only of method implementations). Java still does not permit (and has no plans to add) multiple inheritance of object state.

> In some other languages, notably C++, this problem is known as *diamond inheritance*.

Default methods have a simple set of rules to help resolve any potential ambiguities:

- If a class implements multiple interfaces in such a way as to cause a potential clash of default method implementations, the implementing class must override the clashing method and provide a definition of what is to be done.
- Syntax is provided to allow the implementing class to simply call one of the interface default methods if that is what is required:

```
public class Person implements Vocal, Caller {

    public void call() {
        // Can do our own thing
        // or delegate to either interface
        // e.g.,
```

```
            // Vocal.super.call();
            // or
            // Caller.super.call();
        }
    }
```

As a side effect of the design of default methods, there is a slight, unavoidable usage issue that may arise in the case of evolving interfaces with colliding methods. Consider the case where a bytecode version 51.0 (Java 7) class implements two interfaces `A` and `B` with version numbers `a.0` and `b.0`, respectively. As defaults are not available in Java 7, this class will work correctly. However, if at a later time either or both interfaces adopt a default implementation of a colliding method, then compile-time breakage can occur.

For example, if version `a.1` introduces a default method in `A`, then the implementing class will pick up the implementation when run with the new version of the dependency. If version `b.1` now introduces the same method, it causes a collision:

- If `B` introduces the method as a mandatory (i.e., abstract) method, then the implementing class continues to work—both at compile time and at runtime.
- If `B` introduces the method as a default method, then this is not safe and the implementing class will fail both at compile and at runtime.

Type System

This minor issue is very much a corner case and in practice is a very small price to pay in order to have usable default methods in the language.

When working with default methods, we should be aware that there is a slightly restricted set of operations we can perform from within a default method:

- Call another method present in the interface's public API (whether mandatory or optional); some implementation for such methods is guaranteed to be available.
- Call a private method on the interface (Java 9 and up).
- Call a static method, whether on the interface or defined elsewhere.
- Use the `this` reference (e.g., as an argument to method calls).

The biggest takeaway from these restrictions is that even with default methods, Java interfaces still lack meaningful state; we cannot alter or store state within the interface.

Default methods have had a profound impact on the way that Java practitioners approach object-oriented programming. When combined with the rise of lambda expressions, they have upended many previous conventions of Java coding; we will discuss this in detail in the next chapter.

## Marker Interfaces

Occasionally it is useful to define an interface that is entirely empty. A class can implement this interface simply by naming it in its `implements` clause without having to implement any methods. In this case, any instances of the class become valid instances of the interface as well and can be cast to the type. Java code can check whether an object is an instance of the interface using the `instanceof` operator, so this technique is a useful way to provide additional information about an object. It can be thought of as providing additional, auxiliary type information about a class.

> Marker interfaces are much less widely used than they once were. Java's *annotations* (which we shall meet presently) have largely replaced them due to their much greater flexibility at conveying extended type information.

The interface `java.util.RandomAccess` is an example of a marker interface: `java.util.List` implementations use this interface to advertise that they provide fast random access to the elements of the list. For example, `ArrayList` implements `RandomAccess`, while `LinkedList` does not. Algorithms that care about the performance of random-access operations can test for `RandomAccess` like this:

```
// Before sorting the elements of a long arbitrary list, we may want
// to make sure that the list allows fast random access.  If not,
// it may be quicker to make a random-access copy of the list before
// sorting it. Note that this is not necessary when using
// java.util.Collections.sort().
List l = ...;  // Some arbitrary list we're given
if (l.size() > 2 && !(l instanceof RandomAccess)) {
    l = new ArrayList(l);
}
sortListInPlace(l);
```

As we will see later, Java's type system is very tightly coupled to the names that types have—an approach called *nominal typing*. A marker interface is a great example of this: it has nothing at all *except* a name.

# Java Generics

One of the great strengths of the Java platform is the standard library it ships. It provides a great deal of useful functionality—and in particular robust implementations of common data structures. These implementations are relatively simple to develop with and are well documented. The libraries are known as the Java Collections, and we will spend a big chunk of Chapter 8 discussing them. For a far more complete treatment, see the book *Java Generics and Collections* by Maurice Naftalin and Philip Wadler (O'Reilly).

Although they were still very useful, the earliest versions of the collections had a fairly major limitation: the data structure (sometimes called the *container*) essentially obscured the type of the data being stored in it.

> Data hiding and encapsulation is a great principle of object-oriented programming, but in this case, the opaque nature of the container caused a lot of problems for the developer.

Let's kick off the section by demonstrating the problem and showing how the introduction of *generic types* solved it and made life much easier for Java developers.

## Introduction to Generics

If we want to build a collection of `Shape` instances, we can use a `List` to hold them, like this:



```
List shapes = new ArrayList();   // Create a List to hold shapes

// Create some centered shapes, and store them in the list
shapes.add(new CenteredCircle(1.0, 1.0, 1.0));
// This is legal Java-but is a very bad design choice
shapes.add(new CenteredSquare(2.5, 2, 3));

// List::get() returns Object, so to get back a
// CenteredCircle we must cast
CenteredCircle c = (CenteredCircle)shapes.get(0);

// Next line causes a runtime failure
CenteredCircle c = (CenteredCircle)shapes.get(1);
```

A problem with this code stems from the requirement to perform a cast to get the shape objects back out in a usable form—the `List` doesn't know what type of objects it contains. Not only that, but it's actually possible to put different types of objects into the same container, and everything will work fine until an illegal cast is used and the program crashes.

What we really want is a form of `List` that understands what type it contains. Then, `javac` could detect when an illegal argument was passed to the methods of `List` and cause a compilation error, rather than deferring the issue to runtime.

> Collections that have all elements of the same type are called *homogeneous*, while the collections that can have elements of potentially different types are called *heterogeneous* (sometimes called "mystery meat collections").

Java provides a simple syntax to cater to homogeneous collections. To indicate that a type is a container that holds instances of another reference type, we enclose the *payload* type that the container holds within angle brackets:

```
// Create a List-of-CenteredCircle
List<CenteredCircle> shapes = new ArrayList<CenteredCircle>();

// Create some centered shapes, and store them in the list
shapes.add(new CenteredCircle(1.0, 1.0, 1.0));

// Next line will cause a compilation error
shapes.add(new CenteredSquare(2.5, 2, 3));

// List<CenteredCircle>::get() returns a CenteredCircle, no cast needed
CenteredCircle c = shapes.get(0);
```

This syntax ensures that a large class of unsafe code is caught by the compiler, before it gets anywhere near runtime. This is, of course, the whole point of static type systems—to use compile-time knowledge to help eliminate runtime problems wherever possible.

The resulting types, which combine an enclosing container type and a payload type, are usually called *generic types*, and they are declared like this:

```
interface Box<T> {
  void box(T t);
  T unbox();
}
```

This indicates that the `Box` interface is a general construct, which can hold any type of payload. It isn't really a complete interface by itself—it's more like a general description of a whole family of interfaces, one for each type that can be used in place of `T`.

## Generic Types and Type Parameters

We've seen how to use a generic type to provide enhanced program safety by using compile-time knowledge to prevent simple type errors. In this section, let's dig deeper into the properties of generic types.

The syntax `<T>` has a special name, *type parameter*, and another name for a generic type is a *parameterized type*. This should convey the sense that the container type (e.g., `List`) is parameterized by another type (the payload type). When we write a type like `Map<String, Integer>`, we are assigning concrete values to the type parameters.

When we define a type that has parameters, we need to do so in a way that does not make assumptions about the type parameters. So the `List` type is declared in a generic way as `List<E>`, and the type parameter `E` is used all the way through to stand as a placeholder for the actual type that programmers will use for the payload when they use the `List` data structure.

Type parameters always stand in for reference types. It is not possible to use a primitive type as a value for a type parameter.

The type parameter can be used in the signatures and bodies of methods as though it is a real type, for example:

```
interface List<E> extends Collection<E> {
  boolean add(E e);
  E get(int index);
  // other methods omitted
}
```

Note how the type parameter `E` can be used as a parameter for both return types and method arguments. We don't assume that the payload type has any specific properties and only make the basic assumption of consistency—that the type we put in is the same type that we will later get back out.

This enhancement has effectively introduced a new kind of type to Java's type system. By combining the container type with the value of the type parameter, we are making new types.



## Diamond Syntax

When we create an instance of a generic type, the righthand side of the assignment statement repeats the value of the type parameter. This is usually unnecessary, as the compiler can infer the values of the type parameters. In modern versions of Java, we can leave out the repeated type values in what is called *diamond syntax*.

Let's look at an example of how to use diamond syntax, by rewriting one of our earlier examples:

```
// Create a List-of-CenteredCircle using diamond syntax
List<CenteredCircle> shapes = new ArrayList<>();
```

This is a small improvement in the verbosity of the assignment statement—we've managed to save a few characters of typing. We'll return to the topic of type inference when we discuss lambda expressions later in this chapter.

## Type Erasure

In "Default Methods" on page 158, we discussed the Java platform's strong preference for backward compatibility. The addition of generics in Java 5 was another example of where backward compatibility was an issue for a new language feature.

The central question was how to make a type system that allowed older, nongeneric collection classes to be used alongside with newer, generic collections. The design decision was to achieve this by the use of casts:

```java
List someThings = getSomeThings();
// Unsafe cast, but we know that the
// contents of someThings are really strings
List<String> myStrings = (List<String>)someThings;
```

This means that `List` and `List<String>` are compatible as types, at least at some level. Java achieves this compatibility by *type erasure*. This means that generic type parameters are only visible at compile time—they are stripped out by `javac` and are not reflected in the bytecode.[1]

> The nongeneric type `List` is usually called a *raw type*. It is still perfectly legal Java to work with the raw form of types, even for types that are now generic. This is almost always a sign of poor-quality code, however.

The mechanism of type erasure gives rise to a difference in the type system seen by `javac` and that seen by the JVM—we will discuss this fully in "Compile and Runtime Typing" on page 174.

Type erasure also prohibits some other definitions, which would otherwise seem legal. In this code, we want to count the orders as represented in two slightly different data structures:

```java
// Won't compile
interface OrderCounter {
  // Name maps to list of order numbers
  int totalOrders(Map<String, List<String>> orders);

  // Name maps to total orders made so far
  int totalOrders(Map<String, Integer> orders);
}
```

This seems like perfectly legal Java code, but it will not compile. The issue is that although the two methods seem like normal overloads, after type erasure, the signature of both methods becomes:

```java
  int totalOrders(Map);
```

All that is left after type erasure is the raw type of the container—in this case, `Map`. The runtime would be unable to distinguish between the methods by signature, and so the language specification makes this syntax illegal.

1 Some small traces of generics remain, which can be seen at runtime via reflection.

## Bounded Type Parameters

Consider a simple generic box:

```
public class Box<T> {
    protected T value;

    public void box(T t) {
        value = t;
    }

    public T unbox() {
        T t = value;
        value = null;
        return t;
    }
}
```



This is a useful abstraction, but suppose we want to have a restricted form of box that holds only numbers. Java allows us to achieve this by using a *bound* on the type parameter. This is the ability to restrict the types that can be used as the value of a type parameter, for example:

```
public class NumberBox<T extends Number> extends Box<T> {
    public int intValue() {
        return value.intValue();
    }
}
```

The type bound `T extends Number` ensures that `T` can only be substituted with a type that is compatible with the type `Number`. As a result of this, the compiler knows that `value` will definitely have a method `intValue()` available on it.

> Notice that because the `value` field has protected access, it can be accessed directly in the subclass.

If we attempt to instantiate `NumberBox` with an invalid value for the type parameter, the result will be a compilation error:

```
NumberBox<Integer> ni = new NumberBox<>(); // This compiles fine

NumberBox<Object> no = new NumberBox<>(); // Won't compile
```

Beginning Java programmers should avoid using raw types altogether. Even experienced Java programmers can run into problems when using them. For example, when using raw types when working with a type bound, then the type bound can be evaded, but in doing so, the code is left vulnerable to a runtime exception:

```java
// Compiles
NumberBox n = new NumberBox();
// This is very dangerous
n.box(new Object());
// Runtime error
System.out.println(n.intValue());
```

The call to `intValue()` fails with a `java.lang.ClassCastException`—as `javac` has inserted an unconditional cast of `value` to `Number` before calling the method.

In general, type bounds can be used to write better generic code and libraries. With practice, some fairly complex constructions can be built, for example:

```java
public class ComparingBox<T extends Comparable<T>> extends Box<T>
                            implements Comparable<ComparingBox<T>> {
    @Override
    public int compareTo(ComparingBox<T> o) {
        if (value == null)
            return o.value == null ? 0 : -1;
        return value.compareTo(o.value);
    }
}
```

The definition might seem daunting, but the `ComparingBox` is really just a `Box` that contains a `Comparable` value. The type also extends the comparison operation to the `ComparingBox` type itself, just by comparing the contents of the two boxes.

## Introducing Covariance

The design of Java's generics contains the solution to an old problem. In the earliest versions of Java, before the collections libraries were even introduced, the language had been forced to confront a deep-seated type system design issue.

Put simply, the question is this:

> Should an array of strings be compatible with a variable of type array-of-object?

In other words, should this code be legal?

```java
String[] words = {"Hello World!"};
Object[] objects = words;
```

Without this, then even simple methods like `Arrays::sort` would have been very difficult to write in a useful way, as this would not work as expected:

```java
Arrays.sort(Object[] a);
```

The method declaration would work only for the type `Object[]` and not for any other array type. As a result of these complications, the very first version of the Java Language Standard determined that:

> If a value of type `C` can be assigned to a variable of type `P`, then a value of type `C[]` can be assigned to a variable of type `P[]`.

That is, arrays' assignment syntax *varies with* the base type that they hold, or arrays are *covariant*.

This design decision is rather unfortunate, as it leads to immediate negative consequences:

```
String[] words = {"Hello", "World!"};
Object[] objects = words;

// Oh, dear, runtime error
objects[0] = new Integer(42);
```

The assignment to `objects[0]` attempts to store an `Integer` into a piece of storage that is expecting to hold a `String`. This obviously will not work and will throw an `ArrayStoreException`.

> The usefulness of covariant arrays led to them being seen as a necessary evil in the very early days of the platform, despite the hole in the static type system that the feature exposes.



However, more recent research on modern open-source codebases indicates that array covariance is extremely rarely used and is a language misfeature.[2] You should avoid it when writing new code.

When considering the behavior of generics in the Java platform, a very similar question can be asked: "Is `List<String>` a subtype of `List<Object>`?" That is, can we write this:

```
// Is this legal?
List<Object> objects = new ArrayList<String>();
```

At first glance, this seems entirely reasonable—`String` is a subclass of `Object`, so we know that any `String` element in our collection is also a valid `Object`.

However, consider the following code (which is just the array covariance code translated to use `List`):

```
// Is this legal?
List<Object> objects = new ArrayList<String>();

// What do we do about this?
objects.add(new Object());
```

2 Raoul-Gabriel Urma and Janina Voigt, "Using the OpenJDK to Investigate Covariance in Java," *Java Magazine* (May/June 2012): 44–47.

As the type of `objects` was declared to be `List<Object>`, then it should be legal to add an `Object` instance to it. However, as the actual instance holds strings, then trying to add an `Object` would not be compatible, and so this would fail at runtime.

This would have changed nothing from the case of arrays, and so the resolution is to realize that although this is legal:

```
Object o = new String("X");
```

that does not mean that the corresponding statement for generic container types is also true, and as a result:

```
// Won't compile
List<Object> objects = new ArrayList<String>();
```

Another way of saying this is that `List<String>` is *not* a subtype of `List<Object>` or that generic types are *invariant*, not *covariant*. We will have more to say about this when we discuss bounded wildcards.

## Wildcards

A parameterized type, such as `ArrayList<T>`, is not *instantiable*; we cannot create instances of them. This is because `<T>` is just a type parameter, merely a placeholder for a genuine type. It is only when we provide a concrete value for the type parameter (e.g., `ArrayList<String>`) that the type becomes fully formed and we can create objects of that type.

This poses a problem if the type that we want to work with is unknown at compile time. Fortunately, the Java type system is able to accommodate this concept. It does so by having an explicit concept of the *unknown type*, which is represented as `<?>`. This is the simplest example of Java's *wildcard types*.

We can write expressions that involve the unknown type:

```
ArrayList<?> mysteryList = unknownList();
Object o = mysteryList.get(0);
```

This is perfectly valid Java: `ArrayList<?>` is a complete type that a variable can have, unlike `ArrayList<T>`. We don't know anything about `mysteryList`'s payload type, but that may not be a problem for our code.

For example, when we get an item out of `mysteryList`, it has a completely unknown type. However, we can be sure that the object is assignable to `Object`—because all valid values of a generic type parameter are reference types and all reference values can be assigned to a variable of type `Object`.

On the other hand, when we're working with the unknown type, there are some limitations on its use in user code. For example, this code will not compile:

```
// Won't compile
mysteryList.add(new Object());
```

The reason for this is simple: we don't know what the payload type of mysteryList is! For example, if mysteryList was really a instance of ArrayList<String>, then we wouldn't expect to be able to put an Object into it.

The only value that we know we can always insert into a container is null, as we know that null is a possible value for any reference type. This isn't that useful, and for this reason, the Java language spec also rules out instantiating a container object with the unknown type as payload, for example:

```
// Won't compile
List<?> unknowns = new ArrayList<?>();
```

The unknown type may seem to be of limited utility, but one very important use for it is as a starting point for resolving the covariance question. We can use the unknown type if we want to have a subtyping relationship for containers, like this:

```
// Perfectly legal
List<?> objects = new ArrayList<String>();
```



This means that List<String> *is* a subtype of List<?>—although when we use an assignment like the preceding one, we have lost some type information. For example, the return type of objects.get() is now effectively Object.

> For any value of the type parameter T, List<?> is not a subtype of the type List<T>.

The unknown type sometimes confuses developers—provoking questions like, "Why wouldn't you just use Object instead of the unknown type?" However, as we've seen, the need to have subtyping relationships between generic types essentially requires us to have a notion of the unknown type.

### Bounded wildcards

In fact, Java's wildcard types extend beyond just the unknown type, with the concept of *bounded wildcards*.

These are used to describe the inheritance hierarchy of a mostly unknown type—effectively making statements like, for example, "I don't know anything about this type, except that it must implement List."

This would be written as ? extends List in the type parameter. This provides a useful lifeline to programmers. Instead of being restricted to the totally unknown type, they know that at least the capabilities of the type bound are available.

The `extends` keyword is always used, regardless of whether the constraining type is a class or interface type.

This is an example of a concept called *type variance*, which is the general theory of how inheritance between container types relates to the inheritance of their payload types.

*Type covariance*
: This means that the container types have the same relationship to each other as the payload types do. This is expressed using the `extends` keyword.

*Type contravariance*
: This means that the container types have the inverse relationship to each other as the payload types. This is expressed using the `super` keyword.

These ideas tend to appear when discussing container types. For example, if `Cat` extends `Pet`, then `List<Cat>` is a subtype of `List<? extends Pet>`, and so:

```
List<Cat> cats = new ArrayList<Cat>();
List<? extends Pet> pets = cats;
```

However, this differs from the array case, because type safety is maintained in the following way:

```
pets.add(new Cat()); // won't compile
pets.add(new Pet()); // won't compile
cats.add(new Cat());
```

The compiler cannot prove that the storage pointed at by `pets` is capable of storing a `Cat` and so it rejects the call to `add()`. However, as `cats` definitely points at a list of `Cat` objects, then it must be acceptable to add a new one to the list.

As a result, it is very commonplace to see these types of generic constructions with types that act as producers or consumers of payload types.

For example, when the `List` is acting as a *producer* of `Pet` objects, then the appropriate keyword is `extends`.

```
Pet p = pets.get(0);
```

Note that for the producer case, the payload type appears as the return type of the producer method.

For a container type that is acting purely as a *consumer* of instances of a type, we would use the `super` keyword, and we would expect to see the payload type as the type of a method argument.

This is codified in the *Producer Extends, Consumer Super* (PECS) principle coined by Joshua Bloch.

As we will discuss in Chapter 8, both covariance and contravariance appear throughout the Java Collections. They largely exist to ensure that the generics just "do the right thing" and behave in a manner that should not surprise the developer.

## Generic Methods

A *generic method* is a method that is able to take instances of any reference type.

Let's look at an example. In Java, the comma is used to allow multiple declarations in a single line (usually referred to as a *compound declaration*). Other languages, such as Javascript or C, have a comma operator that is much more general. The JS comma operator `(,)` evaluates both expressions provided to it (from left to right) and returns the value of the last expression. The aim is to create a compound expression in which multiple expressions are evaluated, with the compound expression's value being the value of the rightmost of its member expressions. Note that any side effects from evaluating the expressions to the comma are always triggered, unlike in a short-circuiting logic operator.



Java's comma is much more restrictive than this, by design. This is because the comma in other languages can lead to some very hard-to-understand code and can be a fantastic source of bugs. However, if we did want to emulate the behavior of the comma operator from other language, we could do so by creating a generic method:

```
// Note that this class is not generic
public class Utils {
  public static <T> T comma(T a, T b) {
    return b;
  }
}
```

Calling the method `Utils.comma()` will cause the values of the expressions `a` and `b` to be computed, and any side effects to be triggered, before the method call, which is the behavior we want.

However, notice that even though a type parameter is used in the definition of the method, the class it is defined in (`Utils`) is not generic. Instead, we see that a new syntax is used to indicate that the method can be used freely, and that the return type is the same as the argument.

Let's look at another example, from the Java Collections library. In the `ArrayList` class we can find a method to create a new array object from an arraylist instance:

```
@SuppressWarnings("unchecked")
public <T> T[] toArray(T[] a) {
    if (a.length < size)
```

```
            // Make a new array of a's runtime type, but my contents:
            return (T[]) Arrays.copyOf(elementData, size, a.getClass());
        System.arraycopy(elementData, 0, a, 0, size);
        if (a.length > size)
            a[size] = null;
        return a;
    }
```

This method uses the low-level arraycopy() method to do the actual work.

> If we look at the class definition for ArrayList we can see that it is a generic class—but the type parameter is <E>, not <T>, and the type parameter <E> does not appear at all in the definition of toArray().

The toArray() method provides one half of a bridge API between the collections and Java's original arrays. The other half of the API—moving from arrays to collections—involves a few additional subtleties, as we will discuss in Chapter 8.

## Compile and Runtime Typing

Consider an example piece of code:

```
List<String> l = new ArrayList<>();
System.out.println(l);
```

We can ask the following question: what is the type of l? The answer to that question depends on whether we consider l at compile time (i.e., the type seen by javac) or at runtime (as seen by the JVM).

javac will see the type of l as List-of-String and will use that type information to carefully check for syntax errors, such as an attempted add() of an illegal type.

Conversely, the JVM will see l as an object of type ArrayList, as we can see from the println() statement. The runtime type of l is a raw type due to type erasure.

The compile-time and runtime types are therefore slightly different from each other. The slightly strange thing is that in some ways, the runtime type is both more *and* less specific than the compile-time type.

The runtime type is less specific than the compile-time type, because the type information about the payload type is gone—it has been erased, and the resulting runtime type is just a raw type.

The compile-time type is less specific than the runtime type, because we don't know exactly what concrete type l will be; all we know is that it will be of a type compatible with List.

The differences between compile-time and runtime typing sometimes confuse new Java programmers, but the distinction quickly comes to be seen as a normal part of working in the language.

## Using and Designing Generic Types

When working with Java's generics, it can be helpful to think in terms of two different levels of understanding:

*Practitioner*
: A practitioner needs to use existing generic libraries and to build some fairly simple generic classes. At this level, the developer should also understand the basics of type erasure, as several Java syntax features are confusing without at least an awareness of the runtime handling of generics.

*Designer*
: The designer of new libraries that use generics needs to understand much more of the capabilities of generics. There are some nastier parts of the spec, including a full understanding of wildcards, and advanced topics such as "capture-of" error messages.

Java generics are one of the most complex parts of the language specification with a lot of potential corner cases. Not every developer needs to fully understand this part of the language, at least not on their first encounter with this part of Java's type system.



# Enums and Annotations

We have already met records, but Java has additional specialized forms of classes and interfaces used to fulfill specific roles in the type system. They are known as *enumerated types* and *annotation types*, or normally just *enums* and *annotations*.

## Enums

Enums are a variation of classes that have limited functionality and the specific semantic meaning that the type has only a small number of possible permitted values.

For example, suppose we want to define a type to represent the primary colors of red, green, and blue, and we want these to be the only possible values of the type. We can do this by using the `enum` keyword:

```
public enum PrimaryColor {
  // The ; is not required at the end of the list of instances
  RED, GREEN, BLUE
}
```

The only available instances of the type `PrimaryColor` can then be referenced as static fields: `PrimaryColor.RED`, `PrimaryColor.GREEN`, and `PrimaryColor.BLUE`.

In other languages, such as C++, the role of enum types is fulfilled by using constant integers, but Java's approach provides better type safety and more flexiblity.

As enums are specialized classes, enums can have member fields and methods. If they do have a body (consisting of fields or methods), then the semicolon at the end of the list of instances is required, and the list of enum constants must precede the methods and fields.

For example, suppose that we want to have an enum that encompasses the suits of standard playing cards. We can achieve this by using an enum that takes a value as a parameter, like this:

```
public enum Suit {
    // ; at the end of list required for enums with parameters
    HEART('♥'),
    CLUB('♣'),
    DIAMOND('♦'),
    SPADE('♠');

    private char symbol;
    private char letter;

    public char getSymbol() {
        return symbol;
    }

    public char getLetter() {
        return letter;
    }

    private Suit(char symbol) {
        this.symbol = symbol;
        this.letter = switch (symbol) {
            case '♥' -> 'H';
            case '♣' -> 'C';
            case '♦' -> 'D';
            case '♠' -> 'S';
            default -> throw new RuntimeException("Illegal:" + symbol);
        };
    }
}
```

The parameters (only one of them in this example) are passed to the constructor to create the individual enum instances. As the enum instances are created by the Java runtime, and can't be instantiated from outside, the constructor is declared as private.

Enums have some special properties:

- All (implicitly) extend `java.lang.Enum`
- May not be generic
- May implement interfaces
- Cannot be extended
- May have only abstract methods if all enum values provide an implementation body
- May not be directly instantiated by `new`

## Annotations

Annotations are a specialized kind of interface that, as the name suggests, annotate some part of a Java program.

For example, consider the `@Override` annotation. You may have seen it on some methods in some of the earlier examples and may have asked the following question: what does it do?

The short, and perhaps surprising, answer is that it does nothing at all.

The less short (and flippant) answer is that, like all annotations, it has no direct effect but instead acts as additional information about the method that it annotates; in this case, it denotes that a method overrides a superclass method.

This acts as a useful hint to compilers and integrated development environments (IDEs)—if a developer has misspelled the name of a method intended to be an override of a superclass method, then the presence of the `@Override` annotation on the misspelled method (which does not override anything) alerts the compiler to the fact that something is not right.

Annotations, as originally conceived, were not supposed to alter program semantics; instead, they were to provide optional metadata. In its strictest sense, this means that they should not affect program execution and instead should only provide information for compilers and other pre-execution phases.

In practice, modern Java applications make heavy use of annotations, and this now includes many use cases that essentially render the annotated classes useless without additional runtime support.

For example, classes bearing annotations such as `@Inject`, `@Test`, or `@Autowired` cannot realistically be used outside of a suitable container. As a result, it is difficult to argue that such annotations do not violate the "no semantic meaning" rule.

The platform defines a small number of basic annotations in `java.lang`. The original set were `@Override`, `@Deprecated`, and `@SuppressWarnings`, which were used to indicate that a method was overriden, deprecated, or that it generated some compiler warnings that should be suppressed.

These were augmented by `@SafeVarargs` in Java 7 (which provides extended warning suppression for varargs methods) and `@FunctionalInterface` in Java 8.

This last annotation indicates an interface can be used as a target for a lambda expression—it is a useful marker annotation although not mandatory, as we will see.

Annotations have some special properties, compared to regular interfaces:

- All (implicitly) extend `java.lang.annotation.Annotation`
- May not be generic
- May not extend any other interface
- May only define zero-arg methods
- May not define methods that throw exceptions
- Have restrictions on the return types of methods
- Can have a default return value for methods

In practice, annotations do not typically have a great deal of functionality and instead are a fairly simple language concept.

## Defining Custom Annotations

Defining custom annotation types for use in your own code is not that hard. The `@interface` keyword allows the developer to define a new annotation type, in much the same way that `class` or `interface` is used.

> The key to writing custom annotations is the use of "meta-annotations." These are special annotations that appear on the definition of new (custom) annotation types.

The meta-annotations are defined in `java.lang.annotation` and allow the developer to specify policy for where the new annotation type is to be used and how it will be treated by the compiler and runtime.

There are two primary meta-annotations that are both required when creating a new annotation type—`@Target` and `@Retention`. These both take values that are represented as enums.

The `@Target` meta-annotation indicates where the new custom annotation can be legally placed within Java source code. The enum `ElementType` has the possible values `TYPE`, `FIELD`, `METHOD`, `PARAMETER`, `CONSTRUCTOR`, `LOCAL_VARIABLE`, `ANNOTATION_TYPE`, `PACKAGE`, `TYPE_PARAMETER`, and `TYPE_USE`, and annotations can indicate that they intend to be used at one or more of these locations.

The other meta-annotation is `@Retention`, which indicates how `javac` and the Java runtime should process the custom annotation type. It can have one of three values, which are represented by the enum `RetentionPolicy`:

`SOURCE`
: Annotations with this retention policy are discarded by `javac` during compilation.

`CLASS`
: This means that the annotation will be present in the class file but will not necessarily be accessible at runtime by the JVM. This is rarely used but is sometimes seen in tools that do offline analysis of JVM bytecode.

`RUNTIME`
: This indicates that the annotation will be available for user code to access at runtime (by using reflection).

Let's take a look at an example, a simple annotation called `@Nickname`, which allows the developer to define a nickname for a method, which can then be used to find the method reflectively at runtime:

```
@Target(ElementType.METHOD)
@Retention(RetentionPolicy.RUNTIME)
public @interface Nickname {
    String[] value() default {};
}
```

This is all that's required to define the annotation—a syntax element where the annotation can appear, a retention policy, and the name of the element. As we need to be able to supply the nickname we're assigning to the method, we also need to define a method on the annotation. Despite this, defining new custom annotations is a remarkably compact undertaking.

In addition to the two primary meta-annotations, there are also the `@Inherited` and `@Documented` meta-annotations. These are much less frequently encountered in practice, and details on them can be found in the platform documentation.

## Type Annotations

With the release of Java 8, two new values for `ElementType` were added: `TYPE_PARAMETER` and `TYPE_USE`. These new values allow the use of annotations in places where they were previously not legal, such as at any site where a type is used. This enables the developer to write code such as:

```
@NotNull String safeString = getMyString();
```

The extra type information conveyed by the `@NotNull` can then be used by a special type checker to detect problems (a possible `NullPointerException`, in this example) and to perform additional static analysis. The basic Java 8 distribution ships with some basic pluggable type checkers, but it also provides a framework for allowing developers and library authors to create their own.

In this section, we've met Java's enum and annotation types. Let's move on to consider the next important part of Java's type system: lambda expressions.

## Lambda Expressions

One of the most eagerly anticipated features of Java 8 was the introduction of lambda expressions (frequently referred to as just lambdas).

This major upgrade to the Java platform was driven by five goals, in roughly descending order of priority:

- More expressive programming
- Better libraries
- Concise code
- Improved programming safety
- Potentially increased data parallelism

Lambdas have three key aspects that help define the essential nature of the feature:

- They allow small bits of code to be written inline as literals in a program.
- They relax the strict grammar of Java code by using type inference.
- They facilitate a more functional style of programming Java.

As we saw in Chapter 2, the syntax for a lambda expression is to take a list of parameters (the types of which are typically inferred), and to attach that to a method body, like this:

```
(p, q) -> { /* method body */ }
```

This can provide a very compact way to represent what is effectively a single method. It is also a major departure from earlier versions of Java—until now, we always required a class declaration and then a complete method declaration, all of which add to the verboseness of the code.

In fact, before the arrival of lambdas, the only way to approximate this coding style was to use *anonymous classes*, which we will discuss later in this chapter. However, since Java 8, lambdas have proved to be very popular with Java programmers and now have mostly taken over the role of anonymous classes.

> Despite the similarities between lambda expressions and anonymous classes, lambdas are *not* simply syntactic sugar over anonymous classes. In fact, lambdas are implemented using method handles (which we will meet in Chapter 11) and a special JVM bytecode called `invokedynamic`.

Lambda expressions represent the creation of an object of a specific type. The type of the instance that is created is known as the *target type* of the lambda.

Only certain types are eligible to be the target of a lambda.

Target types are also called *functional interfaces* and they must:

- Be interfaces
- Have only one nondefault method (but may have other methods that are default)

Some developers also like to use the *single abstract method* (or SAM) type to refer to the interface type that the lambda is converted into. This draws attention to the fact that to be usable by the lambda expression mechanism, an interface must have only a single nondefault method.

> A lambda expression has almost all of the component parts of a method, with the obvious exception that a lambda doesn't have a name. In fact, many developers like to think of lambdas as "anonymous methods."



As a result, this means that the single line of code:

```
Runnable r  = () -> System.out.println("Hello");
```

does not result in the execution of the `println()` but instead creates an object, which is assigned to a variable `r`, of type `Runnable`. This object, `r`, will execute the `println()` statement, but only when `r.run()` is called, and not until then.

## Lambda Expression Conversion

When `javac` encounters a lambda expression, it interprets it as the body of a method with a specific signature—but which method?

To resolve this question, `javac` looks at the surrounding code. To be legal Java code, the lambda expression must satisfy the following properties:

- The lambda must appear where an instance of an interface type is expected.
- The expected interface type should have exactly one mandatory method.
- The expected interface method should have a signature that exactly matches that of the lambda expression.

If this is the case, then an instance is created of a type that implements the expected interface and uses the lambda body as the implementation for the mandatory method.

This slightly complex conversion approach comes from the desire to keep Java's type system as purely *nominative* (based on names). The lambda expression is said to be *converted* to an instance of the correct interface type.

From this discussion, we can see that although Java 8 has added lambda expressions, they have been specifically designed to fit into Java's existing type system—which has a very strong emphasis on nominal types (rather than the other possible sorts of types that exist in some other programming languages).

Let's consider an example of lambda conversion—the `list()` method of the `java.io.File` class. This method lists the files in a directory. Before it returns the list, though, it passes the name of each file to a `FilenameFilter` object that the programmer must supply. This `FilenameFilter` object accepts or rejects each file and is a SAM type defined in the `java.io` package:

```
@FunctionalInterface
public interface FilenameFilter {
    boolean accept(File dir, String name);
}
```

The type `FilenameFilter` carries the `@FunctionalInterface` to indicate that it is a suitable type to be used as the target type for a lambda. However, this annotation is not required, and any type that meets the requirements (by being an interface and a SAM type) can be used as a target type.

This is because the JDK and the existing corpus of Java code already had a huge number of SAM types available before Java 8 was released. To require potential target types to carry the annotation would have prevented lambdas from being retrofitted to existing code for no real benefit.

In code that you write, you should always try to indicate when your types are usable as target types, which you can do by adding the `@FunctionalInterface` to them. This aids readability and can help some automated tools as well.

Here's how we can define a `FilenameFilter` class to list only those files whose names end with *.java*, using a lambda:

```
File dir = new File("/src");      // The directory to list

String[] filelist = dir.list((d, fName) -> fName.endsWith(".java"));
```

For each file in the list, the block of code in the lambda expression is evaluated. If the method returns `true` (which happens if the filename ends in *.java*), then the file is included in the output—which ends up in the array `filelist`.

This pattern, where a block of code is used to test if an element of a container matches a condition, and to return only the elements that pass the condition, is called a *filter idiom*. It is one of the standard techniques of functional programming, which we will discuss in more depth presently.

## Method References

Recall that we can think of lambda expressions as objects representing methods that don't have names. Now, consider this lambda expression:

```
// In real code this would probably be
// shorter because of type inference
(MyObject myObj) -> myObj.toString()
```

This will be autoconverted to an implementation of a `@FunctionalInterface` type that has a single nondefault method that takes a single `MyObject` and returns a `String`—specifically, the string obtained by calling `toString()` on the instance of `MyObject`. However, this seems like excessive boilerplate, and so Java 8 provides a syntax for making this easier to read and write:

```
MyObject::toString
```

This shorthand, known as a *method reference*, uses an existing method as a lambda expression. The method reference syntax is completely equivalent to the previous form expressed as a lambda. It can be thought of as using an existing method but ignoring the name of the method, so it can be used as a lambda and then autoconverted in the usual way. Java defines four types of method reference, which are equivalent to four slightly different lambda expression forms (see Table 4-1).

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*Table 4-1. Method references*

| Name | Method reference | Equivalent lambda |
|---|---|---|
| Unbound | `Trade::getPrice` | `trade -> trade.getPrice()` |
| Bound | `System.out::println` | `s -> System.out.println(s)` |
| Static | `System::getProperty` | `key -> System.getProperty(key)` |
| Constructor | `Trade::new` | `price -> new Trade(price)` |

The form we originally introduced can be seen to be an *unbound method reference*. When we use an unbound method reference, it is equivalent to a lambda that is expecting an instance of the type that contains the method reference—in Table 4-1 that is a `Trade` object.

It is called an unbound method reference because the receiver object needs to be supplied (as the first argument to the lambda) when the method reference is used. That is, we are going to call `getPrice()` on some `Trade` object, but the supplier of the method reference has not defined which one. That is left up to the user of the reference.

By contrast, a *bound method reference* always includes the receiver as part of the instantiation of the method reference. In Table 4-1, the receiver is `System.out` so, when the reference is used, the `println()` method will always be called on `System.out`, and all the parameters of the lambda will be used as method parameters to `println()`.

We will discuss use cases for method references versus lambda expressions in more detail in the next chapter.

## Functional Programming

Java is fundamentally an object-oriented language. However, with the arrival of lambda expressions, it becomes much easier to write code that is closer to the functional approach.

> There's no single definition of exactly what constitutes a *functional language*—but there is at least consensus that it should at a minimum contain the ability to represent a function as a value that can be put into a variable.

Java has always (since version 1.1) been able to represent functions via inner classes (see next section), but the syntax was complex and lacking in clarity. Lambda expressions greatly simplify that syntax, and so it is only natural that more developers will be seeking to use aspects of functional programming in their Java code.

The first taste of functional programming that Java developers are likely to encounter are three basic idioms that are remarkably useful:

`map()`
: The map idiom is used with lists and list-like containers. The idea is that a function is passed in that is applied to each element in the collection, and a new collection is created that consists of the results of applying the function to each element in turn. This means that a map idiom converts a collection of one type to a collection of potentially a different type.

`filter()`
: We have already met an example of the filter idiom, when we discussed how to replace an anonymous implementation of `FilenameFilter` with a lambda. The filter idiom is used for producing a new subset of a collection, based on some selection criteria. Note that in functional programming, it is normal to produce a new collection rather than modifying an existing one in place.

`reduce()`
: The reduce idiom has several different guises. It is an aggregation operation, which can be called *fold*, *accumulate*, or *aggregate* as well as reduce. The basic idea is to take an initial value and an aggregation (or reduction) function, and apply the reduction function to each element in turn, building up a final result

for the whole collection by making a series of intermediate results—similar to a "running total"—as the reduce operation traverses the collection.

Java has full support for these key functional idioms (and several others). The implementation is explained in some depth in Chapter 8, where we discuss Java's data structures and collections, and in particular the *stream* abstraction, which makes all of this possible.

Let's conclude this introduction with some words of caution. It's worth noting that Java is best regarded as having support for "slightly functional programming." It is not an especially functional language, nor does it try to be. Some particular aspects of Java that militate against any claims to being a functional language include:

- Java has no structural types, which means no "true" function types. Every lambda is automatically converted to the appropriate target type.
- Type erasure causes problems for functional programming—type safety can be lost for higher-order functions.
- Java is inherently mutable (as we'll discuss in Chapter 6)—mutability is often regarded as highly undesirable for functional languages.
- The Java collections are imperative, not functional. Collections must be converted to streams to use functional style.

Despite this, easy access to the basics of functional programing—and especially idioms such as map, filter, and reduce—is a huge step forward for the Java community. These idioms are so useful that a large majority of Java developers will never need or miss the more advanced capabilities provided by languages with a more thoroughbred functional pedigree.

In truth, many of these techniques were possible using nested types (see next section for details), via patterns like callbacks and handlers, but the syntax was always quite cumbersome, especially given that you had to explicitly define a completely new type even when you needed to express only a single line of code in the callback.

## Lexical Scoping and Local Variables

A local variable is defined within a block of code that defines its *scope* and, outside of that scope, a local variable cannot be accessed and ceases to exist. Only code within the curly braces that define the boundaries of a block can use local variables defined in that block. This type of scoping is known as *lexical scoping*, and it just defines a section of source code within which a variable can be used.

It is common for programmers to think of such a scope as *temporal* instead—that is, to think of a local variable as existing from the time the JVM begins executing the block until the time control exits the block. This is usually a reasonable way to think about local variables and their scope. However, lambda expressions (and anonymous and local classes, which we will meet later) have the ability to bend or break this intuition.

This can cause effects that some developers initially find surprising. Because lambdas can use local variables, they can contain copies of values from lexical scopes that no longer exist. This can been seen in the following code:

```
public interface IntHolder {
    public int getValue();
}

public class Weird {
    public static void main(String[] args) {
        IntHolder[] holders = new IntHolder[10];
        for (int i = 0; i < 10; i++) {
            final int fi = i;

            holders[i] = () -> {
                return fi;
            };
        }
      // The lambda is now out of scope, but we have 10 valid instances
      // of the class the lambda has been converted to in our array.
      // The local variable fi is not in our scope here, but is still
      // in scope for the getValue() method of each of those 10 objects.
      // So call getValue() for each object and print it out.
      // This prints the digits 0 to 9.
        for (int i = 0; i < 10; i++) {
            System.out.println(holders[i].getValue());
        }
    }
}
```

Each instance of a lambda has an automatically created private copy of each of the final local variables it uses, so, in effect, it has its own private copy of the scope that existed when it was created. This is sometimes referred to as a *captured* variable.

Lambdas that capture variables like this are referred to as *closures*, and the variables are said to have been *closed over*.

Other programming languages may have a slightly different definition of a closure. In fact, some theorists would dispute that Java's mechanism counts as a closure because, technically, it is the contents of the variable (a value) and not the variable itself that is captured.

In practice, the preceding closure example is more verbose than it needs to be in two separate ways:

- The lambda has an explicit scope `{}` and `return` statement.
- The variable `fi` is explicitly declared `final`.

The compiler `javac` helps with both of these.

Lambdas that return the value of only a single expression need not include a scope or `return`; instead, the body of the lambda is just the expression without the need for curly braces. In our example, we have explicitly included the braces and `return` statement to spell out that the lambda is defining its own scope.

In early versions of Java, there were two hard requirements when closing over a variable:

- The captures must not be modified after they have been captured (e.g., after the lambda)
- The captured variables must be declared `final`

However, in recent Java versions, `javac` can analyze the code and detect whether the programmer attempts to modify the captured variable after the scope of the lambda. If not, then the `final` qualifier on the captured variable can be omitted (such a variable is said to be *effectively final*). If the `final` qualifier is omitted, then it is a compile-time error to attempt to modify a captured variable after the lambda's scope.

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The reason for this is that Java implements closures by copying the bit pattern of the contents of the variable into the scope created by the closure. Further changes to the contents of the closed-over variable would not be reflected in the copy contained in closure scope, so the design decision was made to make such changes illegal and a compile-time error.

These assists from `javac` mean that we can rewrite the inner loop of the preceding example to the very compact form:

```
for (int i = 0; i < 10; i++) {
    int fi = i;
    holders[i] = () -> fi;
}
```

Closures are very useful in some styles of programming, and different programming languages define and implement closures in different ways. Java implements closures as lambda expressions, but local classes and anonymous classes can also capture state—and in fact this is how Java implemented closures before lambdas were available.

# Nested Types

The classes, interfaces, and enum types we have seen so far in this book have all been defined as *top-level types*. This means that they are direct members of packages, defined independently of other types. However, type definitions can also be nested within other type definitions. These *nested types*, commonly known as "inner classes," are a powerful feature of the Java language.

In general, nested types are used for two separate purposes, both related to encapsulation. First, a type may be nested because it needs especially intimate access to the internals of another type. By being a nested type, it has access in the same way that member variables and methods do. This means that nested types have privileged access and can be thought of as "slightly bending the rules of encapsulation."

Another way of thinking about this use case of nested types is that they are types that are somehow tied together with another type. This means that they don't really have a completely independent existence as an entity and only coexist.

Alternatively, a type may be only required for a very specific reason and in a very small section of code. This means that it should be tightly localized, as it is really part of the implementation detail.

In older versions of Java, the only way to do this was with a nested type, such as an anonymous implementation of an interface. In practice, with the advent of Java 8, this use case has substantially been taken over by lambda expressions. The use of anonymous types as closely localized types has dramatically declined as a result, although it still persists for some cases.

Types can be nested within another type in four different ways:

*Static member types*
: A static member type is any type defined as a `static` member of another type. Nested interfaces, enums, and annotations are always static (even if you don't use the keyword).

*Nonstatic member classes*
: A "nonstatic member type" is simply a member type that is not declared `static`. Only classes can be nonstatic member types.

*Local classes*
: A local class is a class that is defined and only visible within a block of Java code. Interfaces, enums, and annotations may not be defined locally.

*Anonymous classes*
: An anonymous class is a kind of local class that has no meaningful name that is useful to humans; it is merely an arbitrary name assigned by the compiler, which programmers should not use directly. Interfaces, enums, and annotations cannot be defined anonymously.

The term "nested types," while correct and precise, is not widely used by developers. Instead, most Java programmers use the much vaguer term "inner class." Depending on the situation, this can refer to a nonstatic member class, local class, or anonymous class, but not a static member type, with no real way to distinguish between them.

Fortunately, although the terminology for describing nested types is not always clear, the syntax for working with them is, and it is usually apparent from context which kind of nested type is being discussed.

> Until Java 11, nested types were implemented using a compiler trick and were mostly syntactic sugar. Experienced Java programmers should note that this detail changed in Java 11, and it is no longer done in quite the same way as it used to be.

Let's move on to describe each of the four kinds of nested types in greater detail. Each section describes the features of the nested type, the restrictions on its use, and any special Java syntax used with the type.

## Static Member Types

A *static member type* is much like a regular top-level type. For convenience, however, it is nested within the namespace of another type. Static member types have the following basic properties:

- A static member type is like the other static members of a class: static fields and static methods.
- A static member type is not associated with any instance of the containing class (i.e., there is no `this` object).
- A static member type can access (only) the `static` members of the class that contains it.
- A static member type has access to all the `static` members (including any other static member types) of its containing type.
- Nested interfaces, enums, and annotations are implicitly static, whether or not the `static` keyword appears.
- Any type nested within an interface or annotation is also implicitly `static`.
- Static member types may be defined within top-level types or nested to any depth within other static member types.
- A static member type may not be defined within any other kind of nested type.

Let's look at a quick example of the syntax for static member types. Example 4-1 shows a helper interface defined as a static member of a containing interface, in this case Java's `Map`.

*Example 4-1. Defining and using a static member interface*

```
public interface Map<K, V> {
    // ...

    Set<Map.Entry<K, V>> entrySet();

    // All nested interfaces are automatically static
    interface Entry<K, V> {
        K getKey();
```

```
        V getValue();
        V setValue(V value);

        // other members elided
    }

    // other members elided
}
```

When used by an external class, `Entry` will be referred to by its hierarchical name `Map.Entry`.

### Features of static member types

A static member type has access to all static members of its containing type, including `private` members. The reverse is true as well: the methods of the containing type have access to all members of a static member type, including the `private` members. A static member type even has access to all the members of any other static member types, including the `private` members of those types. A static member type can use any other static member without qualifying its name with the name of the containing type.

Top-level types can be declared as either `public` or package-private (if they're declared without the `public` keyword). But declaring top-level types as `private` and `protected` wouldn't make a great deal of sense—`protected` would just mean the same as package-private, and a `private` top-level class would be unable to be accessed by any other type.

Static member types, on the other hand, are members and so can use any access control modifiers that other members of the containing type can. These modifiers have the same meanings for static member types as they do for other members of a type.

Under most circumstances, the `Outer.Inner` syntax for class names provides a helpful reminder that the inner class is interconnected with its containing type. However, the Java language does permit you to use the `import` directive to directly import a static member type:

```
    import java.util.Map.Entry;
```

You can then reference the nested type without including the name of its enclosing type (e.g., just as `Entry`).

> You can also use the `import static` directive to import a static member type. See "Packages and the Java Namespace" on page 98 in Chapter 2 for details on `import` and `import static`.

However, importing a nested type obscures the fact that that type is closely associated with its containing type—which is usually important information—and as a result it is not commonly done.

## Nonstatic Member Classes

A *nonstatic member class* is a class that is declared as a member of a containing class or enumerated type without the `static` keyword:

- If a static member type is analogous to a class field or class method, a nonstatic member class is analogous to an instance field or instance method.
- Only classes can be nonstatic member types.
- An instance of a nonstatic member class is always associated with an instance of the enclosing type.
- The code of a nonstatic member class has access to all the fields and methods (both `static` and non-`static`) of its enclosing type.
- Several Java syntax features exist specifically to work with the enclosing instance of a nonstatic member class.

Example 4-2 shows how a member class can be defined and used. This example shows a `LinkedStack` example: it defines a nested interface that describes the nodes of the linked list underlying the stack and a nested class to allow enumeration of the elements on the stack. The member class defines an implementation of the `java.util.Iterator` interface.

*Example 4-2. An iterator implemented as a member class*

```
import java.util.Iterator;

public class LinkedStack {

    // Our static member interface
    public interface Linkable {
        public Linkable getNext();
        public void setNext(Linkable node);
    }

    // The head of the list
    private Linkable head;

    // Method bodies omitted here
    public void push(Linkable node) { ... }
    public Linkable pop() { ... }

    // This method returns an Iterator object for this LinkedStack
    public Iterator<Linkable> iterator() { return new LinkedIterator(); }
```

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```
    // Here is the implementation of the Iterator interface,
    // defined as a nonstatic member class.
    protected class LinkedIterator implements Iterator<Linkable> {
        Linkable current;

        // The constructor uses a private field of the containing class
        public LinkedIterator() { current = head; }

        // The following three methods are defined
        // by the Iterator interface
        public boolean hasNext() {  return current != null; }

        public Linkable next() {
            if (current == null)
              throw new java.util.NoSuchElementException();
            Linkable value = current;
            current = current.getNext();
            return value;
        }

        public void remove() { throw new UnsupportedOperationException(); }
    }
}
```

Notice how the LinkedIterator class is nested within the LinkedStack class. LinkedIterator is a helper class used only within LinkedStack, so having it defined close to where it is used by the containing class makes for a clean design.

### Features of member classes

Like instance fields and instance methods, every instance of a nonstatic member class is associated with an instance of the class in which it is defined. This means that the code of a member class has access to all the instance fields and instance methods (as well as the static members) of the containing instance, including any that are declared private.

This crucial feature was already illustrated in Example 4-2. Here is the LinkedStack.LinkedIterator() constructor again:

```
public LinkedIterator() { current = head; }
```

This single line of code sets the current field of the inner class to the value of the head field of the containing class. The code works as shown, even though head is declared as a private field in the containing class.

A nonstatic member class, like any member of a class, can be assigned one of the standard access control modifiers. In Example 4-2, the LinkedIterator class is declared protected, so it is inaccessible to code (in a different package) that uses the LinkedStack class but is accessible to any class that subclasses LinkedStack.

Member classes have two important restrictions:

- A nonstatic member class cannot have the same name as any containing class or package. This is an important rule, one that is *not* shared by fields and methods.
- Nonstatic member classes cannot contain any `static` fields, methods, or types, except for constant fields declared both `static` and `final`.

### Syntax for member classes

The most important feature of a member class is that it can access the instance fields and methods in its containing object.

If we want to use explicit references, and make use of `this`, then we have to use a special syntax for explicitly referring to the containing instance of the `this` object. For example, if we want to be explicit in our constructor, we can use the following syntax:

```
public LinkedIterator() { this.current = LinkedStack.this.head; }
```



The general syntax is *`classname.this`*, where *`classname`* is the name of a containing class. Note that member classes can themselves contain member classes, nested to any depth.

However, no member class can have the same name as any containing class, so the use of the enclosing class name prepended to `this` is a perfectly general way to refer to any containing instance. Another way of saying this is that the syntax construction `EnclosingClass.this` is an unambiguous way of referring to the containing instance as an *uplevel reference*.

## Local Classes

A *local class* is declared locally within a block of Java code rather than as a member of a class. Only classes may be defined locally: interfaces, enumerated types, and annotation types must be top-level or static member types. Typically, a local class is defined within a method, but it can also be defined within a static initializer or instance initializer of a class.

Just as all blocks of Java code appear within class definitions, all local classes are nested within containing blocks. For this reason, although local classes share many of the features of member classes, it is usually more appropriate to think of them as an entirely separate kind of nested type.

> See Chapter 5 for details as to when it's appropriate to choose a local class versus a lambda expression.

The defining characteristic of a local class is that it is local to a block of code. Like a local variable, a local class is valid only within the scope defined by its enclosing block. Example 4-3 illustrates how we can modify the `iterator()` method of the `LinkedStack` class so it defines `LinkedIterator` as a local class instead of a member class.

By doing this, we move the definition of the class even closer to where it is used and hopefully improve the clarity of the code even further. For brevity, Example 4-3 shows only the `iterator()` method, not the entire `LinkedStack` class that contains it.

*Example 4-3. Defining and using a local class*

```
// This method returns an Iterator object for this LinkedStack
public Iterator<Linkable> iterator() {
    // Here's the definition of LinkedIterator as a local class
    class LinkedIterator implements Iterator<Linkable> {
        Linkable current;

        // The constructor uses a private field of the containing class
        public LinkedIterator() { current = head; }

        // The following three methods are defined
        // by the Iterator interface
        public boolean hasNext() {  return current != null; }

        public Linkable next() {
            if (current == null)
              throw new java.util.NoSuchElementException();
            Linkable value = current;
            current = current.getNext();
            return value;
        }

        public void remove() { throw new UnsupportedOperationException(); }
    }

    // Create and return an instance of the class we just defined
    return new LinkedIterator();
}
```

### Features of local classes

Local classes have the following interesting features:

- Like member classes, local classes are associated with a containing instance and can access any members, including `private` members, of the containing class.

- In addition to accessing fields defined by the containing class, local classes can access any local variables, method parameters, or exception parameters that are in the scope of the local method definition and are declared `final`.

Local classes are subject to the following restrictions:

- The name of a local class is defined only within the block that defines it; it can never be used outside that block. (Note, however, that instances of a local class created within the scope of the class can continue to exist outside of that scope. This situation is described in more detail later in this section.)
- Local classes cannot be declared `public`, `protected`, `private`, or `static`.
- Like member classes, and for the same reasons, local classes cannot contain `static` fields, methods, or classes. The only exception is for constants that are declared both `static` and `final`.
- Interfaces, enumerated types, and annotation types cannot be defined locally.
- A local class, like a member class, cannot have the same name as any of its enclosing classes.
- As noted earlier, a local class can close over the local variables, method parameters, and even exception parameters that are in its scope but only if those variables or parameters are effectively `final`.



#### Scope of a local class

In discussing nonstatic member classes, we saw that a member class can access any members inherited from superclasses and any members defined by their containing classes.

The same is true for local classes, but local classes can also behave like lambdas and access effectively `final` local variables and parameters. Example 4-4 illustrates the different kinds of fields and variables that may be accessible to a local class (or a lambda, for that matter).

*Example 4-4. Fields and variables available to a local class*

```
class A { protected char a = 'a'; }
class B { protected char b = 'b'; }

public class C extends A {
  private char c = 'c';         // Private fields visible to local class
  public static char d = 'd';
  public void createLocalObject(final char e)
  {
    final char f = 'f';
    int i = 0;                  // i not final; not usable by local class
    class Local extends B
```

```
    {
      char g = 'g';
      public void printVars()
      {
        // All of these fields and variables are accessible to this class
        System.out.println(g);  // (this.g) g is a field of this class
        System.out.println(f);  // f is a final local variable
        System.out.println(e);  // e is a final local parameter
        System.out.println(d);  // (C.this.d) d field of containing class
        System.out.println(c);  // (C.this.c) c field of containing class
        System.out.println(b);  // b is inherited by this class
        System.out.println(a);  // a is inherited by the containing class
      }
    }
    Local l = new Local();      // Create an instance of the local class
    l.printVars();              // and call its printVars() method.
  }
}
```

Local classes have quite a complex scoping structure, therefore. To see why, notice that instances of a local class can have a lifetime that extends past the time that the JVM exits the block where the local class is defined.

> In other words, if you create an instance of a local class, that instance does not automatically go away when the JVM finishes executing the block that defines the class. So, even though the definition of the class was local, instances of that class can escape the place they were defined.

Local classes, therefore, behave like lambdas in many regards, although the use case of local classes is more general than that of lambdas. However, in practice, the extra generality is rarely required, and lambdas are preferred wherever possible.

## Anonymous Classes

An *anonymous class* is a local class without a name. It is defined and instantiated in a single expression using the `new` operator. While a local class definition is a statement in a block of Java code, an anonymous class definition is an expression, which means that it can be included as part of a larger expression, such as a method call.

> For the sake of completeness, we cover anonymous classes here, but for most use cases, lambda expressions (see "Lambda Expressions" on page 180) have replaced anonymous classes.

Consider Example 4-5, which shows the `LinkedIterator` class implemented as an anonymous class within the `iterator()` method of the `LinkedStack` class. Compare it with Example 4-4, which shows the same class implemented as a local class.

*Example 4-5. An enumeration implemented with an anonymous class*

```
public Iterator<Linkable> iterator() {
    // The anonymous class is defined as part of the return statement
    return new Iterator<Linkable>() {
        Linkable current;
        // Replace constructor with an instance initializer
        { current = head; }

        // The following three methods are defined
        // by the Iterator interface
        public boolean hasNext() {  return current != null; }
        public Linkable next() {
            if (current == null)
              throw new java.util.NoSuchElementException();
            Linkable value = current;
            current = current.getNext();
            return value;
        }
        public void remove() { throw new UnsupportedOperationException(); }
    };  // Note the required semicolon. It terminates the return statement
}
```



As you can see, the syntax for defining an anonymous class and creating an instance of that class uses the `new` keyword, followed by the name of a type and a class body definition in curly braces. If the name following the `new` keyword is the name of a class, the anonymous class is a subclass of the named class. If the name following `new` specifies an interface, as in the two previous examples, the anonymous class implements that interface and extends `Object`.

> The syntax for anonymous classes deliberately does not include any way to specify an `extends` clause, an `implements` clause, or a name for the class.

Because an anonymous class has no name, it is not possible to define a constructor for it within the class body. This is one of the basic restrictions on anonymous classes. Any arguments you specify between the parentheses following the superclass name in an anonymous class definition are implicitly passed to the superclass constructor. Anonymous classes are commonly used to subclass simple classes that do not take any constructor arguments, so the parentheses in the anonymous class definition syntax are often empty.

Because an anonymous class is just a type of local class, anonymous classes and local classes share the same restrictions. An anonymous class cannot define any `static` fields, methods, or classes, except for `static final` constants. Interfaces, enumerated types, and annotation types cannot be defined anonymously. Also, like local classes, anonymous classes cannot be `public`, `private`, `protected`, or `static`.

The syntax for defining an anonymous class combines definition with instantiation, similar to a lambda expression. Using an anonymous class instead of a local class is not appropriate if you need to create more than a single instance of the class each time the containing block is executed.

# Describing the Java Type System

At this point, we have met all of the major aspects of the Java type system, and so it is possible for us to describe and characterize it.

The most important and obvious characteristics of Java's type system are that it is:

- Static
- Not single-rooted
- Nominal

Static typing, which is the most widely recognized of the three aspects, means that in Java, every piece of data storage (such as variables, fields, etc.) has a type, and that type is declared when the storage is first introduced. It is a compile-time error to try to put an incompatible value into storage that does not support it.

That Java's type system is not single-rooted is also immediately apparent. Java has both primitive types and reference types. Every object in Java belongs to a class, and every class, except `Object`, has a single parent. This means that the set of classes in any Java program forms a tree structure with `Object` at the root.

However, there is no inheritance relationship between any of the primitive types and `Object`. As a result, the overall graph of Java classes consists of a large tree of reference types and eight disjoint, isolated points that correspond to the primitives. This leads to the need to use wrapper types, such as `Integer`, to represent primitive values as objects where necessary (such as in the Java Collections).

The final aspect, though, requires a bit more of a detailed discussion.

## Nominal Typing

In Java, each type has a name. In the normal course of Java programming, this will be a simple string of letters (and sometimes numbers) that has some semantic meaning that reflects the purpose of the type. This approach is known as *nominal typing*.

Not all languages have purely nominal typing; for example, some languages can express the idea that "this type has a method with a certain signature" without needing to explicitly refer to the name of the type, sometimes known as a *structural type*.

For example, in Python, you can call `len()` on any object that defines a `__len__()` method. Of course, Python is a dynamically typed language and so will throw a runtime exception if the call to `len()` cannot be made. However, it is also possible to express a similar idea in statically typed languages, such as Scala.

Java, on the other hand, has no way to express this idea without using an interface, which, of course, has a name. Java also maintains type compatibility based strictly on inheritance and implementation. Let's look at an example:

```
@FunctionalInterface
public interface MyRunnable {
    void run();
}
```

The interface `MyRunnable` has a single method that exactly matches that of `Runnable`. However, the two interfaces have no inheritance or other relationship to each other and so code like this:

```
MyRunnable myR = () -> System.out.println("Hello");
Runnable r = (Runnable)myR;
r.run();
```

will compile cleanly but will fail with a `ClassCastException` at runtime. The fact that a `run()` method with an identical signature exists on both interfaces is not considered, and in fact the program never even makes it to the point where `run()` would be called: it fails on the previous line where the cast is attempted.

Another important point is that the entire construction of Java's lambda expressions, and especially the use of target typing to a functional interface, is to ensure that lambdas fit into the nominal typing approach. For example, consider an interface such as:

```
@FunctionalInterface
public interface MyIntProvider {
    int run() throws InterruptedException;
}
```

then a lambda expression that yields a constant, e.g., `() -> 42`, can be used in a number of different ways:

```
MyIntProvider prov       = () -> 42;
Supplier<Integer> sup    = () -> 42;
Callable<Integer> callMe = () -> 42;
```

From this, we can see that the expression `() -> 42` is, by itself, incomplete. Java lambdas rely upon type inference, and so we need to see the expression in context with its target type for it to be meaningful. When combined with a target type, the lambda's class type is "an unknown-at-compile-time implementation of the target

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interface," and the programmer must use the interface type as the type of the lambda.

Beyond lambdas, there are some corner cases of nominal typing in Java. One example is anonymous classes, but even here the types still have names. However, the type names of anonymous types are automatically generated by the compiler and are specially chosen so as to be usable by the JVM but not accepted by the Java source code compiler.

There is one other corner case that we should consider, and it relates to the enhanced type inference introduced in recent Java versions.

## Nondenotable Types and var

From Java 11 onwards (actually introduced in the Java 10 non-LTS release), Java developers can make use of a new language feature *Local Variable Type Inference* (LVTI), otherwise known as `var`. This is an enhancement to Java's type inference capabilities that may prove to be more significant than it first appears. In the simplest case, it allows code such as:

```
var ls = new ArrayList<String>();
```

which moves the inference from the type of values to the type of variables.

The implementation achieves this by making `var` a reserved type name rather than a keyword. This means that code can still use `var` as a variable, method, or package name without being affected by the new syntax. However, code that has previously used `var` as the name of a type will have to be recompiled.

This simple case is designed to reduce verbosity and to make programmers coming to Java from other languages (especially Scala, .NET, and JavaScript) feel more comfortable. However, it does carry the risk that overuse will potentially obscure the intent of the code being written, so it should be used sparingly.

As well as the simple cases, `var` actually permits programming constructs that were not possible before. To see the differences, let's consider that `javac` has always permitted a very limited form of type inference:

```
public class Test {
    public static void main(String[] args) {
        (new Object() {
            public void bar() {
                System.out.println("bar!");
            }
        }).bar();
    }
}
```

The code will compile and run, printing out `bar!`. This slightly counterintuitive result occurs because `javac` preserves enough type information about the anonymous class (i.e., that it has a `bar()` method) for just long enough that the compiler can conclude that the call to `bar()` is valid.

In fact, this edge case has been known in the Java community since at least 2009, long before the arrival of Java 7.

The problem with this form of type inference is that it has no real practical applications: the type of "Object-with-a-bar-method" exists within the compiler, but the type is impossible to express as the type of a variable—it is not a *denotable type*. This means that before Java 10, the existence of this type is restricted to a single expression and cannot be used in a larger scope.

With the arrival of LVTI, however, the type of variables does not always need to be made explicit. Instead, we can use `var` to allow us to preserve the static type information by avoiding denoting the type.

This means we can now modify our example and write:

```
var o = new Object() {
    public void bar() {
        System.out.println("bar!");
    }
};

o.bar();
```

This has allowed us to preserve the true type of `o` beyond a single expression. The type of `o` cannot be denoted, and so it cannot appear as the type of either a method parameter or return type. This means the type is still limited to only a single method, but it is still useful to express some constructions that would be awkward or impossible otherwise.

This use of `var` as a "magic type" allows the programmer to preserve type information for each distinct usage of `var`, in a way that is somewhat reminiscent of bounded wildcards from Java's generics.

More advanced usages of `var` with nondenotable types are possible. While the feature is not able to satisfy every criticism of Java's type system, it does represent a definite (if cautious) step forward.

# Summary

By examining Java's type system, we have been able to build up a clear picture of the worldview that the Java platform has about data types. Java's type system can be characterized as:

*Static*
: All Java variables have types that are known at compile time.

*Nominal*
: The name of a Java type is of paramount importance. Java does not permit structural types and has only limited support for nondenotable types.

*Object/imperative*
: Java code is object-oriented, and all code must live inside methods, which must live inside classes. However, Java's primitive types prevent full adoption of the "everything is an object" worldview.

*Slightly functional*
: Java provides support for some of the more common functional idioms but more as a convenience to programmers than anything else.

*Type-inferred*
: Java is optimized for readability (even by novice progammers) and prefers to be explicit but uses type inference to reduce boilerplate where it does not impact the legibility of the code.

*Strongly backward compatible*
: Java is primarily a business-focused language, and backward compatibility and protection of existing codebases are very high priorities.

*Type erased*
: Java permits parameterized types, but this information is not available at runtime.

Java's type system has evolved (albeit slowly and cautiously) over the years—and is now on par with the type systems of other mainstream programming languages. Lambda expressions, along with default methods, represent the greatest transformation since the advent of Java 5 and the introduction of generics, annotations, and related innovations.

Default methods represent a major shift in Java's approach to object-oriented programming—perhaps the biggest since the language's inception. From Java 8 onward, interfaces can contain implementation code. This fundamentally changes Java's nature. Previously a single-inherited language, Java is now multiply inherited (but only for behavior—there is still no multiple inheritance of state).

Despite all of these innovations, Java's type system is not (and is not intended to be) equipped with the power of the type systems of languages such as Scala or Haskell. Instead, Java's type system is strongly biased in favor of simplicity, readability, and a simple learning curve for newcomers.

Java has also benefited enormously from the approaches to types developed in other languages over the last 10 years. Scala's example of a statically typed language that nevertheless achieves much of the feel of a dynamically typed language through the use of type inference has been a good source of ideas for features to add to Java, even though the languages have quite different design philosophies.

One remaining question is whether the modest support for functional idioms that lambda expressions provide in Java is sufficient for the majority of Java programmers.

> The long-term direction of Java's type system is being explored in research projects such as Valhalla, where concepts such as data classes, pattern matching, and sealed classes are being explored.

It remains to be seen whether the majority of ordinary Java programmers require the added power—and attendant complexity—that comes from an advanced (and much less nominal) type system such as Scala's, or whether the "slightly functional programming" introduced in Java 8 (e.g., *map*, *filter*, *reduce*, and their peers) will suffice for most developers' needs.

# 5
# Introduction to Object-Oriented Design in Java

In this chapter, we will consider several techniques relevant to object-oriented design (OOD) in Java.

We'll look at how to work with Java's objects, covering the key methods of `Object`, aspects of object-oriented design, and implementing exception handling schemes. Throughout the chapter, we will be introducing some *design patterns*—essentially best practices for solving some very common situations that arise in software design. Toward the end of the chapter, we'll also consider *safe* programs—those that are designed so as not to become inconsistent over time.

> This chapter is intended to showcase some examples of a complex topic and a few underlying principles. We encourage you to consult additional resources, such as *Effective Java* by Josh Bloch.

We'll get started by considering the subject of Java's calling and passing conventions and the nature of Java values.

## Java Values

Java's values, and their relationship to the type system, are quite straightforward. Java has two types of values: primitives and object references.

There are only eight different primitive types in Java, and new primitive types cannot be defined by the programmer.

The key difference between primitive values and references is that primitive values cannot be altered; the value `2` is always the same value. By contrast, the contents of object references can usually be changed—often referred to as *mutation* of object contents.

Also note that variables can contain values only of the appropriate type. In particular, variables of reference type always contain a reference to the memory location holding the object—they do not contain the object contents directly. This means that in Java there is no equivalent of a dereference operator or a `struct`.

Java tries to simplify a concept that often confused C++ programmers: the difference between "contents of an object" and "reference to an object." Unfortunately, it's not possible to completely hide the difference, and so it is necessary for the programmer to understand how reference values work in the platform.

## Is Java "Pass by Reference"?

Java handles objects "by reference," but we must not confuse this with the phrase "pass by reference," a term used to describe the method-calling conventions of various programming languages. In a pass-by-reference language, values—even primitive values—are not passed directly to methods. Instead, methods are always passed by references to values. Thus, if the method modifies its parameters, those modifications are visible when the method returns, even for primitive types.

Java does *not* do this; it is a "pass by value" language. However, when a reference type is involved, the value that is passed is a copy of the reference (as a value). But this is not the same as pass by reference. If Java were a pass-by-reference language, when a reference type is passed to a method, it would be passed as a reference to the reference.

The fact that Java is pass by value can be demonstrated very simply, e.g., by running the following code:

```
public void manipulate(Circle circle) {
    circle = new Circle(3);
}

Circle c = new Circle(2);
System.out.println("Radius: "+ c.getRadius());
manipulate(c);
System.out.println("Radius: "+ c.getRadius());
```

This outputs `Radius: 2` twice and thus shows that even after the call to `manipulate()`, the value contained in variable `c` is unaltered—it is still holding a reference to a `Circle` object of radius 2. If Java was a pass-by-reference language, it would instead be holding a reference to a radius 3 `Circle`:

If we're scrupulously careful about the distinction, and about referring to object references as one of Java's possible kinds of values, then some otherwise surprising features of Java become obvious. Be careful! Some older texts are ambiguous on this point. We will meet this concept of Java's values again when we discuss memory and garbage collection in Chapter 6.

## Important Common Methods

As we've noted, all classes extend, directly or indirectly, `java.lang.Object`. This class defines a number of useful methods, some of which were designed to be overridden by classes you write. Example 5-1 shows a class that overrides these methods. The sections that follow this example document the default implementation of each method and explain why you might want to override it.

Note that this example is for demonstration purposes only; in reality, we would represent classes like `Circle` as records and get a lot of these methods implemented automatically by the compiler.



*Example 5-1. A class that overrides important Object methods*

```
// This class represents a circle with immutable position and radius.
public class Circle implements Comparable<Circle> {
    // These fields hold the coordinates of the center and the radius.
    // They are private for data encapsulation and final for immutability
    private final int x, y, r;

    // The basic constructor: initialize the fields to specified values
    public Circle(int x, int y, int r) {
        if (r < 0) throw new IllegalArgumentException("negative radius");
        this.x = x; this.y = y; this.r = r;
    }

    // This is a "copy constructor"--a useful alternative to clone()
    public Circle(Circle original) {
        x = original.x;   // Just copy the fields from the original
        y = original.y;
        r = original.r;
    }

    // Public accessor methods for the private fields.
    // These are part of data encapsulation.
    public int getX() { return x; }
    public int getY() { return y; }
    public int getR() { return r; }
```

```java
    // Return a string representation
    @Override public String toString() {
        return String.format("center=(%d,%d); radius=%d", x, y, r);
    }

    // Test for equality with another object
    @Override public boolean equals(Object o) {
        // Identical references?
        if (o == this) return true;
        // Correct type and non-null?
        if (!(o instanceof Circle)) return false;
        Circle that = (Circle) o;                // Cast to our type
        if (this.x == that.x && this.y == that.y && this.r == that.r)
            return true;                         // If all fields match
        else
            return false;                        // If fields differ
    }

    // A hash code allows an object to be used in a hash table.
    // Equal objects must have equal hash codes.  Unequal objects are
    // allowed to have equal hash codes, but we try to avoid that.
    // We must override this method because we also override equals().
    @Override public int hashCode() {
        int result = 17;          // This hash code algorithm from
        result = 37*result + x;   // Effective Java, by Joshua Bloch
        result = 37*result + y;
        result = 37*result + r;
        return result;
    }

    // This method is defined by the Comparable interface. Compare
    // this Circle to that Circle.  Return a value < 0 if this < that
    // Return 0 if this == that. Return a value > 0 if this > that.
    // Circles are ordered top to bottom, left to right, then by radius
    public int compareTo(Circle that) {
        // Smaller circles have bigger y
        long result = (long)that.y - this.y;
        // If same compare l-to-r
        if (result==0) result = (long)this.x - that.x;
        // If same compare radius
        if (result==0) result = (long)this.r - that.r;

        // We have to use a long value for subtraction because the
        // differences between a large positive and large negative
        // value could overflow an int. But we can't return the long,
        // so return its sign as an int.
        return Long.signum(result);
    }
}
```

Example 5-1 uses a lot of the extended features of the type system that we introduced in Chapter 4. First, this example implements a parameterized, or generic, version of the `Comparable` interface. Second, it uses the `@Override` annotation to emphasize (and have the compiler verify) that certain methods override `Object`.

## toString()

The purpose of the `toString()` method is to return a textual representation of an object. The method is invoked automatically on objects during string concatenation and by methods such as `System.out.println()`. Giving objects a textual representation can be quite helpful for debugging or logging output, and a well-crafted `toString()` method can even help with tasks such as report generation.

The version of `toString()` inherited from `Object` returns a string that includes the name of the class of the object as well as a hexadecimal representation of the `hashCode()` value of the object (discussed later in this chapter). This default implementation provides basic type and identity information for an object but is not very useful. The `toString()` method in Example 5-1 instead returns a human-readable string that includes the value of each of the fields of the `Circle` class.

## equals()

The == operator tests two references to see if they refer to the same object. If you want to test whether two distinct objects are equal to one another, you must use the `equals()` method instead. Any class can define its own notion of equality by overriding `equals()`. The `Object.equals()` method simply uses the == operator: this default method considers two objects equal only if they are actually the very same object.

The `equals()` method in Example 5-1 considers two distinct `Circle` objects to be equal if their fields are all equal. Note that it first does a quick identity test with == as an optimization and then checks the type of the other object with `instanceof`: a `Circle` can be equal only to another `Circle`, and it is not acceptable for an `equals()` method to throw a `ClassCastException`. Note that the `instanceof` test also rules out `null` arguments: `instanceof` always evaluates to `false` if its lefthand operand is `null`.

## hashCode()

Whenever you override `equals()`, you also must override `hashCode()`. This method returns an integer for use by hash table data structures. It is critical that two objects have the same hash code if they are equal according to the `equals()` method.

It is important (for efficient operation of hash tables) but not required that unequal objects have unequal hash codes, or at least that unequal objects are unlikely to share a hash code. This second criterion can lead to `hashCode()` methods that involve mildly tricky arithmetic or bit manipulation.

The `Object.hashCode()` method works with the `Object.equals()` method and returns a hash code based on object identity rather than object equality. (If you ever need an identity-based hash code, you can access the functionality of `Object.hashCode()` through the static method `System.identityHashCode()`.)

> When you override `equals()`, you must always override `hashCode()` to guarantee that equal objects have equal hash codes. Failing to do this can cause subtle bugs in your programs.

Because the `equals()` method in Example 5-1 bases object equality on the values of the three fields, the `hashCode()` method computes its hash code based on these three fields as well. It is clear from the code that if two `Circle` objects have the same field values, they will have the same hash code.

Note that the `hashCode()` method in Example 5-1 does not simply add the three fields and return their sum. Such an implementation would be legal but not efficient because two circles with the same radius but whose *x* and *y* coordinates were reversed would then have the same hash code. The repeated multiplication and addition steps "spread out" the range of hash codes and dramatically reduce the likelihood that two unequal `Circle` objects have the same code.

In practice, modern Java programmers will either autogenerate `hashCode()`, `equals()`, and `toString()` from within their IDE (for classes), or use records where the source code compiler produces a standard form of these methods. For the extremely rare cases where the programmer chooses not to use either of these approaches, *Effective Java* by Joshua Bloch (Addison Wesley) includes a helpful recipe for constructing efficient `hashCode()` methods.

## Comparable::compareTo()

Example 5-1 includes a `compareTo()` method. This method is defined by the `java.lang.Comparable` interface rather than by `Object`, but it is such a common method to implement that we include it in this section. The purpose of `Comparable` and its `compareTo()` method is to allow instances of a class to be compared to each other in a similar way to how the `<`, `<=`, `>`, and `>=` operators compare numbers. If a class implements `Comparable`, we can call methods to allow us to say that one instance is less than, greater than, or equal to another instance. This also means that instances of a `Comparable` class can be sorted.

> The method `compareTo()` sets up a *total ordering* of the objects of the type. This is referred to as the *natural order* of the type, and the method is called the *natural comparison method*.

Because compareTo() is not declared by the Object class, it is up to each individual class to determine whether and how its instances should be ordered and to include a compareTo() method that implements that ordering.

The ordering defined by Example 5-1 compares Circle objects as if they were words on a page. Circles are first ordered from top to bottom: circles with larger *y* coordinates are less than circles with smaller *y* coordinates. If two circles have the same *y* coordinate, they are ordered from left to right. A circle with a smaller *x* coordinate is less than a circle with a larger *x* coordinate. Finally, if two circles have the same *x* and *y* coordinates, they are compared by radius. The circle with the smaller radius is smaller.

Note that under this ordering, two circles are equal only if all three of their fields are equal. This means that the ordering defined by compareTo() is consistent with the equality defined by equals(). This is not strictly required but is very desirable, and you should aim for it wherever possible.

The compareTo() method returns an int value that requires further explanation. compareTo() should return a negative number if the this object is less than the object passed to it. It should return 0 if the two objects are equal. And compareTo() should return a positive number if this is greater than the method argument.

## clone()

Object defines a method named clone() whose purpose is to return an object with fields set identically to those of the current object. This is an unusual method for several reasons.

First, clone() is declared as protected. Therefore, if you want your object to be cloneable by other classes, you must override the clone() method, making it public. Next, the default implementation of clone() in Object throws a checked exception, CloneNotSupportedException, unless the class implements the java.lang.Cloneable interface. Note that this interface does not define any methods (it is a marker interface), so implementing it is simply a matter of listing it in the implements clause of the class signature.

The original intent of clone() was to provide a mechanism to produce "deep copies" of objects, but it is fundamentally flawed and its use is not recommended. Instead, developers should prefer declaring a *copy constructor* for making copies of their objects, for example:

```
Circle original = new Circle(1, 2, 3);  // regular constructor
Circle copy = new Circle(original);     // copy constructor
```

We will meet copy constructors again when we consider factory methods, later in this chapter.

## Constants

In Java a constant is a `static final` field. This combination of modifiers gives a single value (per class) with the given name, and it is initialized as soon as the class is loaded and then cannot be changed.

By convention, Java's constants are named in all-capitals, using *snake case*, for example `NETWORK_SERVER_SOCKET`[1] as opposed to the "camel case" (or "camelCase") convention `networkServerSocket` for a regular field.

There are essentially three different subcases of constants that can appear:

- `public` constants: these form part of the public API of the class
- `private` constants: these are used when the constant is an internal implementation detail for this class only
- Package-level constants: these have no additional access keyword and are used when the constant is an internal implementation detail that needs to be seen by different classes within the same package

The final case might arise, for example, when client and server classes implement a network protocol whose details (such as the port number to connect to and listen on) are captured in a set of symbolic constants.

As discussed earlier, an alternative approach is for constants to appear in an interface definition. Any class that implements an interface inherits the constants it defines and can use them as if they were defined directly in the class itself. This has the advantage that there is no need to prefix the constants with the name of the interface or provide any kind of implementation of the constants.

However, this is rather overcomplicated and so the preferred approach is to define constants (as either public or package-level) in a class and use them by importing the constants from their defining class with the `import static` declaration. See "Packages and the Java Namespace" on page 98 for details.

## Working with Fields

Java provides a variety of access control keywords that can be used to define how fields can be accessed. It is perfectly legal to use any of these possibilities, but in practice there are three primary choices for field access that Java developers typically use:

- Constants (`static final`): the case that we just met, which may have an additional access control keyword as well

1 Technically, this should probably be called `SCREAMING_SNAKE_CASE`

- Immutable fields (`private final`): fields with this combination cannot be altered after object creation
- Mutable fields (`private`): this combination should only be used if the programmer is sure that the field's value will change during the object's lifetime

In recent years, many developers have adopted the practice of using immutable data wherever possible. There are several benefits to this approach, but the main one is that if objects can be designed so that they cannot be modified after creation, then they can be freely shared between threads.

When writing classes, we recommend using the above three choices for field modifiers, depending on the circumstances. Instance fields should always be initially written as `final` and made mutable only if necessary.

In addition, direct field access should not be used, except for constants. Instead, getter methods (and setters, for the case of mutable state) should be preferred. The primary reason for this is that direct field access is a very tight coupling between the defining class and any client code. If accessor methods are used, then the implementation code for those methods can later be modified without changing the client code—this is impossible with field access.

We should also call out one common mistake in field handling: Developers coming from C++ frequently make the mistake of omitting any access modifiers for fields. This is a serious defect, because C++ has a default visibility of private, whereas Java's default access is considerably more open. This represents a failure of encapsulation in Java, and developers should take care to avoid it.

OO Design

## Field Inheritance and Accessors

As well as the above considerations, Java offers multiple potential approaches to the design issue of the inheritance of state. The programmer could choose to mark fields as `protected` and allow them to be accessed directly by subclasses (including writing to them). Alternatively, we can provide *accessor methods* to read (and write, if desired) the actual object fields, while retaining encapsulation and leaving the fields as `private`.

Let's revisit our earlier `PlaneCircle` example from the end of Chapter 3 and explicitly show the field inheritance:

```
public class Circle {
  // This is a generally useful constant, so we keep it public
  public static final double PI = 3.14159;

  protected double r;     // State inheritance via a protected field

  // A method to enforce the restriction on the radius
  protected void checkRadius(double radius) {
    if (radius < 0.0)
      throw new IllegalArgumentException("radius may not < 0");
```

```java
  }

  // The non-default constructor
  public Circle(double r) {
    checkRadius(r);
    this.r = r;
  }

  // Public data accessor methods
  public double getRadius() { return r; }
  public void setRadius(double r) {
    checkRadius(r);
    this.r = r;
  }

  // Methods to operate on the instance field
  public double area() { return PI * r * r; }
  public double circumference() { return 2 * PI * r; }
}

public class PlaneCircle extends Circle {
  // We automatically inherit the fields and methods of Circle,
  // so we only have to put the new stuff here.
  // New instance fields that store the center point of the circle
  private final double cx, cy;

  // A new constructor to initialize the new fields
  // It uses a special syntax to invoke the Circle() constructor
  public PlaneCircle(double r, double x, double y) {
    super(r);       // Invoke the constructor of the superclass
    this.cx = x;    // Initialize the instance field cx
    this.cy = y;    // Initialize the instance field cy
  }

  public double getCenterX() {
    return cx;
  }

  public double getCenterY() {
    return cy;
  }

  // The area() and circumference() methods are inherited from Circle
  // A new instance method that checks whether a point is inside the
  // circle; note that it uses the inherited instance field r
  public boolean isInside(double x, double y) {
    double dx = x - cx, dy = y - cy;
    // Pythagorean theorem
    double distance = Math.sqrt(dx*dx + dy*dy);
    return (distance < r);                   // Returns true or false
  }
}
```

Instead of the preceding code, we can rewrite `PlaneCircle` using accessor methods, like this:

```
public class PlaneCircle extends Circle {
  // Rest of class is the same as above; the field r in
  // the superclass Circle can be made private because
  // we no longer access it directly here

  // Note that we now use the accessor method getRadius()
  public boolean isInside(double x, double y) {
    double dx = x - cx, dy = y - cy;           // Distance to center
    double distance = Math.sqrt(dx*dx + dy*dy); // Pythagorean theorem
    return (distance < getRadius());
  }
}
```

Both approaches are legal Java, but they have some differences. As we discussed in "Data Hiding and Encapsulation" on page 135, fields that are writable outside of the class are usually not a correct way to model object state. In fact, as we will see later in this chapter and again in "Java's Support for Concurrency" on page 249, they can damage the running state of a program irreparably.

It is therefore unfortunate that the `protected` keyword in Java allows access to fields (and methods) from both subclasses *and* classes in the same packages as the declaring class. This, combined with the ability for anyone to write a class that belongs to any given package (except system packages), means that protected inheritance of state is potentially flawed in Java.



Java does not provide a mechanism for a member to be visible only in the declaring class and its subclasses.

For all of these reasons, it is almost always better to use accessor methods (either public or protected) to provide access to state for subclasses—unless the inherited state is declared `final`, in which case protected inheritance of state is perfectly permissible.

## Singleton

The *singleton pattern* is a very well-known design pattern. It is intended to solve the design issue where only a single instance of a class is required or desired. Java provides a number of different possible ways to implement the singleton pattern. In our discussion, we will use a slightly more verbose form, which has the benefit of being very explicit in what needs to happen for a safe singleton:

```
public class Singleton {
  private final static Singleton instance = new Singleton();
  private static boolean initialized = false;
```

```
  // Constructor
  private Singleton() {
    super();
  }

  private void init() {
    /* Do initialization */
  }

  // This method should be the only way to get a reference
  // to the instance
  public static synchronized Singleton getInstance() {
    if (initialized) return instance;
    instance.init();
    initialized = true;
    return instance;
  }
}
```

The crucial point is that for the singleton pattern to be effective, it must be impossible to create more than one of them, and it must be impossible to get a reference to the object in an uninitialized state (see later in this chapter for more on this important point).

To achieve this, we require a `private` constructor, which is called only once, ever. In our version of `Singleton`, we only call the constructor when we initialize the private static variable `instance`. We also separate the creation of the only `Singleton` object from its initialization—which occurs in the private method `init()`.

With this mechanism in place, the only way to get a reference to the lone instance of `Singleton` is via the static helper method, `getInstance()`. This method checks the flag `initialized` to see if the object is already in an active state. If it is, then a reference to the singleton object is returned. If not, then `getInstance()` calls `init()` to activate the object and flicks the flag to `true`, so that next time a reference to the `Singleton` is requested, further initialization will not occur.

Finally, we also note that `getInstance()` is a `synchronized` method. See Chapter 6 for full details of what this means and why it is necessary, but for now, know that it is present to guard against unintended consequences if `Singleton` is used in a multithreaded program.

> Singleton, being one of the simplest patterns, is often overused. When used correctly, it can be a useful technique, but too many singleton classes in a program is a classic sign of badly engineered code.

The singleton pattern has some drawbacks—in particular, it can be hard to test and to separate from other classes. It also requires care when used in mulithreaded code. Nevertheless, it is important that developers are familiar with it and do not accidentally reinvent it. The singleton pattern is often used in configuration management, but modern code will typically use a framework (often a *dependency injection* framework) to provide the programmer with singletons automatically, rather than via an explicit `Singleton` (or equivalent) class.

## Factory Methods

An alternative to using constructors directly is the *Factory Method* pattern. The basic form of this technique is to make the constructor private (or other nonpublic modifier, in some variants) and to provide a static method that returns the desired type. This static method is then used by client code that wants an instance of the type.

There are various reasons why, as a code author, we may not want to expose our constructors directly and may choose to use factories instead. For example, caching factories that do not necessarily create a new object, or because there are several valid ways of constructing an object.

> The static factory approach is not the same as the *Abstract Factory* pattern from the classic book *Design Patterns*.



Let's rewrite the constructor from Example 5-1 and introduce some factory methods:

```
public final class Circle implements Comparable<Circle> {
    private final int x, y, r;

    // Main constructor
    private Circle(int x, int y, int r) {
        if (r < 0) throw new IllegalArgumentException("radius < 0");
        this.x = x; this.y = y; this.r = r;
    }

    // Usual factory method
    public static Circle of(int x, int y, int r) {
        return new Circle(x, y, r);
    }

    // Factory method playing the role of the copy constructor
    public static Circle of(Circle original) {
        return new Circle(original.x, original.y, original.r);
    }
```

```
    // Third factory with intent given by name
    public static Circle ofOrigin(int r) {
        return new Circle(0, 0, r);
    }

    // other methods elided
}
```

This class contains a private constructor and three separate factory methods: a "usual" one with the same signature as the constructor, and two additional. One of these additional factories is effectively a copy constructor, and the other is used to handle a special case: circles at the origin.

One advantage of using factory methods is that, unlike constructors, the method has a name and so can indicate its intent using part of the name. In our example, the factory methods are `of()`, which is one very common choice, and we distinguish the case of the origin circles by using a name `ofOrigin()` that expresses it.

# Builders

Factory methods are a useful technique for when you don't want to expose a constructor to client code. However, there are limitations to factories. They work well when only a few parameters, all of which are required, need to be passed. But in some circumstances, we need to model data where much of it is optional, or when there are many valid, different possible constructions for our domain objects. In this case, the number of factory methods can quickly multiply to represent all possible combinations and overwhelm us, cluttering the API.

An alternative approach is the *Builder* pattern. This pattern uses a secondary builder object that exactly parallels the state of the real domain object (which is assumed to be immutable). For every field that the domain object has, the builder has the same field—the same name, and the same type. However, while the domain object is immutable, the builder object is explicitly mutable. In fact, the builder has a setter method, named in the same way as the field (i.e. in "record convention") that the developer will use to set up a piece of state.

The overall intent of the Builder pattern is to start from a "blank" builder object and add state to it, until the builder is ready to be converted into an actual domain object, usually by calling the `build()` method on the builder.

Let's take a look at a simple example:

```
// Generic builder interface
public interface Builder<T> {
    T build();
}

public class BCircle {
    private final int x, y, r;

    // The main constructor is now private
```

```
    private BCircle(CircleBuilder cb) {
        if (cb.r < 0)
        throw new IllegalArgumentException("negative radius");
        this.x = cb.x; this.y = cb.y; this.r = cb.r;
    }

    public static class CircleBuilder implements Builder<BCircle> {
        private int x = 0, y = 0, r = 0;

        public CircleBuilder x(int x) {
            this.x = x;
            return this;
        }

        public int x() {
            return x;
        }

        // Similarly for y and r

        @Override
        public BCircle build() {
            return new BCircle(this);
        }
    }

    // Other methods elided
}
```

Notice that the builder interface is typically generic. This is because in practice we may well have a large number of domain classes, all of which will require builders, so the use of a generic builder interface removes duplication. The `Builder` interface contains only one method, so it technically is a candidate for lambda target typing. But in practice this is almost never the intent, and so it is not tagged with `@FunctionalInterface`. The implementation of the `build()` method also contains a nonoptional use of the `this` reference.

The builder can be driven by a simple bit of code like this:

```
var cb = new BCircle.CircleBuilder();
cb.x(1).y(2).r(3);
var circle = cb.build();
```

Note that first we instantiate the builder. Then, we call the methods to set the various parameters on the builder. Finally, we create an immutable object from the builder, by calling `build()`.

You may notice that the methods on the builder that accrete state all return `this`. The point of this interface design is so that the calls can be *chained*—so that methods can be called one after another on the same mutable object—for example as `cb.x(1).y(2).r(3)`. Another way of describing this style of interface design is as a *fluent interface*. As each method returns `this`, we know that all of these calls are safe: there can't be a `NullPointerException`.

Our example is very simple and is somewhat contrived; it only has three parameters and all of them are required. In practice, builders are more useful with a larger number of object parameters and when there are multiple possibilities for "spanning sets" of valid object states. There exists an overlap between the cases where one should use a factory versus a builder; determining exactly where that boundary is for your own code is part of the development of OO design skills.

## Interfaces Versus Abstract Classes

Java 8 fundamentally changed Java's object-oriented programming model. Before Java 8, interfaces were pure API specification and contained no implementation. This could (and often did) lead to duplication of code when the interface had multiple implementations.

To prevent this wasted effort, a simple coding pattern developed that takes advantage of the fact that an abstract class can contain a partial implementation that subclasses can build upon. Numerous subclasses can rely on method implementations provided by an abstract superclass (also called an *abstract base*).

The pattern consists of an interface that contains the API spec for the basic methods, paired with a primary partial implementation as an abstract class. A good example would be `java.util.List`, which is paired with `java.util.AbstractList`. Two of the main implementations of `List` that ship with the JDK (`ArrayList` and `LinkedList`) are subclasses of `AbstractList`.

As another example:

```
// Here is a basic interface. It represents a shape that fits inside
// of a rectangular bounding box. Any class that wants to serve as a
// RectangularShape can implement these methods from scratch.
public interface RectangularShape {
    void setSize(double width, double height);
    void setPosition(double x, double y);
    void translate(double dx, double dy);
    double area();
    boolean isInside();
}

// Here is a partial implementation of that interface. Many
// implementations may find this a useful starting point.
public abstract class AbstractRectangularShape
                        implements RectangularShape {
    // The position and size of the shape
    protected double x, y, w, h;

    // Default implementations of some of the interface methods
    public void setSize(double width, double height) {
     w = width; h = height;
```

```
    }
    public void setPosition(double x, double y) {
     this.x = x; this.y = y;
    }
    public void translate (double dx, double dy) { x += dx; y += dy; }
}
```

The arrival of default methods in Java 8 changed this landscape considerably. Interfaces can now contain implementation code, as we saw in "Default Methods" on page 158.

This means that when defining an abstract type (e.g., `Shape`) that you expect to have many subtypes (e.g., `Circle`, `Rectangle`, `Square`), you are faced with a choice between interfaces and abstract classes. As they now have potentially similar features, it is not always clear which to use.

Remember that a class that extends an abstract class cannot extend any other class, and that interfaces still cannot contain any nonconstant fields. This means there are still some restrictions on how we can use inheritance in our Java programs.

Another important difference between interfaces and abstract classes has to do with compatibility. If you define an interface as part of a public API and then later add a new mandatory method to the interface, you break any classes that implemented the previous version of the interface—in other words, any new interface methods must be declared as default and an implementation provided.

If you use an abstract class, however, you can safely add nonabstract methods to that class without requiring modifications to existing classes that extend the abstract class.

In both cases, adding new methods can cause a clash with subclass methods of the same name and signature—with the subclass methods always winning. For this reason, think carefully when adding new methods, especially when the method names are "obvious" for this type or where the method could have several possible meanings.

In general, the suggested approach is to prefer interfaces when an API specification is needed. The mandatory methods of the interface are nondefault, as they represent the part of the API that must be present for an implementation to be considered valid. Default methods should be used only if a method is truly optional, or if they are really only intended to have a single possible implementation.

Finally, the older (pre-Java 8) technique of declaring in documentation which methods of an interface are considered "optional" and directing to implementations to throw a `java.lang.UnsupportedOperationException` if the programmer does not want to implement them is fraught with problems and should not be used in new code.

## Do Default Methods Change Java's Inheritance Model?

Before Java 8, the strict single inheritance model of the language was clear. Every class (except `Object`) had exactly one direct superclass, and method implementations could only either be defined in a class, or be inherited from the superclass hierarchy.

Default methods change this picture, because they allow method implementations to be inherited from multiple places—either from the superclass hierarchy or from default implementation provided in interfaces. Any potential conflicts between different default methods from separate interfaces will result in a compile-time error.

This means there is no possibility of conflicting multiple inheritance of implementation, as in any clash the programmer is required to manually disambiguate the methods.

There is also no multiple inheritance of state: interfaces still do not have non-constant fields.

This means that Java's multiple inheritance is different from the general multiple inheritance found in, e.g., C++. In fact, default methods are effectively the *Mixin* pattern from C++ (for readers who are familiar with that language). Some developers also view default members as a form of the *trait* language feature that appears in some OO languages (e.g., Scala).

However, the official position from Java's language designers is that default methods fall short of being full traits. This view is somewhat undermined by the code that ships within the JDK—even the interfaces within `java.util.function` (such as `Function` itself) behave as simple traits.

For example, consider this example:

```
public interface IntFunc {
    int apply(int x);

    default IntFunc compose(IntFunc before) {
        return (int y) -> apply(before.apply(y));
    }

    default IntFunc andThen(IntFunc after) {
        return (int z) -> after.apply(apply(z));
    }

    static IntFunc id() {
        return x -> x;
    }
}
```

It is a simplified version of the `Function` interface in `java.util.function` that removes the generics and deals with `int` only as a data type.

This case shows an important point for the functional composition methods (`compose()` and `andThen()`) present: these functions will only be composed in the standard way, and it is highly implausible that any sane override of the default `compose()` method could exist.

This is, of course, also true for the function types present in `java.util.function`, and it shows that within the limited domain provided, default methods can indeed be treated as a form of stateless trait.

## OOD Using Lambdas

Consider this simple lambda expression:

```
Runnable r = () -> System.out.println("Hello World");
```

The type of the *lvalue* (lefthand side of the assignment) is `Runnable`, which is an interface type. For this statement to make sense, the *rvalue* (right-hand side of the assignment) must contain an instance of some class type (because interfaces cannot be instantiated) that implements `Runnable`. The minimal implementation that satisfies these constraints is a class type (of inconsequential name) that directly extends `Object` and implements `Runnable`.

Recall that the intention of lambda expressions is to allow Java programmers to express a concept that is as close as possible to the anonymous or inline methods seen in other languages.



Furthermore, given that Java is a statically typed language, this leads directly to the design of lambdas as implemented.

> Lambdas are a shorthand for the construction of a new instance of a class type that is essentially `Object` enhanced by a single method.

A lambda's single extra method has a signature provided by the interface type, and the compiler will check that the `rvalue` is consistent with this type signature.

### Lambdas Versus Nested Classes

The addition of lambdas to the language in Java 8 was relatively late, as compared to other programming languages. As a consequence, the Java community had established patterns to work around the absence of lambdas. This manifests in a heavy use of very simple nested (aka inner) classes to fill the niche that lambdas usually occupy.

In modern Java projects developed from scratch, developers will typically use lambdas wherever possible. We also strongly suggest that, when refactoring old code, you take some time to convert inner classes to lambdas wherever possible. Some IDEs even provide an automatic conversion facility.

However, this still leaves the design question of when to use lambdas and when nested classes are still the correct solution.

Some cases are obvious; for example, when extending a default implementation for some functionality, a nested class approach is appropriate, for two reasons:

1. The custom implementation may have to override multiple methods
2. The base implementation is a class, not an interface

Another major use case to consider is that of stateful lambdas. As there is nowhere to declare any fields, it would appear at first glance that lambdas cannot directly be used for anything that involves state—the syntax only gives the opportunity to declare a method body.

However, a lambda can refer to a variable defined in the scope that the lambda is created in, so we can create a closure, as discussed in Chapter 4, to fill the role of a stateful lambda.

## Lambdas Versus Method References

The question of when to use a lambda and when to use a method reference is largely a matter of personal taste and style. There are, of course, some circumstances where it is essential to create a lambda. However, in many simple cases, a lambda can be replaced by a method reference.

One possible approach is to consider whether the lambda notation adds anything to the readability of the code. For example, in the streams API, there is a potential benefit in using the lambda form, as it uses the `->` operator. This provides a form of visual metaphor—the stream API is a lazy abstraction that can be visualized as data items "flowing through a functional pipeline."

For example, let's consider a `Person` object, which has standard characteristics, such as name, age, etc. We can compute the average using a pipeline, like this:

```
List<Person> persons = ... // derived from somewhere
double aveAge = persons.stream()
        .mapToDouble(o -> o.getAge())
        .reduce(0, (x, y) -> x + y ) / persons.size();
```

The idea that the `mapToDouble()` method has an aspect of motion, or transformation, is strongly implied by the usage of an explicit lambda. For less experienced programmers, it also draws attention to the use of a functional API.

For other use cases (e.g., *dispatch tables*), method references may well be more appropriate. For example:

```
public class IntOps {
    private Map<String, BinaryOperator> table =
```

```
        Map.of("add", IntOps::add, "subtract", IntOps::sub);

    private static int add(int x, int y) {
        return x + y;
    }

    private static int sub(int x, int y) {
        return x - y;
    }

    public int eval(String op, int x, int y) {
        return table.get(op).apply(x, y);
    }
}
```

In situations where either notation could be used, you will come to develop a preference that fits your individual style over time. The key consideration is whether, when returning to reread code written several months (or years) ago, the choice of notation still makes sense and the code is easy to read.

## OOD Using Sealed Types

We met sealed classes for the first time in Chapter 3 and introduced sealed interfaces in Chapter 4. As well as the cases we've already met, there is also a simpler possibility, in which a sealed type can be extended only by classes that are defined inside the same compilation unit (i.e., Java source file), like this:

```
// Note the absence of a permits clause
public abstract sealed class Shape {

    public static final class Circle extends Shape {
        // ...
    }

    public static final class Rectangle extends Shape {
        // ...
    }
}
```

The classes `Shape.Circle` and `Shape.Rectangle` are the only permitted subclasses of `Shape`: any other attempt to extend `Shape` will result in a compilation error. This is really just additional detail, as the general concept remains the same; `sealed` indicates a type that has only a finite number of possible types that are compatible with it.

There is an interesting duality here:

- Enums are classes that have only a finite number of instances—any enum object is one of those instances

- Sealed types have only a finite number of compatible classes—any sealed object belongs to one of those classes

Now consider a switch expression that accepts an enum, for example:

```
var temp = switch(season) {
    case WINTER -> 2.0;
    case SPRING -> 10.5;
    case SUMMER -> 24.5;
    case AUTUMN -> 16.0;
};
System.out.println("Average temp: "+ temp);
```

All the possible enum constants for seasons are present in this switch expression, and so the match is said to be *total*. In this case, it is not necessary to include a `default`, as the compiler can use the *exhaustiveness* of the enum constants to infer that the default case would never be activated.

It isn't hard to see that we could do something similar with sealed types. Some code like this:

```
Shape shape = ...

if (shape instanceof Shape.Circle c) {
    System.out.println("Circle: "+ c.circumference());
} else if (shape instanceof Shape.Rectangle r) {
    System.out.println("Rectangle: "+ r.circumference());
}
```

is obviously exhaustive to a human but is not currently (as of Java 17) directly recognized by the compiler.

This is because, as of Java 17, sealed types are essentially an incomplete feature. In a future version of Java, the intent is to extend the switch expressions feature and combine it with the new form of `instanceof` (and other new language features) to deliver a capability called *pattern matching*.

This new feature will enable developers to write code that, for example, "switches over a variable's type," and this will unlock new design patterns inspired by functional programming, which have not been easy to achieve in Java.

> Appendix has more information about pattern matching and other future features.

Despite not being entirely complete as of Java 17, sealed types are still very useful in their current form and can also be combined with records to produce some compelling designs.

## OOD Using Records

Records were introduced in Chapter 3, and in their simplest form they represent a data entity that is "just fields" or a "bag of data." In some other programming languages, this is represented by a *tuple*, but Java's records are different from tuples in two important ways:

1. Java records are named types, whereas tuples are anonymous
2. Java records can have methods, auxiliary constructors and almost everything a class can

Both of these stem from the fact that records are a special type of class. This allows the programmer to start their design by using a record as a basic collection of fields, and then to evolve from there.

For example, let's rewrite Example 5-1 as a record (eliding the `Comparable` interface for simplicity):

```
public record Circle(int x, int y, int r) {
    // Primary (compact) constructor
    public Circle {
        // Validation code in the constructor
        // This would be impossible in a tuple
        if (r < 0) {
            throw new IllegalArgumentException("negative radius");
        }
    }

    // Factory method playing the role of the copy constructor
    public static Circle of(Circle original) {
        return new Circle(original.x, original.y, original.r);
    }
}
```

Note that we have introduced a new type of constructor, called a *compact constructor*. It is available only for records and is used in the case where we want to do a bit of extra work in the constructor as well as initialize the fields. Compact constructors don't have (or need) a parameter list, as they always have the same parameter list as the declaration of the record.

This code is much shorter than Example 5-1 and clearly distinguishes the case of the primary constructor (the "true form") of the record from the copy constructor and any other factories that may be present.

The design of Java's records means that they are a very flexible choice for the programmer. An entity can be initially modeled as just fields, and over time, can acquire more methods, implement interfaces, and so on.

One other important aspect is that records also can be used very effectively in combination with sealed interfaces. Let's take a look at an example: a delivery company that has different types of orders: basic orders (delivered free), and express orders (arrive quicker but for an additional charge).

The basic interface for the orders looks like this:

```
sealed interface Order permits BasicOrder, ExpressOrder {
    double price();
    String address();
    LocalDate delivery();
}
```

and has two implementations:

```
public record BasicOrder(double price,
                         String address,
                         LocalDate delivery) implements Order {}

public record ExpressOrder(double price,
                           String address,
                           LocalDate delivery,
                           double deliveryCharge) implements Order {}
```

Remember that the supertype of all record types is `java.lang.Record`, so for this type of use case we have to use interfaces; it would not be possible to have the different order types extend an abstract base. Our choices are:

- Model the entities as classes and use a `sealed abstract` base class
- Model the entities as records and use a sealed interface

In the second case, any common record components need to be hoisted up into the interface, just as we saw for the `Order` example.

## Instance Methods or Class Methods?

Instance methods are one of the key features of object-oriented programming. That doesn't mean, however, that you should shun class methods. In many cases, it is perfectly reasonable to define class methods.

> Remember that in Java, class methods are declared with the `static` keyword, and the terms *static method* and *class method* are used interchangeably.

For example, when working with the `Circle` class you might find that you often want to compute the area of a circle with a given radius but don't want to bother creating a `Circle` object to represent that circle. In this case, a class method is more convenient:

```
public static double area(double r) { return PI * r * r; }
```

It is perfectly legal for a class to define more than one method with the same name, as long as the methods have different parameter lists. This version of the `area()` method is a class method, so it does not have an implicit `this` parameter and must have a parameter that specifies the radius of the circle. This parameter keeps it distinct from the instance method of the same name.

As another example of the choice between instance methods and class methods, consider defining a method named `bigger()` that examines two `Circle` objects and returns whichever has the larger radius. We can write `bigger()` as an instance method as follows:

```
// Compare the implicit "this" circle to the "that" circle passed
// explicitly as an argument and return the bigger one.
public Circle bigger(Circle that) {
  if (this.r > that.r) return this;
  else return that;
}
```

We can also implement `bigger()` as a class method as follows:

```
// Compare circles a and b and return the one with the larger radius
public static Circle bigger(Circle a, Circle b) {
  if (a.r > b.r) return a;
  else return b;
}
```

Given two `Circle` objects, `x` and `y`, we can use either the instance method or the class method to determine which is bigger. The invocation syntax differs significantly for the two methods, however:

```
// Instance method: also y.bigger(x)
Circle biggest = x.bigger(y);
Circle biggest = Circle.bigger(x, y);  // Static method
```

Both methods work well, and, from an object-oriented design standpoint, neither of these methods is "more correct" than the other. The instance method is more formally object-oriented, but its invocation syntax suffers from a kind of asymmetry. In a case like this, the choice between an instance method and a class method is simply a design decision. Depending on the circumstances, one or the other will likely be the more natural choice.

## A word about System.out.println()

We've frequently encountered the method `System.out.println()`—it's used to display output to the terminal window or console. We've never explained why this method has such a long, awkward name or what those two periods are doing in it. Now that you understand class and instance fields and class and instance methods, it is easier to understand what is going on: `System` is a class. It has a public class field named `out`. This field is an object of type `java.io.PrintStream`, and it has an instance method named `println()`.

We can use static imports to make this a bit shorter with `import static java.lang.System.out;`—this will enable us to refer to the printing method as `out.println()` but as this is an instance method, we cannot shorten it further.

## Composition Versus Inheritance

Inheritance is not the only technique at our disposal in object-oriented design. Objects can contain references to other objects, so a larger conceptual unit can be aggregated out of smaller component parts; this is known as *composition*.

An important related technique is *delegation*, where an object of a particular type holds a reference to a secondary object of a compatible type and forwards all operations to the secondary object. This is frequently done using interface types, as shown in this example where we model the employment structure of software companies:

```
public interface Employee {
  void work();
}

public class Programmer implements Employee {
  public void work() { /* program computer */ }
}

public class Manager implements Employee {
  private Employee report;

  public Manager(Employee staff) {
    report = staff;
  }

  public Employee setReport(Employee staff) {
    report = staff;
  }

  public void work() {
    report.work();
  }
}
```

The `Manager` class is said to *delegate* the `work()` operation to their direct report, and no actual work is performed by the `Manager` object. Variations of this pattern involve some work being done in the delegating class, with only some calls being forwarded to the delegate object.

Another useful, related technique is called the *decorator pattern*. This provides the capability to extend objects with new functionality, including at runtime. The slight overhead is some extra work needed at design time. Let's look at an example of the decorator pattern as applied to modeling burritos for sale at a taqueria. To keep things simple, we've modeled only a single aspect to be decorated—the price of the burrito:

```
// The basic interface for our burritos
interface Burrito {
  double getPrice();
}

// Concrete implementation-standard size burrito
public class StandardBurrito implements Burrito {
  private static final double BASE_PRICE = 5.99;

  public double getPrice() {
    return BASE_PRICE;
  }
}

// Larger, super-size burrito
public class SuperBurrito implements Burrito {
  private static final double BASE_PRICE = 6.99;

  public double getPrice() {
    return BASE_PRICE;
  }
}
```

These cover the basic burritos that can be offered—two different sizes, at different prices. Let's enhance this by adding some optional extras—jalapeño chilies and guacamole. The key design point here is to use an abstract base class that all of the optional decorating components will subclass:

```
/*
 * This class is the Decorator for Burrito. It represents optional
 * extras that the burrito may or may not have.
 */
public abstract class BurritoOptionalExtra implements Burrito {
    private final Burrito burrito;
    private final double price;

    protected BurritoOptionalExtra(Burrito toDecorate,
          double myPrice) {
        burrito = toDecorate;
        price = myPrice;
    }

    public final double getPrice() {
        return (burrito.getPrice() + price);
    }
}
```

Combining an `abstract` base, `BurritoOptionalExtra`, with a `protected` constructor means that the only valid way to get a `BurritoOptionalExtra` is to construct an



OO Design

instance of one of the subclasses, as they have public constructors. This approach also hides the setup of the price of the component from client code.

> Decorators can, of course, also be combined with sealed types to allow only a known, finite list of possible decorators.

Let's test the implementation:

```
Burrito lunch = new Jalapeno(new Guacamole(new SuperBurrito()));
// The overall cost of the burrito is the expected $8.09.
System.out.println("Lunch cost: "+ lunch.getPrice());
```

The decorator pattern is very widely used, not least in the JDK utility classes. When we discuss Java I/O in Chapter 10, we will see more examples of decorators in the wild.

# Exceptions and Exception Handling

We met checked and unchecked exceptions in "Checked and Unchecked Exceptions" on page 79. In this section, we discuss some additional aspects of the design of exceptions and how to use them in your own code.

Recall that an exception in Java is an object. The type of this object is `java.lang.Throwable`, or more commonly, some subclass of `Throwable` that more specifically describes the type of exception that occurred. `Throwable` has two standard subclasses: `java.lang.Error` and `java.lang.Exception`. Exceptions that are subclasses of `Error` generally indicate unrecoverable problems: the virtual machine has run out of memory, or a class file is corrupted and cannot be read, for example. Exceptions of this sort can be caught and handled, but it is rare to do so—these are the unchecked exceptions previously mentioned.

Exceptions that are subclasses of `Exception`, on the other hand, indicate less severe conditions. These exceptions can be reasonably caught and handled. They include such exceptions as `java.io.EOFException`, which signals the end of a file, and `java.lang.ArrayIndexOutOfBoundsException`, which indicates that a program has tried to read past the end of an array. These are the checked exceptions from Chapter 2 (except for subclasses of `RuntimeException`, which are also a form of unchecked exception). In this book, we use the term "exception" to refer to any exception object, regardless of whether the type of that exception is `Exception` or `Error`.

Because an exception is an object, it can contain data, and its class can define methods that operate on that data. The `Throwable` class and all its subclasses include a `String` field that stores a human-readable error message that describes the exceptional condition. It's set when the exception object is created and can be read from the exception with the `getMessage()` method. Most exceptions contain only this single message, but a few add other data. The `java.io.InterruptedIOException`, for example, adds a field named `bytesTransferred` that specifies how much input or output was completed before the exceptional condition interrupted it.

When designing your own exceptions, you should consider what other additional modeling information is relevant to the exception object. This is usually situation-specific information about the aborted operation, and the exceptional circumstance that was encountered (as we saw with `java.io.InterruptedIOException`).

There are some trade-offs in the use of exceptions in application design. Using checked exceptions means that the compiler can enforce the handling (or propagation up the call stack) of known conditions that have the potential of recovery or retry. It also means that it's more difficult to forget to actually handle errors—thus reducing the risk that a forgotten error condition causes a system to fail in production.

On the other hand, some applications will not be able to recover from certain conditions, even conditions that are theoretically modeled by checked exceptions. For example, if an application requires a config file to be placed at a specific place in the filesystem and can't locate it at startup, it may have no option but to print an error message and exit—despite the fact that `java.io.FileNotFoundException` is a checked exception. Forcing exceptions that cannot be recovered from to be either handled or propagated is, in these circumstances, bordering on perverse; in this situation, printing the error and exiting is the only really sensible action.



When designing exception schemes, here are some good practices you should follow:

- Consider what additional state needs to be placed on the exception—remember that it's also an object like any other.
- `Exception` has four public constructors—under normal circumstances, custom exception classes should implement all of them—to initialize the additional state or to customize messages.
- Don't create many fine-grained custom exception classes in your APIs—the Java I/O and reflection APIs both suffer from this, and it needlessly complicates working with those packages.
- Don't overburden a single exception type with describing too many conditions.
- Never create an exception until you're sure you need to throw it. Exception creation can be a costly operation.

Finally, two exception-handling antipatterns you should avoid:

```
// Never just swallow an exception
try {
  someMethodThatMightThrow();
} catch(Exception e){
```

```
}

// Never catch, log, and rethrow an exception
try {
  someMethodThatMightThrow();
} catch(SpecificException e){
  log(e);
  throw e;
}
```

The former just ignores a condition that almost certainly required some action (even if just a notification in a log). This increases the likelihood of failure elsewhere in the system—potentially far from the original, real source.

The second just creates noise. We're logging a message but not actually doing anything about the issue; we still require some other code higher up in the system to actually deal with the problem.

## Safe Java Programming

Programming languages are sometimes described as being *type safe*; however, this term is used rather loosely by working programmers. There are a number of different viewpoints on and definitions for type safety, not all of which are mutually compatible. The most useful view for our purposes is that *type safety* is the property of a programming language that prevents the type of data being incorrectly identified at runtime. This should be thought of as a sliding scale—it is more helpful to think of languages as being more (or less) type safe than each other, rather than a simple binary property of safe/unsafe.

In Java, the static nature of the type system helps prevent a large class of possible errors by producing compilation errors if, for example, the programmer attempts to assign an incompatible value to a variable. However, Java is not perfectly type safe, as we can perform a cast between any two reference types—this will fail at runtime with a `ClassCastException` if the value is not compatible.

In this book, we prefer to think of safety as inseparable from the broader topic of correctness. This means that we should think in terms of programs, rather than languages. This emphasizes the point that safe code is not guaranteed by any widely used language, and instead considerable programmer effort (and adherence to rigorous coding discipline) must be employed if the end result is to be truly safe and correct.

We approach our view of safe programs by working with the state model abstraction as shown in Figure 5-1. A *safe* program is one in which:

- All objects start off in a legal state after creation
- Externally accessible methods transition objects between legal states

- Externally accessible methods must not return with objects in an inconsistent state
- Externally accessible methods must reset objects to a legal state before throwing

In this context, "externally accessible" means `public`, package-private, or `protected`. This defines a reasonable model for safety of programs, and as it is bound up with defining our abstract types in such a way that their methods ensure consistency of state, it's reasonable to refer to a program satisfying these requirements as a "safe program," regardless of the language in which such a program is implemented.

Private methods do not have to start or end with objects in a legal state, as they cannot be called by an external piece of code.

As you might imagine, actually engineering a substantial piece of code so that we can be sure that the state model and methods respect these properties can be quite an undertaking. In languages such as Java, in which programmers have direct control over the creation of preemptively multitasked execution threads, this problem is a great deal more complex.



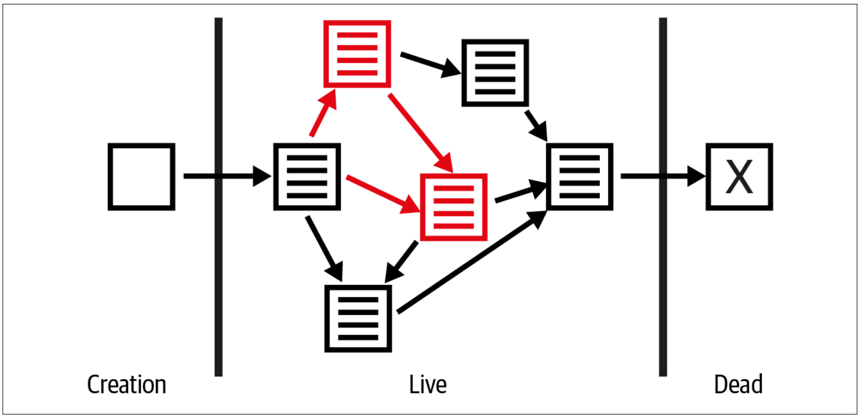



*Figure 5-1. Program state transitions*

Moving on from our introduction of object-oriented design, one final aspect of the Java language and platform needs to be understood for a sound grounding. That is the nature of memory and concurrency—one of the most complex of the platform, but also one that rewards careful study with large dividends. It is the subject of our next chapter and concludes Part I.

# 6
# Java's Approach to Memory and Concurrency

This chapter is an introduction to the handling of concurrency (multithreading) and memory in the Java platform. These topics are inherently intertwined, so it makes sense to treat them together. We will cover:

- Introduction to Java's memory management
- The basic mark-and-sweep garbage collection (GC) algorithm
- How the HotSpot JVM optimizes GC according to the lifetime of the object
- Java's concurrency primitives
- Data visibility and mutability

## Basic Concepts of Java Memory Management

In Java, the memory occupied by an object is automatically reclaimed when the object is no longer needed. This is done through a process known as *garbage collection* (or GC). Garbage collection is a technique that has been around for years and was pioneered by languages such as Lisp. It takes some getting used to for those programmers accustomed to languages such as C and C++, in which you must call the `free()` function or the `delete` operator to reclaim memory.

The fact that you don't need to remember to destroy every object you create is one of the features that makes Java a pleasant language to work with. It is also one of the features that makes programs written in Java less prone to bugs than those written in languages that don't support automatic garbage collection.

Different VM implementations handle garbage collection in different ways, and the specifications do not impose very stringent restrictions on how GC must be implemented. Later in this chapter, we will discuss the HotSpot JVM (which is the basis of both the Oracle and OpenJDK implementations of Java). Although this is not the only JVM that you may encounter, it is by far the most common among server-side deployments and provides the reference example of a modern production JVM.

## Memory Leaks in Java

The fact that Java supports garbage collection dramatically reduces the incidence of *memory leaks*. A memory leak occurs when memory is allocated and never reclaimed. At first glance, it might seem that garbage collection prevents all memory leaks because it reclaims all unused objects.

A memory leak can still occur in Java, however, if a valid (but unused) reference to an unused object is left hanging around. For example, when a method runs for a long time (or forever), the local variables in that method can retain object references much longer than they are actually required. The following code illustrates:

```
public static void main(String args[]) {
  int bigArray[] = new int[100000];

  // Do some computations with bigArray and get a result.
  int result = compute(bigArray);

  // We no longer need bigArray. It will get garbage collected when
  // there are no more references to it. Because bigArray is a local
  // variable, it refers to the array until this method returns. But
  // this method doesn't return.
  // If we explicitly sever the reference by assigning it to
  // null then the garbage collector knows it can reclaim the array.
  bigArray = null;

  // Loop forever, handling the user's input
  for(;;) handle_input(result);
}
```

Memory leaks can also occur when you use a `HashMap` or similar data structure to associate one object with another. Even when neither object is required anymore, the association remains in the map, preventing the objects from being reclaimed until the map itself is reclaimed. If the map has a substantially longer lifetime than the objects it holds, this can cause memory leaks.

## Introducing Mark-and-Sweep

Java GC typically relies on an algorithm from a family broadly known as *mark-and-sweep*. To understand these algorithms, recall that all Java objects are created in the heap, and a reference (basically a pointer) to them is stored in a Java local variable (or field) when an object is created. Local variables live in the method's stack frame, and if an object is returned from a method, then the reference is passed back to the caller's stack frame when the method exits.

As all objects are allocated in the heap, GC will trigger when the heap gets full (or before, depending on the details). The basic idea of mark-and-sweep is to *trace* the heap and identify which objects are still in use. This can be done by examining the stack frames of each Java thread (and a few other sources of references) and following any references into the heap. Each object located is *marked* as still alive and can then be checked to see if it has any fields that are of reference type. If so, these references can be traced and marked as well.

When the recursive tracing activity has completed, all remaining unmarked objects are known to be no longer needed and the heap space they occupy can be *swept* as garbage, i.e., the memory they used is reclaimed to use in further object allocations. If this analysis can be carried out exactly, then this type of collector is known, unsurprisingly enough, as an *exact garbage collector*. For all practical purposes, all Java GCs can be considered to be exact, but this may not be true in other software environments.

In a real JVM, there will very likely be different areas of heap memory, and real programs will use all of them in normal operation. In Figure 6-1 we show one possible layout of the heap, with two threads (T1 and T2) holding references that point into the heap.

The different areas are called *Eden*, *Survivor* and *Tenured*; we'll meet each of these later in the chapter and see how they relate to each other. For the sake of simplicity, the figures show an older form of the Java heap, where each memory area is a single lump of memory. Modern collectors don't actually lay objects out this way, but it's easier to understand by thinking about it this way first!

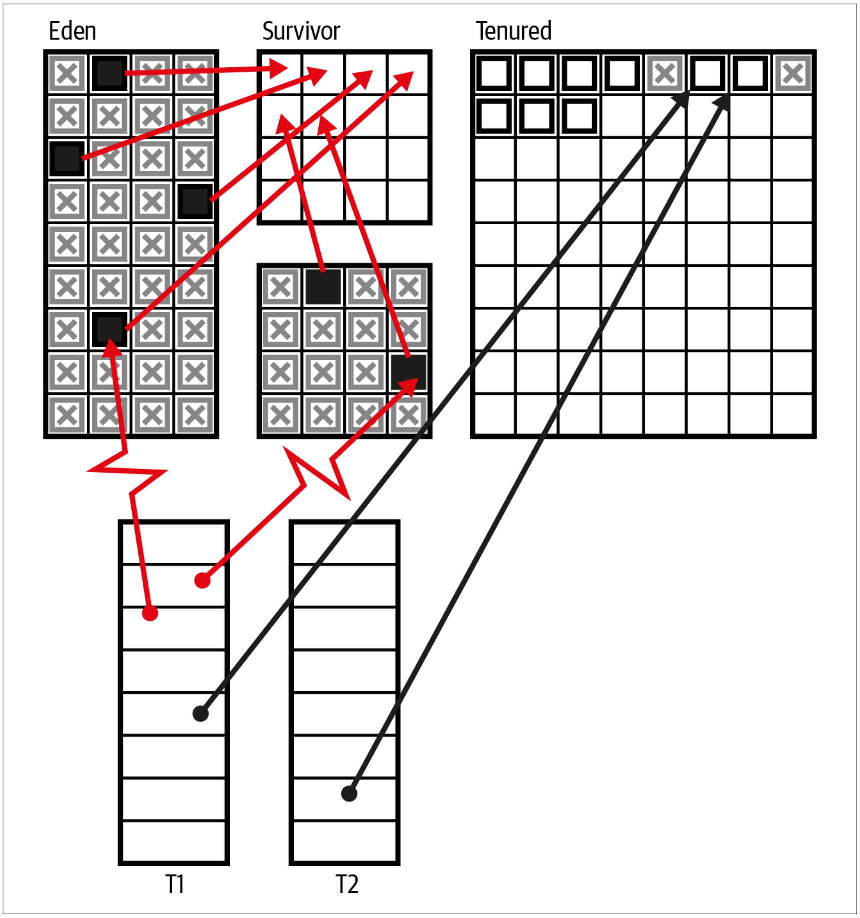



*Figure 6-1. Heap structure*

The figure also shows that it would be dangerous to move objects that application threads have references to while the program is running.

To avoid this, a simple tracing GC like the one just described will cause a *stop-the-world* (STW) pause when it runs. This works because all application threads are stopped, then GC occurs, and finally application threads are started up again. The runtime takes care of this by halting application threads as they reach a *safepoint*—for example, the start of a loop or just before a method call returns. At these execution points, the runtime knows that it can stop an application thread without a problem.

These pauses sometimes worry developers, but for most mainstream usages, Java is running on top of an operating system (and possibly multiple virtualization layers) that is constantly swapping processes on and off processor cores, so this slight additional stoppage is usually not a concern. In the HotSpot case, a large amount of work has been done to optimize GC and to reduce STW times, for those cases where it is important to an application's workload. We will discuss some of those optimizations in the next section.

## How the JVM Optimizes Garbage Collection

The *weak generational hypothesis* (WGH) is a great example of one of the runtime facts about software that we introduced in Chapter 1. Simply put, it is that objects tend to have one of a small number of possible life expectancies (referred to as *generations*).

Usually objects are alive for only a very short amount of time (sometimes called transient objects) and then become eligible for garbage collection. However, some small fraction of objects live longer and are destined to become part of the longer-term state of the program (sometimes referred to as the *working set*). This can be seen in Figure 6-2 where we see volume of memory (or number of objects created) plotted against expected lifetime.

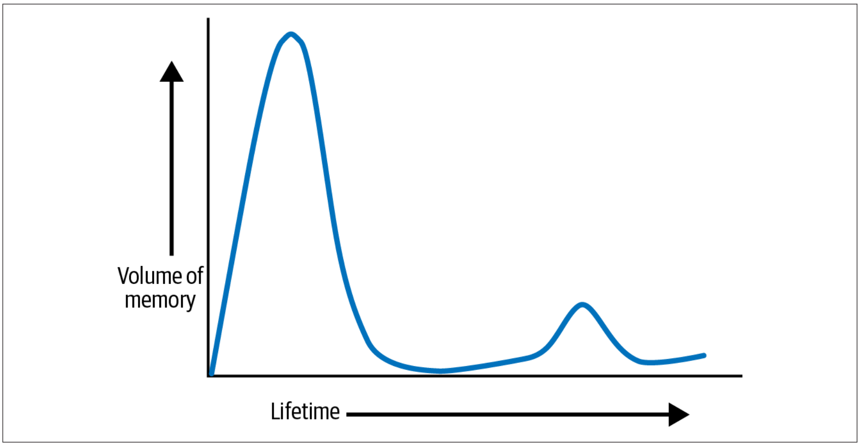



*Figure 6-2. Weak generational hypothesis*

This fact is not deducible from static analysis of programs, and yet when we measure the runtime behavior of software, we see that it is broadly true across a wide range of workloads.

The HotSpot JVM has a garbage collection subsystem that is designed specifically to take advantage of the weak generational hypothesis, and in this section, we will discuss how these techniques apply to short-lived objects (which is the majority case). This discussion is directly applicable to HotSpot, but other JVMs often employ similar or related techniques.

In its simplest form, a *generational garbage collector* is one that takes notice of the WGH. They take the position that some extra bookkeeping to monitor memory will be more than paid for by gains obtained by being friendly to the WGH. In the simplest forms of generational collector, there are usually just two generations—usually referred to as young and old generation.

## Evacuation

In our original formulation of mark-and-sweep, during the cleanup phase, the GC reclaimed individual objects for reuse. This is fine, as far as it goes, but it leads to issues such as memory fragmentation and the GC needing to maintain a "free list" of memory blocks that are available. However, if the WGH is true, and on any given GC cycle most objects are dead, then it may make sense to use an alternative approach to reclaiming space.

This works by dividing the heap up into separate memory spaces; new objects are created in a space called *Eden*. Then, on each GC run, we locate only the live objects and move them to a different space, in a process called *evacuation*. Collectors that do this are referred to as *evacuating collectors*, and they have the property that the entire memory space can be wiped at the end of the collection, to be reused again and again.

Figure 6-3 shows an evacuating collector in action, with solid blocks representing surviving objects, and hatched boxes representing allocated but now dead (and unreachable) objects.

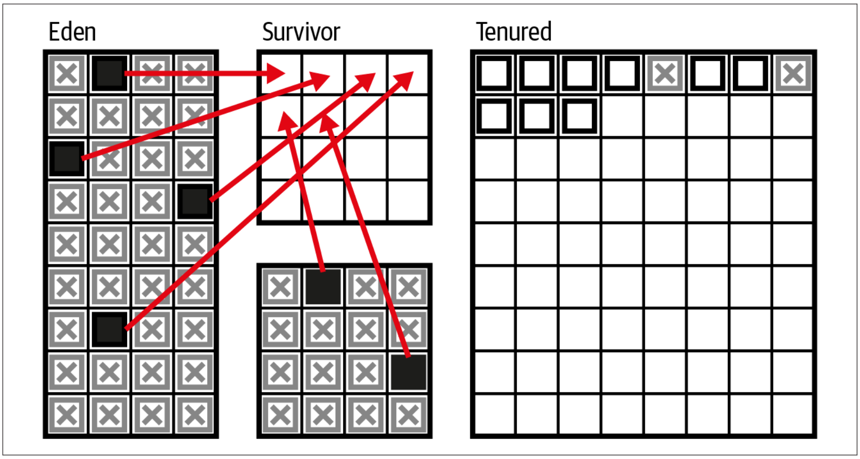



*Figure 6-3. Evacuating collectors*

This is potentially much more efficient than the naive collection approach, because the dead objects are never touched. This means that the GC time is proportional to the number of live objects, rather than the number of allocated objects. The only downside is slightly more bookkeeping—we have to pay the cost of copying the live objects, but this is almost always a very small price compared to the huge gains realized by evacuation strategies.

The use of an evacuating collector also allows the use of per-thread allocation. This means that each application thread can be given a contiguous chunk of memory (called a *thread-local allocation buffer* or TLAB) for its exclusive use when allocating new objects. When new objects are allocated, this just involves bumping a pointer in the allocation buffer, an extremely cheap operation.

If an object is created just before a collection starts, then it will not have time to fulfill its purpose and die before the GC cycle starts. In a collector with only two generations, this short-lived object will be moved into the long-lived region, die almost immediately, and then stay there until the next full collection. As these are a lot less frequent (and typically a lot more expensive), this seems rather wasteful.

To mitigate this, HotSpot has a concept of a *survivor space*, an area used to house objects that have survived previous collections of young objects. A surviving object is copied by the evacuating collector between survivor spaces until a *tenuring threshold* is reached, when the object will be *promoted* to the old generation, known as *Tenured* or *OldGen*. This solves the problem of short-lived objects cluttering up the old generation, at the cost of more complexity in the GC subsystem.

## Compaction

A different form of collection algorithm is known as a *compacting collector*. The main feature of these collectors is that, at the end of the collection cycle, allocated memory (i.e., surviving objects) is arranged as a single contiguous area within the collected region.

The normal case is that all the surviving objects have been "shuffled up" within the memory pool (or region) usually to the start of the memory range, and there is now a pointer indicating the start of empty space available for objects to be written into once application threads restart.

Compacting collectors will avoid memory fragmentation but typically are much more expensive in terms of amount of CPU consumed than evacuating collectors. There are design trade-offs between the two algorithms (the details of which are beyond the scope of this book), but both techniques are used in production collectors in Java (and in many other programming languages). The space where long-lived objects end up is typically cleaned using a compacting collector.

A full discussion of the details of the GC subsystem is outside the scope of this book. For production applications that have to care about these details, specialist material such as *Optimizing Java* (O'Reilly) should be consulted.

# The HotSpot Heap

The HotSpot JVM is a relatively complex piece of code, made up of an interpreter and a just-in-time compiler, as well as a user-space memory management subsystem. It is composed of a mixture of C, C++, and a fairly large amount of platform-specific assembly code.

HotSpot manages the JVM heap itself, more-or-less completely in user space, and does not need to perform system calls to allocate or free memory. The area where objects are initially created is usually called Eden (or the Nursery), and most production JVMs will use an evacuating strategy when collecting Eden.

At this point, let's summarize our description of the HotSpot heap and recap its basic features:

- The Java heap is a contiguous block of memory, which is reserved at JVM startup.
- Only some of the heap is initially allocated to the various memory pools.
- As the application runs, memory pools are resized as needed.
- These resizes are performed by the GC subsystem.
- Objects are created in Eden by application threads and are removed by a nondeterministic GC cycle.
- The GC cycle runs when necessary (i.e., when memory is getting low).
- The heap is divided into two generations, young and old.
- The young generation is made up of Eden and survivor spaces, whereas the old generation is just one memory space.
- After surviving several GC cycles, objects get promoted to the old generation.
- Collections that collect only the young generation are usually very cheap (in terms of computation required).
- HotSpot uses an advanced form of mark-and-sweep and is prepared to do extra bookkeeping to improve GC performance.

When discussing garbage collectors, developers should know one other important terminology distinction:

*Parallel collector*
: A garbage collector that uses multiple threads to perform collection

*Concurrent collector*
: A garbage collector that can run at the same time as application threads are still running

In the discussion so far, the collection algorithms we have been describing have implicitly all been parallel, but not concurrent, collectors.

> In modern approaches to GC, there is a growing trend toward using partially concurrent algorithms. These types of algorithms are much more elaborate and computationally expensive than STW algorithms and involve trade-offs. However, today's applications are typically willing to trade some extra computation for reduced application pauses.

In legacy Java versions (version 8 and older), the heap has a simple structure: each memory pool (Eden, survivor spaces, and Tenured) is a contiguous block of memory. This is the structure that we've shown in the diagrams, as it's easier for beginners to visualize. The default collector for the old generation in these older versions is called *Parallel*. However, in modern versions of HotSpot, a new, partially concurrent collection algorithm known as *Garbage First* (G1) has become the default.

## G1

G1 is an example of a *region-based collector* and has a different heap layout than the old-style heap. A region is an area of memory (usually 1M in size, but larger heaps may have regions of 2, 4, 8, 16, or 32M) where all the objects belong to the same memory pool. However, in a regional collector, the different regions that make up a pool are not necessarily located next to each other in memory. This is unlike the Java 8 heap, where each pool is contiguous, although in both cases the entire heap remains contiguous.

> G1 uses a different version of the algorithm in each Java version, and there are some important differences in terms of performance and other behavior between versions. It is very important that, when upgrading from Java 8 to a later version and adopting G1, you undertake a full performance retest. You may find that when switching to Java 11 or 17, you require fewer resources (and may even save money).



G1 focuses its attention on regions that are mostly garbage, as they have the best free memory recovery. It is an evacuating collector and does *incremental compaction* when evacuating individual regions.

The G1 collector was originally intended to take over from a previous collector, CMS, as the low-pause collector, and it allows the user to specify *pause goals* in terms of how long and how often to pause when doing GC.

The JVM provides a command-line switch that controls how long the collector will aim to pause: `-XX:MaxGCPauseMillis=200`. This means that the default pause time goal is 200 ms, but you can change this value depending on your needs.

There are, of course, limits to how far the collector can be pushed. Java GC is driven by the rate at which new memory is allocated, which can be highly unpredictable for many Java applications.

As noted, G1 was originally intended to be a replacement low-pause collector. However, the overall characteristics of its behavior have meant that it has actually evolved into a more general-purpose collector (which is why it has now become the default).

Note that the development of a new production-grade collector that is suitable for general use is not a quick process. In the next section, let's move on to discuss the alternative collectors that are provided by HotSpot (including the parallel collector of Java 8).

A detailed full treatment is outside the scope of the book, but it is worth knowing about the existence of alternate collectors. For non-HotSpot users, you should consult your JVM's documentation to see what options may be available for you.

## ParallelOld

By default, in Java 8 the collector for the old generation is a parallel (but not concurrent) mark-and-sweep collector. It seems, at first glance, to be similar to the collector used for the young generation. However, it differs in one very important respect: it is *not* an evacuating collector. Instead, the old generation is compacted when collection occurs. This is important so that the memory space does not become fragmented over time.

The `ParallelOld` collector is very efficient, but it has two properties that make it less desirable for modern applications. It is:

- Fully STW
- Linear in pause time with the size of the heap

This means that once GC has started, it cannot be aborted early, and the cycle must be allowed to finish. As heap sizes increase, this makes `ParallelOld` a less attractive option than G1, which can often keep a constant pause time regardless of heap size (assuming the allocation rate is manageable).

In modern deployments, especially for Java 11+, G1 gives typically better performance on a large majority of applications that previously used `ParallelOld`. The `ParallelOld` collector is still available as of Java 17, for those (hopefully few) apps that still need it, but the direction of the platform is clear—toward using G1 wherever possible.

## Serial

The Serial and SerialOld collectors operate in a similar fashion to the Parallel collectors, with one important difference: they use only a single CPU core to perform fully STW GC.

On modern multicore systems, there is no benefit from using these collectors, and so they should not be used, as they are just an inefficient form of the parallel collectors. However, one place where you may still encounter these collectors is when running Java applications in containers. A full discussion of containerized Java is outside the scope of this book. However, if your application is run in too small a container (either too little memory or with only a single CPU), then the JVM will automatically select the Serial collector.

Therefore, we do not recommend running Java in a single-core container, as the Serial collector performs noticeably worse than G1 under almost all realistic load scenarios.

## Shenandoah

Shenandoah is a new GC algorithm developed by Red Hat to work effectively with certain use cases where G1 and other algorithms do not perform well.

The aim of Shenandoah is to bring down pause times, especially on large heaps, and to guarantee (as far as possible) that pause times will not exceed 1 ms, no matter the size of the heap.

Like G1, Shenandoah is an evacuating regional collector that performs concurrent marking. The evacuation of regions causes incremental compaction but the key difference is that in G1, evacuation happens during a STW phase, whereas in Shenandoah the evacuation is concurrent with application threads.

There is no such thing as a free lunch, however, and users of Shenandoah could experience up to 15% overhead (i.e., reduction in application throughput), but the exact figure will depend on the details of the workload. For example, on some targeted benchmarks you can observe a significant overhead, towards the upper end of the expected range.

Shenandoah can be activated with this command line switch:

```
-XX:+UseShenandoahGC
```

One important point to note is that, at time of writing, Shenandoah is not yet a generational collector, although work is underway to add generations to the implementation.

## ZGC

As well as Shenandoah, Oracle has also created a new ultra-low-pause collector, known as ZGC. It is designed to appeal to the same sorts of workloads as Shenandoah and is broadly similar in intent, effect, and overhead. ZGC is a single-generation, region-based, NUMA-aware, compacting collector. However, the implementation of ZGC is quite different from Shenandoah.

ZGC can be activated with this command line switch:

```
-XX:+UseZGC
```

ZGC needs only a stop-the-world pause to perform root scanning, which means that GC pause times do not increase with the size of the heap or the number of live objects. Due to its intended domain of applicability (ultra-low pause on large heaps), ZGC is most commonly used by Oracle customers on the Oracle-supported builds of Java.

# Finalization

For completeness, developers should be aware of an old technique for resource management known as *finalization*. However, this technique is *extremely* heavily deprecated and the vast majority of Java developers should *not* directly use it under any circumstances.

> Finalization has been deprecated and will be removed in a future release. The mechanism remains enabled by default for now but can be disabled with a switch. In a future release, it will be disabled by default and then eventually removed.

The finalization mechanism was intended to automatically release resources once they are no longer needed. Garbage collection automatically frees up the memory resources used by objects, but objects can hold other kinds of resources, such as open files and network connections. The garbage collector cannot free these additional resources for you, so the finalization mechanism was intended to allow the developer to perform cleanup tasks as closing files, terminating network connections, deleting temporary files, and so on.

The finalization mechanism works as follows: if an object has a `finalize()` method (usually called a *finalizer*), this is invoked some time after the object becomes unused (or unreachable) but before the garbage collector reclaims the space allocated to the object. The finalizer is used to perform resource cleanup for an object.

The central problem with finalization is that Java makes no guarantees about when garbage collection will occur or in what order objects will be collected. Therefore, the platform can make no guarantees about when (or even whether) a finalizer will be invoked or in what order finalizers will be invoked.

## Finalization Details

The finalization mechanism is an attempt to implement a similar concept present in other languages and environments. In particular, C++ has a pattern known as RAII (Resource Acquisition Is Initialization) that provides automatic resource management in a similar way. In that pattern, a destructor method (which would be called `finalize()` in Java) is provided by the programmer, to perform cleanup and release resources when the object is destroyed.

The basic use case for this is fairly simple: when an object is created, it takes ownership of some resource, and the object's ownership of that resource is tied to the lifetime of the object. When the object dies, the ownership of the resource is automatically relinquished, as the platform calls the destructor without any programmer intervention.

While finalization superficially sounds similar to this mechanism, in reality it is fundamentally different. In fact, the finalization language feature is fatally flawed, due to differences in the memory management schemes of Java versus C++.

In the C++ case, memory is handled manually, with explicit lifetime management of objects under the control of the programmer. This means that the destructor can be called immediately after the object is deleted (the platform guarantees this), and so the acquisition and release of resources is directly tied to the lifetime of the object.

On the other hand, Java's memory management subsystem is a garbage collector that runs as needed, in response to running out of available memory to allocate. It therefore runs at variable (and nondeterministic) intervals and so `finalize()` is run only when the object is collected, and this will be at an unknown time.

If the `finalize()` mechanism was used to automatically release resources (e.g., filehandles), then there is no guarantee as to when (if ever) those resources will actually become available. This has the result of making the finalization mechanism fundamentally unsuitable for its stated purpose—automatic resource management. We cannot guarantee that finalization will happen fast enough to prevent us from running out of resources. As an automatic cleanup mechanism for protecting scarce resources (such as filehandles), finalization is broken by design.

Finalization has only a very small number of legitimate use cases, and only a tiny minority of Java developers will ever encounter them. If in any doubt, do not use finalization—try-with-resources is usually the correct alternative. More details about `try`-with-resources can be found in Chapter 10.

# Java's Support for Concurrency



The idea of a *thread* is that of a lightweight unit of execution—smaller than a process, but still capable of executing arbitrary Java code. The usual way that this is implemented is for each thread to be a fully fledged unit of execution to the operating system but to belong to a process, with the address space of the process being shared between all threads comprising that process. This means each thread can be scheduled independently and has its own stack and program counter but shares memory and objects with other threads in the same process.

The Java platform has supported multithreaded programming from the very first version. The platform exposes the ability to create new threads of execution to the developer.

To understand this, first we must consider what happens in detail when a Java program starts up and the original application thread (usually referred to as *main* thread) appears:

1. The programmer executes `java Main` (other startup cases are possible).
2. This causes the Java Virtual Machine, the context within which all Java programs run, to start up.

3. The JVM examines its arguments and sees that the programmer has requested execution starting at the entry point (the `main()` method) of `Main.class`.
4. Assuming that `Main` passes classloading checks, a dedicated thread for the execution of the program is started (main thread).
5. The JVM bytecode interpreter is started on main thread.
6. Main thread's interpreter reads the bytecode of `Main::main()` and execution begins, one bytecode at a time.

Every Java program starts this way, but this also means:

- Every Java program starts as part of a managed model with one interpreter per thread.
- Every Java program always runs as part of a multithreaded operating system process.
- The JVM has a certain ability to control a Java application thread.

Following from this, when we create new threads of execution in Java code, this is usually as simple as:

```
Thread t = new Thread(() -> {System.out.println("Hello Thread");});
t.start();
```

This small piece of code creates and starts a new thread, which executes the body of the lambda expression and then executes. Technically speaking, the lambda is converted to an instance of the `Runnable` interface before being passed to the `Thread` constructor.

The threading mechanism allows new threads to execute concurrently with the original application thread and the threads that the JVM itself starts up for various purposes.

For mainstream implementations of the Java platform, every time we call `Thread::start()` this call is delegated to the operating system, and a new OS thread is created. This new OS thread `exec()`'s a new copy of the JVM bytecode interpreter. The interpreter starts executing at the `run()` method (or, equivalently, at the body of the lambda).

This means that application threads have their access to the CPU controlled by the operating system *scheduler*—a built-in part of the OS that is responsible for managing timeslices of processor time (and that will not allow an application thread to exceed its allocated time).

In more recent versions of Java, an increasing trend toward *runtime-managed concurrency* has appeared. This is the idea that for many purposes it's not desirable for developers to explicitly manage threads. Instead, the runtime should provide "fire and forget" capabilities, whereby the program specifies what needs to be done, but the low-level details of how this is to be accomplished are left to the runtime.

This viewpoint can be seen in the concurrency toolkit contained in `java.util.concurrent`, which we discuss briefly in Chapter 8.

For the remainder of this chapter, we will introduce the low-level concurrency mechanisms that the Java platform provides and that every Java developer should be aware of. The reader is strongly encouraged to understand both the low-level `Thread`-based and the runtime-managed approaches before doing any significant concurrent programming.

## Thread Lifecycle

Let's start by looking at the lifecycle of an application thread. Every operating system has a view of threads that can differ in the details (but in most cases is broadly similar at a high level). Java tries hard to abstract these details away and has an enum called `Thread.State`, which wrappers over the operating system's view of the thread's state. The values of `Thread.State` provide an overview of the lifecycle of a thread:

`NEW`
: The thread has been created, but its `start()` method has not yet been called. All threads start in this state.

`RUNNABLE`
: The thread is running or is available to run when the operating system schedules it.

`BLOCKED`
: The thread is not running because it is waiting to acquire a lock so that it can enter a `synchronized` method or block. We'll see more about `synchronized` methods and blocks later in this section.

`WAITING`
: The thread is not running because it has called `Object.wait()` or `Thread.join()`.

`TIMED_WAITING`
: The thread is not running because it has called `Thread.sleep()` or has called `Object.wait()` or `Thread.join()` with a timeout value.

`TERMINATED`
: The thread has completed execution. Its `run()` method has exited normally or by throwing an exception.

These states represent the view of a thread that is common (at least across mainstream operating systems), leading to a view like Figure 6-4.

Memory and Concurrency

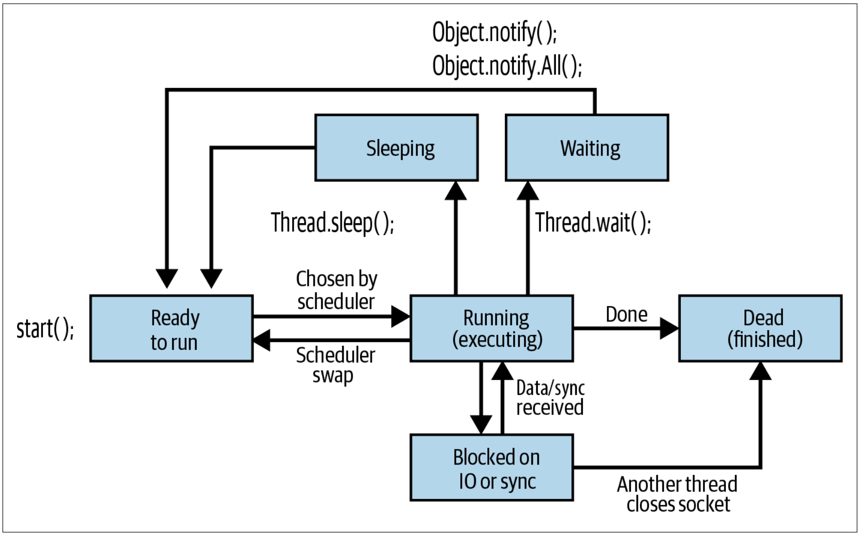
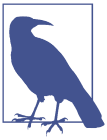



*Figure 6-4. Thread lifecycle*

Threads can also be made to sleep, by using the `Thread.sleep()` method. This takes an argument in milliseconds, which indicates how long the thread would like to sleep like this:

```
try {
    Thread.sleep(2000);
} catch (InterruptedException e) {
    e.printStackTrace();
}
```



The argument to sleep is a request to the operating system, not a demand. For example, your program may sleep for longer than requested, depending on load and other factors specific to the runtime environment.

We will discuss the other methods of `Thread` later in this chapter, but first we need to cover some important theory that deals with how threads access memory and that is fundamental to understanding why multithreaded programming is hard and can cause developers a lot of problems.

## Visibility and Mutability

In mainstream Java implementations, all Java application threads in a process have their own call stacks (and local variables) but share a single heap. This makes it very easy to share objects between threads, as all that is required is to pass a reference from one thread to another. This is illustrated in Figure 6-5.

This leads to a general design principle of Java—that objects are *visible by default*. If I have a reference to an object, I can copy it and hand it off to another thread with no restrictions. A Java reference is essentially a typed pointer to a location in heap—and threads share the same heap, so visible by default is a natural model.

In addition to visible by default, Java has another property that is important to fully understand concurrency, which is that objects are *mutable*: the contents of an object instance's fields can usually be changed. We can make individual variables or references constant by using the `final` keyword, but this does not apply to the contents of the object.

As we will see throughout the rest of this chapter, the combination of these two properties—visibility across threads and object mutability—gives rise to a great many complexities when trying to reason about concurrent Java programs.

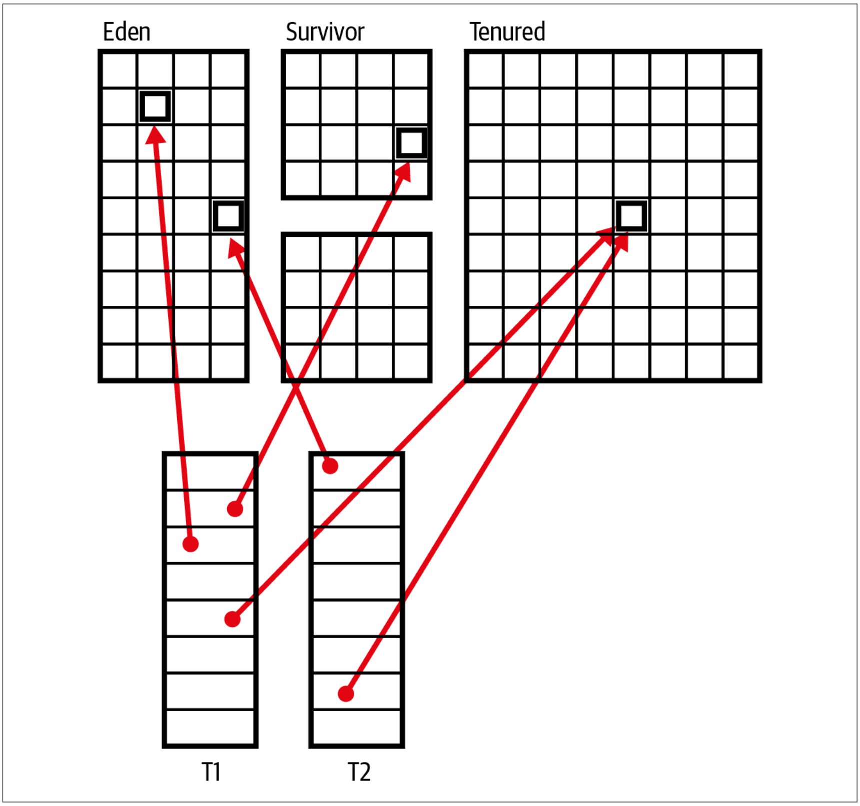



*Figure 6-5. Shared memory between threads*

Memory and Concurrency

### Concurrent safety

If we're to write correct multithreaded code, then we want our programs to satisfy a certain important property.

In Chapter 5, we defined a safe object-oriented program to be one where we move objects from legal state to legal state by calling their accessible methods. This definition works well for single-threaded code. However, there is a particular difficulty that comes about when we try to extend it to concurrent programs.

> A *safe multithreaded program* is one in which it is impossible for any object to be seen in an illegal or inconsistent state by any other object, no matter what methods are called, and no matter in what order the application threads are scheduled by the operating system.

For most mainstream cases, the operating system will schedule threads to run on particular processor cores at seemingly random times, depending on load and what else is running in the system. If load is high, then there may be other processes that also need to run.

The operating system will forcibly remove a Java thread from a CPU core if it needs to. The thread is suspended immediately, no matter what it's doing—including being partway through executing a method. However, as we discussed in Chapter 5, a method can temporarily put an object into an illegal state while it is working on it, providing it corrects it before the method exits.

This means that if a thread is swapped off before it has completed a long-running method, it may leave an object in an inconsistent state, *even if the program follows the safety rules*. Another way of saying this is that even data types that have been correctly modeled for the single-threaded case still need to protect against the effects of concurrency. Code that adds this extra layer of protection is called *concurrently safe* or (more informally) threadsafe.

In the next section, we'll discuss the primary means of achieving this safety, and at the end of the chapter, we'll meet some other mechanisms that can also be useful under some circumstances.

## Exclusion and Protecting State

Any code that modifies *or reads* state that can become inconsistent must be protected. To achieve this, the Java platform provides only one mechanism: *exclusion*.

Consider a method that contains a sequence of operations that, if interrupted partway through, could leave an object in an inconsistent or illegal state. If this illegal state was visible to another object, incorrect code behavior could occur.

For example, consider an ATM or other cash-dispensing machine:

```java
public class Account {
    private double balance = 0.0; // Must be >= 0
    // Assume the existence of other field (e.g., name) and methods
    // such as deposit(), checkBalance(), and dispenseNotes()

    public Account(double openingBal) {
        balance = openingBal;
    }

    public boolean withdraw(double amount) {
        if (balance >= amount) {
            try {
                Thread.sleep(2000); // Simulate risk checks
            } catch (InterruptedException e) {
                return false;
            }
            balance = balance - amount;
            dispenseNotes(amount);
            return true;
        }
        return false;
    }
}
```

The sequence of operations that happens inside `withdraw()` can leave the object in an inconsistent state. In particular, after we've checked the balance, a second thread could come in while the first was sleeping in simulated risk checks, and the account could be overdrawn, in violation of the constraint that `balance >= 0`.

This is an example of a system where the operations on the objects are single-threaded safe (because the objects cannot reach an illegal state (`balance < 0`) if called from a single thread) but not concurrently safe.

To allow the developer to make code like this concurrently safe, Java provides the `synchronized` keyword. This keyword can be applied to a block or to a method, and when it is used, the platform uses it to restrict access to the code inside the block or method.

> Because `synchronized` surrounds code, many developers are led to the conclusion that concurrency in Java is about code. Some texts even refer to the code that is inside the synchronized block or method as a *critical section* and consider that to be the crucial aspect of concurrency. This is not the case; instead, it is the inconsistency of data that we must guard against, as we will see.

The Java platform keeps track of a special token, called a *monitor*, for every object that it ever creates. These monitors (also called *locks*) are used by `synchronized` to indicate that the following code could temporarily render the object inconsistent. The sequence of events for a synchronized block or method is:

1. Thread needs to modify an object and may make it briefly inconsistent as an intermediate step
2. Thread acquires the monitor, indicating it requires temporary exclusive access to the object
3. Thread modifies the object, leaving it in a consistent, legal state when done
4. Thread releases the monitor

If another thread attempts to acquire the lock while the object is being modified, then the attempt to acquire the lock blocks, until the holding thread releases the lock.

Note that you do not have to use the `synchronized` statement unless your program creates multiple threads that share data. If only one thread ever accesses a data structure, there is no need to protect it with `synchronized`.

One point is of critical importance—acquiring the monitor does *not* prevent access to the object. It only prevents any other thread from claiming the lock. Correct concurrently safe code requires developers to ensure that all accesses that might modify *or read* potentially inconsistent state acquire the object monitor before operating on or reading that state.

Put another way, if a `synchronized` method is working on an object and has placed it into an illegal state, and another method (which is not synchronized) reads from the object, it can still see the inconsistent state.

> Synchronization is a cooperative mechanism for protecting state, and it is very fragile as a result. A single bug (such as missing a single `synchronized` keyword from a method it's required on) can have catastrophic results for the safety of the system as a whole.

The reason we use the word `synchronized` as the keyword for "requires temporary exclusive access" is that in addition to acquiring the monitor, the JVM also rereads the current state of the object from main memory when the block is entered. Similarly, when the `synchronized` block or method is exited, the JVM flushes any modified state of the object back to main memory.

Without synchronization, different CPU cores in the system may not see the same view of memory, and memory inconsistencies can damage the state of a running program, as we saw in our ATM example.

The simplest example of this is known as *lost update*, as demonstrated in the following code:

```
public class Counter {
    private int i = 0;

    public int increment() {
        return i = i + 1;
    }
    public int getCounter() { return i; }
}
```

This can be driven via a simple control program:

```
Counter c = new Counter();
int REPEAT = 10_000_000;
Runnable r = () -> {
    for (int i = 0; i < REPEAT; i++) {
        c.increment();
    }
};
Thread t1 = new Thread(r);
Thread t2 = new Thread(r);

t1.start();
t2.start();
t1.join();
t2.join();

int anomaly = (2 * REPEAT) - c.getCounter();
double perc = ((double) anomaly * 100) / (2 * REPEAT);
System.out.println("Lost updates: "+ anomaly +" ; % = " + perc);
```

If this concurrent program was correct, then the value for the anomaly (number of lost updates) should be exactly zero. It is not, and so we may conclude that unsynchronized access is fundamentally unsafe.

By contrast, we also see that the addition of the keyword `synchronized` to the increment method is sufficient to reduce the lost update anomaly to zero—that is, to make the method correct, even in the presence of multiple threads.

## volatile

Java provides another keyword for dealing with concurrent access to data. This is the `volatile` keyword, and it indicates that before being used by application code, the value of the field or variable must be reread from main memory. Equally, after a volatile value has been modified, as soon as the write to the variable has completed, it must be written back to main memory.

One common usage of the `volatile` keyword is in the "run-until-shutdown" pattern. This is used in multithreaded programming where an external user or system needs to signal to a processing thread that it should finish the current job being worked on and then shut down gracefully. This is sometimes called the "graceful completion" pattern. Let's look at a typical example, supposing that this code for our processing thread is in a class that implements `Runnable`:

```
    private volatile boolean shutdown = false;

    public void shutdown() {
        shutdown = true;
    }

    public void run() {
        while (!shutdown) {
            // ... process another task
        }
    }
```

All the time that the `shutdown()` method is not called by another thread, the processing thread continues to sequentially process tasks (this is often combined very usefully with a `BlockingQueue` to deliver work). Once `shutdown()` is called by another thread, the processing thread immediately sees the `shutdown` flag change to `true`. This does not affect the running job, but once the task finishes, the processing thread will not accept another task and instead will shut down gracefully.

However, useful as the `volatile` keyword is, it does not provide a complete protection of state—as we can see by using it to mark the field in `Counter` as `volatile`. We might naively assume that this would protect the code in `Counter`. However, it does not. To see this, modify the previous `Counter` example and add the word `volatile` to the field `i` and rerun the example. The observed nonzero value of the anomaly (and therefore, the presence of the lost update problem) tells us that by itself, `volatile` does not make code threadsafe.

## Useful Methods of Thread

The `Thread` class has a number of methods to make your life easier when you're creating new application threads. This is not an exhaustive list—there are many other methods on `Thread`, but this is a description of some of the more common methods.

### getId()

This method returns the ID number of the thread, as a `long`. This ID will stay the same for the lifetime of the thread and is guaranteed to be unique within this instance of the JVM.

### getPriority() and setPriority()

These methods are used to control the priority of threads. The scheduler decides how to handle thread priorities; for example, one strategy could be to not have any low-priority threads run while there are high-priority threads waiting. In most cases, there is no way to influence how the scheduler will interpret priorities. Thread priorities are represented as an integer between 1 and 10, with 10 being the highest.

### setName() and getName()

These methods allow the developer to set or retrieve a name for an individual thread. Naming threads is good practice, as it can make debugging much, much easier, especially in a tool such as JDK Mission Control (which we will discuss briefly in Chapter 13).

### getState()

This returns a `Thread.State` object that indicates which state this thread is in, as per the values defined in "Thread Lifecycle" on page 251.

### isAlive()

This method is used to test whether a thread is still alive.

### start()

This method is used to create a new application thread, and to schedule it, with the `run()` method being the entry point for execution. A thread terminates normally when it reaches the end of its `run()` method or when it executes a `return` statement in that method.

### interrupt()

If a thread is blocked in a `sleep()`, `wait()`, or `join()` call, then calling `interrupt()` on the `Thread` object that represents the thread will cause the thread to be sent an `InterruptedException` (and to wake up).

If the thread was involved in interruptible I/O, then the I/O will be terminated and the thread will receive a `ClosedByInterruptException`. The interrupt status of the thread will be set to `true`, even if the thread was not engaged in any activity that could be interrupted.

### join()

The current thread waits until the thread corresponding to the `Thread` object has died. It can be thought of as an instruction not to proceed until the other thread has completed.

### setDaemon()

A *user thread* is a thread that will prevent the process from exiting if it is still alive—this is the default for threads. Sometimes, programmers want threads that will not prevent an exit from occurring—these are called *daemon threads*. The status of a thread as a daemon or user thread can be controlled by the `setDaemon()` method and checked using `isDaemon()`.

### setUncaughtExceptionHandler()

When a thread exits by throwing an exception (i.e., one that the program did not catch), the default behavior is to print the name of the thread, the type of the exception, the exception message, and a stack trace. If this isn't sufficient, you can install a custom handler for uncaught exceptions in a thread. For example:

```
// This thread just throws an exception
Thread handledThread =
  new Thread(() -> { throw new UnsupportedOperationException(); });

// Giving threads a name helps with debugging
handledThread.setName("My Broken Thread");

// Here's a handler for the error.
handledThread.setUncaughtExceptionHandler((t, e) -> {
    System.err.printf("Exception in thread %d '%s':" +
        "%s at line %d of %s%n",
        t.getId(),    // Thread id
        t.getName(),  // Thread name
        e.toString(), // Exception name and message
        e.getStackTrace()[0].getLineNumber(),
        e.getStackTrace()[0].getFileName()); });
handledThread.start();
```

This can be useful in some situations; for example, if one thread is supervising a group of other worker threads, then this pattern can be used to restart any threads that die.

There is also `setDefaultUncaughtExceptionHandler()`, a `static` method that sets a backup handler for catching any thread's uncaught exceptions.

## Deprecated Methods of Thread

In addition to the useful methods of `Thread`, there are a number of dangerous methods you should not use. These methods form part of the original Java thread API but were quickly found to be unsuitable for developer use. Unfortunately, due to Java's backward compatibility requirements, it has not been possible to remove them from the API. Developers simply need to be aware of them and to avoid using them under *all* circumstances.

### stop()

`Thread.stop()` is almost impossible to use correctly without violating concurrent safety, as `stop()` kills the thread immediately, without giving it any opportunity to recover objects to legal states. This is in direct opposition to principles such as concurrent safety and so should never be used.

### suspend(), resume(), and countStackFrames()

The `suspend()` mechanism does not release any monitors it holds when it suspends, so any other thread that attempts to access those monitors will deadlock. In practice, this mechanism produces race conditions between these deadlocks and `resume()` that render this group of methods unusable. The method `countStackFrames()` only works when called on a suspended thread so is also made nonfunctional by this restriction.

### destroy()

This method was never implemented—it would have suffered from the same race condition issues as `suspend()` if it had been.

All of these deprecated methods should always be avoided. A set of safe alternative patterns that achieve the same intended aims as the preceding methods have been developed. A good example of one of these patterns is the run-until-shutdown pattern that we already met.

## Working with Threads

To work effectively with multithreaded code, you need the basic facts about monitors and locks at your command. This checklist contains the main facts you should know:

- Synchronization is about protecting object state and memory, not code.
- Synchronization is a cooperative mechanism between threads. One bug can break the cooperative model and have far-reaching consequences.
- Acquiring a monitor only prevents other threads from acquiring the monitor—it does not protect the object.
- Unsynchronized methods can see (and modify) inconsistent state, even while the object's monitor is locked.
- Locking an `Object[]` doesn't lock the individual objects.
- Primitives are not mutable, so they can't (and don't need to) be locked.
- `synchronized` can't appear on a method declaration in an interface.
- Inner classes are just syntactic sugar, so locks on inner classes have no effect on the enclosing class (and vice versa).
- Java's locks are *reentrant*. This means that if a thread holding a monitor encounters a synchronized block for the same monitor, it can enter the block.[1]

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1 Outside of Java, not all implementations of locks have this property.

We've also seen that threads can be asked to sleep for a period of time. It is also useful to go to sleep for an unspecified amount of time and wait until a condition is met. In Java, this is handled by the `wait()` and `notify()` methods that are present on `Object`.

Just as every Java object has a lock associated with it, every object maintains a list of waiting threads. When a thread calls the `wait()` method of an object, any locks the thread holds are temporarily released, and the thread is added to the list of waiting threads for that object and stops running. When another thread calls the `notifyAll()` method of the same object, the object wakes up the waiting threads and allows them to continue running.

For example, let's look at a simplified version of a queue that is safe for multithreaded use:

```java
/*
 * One thread calls push() to put an object on the queue.
 * Another calls pop() to get an object off the queue. If there is no
 * data, pop() waits until there is some, using wait()/notify().
 */
public class WaitingQueue<E> {
    LinkedList<E> q = new LinkedList<E>(); // storage
    public synchronized void push(E o) {
        q.add(o);         // Append the object to the end of the list
        this.notifyAll(); // Tell waiting threads that data is ready
    }
    public synchronized E pop() {
        while(q.size() == 0) {
            try { this.wait(); }
            catch (InterruptedException ignore) {}
        }
        return q.remove();
    }
}
```

This class uses a `wait()` on the instance of `WaitingQueue` if the queue is empty (which would make the `pop()` fail). The waiting thread temporarily releases its monitor, allowing another thread to claim it—a thread that might `push()` something new onto the queue. When the original thread is woken up again, it is restarted where it originally began to wait, and it will have reacquired its monitor.

> `wait()` and `notify()` must be used inside a `synchronized` method or block, because of the temporary relinquishing of locks required for them to work properly.

In general, most developers shouldn't roll their own classes like the one in this example—instead, use the libraries and components that the Java platform provides for you.

## Summary

In this chapter, we've discussed Java's view of memory and concurrency and seen how these topics are intrinsically linked.

Java's garbage collection is one of the major aspects of the platform that simplifies development by removing the need for programmers to manually manage memory. We have seen how Java provides advanced GC capabilities and how modern versions of Java use the partially concurrent G1 collector by default.

We have also discussed how, as processors develop more and more cores, we will need to use concurrent programming techniques to use those cores effectively. In other words, concurrency is key to the future of well-performing applications.

Java's threading model is based on three fundamental concepts:

*Shared, visible-by-default mutable state*
: Objects are easily shared between different threads in a process, and they can be changed ("mutated") by any thread holding a reference to them.

*Preemptive thread scheduling*
: The OS thread scheduler can swap threads on and off cores at more or less any time.

*Object state can only be protected by locks*
: Locks can be hard to use correctly, and state is quite vulnerable—even in unexpected places such as read operations.

Taken together, these three aspects of Java's approach to concurrency explain why multithreaded programming can cause so many headaches for developers.

# II

# Working with the Java Platform

Part II is an introduction to some of the core libraries that ship with Java and some programming techniques that are common to intermediate and advanced Java programs.

# 7
# Programming and Documentation Conventions

This chapter explains a number of important and useful Java programming and documentation conventions. It covers:

- General naming and capitalization conventions
- Portability tips and conventions
- `javadoc` documentation comment syntax and conventions

## Naming and Capitalization Conventions

The following widely adopted naming conventions apply to modules, packages, reference types, methods, fields, and constants in Java. Because these conventions are almost universally followed and because they affect the public API of the classes you define, you should adopt them as well:

*Modules*

As modules are the preferred unit of distribution for Java applications from Java 9 onward, you should take special care when naming them.

Module names must be globally unique—the modules system is essentially predicated on this assumption. As modules are effectively super packages (or aggregates of packages), the module name should be closely related to the package names grouped into the module. One recommended way to do this is to group the packages within a module and use the *root name* of the packages as the module name. For example, if an application's packages all live under `com.mycompany.*`, then `com.mycompany` is a good name for your module.

*Packages*
It is customary to ensure that your publicly visible package names are unique. One common way of doing this is by prefixing them with the inverted name of an internet domain that you own (e.g., `com.oreilly.javanutshell`).

This convention is now followed less strictly than it used to be, with some projects merely adopting a simple, recognizable, and unique prefix instead. All package names should be lowercase.

*Classes*
A type name should begin with a capital letter and be written in mixed case (e.g., `String`). This is usually referred to as *Pascal case*. If a class name consists of more than one word, each word should begin with a capital letter (e.g., `StringBuffer`). If a type name, or one of the words of a type name, is an acronym, the acronym can be written in all capital letters (e.g., `URL`, `HTMLParser`).

Because classes and enumerated types are designed to represent objects, you should choose class names that are nouns (e.g., `Thread`, `Teapot`, `FormatConverter`).

Enum types are a special case of a class with a finite number of instances. They should be named as nouns in all but highly exceptional circumstances. The constants defined by `enum` types are also typically written in all capital letters, as per the rules for constants below.

*Interfaces*
Java programmers typically use interfaces in one of two ways: either to convey that a class has additional, supplementary aspects or behaviors; or to indicate that the class is one possible implementation of an interface for which there are multiple valid implementation choices.

When an interface is used to provide additional information about the classes that implement it, it is common to choose an interface name that is an adjective (i.e., `Runnable`, `Cloneable`, `Serializable`).

When an interface is intended to work more like an abstract superclass, use a name that is a noun (e.g., `Document`, `FileNameMap`, `Collection`). It is conventional to not indicate via the name that it is an interface (i.e., don't use `IDocument` or `DocumentInterface`).

*Methods*
A method name always begins with a lowercase letter. If the name contains more than one word, every word after the first begins with a capital letter (e.g., `insert()`, `insertObject()`, `insertObjectAt()`). This is usually referred to as *camel case*.

Method names are typically chosen so that the first word is a verb. Method names can be as long as is necessary to make their purpose clear, but choose succinct names where possible. Avoid overly general method names, such as `performAction()`, `go()`, or the dreadful `doIt()`.

*Fields and constants*

Nonconstant field names follow the same capitalization conventions as method names. A field name should be chosen to best describe the purpose of the field or the value it holds. Prefixes to indicate types or visibility of fields are discouraged.

If a field is a `static final` constant, it should be written in all uppercase. If the name of a constant includes more than one word, the words should be separated with underscores (e.g., `MAX_VALUE`).

*Parameters*

Method parameters follow the same capitalization conventions as nonconstant fields. The names of method parameters appear in the documentation for a method, so you should choose names that make the purpose of the parameters as clear as possible. Try to keep parameter names to a single word and use them consistently. For example, if a `WidgetProcessor` class defines many methods that accept a `Widget` object as the first parameter, name this parameter `widget`.

*Local variables*

Local variable names are an implementation detail and never visible outside your class. Nevertheless, choosing good names makes your code easier to read, understand, and maintain. Variables are typically named following the same conventions as methods and fields.

In addition to the conventions for specific types of names, there are conventions regarding the characters you should use in your names. Java allows the `$` character in any identifier, but, by convention, its use is reserved for synthetic names generated by source-code processors. For example, it is used by the Java compiler to make inner classes work. You should not use the `$` character in any name that you create.

Java allows names to use any alphanumeric characters from the entire Unicode character set. While this can be convenient for non-English-speaking programmers, Unicode use has never really taken off, and this usage is extremely rare.



# Practical Naming

The names we give to our constructs matter—a lot. Naming is a key part of the process that conveys our abstract designs to our peers. The process of transferring a software design from one human mind to another is hard—harder, in many cases, than the process of transferring our design from our mind to the machines that will execute it.

We must, therefore, do everything we can to ensure that this process is eased. Names are a keystone of this. When reviewing code (and all code should be reviewed), pay particular attention to the names that have been chosen:

- Do the names of the types reflect the purpose of those types?
- Does each method do exactly what its name suggests? Ideally, no more and no less?
- Are the names descriptive enough? Could a more specific name be used instead?
- Are the names well suited for the domain they describe?
- Are the names consistent across the domain?
- Do the names mix metaphors?
- Does the name reuse a common term of software engineering?
- Do the names of boolean-returning methods include negation? These often need more attention to understand when reading (e.g., `notEnabled()` vs. `enabled()`)

Mixed metaphors are common in software, especially after several releases of an application. A system that starts off perfectly reasonably with components called `Receptionist` (for handling incoming connections), `Scribe` (for persisting orders), and `Auditor` (for checking and reconciling orders) can quite easily end up in a later release with a class called `Watchdog` for restarting processes. This isn't terrible, but it breaks the established pattern of people's job titles that previously existed.

It is also incredibly important to realize that software changes a lot over time. A perfectly apposite name on release 1 can become highly misleading by release 4. Care should be taken that as the system focus and intent shift, the names are refactored along with the code. Modern IDEs have no problem with global search and replace of symbols, so there is no need to cling to outdated metaphors once they are no longer useful.

One final note of caution: an overly strict interpretation of these guidelines can lead the developer to some very odd naming constructs. There are a number of excellent descriptions of some of the absurdities that can result by taking these conventions to their extremes.

In other words, none of the conventions described here is mandatory. Following them will, in the vast majority of cases, make your code easier to read and maintain. However, you should not be afraid to deviate from these guidelines if it makes your code easier to read and understand.

> Break any of these rules rather than say anything outright barbarous.
>
> —George Orwell

Above all, you should have a sense of the expected lifetime of the code you are writing. A risk calculation system in a bank may have a lifetime of a decade or more, whereas a prototype for a startup may be relevant for only a few weeks. Document accordingly—the longer the code is likely to be live, the better its documentation and naming need to be.

## Java Documentation Comments

Most ordinary comments within Java code explain the implementation details of that code. By contrast, the Java language specification defines a special type of comment known as a *doc comment* that serves to document the API of your code.

A doc comment is an ordinary multiline comment that begins with `/**` (instead of the usual `/*`) and ends with `*/`. A doc comment appears immediately before a type or member definition and contains documentation for that type or member. The documentation can include simple HTML formatting tags and other special keywords that provide additional information.

Doc comments are ignored by the compiler, but they can be extracted and automatically turned into online HTML documentation by the `javadoc` program. (See Chapter 13 for more information about `javadoc`.)

Here is an example class that contains appropriate doc comments:

```
/**
 * This immutable class represents <i>complex numbers</i>.
 *
 * @author David Flanagan
 * @version 1.0
 */
public class Complex {
    /**
     * Holds the real part of this complex number.
     * @see #y
     */
    protected double x;

    /**
     * Holds the imaginary part of this complex number.
     * @see #x
     */
    protected double y;

    /**
     * Creates a new Complex object that represents the complex number
     * x+yi.
     * @param x The real part of the complex number.
     * @param y The imaginary part of the complex number.
     */
    public Complex(double x, double y) {
        this.x = x;
        this.y = y;
    }

    /**
     * Adds two Complex objects and produces a third object that
     * represents their sum.
     * @param c1 A Complex object
```

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```
     * @param c2 Another Complex object
     * @return  A new Complex object that represents the sum of
     *          <code>c1</code> and <code>c2</code>.
     * @exception java.lang.NullPointerException
     *            If either argument is <code>null</code>.
     */
    public static Complex add(Complex c1, Complex c2) {
        return new Complex(c1.x + c2.x, c1.y + c2.y);
    }
}
```

## Structure of a Doc Comment

The body of a doc comment should begin with a one-sentence summary of the type or member being documented. This sentence may be displayed by itself as summary documentation, so it should be written to stand on its own. The initial sentence may be followed by any number of other sentences and paragraphs that describe the class, interface, method, or field in full detail.

After the descriptive paragraphs, a doc comment can contain any number of other paragraphs, each of which begins with a special doc-comment tag, such as `@author`, `@param`, or `@returns`. These tagged paragraphs provide specific information about the class, interface, method, or field that the `javadoc` program displays in a standard way. The full set of doc-comment tags is listed in the next section.

The descriptive material in a doc comment can contain simple HTML markup tags, such as `<i>` for emphasis; `<code>` for class, method, and field names; and `<pre>` for multiline code examples. It can also contain `<p>` tags to break the description into separate paragraphs and `<ul>`, `<li>`, and related tags to display bulleted lists and similar structures. Remember, however, that the material you write is embedded within a larger, more complex HTML document. For this reason, doc comments should not contain major structural HTML tags, such as `<h2>` or `<hr>`, that might interfere with the structure of the larger document.

Avoid the use of the `<a>` tag to include hyperlinks or cross-references in your doc comments. Instead, use the special `{@link}` doc-comment tag, which, unlike the other doc-comment tags, can appear anywhere within a doc comment. As described in the next section, the `{@link}` tag allows you to specify hyperlinks to other classes, interfaces, methods, and fields without knowing the HTML-structuring conventions and filenames used by `javadoc`.

If you want to include an image in a doc comment, place the image file in a *doc-files* subdirectory of the source code directory. Give the image the same name as the class, with an integer suffix. For example, the second image that appears in the doc comment for a class named `Circle` can be included with this HTML tag:

```
<img src="doc-files/Circle-2.gif">
```

Because the lines of a doc comment are embedded within a Java comment, any leading spaces and asterisks (`*`) are stripped from each line of the comment before processing. Thus, you don't need to worry about the asterisks appearing in the generated documentation or about the indentation of the comment affecting the indentation of code examples included within the comment with a `<pre>` tag.

## Doc-Comment Tags

The `javadoc` program recognizes a number of special tags, each of which begins with an `@` character. These doc-comment tags allow you to encode specific information into your comments in a standardized way, and they allow `javadoc` to choose the appropriate output format for that information. For example, the `@param` tag lets you specify the name and meaning of a single parameter for a method. `javadoc` can extract this information and display it using an HTML `<dl>` list, an HTML `<table>`, or whatever it sees fit.

The following doc-comment tags are recognized by `javadoc`; a doc comment should typically use these tags in the order listed here:

`@author` *`name`*

Adds an "Author:" entry that contains the specified name. This tag should be used for every class or interface definition but must not be used for individual methods and fields. If a class has multiple authors, use multiple `@author` tags on adjacent lines. For example:

```
@author David Flanagan
@author Ben Evans
@author Jason Clark
```

List the authors in chronological order, with the original author first. If the author is unknown, you can use "unascribed." `javadoc` does not output authorship information unless the `-author` command-line argument is specified.

`@version` *`text`*

Inserts a "Version:" entry that contains the specified text. For example:

```
@version 1.32, 08/26/04
```

This tag should be included in every class and interface doc comment but cannot be used for individual methods and fields. This tag is often used in conjunction with the automated version-numbering capabilities of a version control system, such as git, Perforce, or SVN. `javadoc` does not output version information in its generated documentation unless the `-version` command-line argument is specified.

`@param` *`parameter-name description`*

Adds the specified parameter and its description to the "Parameters:" section of the current method. The doc comment for a method or constructor must contain one `@param` tag for each parameter the method expects. These tags should appear in the same order as the parameters specified by the method. The tag can be used only in doc comments for methods and constructors.

You are encouraged to use phrases and sentence fragments where possible to keep the descriptions brief. However, if a parameter requires detailed documentation, the description can wrap onto multiple lines and include as much text as necessary. For readability in source-code form, consider using spaces to align the descriptions with each other. For example:

```
@param o      the object to insert
@param index  the position to insert it at
```

`@return` *`description`*
: Inserts a "Returns:" section that contains the specified description. This tag should appear in every doc comment for a method, unless the method returns `void` or is a constructor. The description can be as long as necessary, but consider using a sentence fragment to keep it short. For example:

```
@return <code>true</code> if the insertion is successful, or
        <code>false</code> if the list already contains the object.
```

`@exception` *`full-classname description`*
: Adds a "Throws:" entry that contains the specified exception name and description. A doc comment for a method or constructor should contain an `@exception` tag for every checked exception that appears in its `throws` clause. For example:

```
@exception java.io.FileNotFoundException
           If the specified file could not be found
```

The `@exception` tag can optionally be used to document unchecked exceptions (i.e., subclasses of `RuntimeException`) the method may throw, when these are exceptions that a user of the method may reasonably want to catch. If a method can throw more than one exception, use multiple `@exception` tags on adjacent lines and list the exceptions in alphabetical order. The description can be as short or as long as necessary to describe the significance of the exception. This tag can be used only for method and constructor comments. The `@throws` tag is a synonym for `@exception`.

`@throws` *`full-classname description`*
: This tag is a synonym for `@exception`.

`@see` *`reference`*
: Adds a "See Also:" entry that contains the specified reference. This tag can appear in any kind of doc comment. The syntax for the *`reference`* is explained in "Cross-References in Doc Comments" on page 277.

`@deprecated` *`explanation`*
: This tag specifies that the following type or member has been deprecated and that its use should be avoided. `javadoc` adds a prominent "Deprecated" entry to the documentation and includes the specified *`explanation`* text. This text should specify when the class or member was deprecated and, if possible, suggest a replacement class or member and include a link to it. For example:

```
@deprecated As of Version 3.0, this method is replaced
            by {@link #setColor}.
```

The `@deprecated` tag is an exception to the general rule that `javac` ignores all comments. When this tag appears, the compiler notes the deprecation in the class file it produces. This allows it to issue warnings for other classes that rely on the deprecated feature.

`@since` *`version`*
: Specifies when the type or member was added to the API. This tag should be followed by a version number or other version specification. For example:

```
@since JNUT 3.0
```

Every doc comment for a type should include an `@since` tag, and any members added after the initial release of the type should have `@since` tags in their doc comments.

`@serial` *`description`*
: Technically, the way a class is serialized is part of its public API. If you write a class that you expect to be serialized, you should document its serialization format using `@serial` and the related tags listed next. `@serial` should appear in the doc comment for any field that is part of the serialized state of a `Serializable` class.

For classes that use the default serialization mechanism, this means all fields that are not declared `transient`, including fields declared `private`. The *`description`* should be a brief description of the field and of its purpose within a serialized object.

You can also use the `@serial` tag at the class and package level to specify whether a "serialized form page" should be generated for the class or package. The syntax is:

```
@serial include
@serial exclude
```

`@serialField` *`name type description`*
: A `Serializable` class can define its serialized format by declaring an array of `ObjectStreamField` objects in a field named `serialPersistentFields`. For such a class, the doc comment for `serialPersistentFields` should include an `@serialField` tag for each element of the array. Each tag specifies the name, type, and description for a particular field in the serialized state of the class.

`@serialData` *`description`*
: A `Serializable` class can define a `writeObject()` method to write data other than that written by the default serialization mechanism. An `Externalizable` class defines a `writeExternal()` method responsible for writing the complete state of an object to the serialization stream. The `@serialData` tag should be used in the doc comments for these `writeObject()` and `writeExternal()`

methods, and the *description* should document the serialization format used by the method.

## Inline Doc-Comment Tags

In addition to the preceding tags, `javadoc` also supports several *inline tags* that may appear anywhere that HTML text appears in a doc comment. Because these tags appear directly within the flow of HTML text, they require the use of curly braces as delimiters to separate the tagged text from the HTML text. Supported inline tags include the following:

`{@link` *`reference`* `}`

The `{@link}` tag is like the `@see` tag except that instead of placing a link to the specified *`reference`* in a special "See Also:" section, it inserts the link inline. An `{@link}` tag can appear anywhere that HTML text appears in a doc comment. In other words, it can appear in the initial description of the class, interface, method, or field and in the descriptions associated with the `@param`, `@returns`, `@exception`, and `@deprecated` tags. The *`reference`* for the `{@link}` tag uses the syntax described next in "Cross-References in Doc Comments" on page 277. For example:

```
@param regexp The regular expression to search for. This string
              argument must follow the syntax rules described for
              {@link java.util.regex.Pattern}.
```

`{@linkplain` *`reference`* `}`

The `{@linkplain}` tag is just like the `{@link}` tag, except that the text of the link is formatted using the normal font rather than the code font used by the `{@link}` tag. This is most useful when *`reference`* contains both a *`feature`* to link to and a *`label`* that specifies alternate text to be displayed in the link. See "Cross-References in Doc Comments" on page 277 for more on the *`feature`* and *`label`* portions of the *`reference`* argument.

`{@inheritDoc}`

When a method overrides a method in a superclass or implements a method in an interface, you can omit a doc comment, and `javadoc` automatically inherits the documentation from the overridden or implemented method. You can use the `{@inheritDoc}` tag to inherit the text of individual tags. This tag also allows you to inherit and augment the descriptive text of the comment. To inherit individual tags, use it like this:

```
@param index {@inheritDoc}
@return {@inheritDoc}
```

`{@docRoot}`

This inline tag takes no parameters and is replaced with a reference to the root directory of the generated documentation. It is useful in hyperlinks that refer to an external file, such as an image or a copyright statement:

```
<img src="{@docroot}/images/logo.gif">
This is <a href="{@docRoot}/legal.html">Copyrighted</a> material.
```

`{@literal` *`text`* `}`
: This inline tag displays *`text`* literally, escaping any HTML in it and ignoring any `javadoc` tags it may contain. It does not retain whitespace formatting but is useful when used within a `<pre>` tag.

`{@code` *`text`* `}`
: This tag is like the `{@literal}` tag but displays the literal *`text`* in code font. Equivalent to:

```
&lt;code&gt;{@literal <replaceable>text</replaceable>}&lt;/code&gt;
```

`{@value}`
: The `{@value}` tag, with no arguments, is used inline in doc comments for `static final` fields and is replaced with the constant value of that field.

`{@value` *`reference`* `}`
: This variant of the `{@value}` tag includes a *`reference`* to a `static final` field and is replaced with the constant value of that field.

## Cross-References in Doc Comments

The `@see` tag and the inline tags `{@link}`, `{@linkplain}`, and `{@value}` all encode a cross-reference to some other source of documentation, typically to the documentation comment for some other type or member.

*`reference`* can take three different forms. If it begins with a quote character, it is taken to be the name of a book or some other printed resource and is displayed as is. If *`reference`* begins with a < character, it is taken to be an arbitrary HTML hyperlink that uses the `<a>` tag, and the hyperlink is inserted into the output documentation as is. This form of the `@see` tag can insert links to other online documents, such as a programmer's guide or user's manual.

If *`reference`* is not a quoted string or a hyperlink, it is expected to have the following form:

```
feature [label]
```

In this case, `javadoc` outputs the text specified by *`label`* and encodes it as a hyperlink to the specified *`feature`*. If *`label`* is omitted (as it usually is), `javadoc` uses the name of the specified *`feature`* instead.

*`feature`* can refer to a package, type, or type member, using one of the following forms:

*`pkgname`*
: A reference to the named package. For example:

```
@see java.lang.reflect
```

Conventions

*pkgname.typename*

A reference to a class, interface, enumerated type, or annotation type specified with its full package name. For example:

```
@see java.util.List
```

*typename*

A reference to a type specified without its package name. For example:

```
@see List
```

`javadoc` resolves this reference by searching the current package and the list of imported classes for a class with this name.

*typename* # *methodname*

A reference to a named method or constructor within the specified type. For example:

```
@see java.io.InputStream#reset
@see InputStream#close
```

If the type is specified without its package name, it is resolved as described for *typename*. This syntax is ambiguous if the method is overloaded or the class defines a field by the same name.

*typename* # *methodname* ( *paramtypes* )

A reference to a method or constructor with the type of its parameters explicitly specified. This is useful when cross-referencing an overloaded method. For example:

```
@see InputStream#read(byte[], int, int)
```

\# *methodname*

A reference to a nonoverloaded method or constructor in the current class or interface or one of the containing classes, superclasses, or superinterfaces of the current class or interface. Use this concise form to refer to other methods in the same class. For example:

```
@see #setBackgroundColor
```

\# *methodname* ( *paramtypes* )

A reference to a method or constructor in the current class or interface or one of its superclasses or containing classes. This form works with overloaded methods because it lists the types of the method parameters explicitly. For example:

```
@see #setPosition(int, int)
```

*typename* # *fieldname*

A reference to a named field within the specified class. For example:

```
@see java.io.BufferedInputStream#buf
```

If the type is specified without its package name, it is resolved as described for `typename`.

`# fieldname`
: A reference to a field in the current type or one of the containing classes, superclasses, or superinterfaces of the current type. For example:

```
@see #x
```

## Doc Comments for Packages

Documentation comments for classes, interfaces, methods, constructors, and fields appear in Java source code immediately before the definitions of the features they document. `javadoc` can also read and display summary documentation for packages. Because a package is defined in a directory, not in a single file of source code, `javadoc` looks for the package documentation in a file named *package.html* in the directory that contains the source code for the classes of the package.

The *package.html* file should contain simple HTML documentation for the package. It can also contain `@see`, `@link`, `@deprecated`, and `@since` tags. Because *package.html* is not a file of Java source code, the documentation it contains should be HTML and should *not* be a Java comment (i.e., it should not be enclosed within `/**` and `*/` characters). Finally, any `@see` and `@link` tags that appear in *package.html* must use fully qualified class names.

In addition to defining a *package.html* file for each package, you can also provide high-level documentation for a group of packages by defining an *overview.html* file in the source tree for those packages. When `javadoc` is run over that source tree, it uses *overview.html* as the highest-level overview it displays.

# Doclets

The `javadoc` tool that is used to generate HTML documentation is based upon a standard API. Since Java 9, this standard interface has been delivered in the module `jdk.javadoc` and tools leveraging this API are typically called *doclets* (with `javadoc` being referred to as the standard doclet).

The Java 9 release also included a major upgrade of the standard doclet. In particular, it now (as of Java 10) generates modern HTML5 by default. This allows for other improvements—such as implementing the WAI-ARIA standard for accessibility. This standard makes it easier for people with visual or other impairments to access `javadoc` output using tools such as screen readers.

> `javadoc` has also been enhanced to understand the new platform modules, and so the semantic meaning of what constitutes an API (and so what should be documented) is now aligned with the modular Java definition.

The standard doclet now also automatically indexes the code as documentation is generated and creates a client-side index in JavaScript. The resulting web pages have a search capability to allow developers to easily find some common program components, such as the names of:

- Modules
- Packages
- Types and members
- Method parameter types

The developer can also add search terms or phrases using an `@index` inline `javadoc` tag.

## Conventions for Portable Programs

One of the earliest slogans for Java was "write once, run anywhere." This emphasizes that Java makes it easy to write portable programs, but it is still possible to write Java programs that do not automatically run successfully on any Java platform. The following tips help to avoid portability problems:

*Native methods*
: Portable Java code can use any methods in the core Java APIs, including methods implemented as `native` methods. However, portable code must not define its own native methods. By their very nature, native methods must be ported to each new platform, so they directly subvert the "write once, run anywhere" promise of Java.

*The* `Runtime.exec()` *method*
: Calling the `Runtime.exec()` method to spawn a process and execute an external command on the native system is rarely allowed in portable code. This is because the native OS command to be executed is never guaranteed to exist or behave the same way on all platforms.

  The only time it is legal to use `Runtime.exec()` in portable code is when the user is allowed to specify the command to run, either by typing the command at runtime or by specifying the command in a configuration file or preferences dialog box.

  If the programmer wishes to control external processes, then this should be done through the enhanced `ProcessHandle` capability introduced in Java 9, rather than by using `Runtime.exec()` and parsing the output. This is not fully portable, but it at least reduces the amount of platform-specific logic necessary to control external processes.

*The* `System.getenv()` *method*
: Using `System.getenv()` is inherently nonportable. Different operating systems have differing casing conventions (e.g., Windows is case-insensitive, where

Unix systems are not). Also, typical values found in an environment vary greatly between operating systems and organizations. Use of `System.getenv()` to parameterize specific values your application expects can be acceptable if well documented; this is frequently done with containerized applications. But reaching out to the broader environment can yield incompatible behavior.

*Undocumented classes*

Portable Java code must use only classes and interfaces that are a documented part of the Java platform. Most Java implementations ship with additional undocumented public classes that are part of the implementation but not part of the Java platform specification.

The modules system prevents a program from using and relying on these implementation classes, but even with the increased restrictions in Java 17 it is still possible to circumvent this protection by using reflection (although the exact runtime switches permitting reflection have changed in recent versions; see Chapter 12 for more details).

However, doing so is not portable because the implementation classes are not guaranteed to exist in all Java implementations or on all platforms, and they may change or disappear in future versions. Even if you don't care much about portability, use of undocumented classes can greatly complicate future JDK version upgrades.

Of particular note is the `sun.misc.Unsafe` class, which provides access to a number of "unsafe" methods, which can allow developers to circumvent key restrictions of the Java platform. Developers should not directly use the `Unsafe` class under any circumstances.

*Implementation-specific features*

Portable code must not rely on features specific to a single implementation. For example, in the early years of Java, Microsoft distributed a version of the Java runtime system that included a number of additional methods that were not part of the Java platform as defined by the specifications. Any program that depends on such extensions is obviously not portable to other platforms.

*Implementation-specific bugs*

Just as portable code must not depend on implementation-specific features, it must not depend on implementation-specific bugs. If a class or method behaves differently than the specification says it should, a portable program cannot rely on this behavior, which may be different on different platforms, and a future version may ultimately fix the bug, hindering JDK upgrades.

*Implementation-specific behavior*

Sometimes different platforms and different implementations present different behaviors, all of which are legal according to the Java specification. Portable code must not depend on any one specific behavior. For example, the Java specification does not indicate whether threads of equal priority share the CPU or if one long-running thread can starve another thread at the same priority. If an application assumes one behavior or the other, it may not run properly on all platforms.

*Defining system classes*
: Portable Java code never attempts to define classes in any of the system or standard extension packages. Doing so violates the protection boundaries of those packages and exposes package-visible implementation details, even in those cases where it is not forbidden by the modules system.

*Hardcoded filenames*
: A portable program contains no hardcoded file or directory names. This is because different platforms have significantly different filesystem organizations and use different directory separator characters. If you need to work with a file or directory, have the user specify the filename, or at least the base directory beneath which the file can be found. This specification can be done at runtime, in a configuration file, or as a command-line argument to the program. When concatenating a file or directory name to a directory name, use the `File()` constructor, the `File.separator` constant, or the `Path.of()` method.

*Line separators*
: Different systems use different characters or sequences of characters as line separators. Do not hardcode `\n`, `\r`, or `\r\n` as the line separator in your program. Instead, use the `println()` method of `PrintStream` or `PrintWriter`, which automatically terminates a line with the line separator appropriate for the platform, or use the value of the `line.separator` system property. You can also use the "%n" format string to `printf()` and `format()` methods of `java.util.Formatter` and related classes.

# Summary

In this chapter, we've seen the standard conventions around naming parts of our Java code. While the language allows many things beyond these conventions, your code will be easier for others to read and understand the more these are followed.

Good documentation is at the heart of creating maintainable systems. The `javadoc` tool allows us to write much of our documentation within our code, keeping it in context when things change. A variety of document tags allow for generating clear and consistent documentation.

Part of the appeal of the JVM is its broad install base across many operating systems and types of hardware. However, you can compromise the portability of your application if you're not careful in a few areas, so this chapter reviewed guidelines around the most typical of those stumbling blocks to avoid.

Next up, we'll take a look at one of the most commonly used parts of Java's standard libraries: collections.

# 8

# Working with Java Collections

This chapter introduces Java's interpretation of fundamental data structures, known as the Java Collections. These abstractions are core to many (if not most) programming types and form an essential part of any programmer's basic toolkit. Accordingly, this is one of the most important chapters of the entire book and provides a toolkit that is essential to virtually all Java programmers.

In this chapter, we will introduce the fundamental interfaces and the type hierarchy, show how to use them, and discuss aspects of their overall design. Both the "classic" approach to handling the collections and the newer approach (using the Streams API and the lambda expressions functionality introduced in Java 8) will be covered.

## Introduction to Collections API

The Java Collections are a set of generic interfaces that describe the most common forms of data structure. Java ships with several implementations of each of the classic data structures, and because the types are represented as interfaces, it is very possible for development teams to develop their own, specialized implementations of the interfaces for use in their own projects.

The Java Collections define two fundamental types of data structures. A `Collection` is a grouping of objects, while a `Map` is a set of mappings, or associations, between objects. The basic layout of the Java Collections is shown in Figure 8-1.

Within this basic description, a `Set` is a type of `Collection` with no duplicates, and a `List` is a `Collection` in which the elements are ordered (but may contain duplicates).

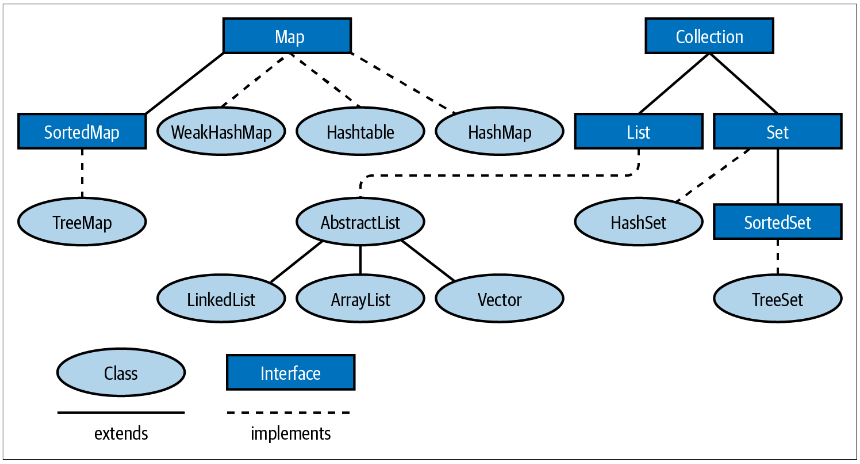


*Figure 8-1. Collections classes and inheritance*

`SortedSet` and `SortedMap` are specialized sets and maps that maintain their elements in a sorted order.

`Collection`, `Set`, `List`, `Map`, `SortedSet`, and `SortedMap` are all interfaces, but the `java.util` package also defines various concrete implementations, such as lists based on arrays and linked lists, and maps and sets based on hash tables or binary trees. Other important interfaces are `Iterator` and `Iterable`, which allow you to loop through the objects in a collection, as we will see later on.

## The Collection Interface

`Collection<E>` is a parameterized interface that represents a generalized grouping of objects of type `E`. We can create a collection of any kind of reference type.

> To work properly with the expectations of collections, you must take care when defining `hashCode()` and `equals()` methods on your classes, as discussed in Chapter 5.

Methods are defined for adding and removing objects from the group, testing an object for membership in the group, and iterating through all elements in the group. Additional methods return the elements of the group as an array and return the size of the collection.

> The grouping within a `Collection` may or may not allow duplicate elements and may or may not impose an ordering on the elements.

The Java Collections Framework provides `Collection` because it defines the features shared by all common forms of data structure. The JDK ships `Set`, `List`, and `Queue` as subinterfaces of `Collection`.

The following code illustrates the operations you can perform on `Collection` objects:

```
// Create some collections to work with.
Collection<String> c = new HashSet<>();  // An empty set

// We'll see these utility methods later. Be aware that there are
// some subtleties to watch out for when using them
Collection<String> d = Arrays.asList("one", "two");
Collection<String> e = Collections.singleton("three");

// Add elements to a collection. These methods return true
// if the collection changes, which is useful with Sets that
// don't allow duplicates.
c.add("zero");           // Add a single element
c.addAll(d);             // Add all of the elements in d

// Copy a collection: most implementations have a copy constructor
Collection<String> copy = new ArrayList<String>(c);

// Remove elements from a collection.
// All but clear return true if the collection changes.
c.remove("zero");        // Remove a single element
c.removeAll(e);          // Remove a collection of elements
c.retainAll(d);          // Remove all elements that are not in d
c.clear();               // Remove all elements from the collection

// Querying collection size
boolean b = c.isEmpty(); // c is now empty, so true
int s = c.size();        // Size of c is now 0.

// Restore collection from the copy we made
c.addAll(copy);

// Test membership in the collection. Membership is based on
// the equals method, not the == operator.
b = c.contains("zero");  // true
b = c.containsAll(d);    // true

// Most Collection implementations have a useful toString()  method
System.out.println(c);
```

```
// Obtain an array of collection elements.  If the iterator guarantees
// an order, this array has the same order. The Object array is a new
// instance, containing references to the same objects as the original
// collection `c` (aka a shallow copy).
Object[] elements = c.toArray();

// If we want the elements in a String[], we must pass one in
String[] strings = c.toArray(new String[c.size()]);

// Or we can pass an empty String[] just to specify the type and
// the toArray method will allocate an array for us
strings = c.toArray(new String[0]);
```

Remember that you can use any of the methods shown here with any `Set`, `List`, or `Queue`. These subinterfaces may impose membership restrictions or ordering constraints on the elements of the collection but still provide the same basic methods.

> Methods such as `addAll()`, `retainAll()`, `clear()`, and `remove()` that alter the collection were conceived of as optional parts of the API. Unfortunately, they were specified a long time ago, when the received wisdom was to indicate the absence of an optional method by throwing `UnsupportedOperationException`. Accordingly, some implementations (notably read-only forms) may throw this unchecked exception.

`Collection`, `Map`, and their subinterfaces do *not* extend the interfaces `Cloneable` or `Serializable`. All of the collection and map implementation classes provided in the Java Collections Framework, however, do implement these interfaces.

Some collection implementations place restrictions on the elements that they can contain. An implementation might prohibit `null` as an element, for example. And `EnumSet` restricts membership to the values of a specified enumerated type.

Attempting to add a prohibited element to a collection always throws an unchecked exception such as `NullPointerException` or `ClassCastException`. Checking whether a collection contains a prohibited element may also throw such an exception, or it may simply return `false`.

## The Set Interface

A *set* is a collection of objects that does not allow duplicates: it may not contain two references to the same object, two references to `null`, or references to two objects `a` and `b` such that `a.equals(b)`. Most general-purpose `Set` implementations impose no ordering on the elements of the set, but ordered sets are not prohibited (see `SortedSet` and `LinkedHashSet`). Sets are further distinguished from ordered collections like lists by the general expectation that they have an efficient `contains` method that runs in constant or logarithmic time.

`Set` defines no methods of its own beyond those defined by `Collection` but places additional restrictions on some methods. The `add()` and `addAll()` methods of a `Set` are required to enforce the no-duplicates rules: they may not add an element to the `Set` if the set already contains that element. Recall that the `add()` and `addAll()` methods defined by the `Collection` interface return `true` if the call resulted in a change to the collection and `false` if it did not. This return value is relevant for `Set` objects because the no-duplicates restriction means that adding an element does not always result in a change to the set.

Table 8-1 lists the implementations of the `Set` interface and summarizes their internal representation, ordering characteristics, member restrictions, and the performance of the basic `add()`, `remove()`, and `contains` operations as well as iteration performance. Note that `CopyOnWriteArraySet` is in the `java.util.concurrent` package; all the other implementations are part of `java.util`. Also note that `java.util.BitSet` is not a `Set` implementation. This legacy class is useful as a compact and efficient list of `boolean` values but is not part of the Java Collections Framework.

*Table 8-1. Set implementations*

| Class | Internal representation | Since | Element order | Member restrictions | Basic operations | Iteration performance | Notes |
|---|---|---|---|---|---|---|---|
| `HashSet` | Hashtable | 1.2 | None | None | O(1) | O(capacity) | Best general-purpose implementation |
| `LinkedHashSet` | Linked hashtable | 1.2 | Insertion order | None | O(1) | O(n) | Preserves insertion order |
| `EnumSet` | Bit fields | 5.0 | Enum declaration | Enum values | O(1) | O(n) | Holds non-`null` enum values only |
| `TreeSet` | Red-black tree | 1.2 | Sorted ascending | Comparable | O(log(n)) | O(n) | `Comparable` elements or `Comparator` |
| `CopyOnWriteArraySet` | Array | 5.0 | Insertion order | None | O(n) | O(n) | Threadsafe without synchronized methods |

The TreeSet implementation uses a red-black tree data structure to maintain a set that is iterated in ascending order according to the natural ordering of Comparable objects or according to an ordering specified by a Comparator object. TreeSet actually implements the SortedSet interface, which is a subinterface of Set.

The SortedSet interface offers several interesting methods that take advantage of its sorted nature. The following code illustrates:

```
public static void testSortedSet(String[] args) {
    // Create a SortedSet
    SortedSet<String> s = new TreeSet<>(Arrays.asList(args));

    // Iterate set: elements are automatically sorted
    for (String word : s) {
        System.out.println(word);
    }

    // Special elements
    String first = s.first();  // First element
    String last = s.last();    // Last element

    // all elements but first
    SortedSet<String> tail = s.tailSet(first + '\0');
    System.out.println(tail);

    // all elements but last
    SortedSet<String> head = s.headSet(last);
    System.out.println(head);

    SortedSet<String> middle = s.subSet(first+'\0', last);
    System.out.println(middle);
}
```

The addition of \0 characters is needed because the tailSet() and related methods use the *successor* of an element, which for strings is the string value with a NULL character (ASCII code 0) appended.

From Java 9 onward, the API has also been upgraded with a helper static method on the Set interface, like this:

```
Set<String> set = Set.of("Hello", "World");
```

This API has several overloads that each take a fixed number of arguments, and also a varargs overload. The latter is used for the case where arbitrarily many elements are wanted in the set and falls back to the standard varargs mechanism (marshaling the elements into an array before the call). It's worth noting as well that the set returned by Set.of is immutable and will throw an UnsupportedOperationException on further attempts to add or remove from it after instantiation.

## The List Interface

A `List` is an ordered collection of objects. Each element of a list has a position in the list, and the `List` interface defines methods to query or set the element at a particular position, or *index*. In this respect, a `List` is like an array whose size changes as needed to accommodate the number of elements it contains. Unlike sets, lists allow duplicate elements.

In addition to its index-based `get()` and `set()` methods, the `List` interface defines methods to add or remove an element at a particular index and also defines methods to return the index of the first or last occurrence of a particular value in the list. The `add()` and `remove()` methods inherited from `Collection` are defined to append to the list and to remove the first occurrence of the specified value from the list. The inherited `addAll()` appends all elements in the specified collection to the end of the list, and another version inserts the elements at a specified index. The `retainAll()` and `removeAll()` methods behave as they do for any `Collection`, retaining or removing multiple occurrences of the same value, if needed.

The `List` interface doesn't define methods that operate on a range of list indexes. Instead, it defines a single `subList()` method that returns a `List` object that represents just the specified range of the original list. The sublist is backed by the parent list, and any changes made to the sublist are immediately visible in the parent list. Examples of `subList()` and the other basic `List` manipulation methods follow:

```
// Create lists to work with
List<String> l = new ArrayList<String>(Arrays.asList(args));
List<String> words = Arrays.asList("hello", "world");
List<String> words2 = List.of("hello", "world");

// Querying and setting elements by index
String first = l.get(0);             // First element of list
String last = l.get(l.size() - 1);   // Last element of list
l.set(0, last);                      // The last shall be first

// Adding and inserting elements.  add  can append or insert
l.add(first);       // Append the first word at end of list
l.add(0, first);    // Insert first at the start of the list again
l.addAll(words);    // Append a collection at the end of the list
l.addAll(1, words); // Insert collection after first word

// Sublists: backed by the original list
List<String> sub = l.subList(1,3);  // second and third elements
sub.set(0, "hi");                   // modifies 2nd element of l

// Sublists can restrict operations to a subrange of backing list
String s = Collections.min(l.subList(0,4));
Collections.sort(l.subList(0,4));

// Independent copies of a sublist don't affect the parent list.
List<String> subcopy = new ArrayList<String>(l.subList(1,3));
```

```java
subcopy.clear();

// Searching lists
int p = l.indexOf(last);  // Where does the last word appear?
p = l.lastIndexOf(last);  // Search backward

// Print the index of all occurrences of last in l.  Note subList
int n = l.size();
p = 0;
while (p < n) {
    // Get a view of the list that includes only the elements we
    // haven't searched yet.
    List<String> list = l.subList(p, n);
    int q = list.indexOf(last);
    if (q == -1) break;
    System.out.printf("Found '%s' at index %d%n", last, p+q);
    p += q+1;
}

// Removing elements from a list
l.remove(last);         // Remove first occurrence of the element
l.remove(0);            // Remove element at specified index
l.subList(0,2).clear(); // Remove a range of elements using subList
l.retainAll(words);     // Remove all but elements in words
l.removeAll(words);     // Remove all occurrences of elements in words
l.clear();              // Remove everything
```

### Foreach loops and iteration

One very important way of working with collections is to process each element in turn, an approach known as *iteration*. This is an older way of looking at data structures, but it is still very useful (especially for small collections of data) and is easy to understand. This approach fits naturally with the `for` loop, as shown in this bit of code, and is easiest to illustrate using a `List`:

```java
List<String> c = new ArrayList<String>();
// ... add some Strings to c

for(String word : c) {
    System.out.println(word);
}
```

The sense of the code should be clear—it takes the elements of `c` one at a time and uses them as a variable in the loop body. More formally, it iterates through the elements of an array or collection (or any object that implements `java.lang.Iterable`). On each iteration it assigns an element of the array or `Iterable` object to the loop variable you declare and then executes the loop body, which typically uses the loop variable to operate on the element. No loop counter or `Iterator` object is involved; the loop performs the iteration automatically, and you need not concern yourself with correct initialization or termination of the loop.

This type of `for` loop is often referred to as a *foreach loop*. Let's see how it works. The following bit of code shows a rewritten (and equivalent) `for` loop, with the method calls explicitly shown:

```
// Iteration with a for loop
for(Iterator<String> i = c.iterator(); i.hasNext();) {
    System.out.println(i.next());
}
```

The `Iterator` object, `i`, is produced from the collection and used to step through the collection one item at a time. It can also be used with `while` loops:

```
// Iterate through collection elements with a while loop.
// Some implementations (such as lists) guarantee an order of iteration
// Others make no guarantees.
Iterator<String> iterator = c.iterator();
while (iterator.hasNext()) {
    System.out.println(iterator.next());
}
```

Here are some more things you should know about the syntax of the foreach loop:

- As noted earlier, *`expression`* must be either an array or an object that implements the `java.lang.Iterable` interface. This type must be known at compile time so that the compiler can generate appropriate looping code.
- The type of the array or `Iterable` elements must be assignment-compatible with the type of the variable declared in the *`declaration`*. If you use an `Iterable` object that is not parameterized with an element type, the variable must be declared as an `Object`.
- The *`declaration`* usually consists of just a type and a variable name, but it may include a `final` modifier and any appropriate annotations (see Chapter 4). Using `final` prevents the loop variable from taking on any value other than the array or collection element the loop assigns it and serves to emphasize that the array or collection cannot be altered through the loop variable.
- The loop variable of the foreach loop must be declared as part of the loop, with both a type and a variable name. You cannot use a variable declared outside the loop as you can with the `for` loop.

To understand in detail how the foreach loop works with collections, we need to consider two interfaces, `java.util.Iterator` and `java.lang.Iterable`:

```
public interface Iterator<E> {
     boolean hasNext();
     E next();
     void remove();
}
```

`Iterator` defines a way to iterate through the elements of a collection or other data structure. It works like this: while there are more elements in the collection (`hasNext()` returns `true`), call `next` to obtain the next element of the collection. Ordered collections, such as lists, typically have iterators that guarantee they'll return elements in order. Unordered collections like `Set` simply guarantee that repeated calls to `next()` return all elements of the set without omissions or duplications, but they do not specify an ordering.

The `next()` method of `Iterator` performs two functions—it advances through the collection and also returns the element of the collection that we have just moved past. This combination of operations can cause problems when you are programming in a functional or immutable style, as it mutates the underlying collection.

The `Iterable` interface was introduced to make the foreach loop work. A class implements this interface to advertise that it is able to provide an `Iterator` to anyone interested:

```
public interface Iterable<E> {
     java.util.Iterator<E> iterator();
}
```

If an object is `Iterable<E>`, that means that it has an `iterator()` method that returns an `Iterator<E>`, which has a `next()` method that returns an object of type `E`.

If you use the foreach loop with an `Iterable<E>`, the loop variable must be of type `E` or a superclass or interface.

For example, to iterate through the elements of a `List<String>`, the variable must be declared `String` or its superclass `Object`, or one of the interfaces it implements: `CharSequence`, `Comparable`, or `Serializable`.

A common pitfall with iterators regards modification. If the collection is modified while iteration is in process, it may throw an error of the type `ConcurrentModificationException`.

```
List<String> l = new ArrayList<>(List.of("one", "two", "three"));
for (String x : l) {
    if (x.equals("one")) {
        l.remove("one");  // throws ConcurrentModificationException
    }
}
```

Avoiding this exception requires rethinking your algorithm so it doesn't modify the collection. This can often be accomplished by working against a local copy instead of the original collection. The newer `Stream` APIs for collections also provide a lot of useful helpers for these situations.

### Random access to Lists

A general expectation of `List` implementations is that they can be efficiently iterated, typically in time proportional to the size of the list. Lists do not all provide efficient random access to the elements at any index, however. Sequential-access lists, such as the `LinkedList` class, provide efficient insertion and deletion operations at the expense of random-access performance. Implementations that provide efficient random access implement the `RandomAccess` marker interface, and you can test for this interface with `instanceof` if you need to ensure efficient list manipulations:

```
// Arbitrary list we're passed to manipulate
List<?> l = ...;

// Ensure we can do efficient random access.  If not, use a copy
// constructor to make a random-access copy of the list before
// manipulating it.
if (!(l instanceof RandomAccess)) l = new ArrayList<?>(l);
```

The `Iterator` returned by the `iterator()` method of a `List` iterates the list elements in the order they occur in the list. `List` implements `Iterable`, and lists can be iterated with a foreach loop just as any other collection can.

To iterate just a portion of a list, you can use the `subList()` method to create a sublist view:

```
List<String> words = ...;  // Get a list to iterate

// Iterate just all elements of the list but the first
for(String word : words.subList(1, words.size()))
    System.out.println(word);
```

Table 8-2 summarizes the five general-purpose `List` implementations in the Java platform. `Vector` and `Stack` are legacy implementations and should not be used. `CopyOnWriteArrayList` is part of the `java.util.concurrent` package and is only really suitable for multithreaded use cases.

*Table 8-2. List implementations*

| Class | Representation | Since | Random access | Notes |
|---|---|---|---|---|
| `ArrayList` | Array | 1.2 | Yes | Best all-around implementation |
| `LinkedList` | Double-linked list | 1.2 | No | More efficient insertion and deletion in middle of list |

| Class | Representation | Since | Random access | Notes |
|---|---|---|---|---|
| `CopyOnWriteArrayList` | Array | 5.0 | Yes | Threadsafe; fast traversal, slow modification |
| `Vector` | Array | 1.0 | Yes | Legacy class; synchronized methods. Do not use. |
| `Stack` | Array | 1.0 | Yes | Extends `Vector`; adds `push()`, `pop()`, `peek()`. Legacy; use `Deque` instead. |

## The Map Interface

A *map* is a set of *key* objects and a mapping from each member of that set to a *value* object. The `Map` interface defines an API for defining and querying mappings. `Map` is part of the Java Collections Framework, but it does not extend the `Collection` interface, so a `Map` is a little-c collection, not a big-C `Collection`. `Map` is a parameterized type with two type variables, `Map<K, V>`. Type variable `K` represents the type of keys held by the map, and type variable `V` represents the type of the values that the keys are mapped to. A mapping from `String` keys to `Integer` values, for example, can be represented with a `Map<String,Integer>`.

The most important `Map` methods are `put()`, which defines a key/value pair in the map; `get()`, which queries the value associated with a specified key; and `remove()`, which removes the specified key and its associated value from the map. The general performance expectation for `Map` implementations is that these three basic methods are quite efficient: they should run in constant time and certainly no worse than in logarithmic time.

An important feature of `Map` is its support for "collection views." These can be summarized as:

- A `Map` is not a `Collection`
- The keys of a `Map` can be viewed as a `Set`
- The values can be viewed as a `Collection`
- The mappings can be viewed as a `Set` of `Map.Entry` objects.

`Map.Entry` is a nested interface defined within `Map`: it simply represents a single key/value pair.

The following sample code shows the `get()`, `put()`, `remove()`, and other methods of a `Map` and demonstrates some common uses of the collection views of a `Map`:

```
// New, empty map
Map<String,Integer> m = new HashMap<>();

// Immutable Map containing a single key/value pair
Map<String,Integer> singleton = Collections.singletonMap("test", -1);

// Note this rarely used syntax to explicitly specify the parameter
// types of the generic emptyMap method. The returned map is immutable
Map<String,Integer> empty = Collections.<String,Integer>emptyMap();

// Populate the map using the put method to define mappings
// from array elements to the index at which each element appears
String[] words = { "this", "is", "a", "test" };
for(int i = 0; i < words.length; i++) {
    m.put(words[i], i);  // Note autoboxing of int to Integer
}

// Each key must map to a single value. But keys may map to the
// same value
for(int i = 0; i < words.length; i++) {
    m.put(words[i].toUpperCase(), i);
}

// The putAll() method copies mappings from another Map
m.putAll(singleton);

// Query the mappings with the get()  method
for(int i = 0; i < words.length; i++) {
    if (m.get(words[i]) != i) throw new AssertionError();
}

// Key and value membership testing
m.containsKey(words[0]);        // true
m.containsValue(words.length);  // false

// Map keys, values, and entries can be viewed as collections
Set<String> keys = m.keySet();
Collection<Integer> values = m.values();
Set<Map.Entry<String,Integer>> entries = m.entrySet();

// The Map and its collection views typically have useful
// toString  methods
System.out.printf("Map: %s%nKeys: %s%nValues: %s%nEntries: %s%n",
                  m, keys, values, entries);

// These collections can be iterated.
// Most maps have an undefined iteration order (but see SortedMap)
for(String key : m.keySet()) System.out.println(key);
for(Integer value: m.values()) System.out.println(value);
```

```java
// The Map.Entry<K,V> type represents a single key/value pair in a map
for(Map.Entry<String,Integer> pair : m.entrySet()) {
    // Print out mappings
    System.out.printf("'%s' ==> %d%n", pair.getKey(), pair.getValue());
    // And increment the value of each Entry
    pair.setValue(pair.getValue() + 1);
}

// Removing mappings
m.put("testing", null);   // Mapping to null can "erase" a mapping:
m.get("testing");         // Returns null
m.containsKey("testing"); // Returns true: mapping still exists
m.remove("testing");      // Deletes the mapping altogether
m.get("testing");         // Still returns null
m.containsKey("testing"); // Now returns false.

// Deletions may also be made via the collection views of a map.
// Additions to the map may not be made this way, however.
m.keySet().remove(words[0]);  // Same as m.remove(words[0]);

// Removes one mapping to the value 2 - usually inefficient and of
// limited use
m.values().remove(2);
// Remove all mappings to 4
m.values().removeAll(Collections.singleton(4));
// Keep only mappings to 2 & 3
m.values().retainAll(Arrays.asList(2, 3));

// Deletions can also be done via iterators
Iterator<Map.Entry<String,Integer>> iter = m.entrySet().iterator();
while(iter.hasNext()) {
    Map.Entry<String,Integer> e = iter.next();
    if (e.getValue() == 2) iter.remove();
}

// Find values that appear in both of two maps.  In general, addAll()
// and retainAll() with keySet() and values() allow union and
// intersection
Set<Integer> v = new HashSet<>(m.values());
v.retainAll(singleton.values());

// Miscellaneous methods
m.clear();                // Deletes all mappings
m.size();                 // Returns number of mappings: currently 0
m.isEmpty();              // Returns true
m.equals(empty);          // true: Maps implementations override equals
```

With the arrival of Java 9, the `Map` interface also has been enhanced with factory methods for spinning up collections easily:

```
Map<String, Double> cities =
        Map.of(
          "Barcelona", 22.5,
          "New York", 28.3);
```

The situation is a little more complicated as compared to `Set` and `List`, as the `Map` type has both keys and values, and Java does not allow more than one varargs parameter in a method declaration. The solution is to have fixed argument size overloads, up to 10 entries and also to provide a new static method, `entry()`, that will construct an object to represent the key/value pair.

The code can then be written to use the varargs form like this:

```
Map<String, Double> cities =
        Map.ofEntries(
          entry("Barcelona", 22.5),
          entry("New York", 28.3));
```

Note that the method name has to be different from `of()` due to the difference in type of the arguments—this is now a varargs method in `Map.Entry`.

The `Map` interface includes a variety of general-purpose and special-purpose implementations, which are summarized in Table 8-3. As always, complete details are in the JDK's documentation and javadoc. All classes in Table 8-3 are in the `java.util` package except `ConcurrentHashMap` and `ConcurrentSkipListMap`, which are part of `java.util.concurrent`.

*Table 8-3. Map implementations*

| Class | Representation | Since | Null keys | Null values | Notes |
|---|---|---|---|---|---|
| `HashMap` | Hashtable | 1.2 | Yes | Yes | General-purpose implementation |
| `ConcurrentHashMap` | Hashtable | 5.0 | No | No | General-purpose threadsafe implementation; see `ConcurrentMap` interface |
| `ConcurrentSkipListMap` | Hashtable | 6.0 | No | No | Specialized threadsafe implementation; see `ConcurrentNavigableMap` interface |
| `EnumMap` | Array | 5.0 | No | Yes | Keys are instances of an enum |
| `LinkedHashMap` | Hashtable plus list | 1.4 | Yes | Yes | Preserves insertion or access order |
| `TreeMap` | Red-black tree | 1.2 | No | Yes | Sorts by key value. Operations are O(log(n)). See `SortedMap` interface. |

| Class | Representation | Since | Null keys | Null values | Notes |
|---|---|---|---|---|---|
| `IdentityHashMap` | Hashtable | 1.4 | Yes | Yes | Compares with == instead of `equals()` |
| `WeakHashMap` | Hashtable | 1.2 | Yes | Yes | Doesn't prevent garbage collection of keys |
| `Hashtable` | Hashtable | 1.0 | No | No | Legacy class; synchronized methods. Do not use. |
| `Properties` | Hashtable | 1.0 | No | No | Extends `Hashtable` with `String` methods |

The `ConcurrentHashMap` and `ConcurrentSkipListMap` classes of the `java.util.concurrent` package implement the `ConcurrentMap` interface of the same package. `ConcurrentMap` extends `Map` and defines some additional atomic operations that are important in multithreaded programming. For example, the `putIfAbsent()` method is like `put()` but adds the key/value pair to the map only if the key is not already mapped.

`TreeMap` implements the `SortedMap` interface, which extends `Map` to add methods that take advantage of the sorted nature of the map. `SortedMap` is quite similar to the `SortedSet` interface. The `firstKey()` and `lastKey()` methods return the first and last keys in the `keySet()`. And `headMap()`, `tailMap()`, and `subMap()` return a restricted range of the original map.

## The Queue and BlockingQueue Interfaces

A *queue* is an ordered collection of elements with methods for extracting elements, in order, from the *head* of the queue. Queue implementations are commonly based on insertion order as in first-in, first-out (FIFO) queues or last-in, first-out (LIFO) queues.

> LIFO queues are also known as stacks, and Java provides a `Stack` class, but its use is strongly discouraged—instead, use implementations of the `Deque` interface.



Other orderings are also possible: a *priority queue* orders its elements according to an external `Comparator` object or according to the natural ordering of `Comparable` elements. Unlike a `Set`, `Queue` implementations typically allow duplicate elements. Unlike `List`, the `Queue` interface does not define methods for manipulating queue elements at arbitrary positions. Only the element at the head of the queue is available for examination. It is common for `Queue` implementations to have a fixed capacity: when a queue is full, it is not possible to add more elements. Similarly, when a queue is empty, it is not possible to remove any more elements. Because full and empty conditions are a normal part of many queue-based algorithms, the `Queue` interface defines methods that signal these conditions with return values rather than by throwing exceptions. Specifically, the `peek()` and `poll()` methods return `null` to indicate that the queue is empty. For this reason, most `Queue` implementations do not allow `null` elements.

A *blocking queue* is a type of queue that defines blocking `put()` and `take()` methods. The `put()` method adds an element to the queue, waiting, if necessary, until there is space in the queue for the element. And the `take()` method removes an element from the head of the queue, waiting, if necessary, until there is an element to remove. Blocking queues are an important part of many multithreaded algorithms, and the `BlockingQueue` interface (which extends `Queue`) is defined as part of the `java.util.concurrent` package.

Queues are not nearly as commonly used as sets, lists, and maps, except perhaps in certain multithreaded programming styles. In lieu of example code here, we'll try to clarify the different possible queue insertion and removal operations.

## Adding Elements to Queues

`add()`
: This `Collection` method simply adds an element in the normal way. In bounded queues, this method may throw an exception if the queue is full.

`offer()`
: This `Queue` method is like `add()` but returns `false` instead of throwing an exception if the element cannot be added because a bounded queue is full.

  `BlockingQueue` defines a timeout version of `offer()` that waits up to a specified amount of time for space to become available in a full queue. Like the basic version of the method, it returns `true` if the element was inserted and `false` otherwise.

`put()`
: This `BlockingQueue` method blocks: if the element cannot be inserted because the queue is full, `put()` waits until some other thread removes an element from the queue and space becomes available for the new element.

## Removing Elements from Queues

`remove()`
: In addition to the `Collection.remove()` method, which removes a specified element from the queue, the `Queue` interface defines a no-argument version of `remove()` that removes and returns the element at the head of the queue. If the queue is empty, this method throws a `NoSuchElementException`.

`poll()`
: This `Queue` method removes and returns the element at the head of the queue, like `remove()` does, but returns `null` if the queue is empty instead of throwing an exception.

  `BlockingQueue` defines a timeout version of `poll()` that waits up to a specified amount of time for an element to be added to an empty queue.

`take()`
: This `BlockingQueue` method removes and returns the element at the head of the queue. If the queue is empty, it blocks until some other thread adds an element to the queue.

`drainTo()`
: This `BlockingQueue` method removes all available elements from the queue and adds them to a specified `Collection`. It does not block to wait for elements to be added to the queue. A variant of the method accepts a maximum number of elements to drain.

### Querying

In this context, querying refers to examining the element at the head without removing it from the queue.

`element()`
: This `Queue` method returns the element at the head of the queue but does not remove that element from the queue. It throws `NoSuchElementException` if the queue is empty.

`peek()`
: This `Queue` method is like `element` but returns `null` if the queue is empty.

> When using queues, it is usually a good idea to pick one particular style of how to deal with a failure. For example, if you want operations to block until they succeed, then choose `put()` and `take()`. If you want to examine the return code of a method to see if the queue operation succeeded, then `offer()` and `poll()` are appropriate choices.

The `LinkedList` class also implements `Queue`. It provides unbounded FIFO ordering, and insertion and removal operations require constant time. `LinkedList` allows `null` elements, although their use is discouraged when the list is being used as a queue.

There are two other `Queue` implementations in the `java.util` package. `PriorityQueue` orders its elements according to a `Comparator` or orders `Comparable` elements according to the order defined by their `compareTo()` methods. The head of a `PriorityQueue` is always the smallest element according to the defined ordering.

Finally, ArrayDeque is a double-ended queue implementation. It is often used when a stack implementation is needed.

The java.util.concurrent package also contains a number of BlockingQueue implementations, which are designed for use in multithreaded programing style; advanced versions that can remove the need for synchronized methods are available.

A full discussion of java.util.concurrent is unfortunately outside the scope of this book. The interested reader should refer to *Java Concurrency in Practice* by Brian Goetz et al. (Addison-Wesley, 2006).

## Utility Methods

The java.util.Collections class is home to quite a few static utility methods designed for use with collections. One important group of these methods is the collection *wrapper* methods: they return a special-purpose collection wrapped around a collection you specify. The purpose of the wrapper collection is to wrap additional functionality around a collection that does not provide it itself. Wrappers exist to provide thread-safety, write protection, and runtime type checking. Wrapper collections are always *backed by* the original collection, which means that the methods of the wrapper simply dispatch to the equivalent methods of the wrapped collection. This means that changes made to the collection through the wrapper are visible through the wrapped collection and vice versa.

The first set of wrapper methods provides threadsafe wrappers around collections. Except for the legacy classes Vector and Hashtable, the collection implementations in java.util do not have synchronized methods and are not protected against concurrent access by multiple threads. If you need threadsafe collections and don't mind the additional overhead of synchronization, create them with code like this:

```
List<String> list =
    Collections.synchronizedList(new ArrayList<>());
Set<Integer> set =
    Collections.synchronizedSet(new HashSet<>());
Map<String,Integer> map =
    Collections.synchronizedMap(new HashMap<>());
```

A second set of wrapper methods provides collection objects through which the underlying collection cannot be modified. They return a read-only view of a collection: an UnsupportedOperationException will result from changing the collection's content. These wrappers are useful when you must pass a collection to a method that must not be allowed to modify or mutate the content of the collection in any way:

```
List<Integer> primes = new ArrayList<>();
List<Integer> readonly = Collections.unmodifiableList(primes);
// We can modify the list through primes
primes.addAll(Arrays.asList(2, 3, 5, 7, 11, 13, 17, 19));
```

```
// But we can't modify through the read-only wrapper
readonly.add(23);  // UnsupportedOperationException
```

The `java.util.Collections` class also defines methods to operate on collections. Some of the most notable are methods to sort and search the elements of collections:

```
Collections.sort(list);
// list must be sorted first
int pos = Collections.binarySearch(list, "key");
```

Here are some other interesting `Collections` methods:

```
// Copy list2 into list1, overwriting list1
Collections.copy(list1, list2);
// Fill list with Object o
Collections.fill(list, o);
// Find the largest element in Collection c
Collections.max(c);
// Find the smallest element in Collection c
Collections.min(c);

Collections.reverse(list);      // Reverse list
Collections.shuffle(list);      // Mix up list
```

It is a good idea to familiarize yourself fully with the utility methods in `Collections` and `Arrays`, as they can save you from writing your own implementation of a common task.

### Special-case collections

In addition to its wrapper methods, the `java.util.Collections` class also defines utility methods for creating immutable collection instances that contain a single element and other methods for creating empty collections. `singleton()`, `singletonList()`, and `singletonMap()` return immutable `Set`, `List`, and `Map` objects that contain a single specified object or a single key/value pair. These methods are useful when you need to pass a single object to a method that expects a collection.

The `Collections` class also includes methods that return empty collections. If you are writing a method that returns a collection, it is usually best to handle the no-values-to-return case by returning an empty collection instead of a special-case value like `null`:

```
Set<Integer> si = Collections.emptySet();
List<String> ss = Collections.emptyList();
Map<String, Integer> m = Collections.emptyMap();
```

Since Java 9, though, these methods are frequently replaced by the `of()` methods on the `Set`, `List` and `Map` interfaces.

```
Set<Integer> si = Set.of();
List<String> ss = List.of();
Map<String, Integer> m = Map.of();
```

These return immutable versions of their type and may also take elements through the same method.

```
Set<Integer> si = Set.of(1);
List<String> ss = List.of("string");
Map<String, Integer> m = Map.of("one", 1);
```

Finally, `nCopies()` returns an immutable `List` that contains a specified number of copies of a single specified object:

```
List<Integer> tenzeros = Collections.nCopies(10, 0);
```

## Arrays and Helper Methods

Arrays of objects and collections serve similar purposes. It is possible to convert from one to the other:

```
String[] a = { "this", "is", "a", "test" };  // An array
// View array as an ungrowable list
List<String> l = Arrays.asList(a);
// Make a growable copy of the view
List<String> m = new ArrayList<>(l);

// asList() is a varargs method so we can do this, too:
Set<Character> abc =
    new HashSet<Character>(Arrays.asList('a', 'b', 'c'));

// Collection defines a toArray method. The no-args version creates
// an Object[] array, copies collection elements to it and returns it
// Get set elements as an array
Object[] members = set.toArray();
// Get list elements as an array
Object[] items = list.toArray();
// Get map key objects as an array
Object[] keys = map.keySet().toArray();
// Get map value objects as an array
Object[] values = map.values().toArray();

// If you want the return value to be something other than Object[],
// pass in an array of the appropriate type. If the array is not
// big enough, another one of the same type will be allocated.
// If the array is too big, the collection elements copied to it
// will be null-filled
String[] c = l.toArray(new String[0]);
```

In addition, there are a number of useful helper methods for working with Java's arrays, which are included here for completeness.

The `java.lang.System` class defines an `arraycopy()` method that is useful for copying specified elements in one array to a specified position in a second array. The second array must be the same type as the first, and it can even be the same array:

```
char[] text = "Now is the time".toCharArray();
char[] copy = new char[100];
// Copy 10 characters from element 4 of text into copy,
// starting at copy[0]
System.arraycopy(text, 4, copy, 0, 10);

// Move some of the text to later elements, making room for
// insertions If target and source are the same, this will involve
// copying to a temporary array
System.arraycopy(copy, 3, copy, 6, 7);
```

There are also a number of useful static methods defined on the `Arrays` class:

```
int[] intarray = new int[] { 10, 5, 7, -3 }; // An array of integers
Arrays.sort(intarray);                        // Sort it in place
// Value 7 is found at index 2
int pos = Arrays.binarySearch(intarray, 7);
// Not found: negative return value
pos = Arrays.binarySearch(intarray, 12);

// Arrays of objects can be sorted and searched too
String[] strarray = new String[] { "now", "is", "the", "time" };
Arrays.sort(strarray);   // sorted to: { "is", "now", "the", "time" }

// Arrays.equals compares all elements of two arrays
String[] clone = (String[]) strarray.clone();
boolean b1 = Arrays.equals(strarray, clone);  // Yes, they're equal

// Arrays.fill  initializes array elements
// An empty array; elements set to 0
byte[] data = new byte[100];
// Set them all to -1
Arrays.fill(data, (byte) -1);
// Set elements 5, 6, 7, 8, 9 to -2
Arrays.fill(data, 5, 10, (byte) -2);

// Creates a new array with elements copied into it
int[] copied = Arrays.copyOf(new int[] { 1, 2, 3 }, 2);
```

Arrays can be treated and manipulated as objects in Java. Given an arbitrary object `o`, you can use code such as the following to find out if the object is an array and, if so, what type of array it is:

```
Class type = o.getClass();
if (type.isArray()) {
  Class elementType = type.getComponentType();
}
```

Java Collections

## Java Streams and Lambda Expressions

One of the major reasons for introducing lambda expressions in Java 8 was to facilitate the overhaul of the Collections API to allow more modern programming styles to be used by Java developers. Until the release of Java 8, the handling of data structures in Java looked a little bit dated. Many languages now support a programming style that allows collections to be treated as a whole, rather than requiring them to be broken apart and iterated over.

In fact, many Java developers had taken to using alternative data structures libraries to achieve some of the expressivity and productivity they felt was lacking in the Collections API. The key to upgrading the APIs was to introduce new classes and methods that would accept lambda expressions as parameters—to define *what* needed to be done, rather than precisely *how*. This is a conception of programming that comes from the functional style.

The introduction of the functional collections—which are called *Java Streams* to make clear their divergence from the older collections approach—is an important step forward. A stream can be created from a collection simply by calling the `stream()` method on an existing collection.

> The desire to add new methods to existing interfaces was directly responsible for the new language feature referred to as *default methods* (see "Default Methods" on page 158 for more details). Without this new mechanism, older implementations of the Collections interfaces would fail to compile under Java 8 and would fail to link if loaded into a Java 8 runtime.

However, the arrival of the Streams API does not erase history. The Collections API is deeply embedded in the Java world, and it is not functional. Java's commitment to backward compatibility and to a rigid language grammar means that the Collections will never go away. Java code, even when written in a functional style, will never be entirely free of boilerplate and will never have the concise syntax that we see in languages such as Haskell or Scala.

This is part of the inevitable trade-off in language design—Java has retrofitted functional capabilities on top of an imperative design and base. This is not the same as designing for functional programming from the ground up. A more important question is: Are the functional capabilities supplied from Java 8 onward what working programmers need to build their applications?

The rapid adoption of Java 8 over previous versions and the community reaction seem to indicate that the new features have been a success and have provided what the ecosystem was looking for.

In this section, we will introduce the use of Java streams and lambda expressions in the Java Collections. For a fuller treatment, see *Java 8 Lambdas* by Richard Warburton (O'Reilly).

## Functional Approaches

The approach that Java 8 Streams wished to enable was derived from functional programming languages and styles. We met some of these key patterns in "Functional Programming" on page 184—let's reintroduce them and look at some examples of each.

### Filter

The filter idiom applies a piece of code returning either true or false (known as a predicate) to each element in a collection. A new collection is built consisting of the elements that "passed the test" (i.e., the bit of code returned `true` when applied to the element).

For example, let's look at some code to work with a collection of cats and pick out the tigers:

```
List<String> cats = List.of("tiger", "cat", "TIGER", "leopard");
String search = "tiger";
String tigers = cats.stream()
                    .filter(s -> s.equalsIgnoreCase(search))
                    .collect(Collectors.joining(", "));
System.out.println(tigers);
```

The key piece is the call to `filter()`, which takes a lambda expression. The lambda takes in a string and returns a Boolean value. This is applied over the whole collection `cats`, and a new collection is created, which contains only tigers (however they were capitalized).

The `filter()` method takes in an instance of the `Predicate` interface, from the package `java.util.function`. This is a functional interface, with only a single nondefault method, and so is a perfect fit for a lambda expression.

Note the final call to `collect()`; this is an essential part of the API and is used to "gather up" the results at the end of the lambda operations. We'll discuss it in more detail in the next section.

`Predicate` has some other very useful default methods, such as for constructing combined predicates by using logic operations. For example, if the tigers want to admit leopards into their group, this can be represented by using the `or()` method:

```
Predicate<String> p = s -> s.equalsIgnoreCase(search);
Predicate<String> combined = p.or(s -> s.equals("leopard"));
String pride = cats.stream()
                   .filter(combined)
                   .collect(Collectors.joining(", "));
System.out.println(pride);
```

Note that it's much clearer if the `Predicate<String>` object `p` is explicitly created, so that the defaulted `or()` method can be called on it and the second lambda expression (which will also be automatically converted to a `Predicate<String>`) passed to it.

## Map

The map idiom makes use of the interface `Function<T, R>` in the package `java.util.function`. Like `Predicate<T>`, this is a functional interface and so only has one nondefaulted method, `apply()`. The map idiom is about transforming one stream into a new stream, where the new stream potentially has different types and values than the original. This shows up in the API as the fact that `Function<T, R>` has two separate type parameters. The name of the type parameter `R` indicates that this represents the return type of the function.

Let's look at a code example that uses `map()`:

```
List<Integer> namesLength = cats.stream()
                .map(String::length)
                .toList();
System.out.println(namesLength);
```

This is called upon the previous `cats` variable (which is a `Stream<String>`) and applies the function `String::length` (a method reference) to each string in turn. The result is a new stream—but of `Integer` this time. We turn that stream into a `List` with the `toList()` method. Note that unlike the collections API, the `map()` method does not mutate the stream in place but returns a new value. This is key to the functional style as used here.

## forEach

The map and filter idioms are used to create one collection from another. In languages that are strongly functional, this would be combined with requiring that the original collection was not affected by the body of the lambda as it touched each element. In computer science terms, this means that the lambda body should be "side effect free."

In Java, of course, we often need to deal with mutable data, so the Streams API provides a way to mutate elements as the collection is traversed—the `forEach()` method. This takes an argument of type `Consumer<T>`, which is a functional interface that is expected to operate by side effects (although whether it actually mutates the data or not is of lesser importance). This means that the signature of lambdas that can be converted to `Consumer<T>` is `(T t) → void`. Let's look at a quick example of `forEach()`:

```
List<String> pets =
  List.of("dog", "cat", "fish", "iguana", "ferret");
pets.stream().forEach(System.out::println);
```

In this example, we are simply printing out each member of the collection. However, we're doing so by using a special kind of method reference as a lambda expression. This type of method reference is called a *bound method reference*, as it involves a specific object (in this case, the object `System.out`, which is a static public field of `System`). This is equivalent to the lambda expression:

```
s -> System.out.println(s);
```

This is of course eligible for conversion to an instance of a type that implements `Consumer<? super String>` as required by the method signature.

> Nothing prevents a `map()` or `filter()` call from mutating elements. It is only a convention that they must not mutate, but it's one that every Java programmer should adhere to.

There's one final functional technique that we should look at before we move on. This is the practice of aggregating a collection down to a single value, and it's the subject of our next section.

## Reduce

Let's look at the `reduce()` method. This implements the reduce idiom, which is really a family of similar and related operations, some referred to as fold, or aggregation, operations.

In Java, `reduce()` takes two arguments. These are the initial value, which is often called the identity (or zero), and a function to apply step by step. This function is of type `BinaryOperator<T>`, which is another functional interface that takes in two arguments of the same type and returns another value of that type. This second argument to `reduce()` is a two-argument lambda. `reduce()` is defined in the `javadoc` like this:

```
T reduce(T identity, BinaryOperator<T> aggregator);
```

The easy way to think about the second argument to `reduce()` is that it creates a "running total" as it runs over the stream. It starts by combining the identity with the first element of the stream to produce the first result, then combines that result with the second element of the stream, and so on.

It can help to imagine that the implementation of `reduce()` works a bit like this:

```
public T reduce(T identity, BinaryOperator<T> aggregator) {
    T runningTotal = identity;
    for (T element : myStream) {
        runningTotal = aggregator.apply(runningTotal, element);
    }

    return runningTotal;
}
```

> In practice, implementations of `reduce()` can be more sophisticated than these and can even execute in parallel if the data structure and operations are amenable to this.

Let's look at a quick example of a `reduce()` and calculate the sum of some primes:

```
double sumPrimes = List.of(2, 3, 5, 7, 11, 13, 17, 19, 23)
        .stream()
        .reduce(0, (x, y) -> x + y);
System.out.println("Sum of some primes: " + sumPrimes);
```

In all of the examples we've met in this section, you may have noticed the presence of a `stream()` method call on the `List` instance. This is part of the evolution of Java Collections—it was originally chosen partly out of necessity but has proved to be an excellent abstraction. Let's move on to discuss the Streams API in more detail.

## The Streams API

The fundamental issue that caused the Java library designers to introduce the Streams API was the large number of implementations of the core collections interfaces present in the wild. As these implementations predate Java 8 and lambdas, they would not have any of the methods corresponding to the new functional operations. Worse still, as method names such as `map()` and `filter()` have never been part of the interface of the Collections, implementations may already have methods with those names.

To work around this problem, a new abstraction called a `Stream` was introduced. The idea is that a `Stream` object can be generated from a collection object via the `stream()` method. This `Stream` type, being new and under the control of the library designers, is then guaranteed to be free of collisions. This then mitigates the risk of clash, as only Collections implementations that contained a `stream()` method would be affected.

A `Stream` object plays a similar role to an `Iterator` in the new approach to collections code. The overall idea is for the developer to build up a sequence (or "pipeline") of operations (such as `map`, `filter`, or `reduce`) that need to be applied to the collection as a whole. The actual content of the operations will usually be expressed as a lambda expression for each operation.

At the end of the pipeline, the results usually need to be gathered up, or "materialized," either as a new collection or another value. This is done either by using a `Collector` or by finishing the pipeline with a "terminal method" such as `reduce()` that returns an actual value, rather than another stream. Overall, the new approach to collections looks like this:

```
        stream()    filter()    map()    collect()
Collection -> Stream -> Stream -> Stream -> Collection
```

The `Stream` class behaves as a sequence of elements that are accessed one at a time (although there are some types of streams that support parallel access and can be used to process larger collections in a naturally multithreaded way). In a similar way to an `Iterator`, the `Stream` is used to take each item in turn.

As is usual for generic classes in Java, `Stream` is parameterized by a reference type. However, in many cases, we actually want streams of primitive types, especially ints and doubles. We cannot have `Stream<int>`, so instead in `java.util.stream` there are special (nongeneric) classes such as `IntStream` and `DoubleStream`. These are known as *primitive specializations* of the `Stream` class and have APIs that are very similar to the general `Stream` methods, except that they use primitives where appropriate.

### Lazy evaluation

In fact, streams are more general than iterators (or even collections), as streams do not manage storage for data. In earlier versions of Java, there was always a presumption that all of the elements of a collection existed (usually in memory). It was possible to work around this in a limited way by insisting on the use of iterators everywhere, as well as by having the iterators construct elements on the fly. However, this was neither very convenient nor that common.

By contrast, streams are an abstraction for managing data, rather than being concerned with the details of storage. This makes it possible to handle more subtle data structures than just finite collections. For example, infinite streams can easily be represented by the `Stream` interface, and they can be used as a way, for example, to handle the set of all square numbers. Let's see how we could accomplish this using a `Stream`:

```
public class SquareGenerator implements IntSupplier {
    private int current = 1;

    @Override
    public synchronized int getAsInt() {
        int thisResult = current * current;
        current++;
        return thisResult;
    }
}

IntStream squares = IntStream.generate(new SquareGenerator());
PrimitiveIterator.OfInt stepThrough = squares.iterator();
for (int i = 0; i < 10; i++) {
    System.out.println(stepThrough.nextInt());
}
System.out.println("First iterator done...");

// We can go on as long as we like...
for (int i = 0; i < 10; i++) {
    System.out.println(stepThrough.nextInt());
}
```

Because our list of possible values is infinite, we must adopt a model in which elements do not all exist ahead of time. Essentially, a bit of code must return the next element as we demand it. The key technique used to accomplish this is *lazy evaluation*.

> Lazy evaluation is a big change for Java, as until JDK 8 the value of an expression was always computed as soon as it was assigned to a variable (or passed into a method). This familiar model, where values are computed immediately, is called "eager evaluation" and it is the default behavior for evaluation of expressions in most mainstream programming languages.

We can see this lazy evaluation in action in our example above if we modify `getAsInt()` slightly to provide output actively when it is called:

```
@Override
public synchronized int getAsInt() {
    int thisResult = current * current;
    System.out.print(String.format("%d... ", thisResult));
    current++;
    return thisResult;
}
```

When this modified program is run, we'll see output that shows each `getAsInt()` call immediately followed by the use of that value in the `for` loop:

```
1... 1
4... 4
9... 9
16... 16
25... 25
36... 36
49... 49
64... 64
81... 81
100... 100
First iterator done...
121... 121
...
```

One significant consequence of modeling the infinite stream is that methods like `collect()` won't work. This is because we can't materialize the whole stream to a collection (we would run out of memory before we created the infinite amount of objects we would need).

Even when a stream isn't infinite, it's important to recognize what parts of the evaluation are lazy. For instance, the following code that tries to show us diagnostic information during a `map` operation doesn't actually yield any output:

```
List.of(1, 2, 3, 4, 5)
    .stream()
    .map((i) - > {
        System.out.println(i);
```

```
            return i;
        });
```

Only once we provide a terminal action such as `collect()` or `toList()` is our `map()` lambda actually executed.

Recognizing which intermediate results are lazy in their evaluation is a topic Java developers should be mindful of when working with the Stream API. The more complicated implementation details, though, fall to library writers rather than users of streams.

While the combination of `filter`, `map`, and `reduce` can accomplish almost any stream-related task we're after, it isn't always the most convenient API. There are a wide variety of additional methods that build on top of these primitives to give us a richer vocabulary to work with stream.

## Further filtering

A common place where working with streams benefits from more elaborate methods is filtering. A number of methods on the `Stream` interface allow more expressive descriptions of how we want to trim our streams for consumption:

```
// Distinct elements only
Stream.of(1, 2, 1, 2, 3, 4)
      .distinct();
// Results in  [1, 2, 3, 4]

// Ignores items until predicate matches, then returns remainder
// Note that later elements aren't required to match the predicate.
Stream.of(1, 2, 3, 4, 5, 3)
      .dropWhile((i) -> i < 4);
// Results in [4, 5, 3]

// Returns items from the stream until the predicate stops matching.
// Note that later elements matching the predicate aren't returned.
Stream.of(1, 2, 3, 4, 3)
      .takeWhile((i) -> i < 4);
// Results in [1, 2, 3]

// Skips the first N items in the stream
Stream.of(1, 2, 3, 4, 5)
      .skip(2);
// Results in [3, 4, 5]

// Limits items taken from stream to an exact value
// Useful with infinite streams to set boundaries
Stream.of(1, 2, 3, 4, 5)
      .limit(3);
// Results in [1, 2, 3]
```

### Matching in streams

Another typical operation is to ask questions of an entire stream of elements, such as whether all (or none) match a given predicate, or alternatively if there's any single element that matches:

```
// Are all the items odd?
Stream.of(1, 1, 3, 5)
      .allMatch((i) -> i % 2 == 1);
// Returns true

// Are none of the items even?
Stream.of(1, 1, 3, 5)
      .noneMatch((i) -> i % 2 == 0);
// Returns true

// Is at least one item even?
Stream.of(1, 1, 3, 5, 6)
      .anyMatch((i) -> i % 2 == 0);
// Returns true
```

## Flattening

Once we've started down the path of modeling our data as streams, it's not unusual to find yet another layer of streams beneath. For instance, if we're processing multiple lines of text and wanted to gather the set of words from the entire block, we might reach first for code like this:

```
var lines = Stream.of(
    "For Brutus is an honourable man",
    "Give me your hands if we be friends and Robin shall restore amends",
    "Misery acquaints a man with strange bedfellows");

lines.map((s) -> s.split(" +"));
// Returns Stream.of(new String[] { "For", "Brutus",...},
//                   new String[] { "Give", "me", "your", ... },
//                   new String[] { "Misery", "acquaints", "a", ... },
```

This isn't quite the plain word list we're after, though. We have an extra layer of nesting, a `Stream<String[]>` instead of `Stream<String>`.

The `flatMap()` method is designed for exactly these situations. For each element in our original stream, the lambda provided to `flatMap()` returns not an individual value but another `Stream`. Then `flatMap()` gathers those multiple streams and joins them, flattening to a single stream of the contained type.

In our example `split()` gives us arrays, which we can trivially convert to streams. From there, `flatMap()` will do the work of turning those multiple streams into the single stream of words we were after:

```
lines.flatMap((s) -> Arrays.stream(s.split(" +")));
// Returns Stream.of("For", "Brutus", "is", "an", ...)
```

## From Streams to Collections

Defining a separate `Stream` interface was a pragmatic way to enable newer styles of development with Java while not breaking existing code. However, sometimes you still need the standard Java Collections, whether to pass to another API or for functionality that isn't present in streams. For the most common cases of returning a simple `List` or array of elements, the methods are provided directly on the `Stream` interface:

```
// Immutable list returned
List<Integer> list =
    Stream.of(1, 2, 3, 4, 5).toList();

// Note the return type is `Object[]`
Object[] array =
    Stream.of(1, 2, 3, 4, 5).toArray();
```

Transforming a stream into a nonstream collection or other object is primarily performed through the `collect()` method. This method receives an instance of the `Collector` interface, allowing for a world of possible ways to gather up our stream results without adding to the `Stream` interface itself.

Standard implementations for a variety of collectors are available on the `Collectors` class as static methods. For instance, we can turn our stream into any of our normal collection types:

```
// In earlier versions of Java, Stream#toList() didn't exist
// This was the commonly used approach so you'll still see it often
List<Integer> list =
    Stream.of(1,2,3,4,5)
          .collect(Collectors.toList());

// Create a standard Set (no duplicates)
Set<Integer> set =
    Stream.of(1,2,3,4,5)
          .collect(Collectors.toSet());

// For Collection types that don't have a specific method, we can
// use toCollection with a function that creates our empty instance
// Each item will be added to that collection
TreeSet<Integer> collection =
    Stream.of(1,2,3,4,5)
          .collect(Collectors.toCollection(TreeSet::new));

// When creating maps we must provide two functions
// The first constructs the key for each element, the second the value
// Here, each int is its own key and the value is its toString()
Map<Integer, String> map =
    Stream.of(1,2,3,4,5)
          .collect(Collectors.toMap(
                     (i) -> i,
                     Object::toString));
```

Unlike `Stream#toList()`, all of these options return a modifiable version of their collection type. `Collectors` also provides specific methods if you want to return an unmodifiable or immutable version. They follow a naming convention `toUnmodifiableX()` where `X` is the collection type as seen above.

A final variation on gathering collections is when you want to group the elements by some property. In this example, we want to group the numbers by their first digit:

```
Map<Character, List<Integer>> grouped =
        Stream.of(10, 11, 12, 20, 30)
                .collect(Collectors.groupingBy((i) -> {
                    return i.toString().charAt(0);
                }));
// Returns map with {"1"=[10, 11, 12], "2"=[20], "3"=[30]}
```

### From Streams to values

We don't always want to retrieve collections from our streams—sometimes we need a single value, much like the `reduce()` method gave us.

`Stream` has a few built-in methods for the most common values we might want from our stream:

```
var count = Stream.of(1,2,3).count();
var max = Stream.of(1,2,3).max(Integer::compareTo);
var min = Stream.of(1,2,3).min(Integer::compareTo);
```

The `collect()` method isn't limited to returning collection types either. A wide variety of result gathering methods are available from `Collectors` to aid in common calculations, particularly on streams of numbers. These methods all require a function for turning the incoming item from the stream to a number, which allows it to be easily used with objects as well as primitive values:

```
var average =
    Stream.of(1,2,3)
          .collect(Collectors.averagingInt(Integer::intValue));

var sum =
    Stream.of(1,2,3)
          .collect(Collectors.summingInt(Integer::intValue));

var summary =
    Stream.of(1,2,3)
          .collect(Collectors.summarizingInt(Integer::intValue));
// IntSummaryStatistics{count=3, sum=6, min=1, average=2.0, max=3}
```

Similar methods are available for long and double types in addition to integers.

A final way of getting a result from a stream helps us with strings. A classic issue is turning a series of smaller strings into one larger delimited string. Streams make this quite simple.

```java
var words = Stream.of("This", "is", "some", "text");
var csv = words.collect(Collectors.joining(", "));
// Returns string "This, is, some, text"
```

### Streams utility default methods

Java Streams took the opportunity to introduce a number of new methods to the Java Collections libraries. Using default methods, it was possible to add new methods to the Collections without breaking backward compatibility.

Some of these methods are *scaffold methods* for creating Streams from our existing collections. These include methods such as `Collection::stream`, `Collection::parallelStream`, and `Collection::spliterator` (which has specialized forms `List::spliterator` and `Set::spliterator`).

Other methods provide shortcuts to functionality that existed elsewhere in previous versions. For instance, `List::sort` method essentially delegates to the more cumbersome version already available on the `Collections` class:

```java
// Essentially just forwards to the helper method in Collections
public default void sort(Comparator<? super E> c) {
    Collections.<E>sort(this, c);
}
```

The remaining methods provide additional functional techniques using the interfaces of `java.util.function`:

`Collection::removeIf`
: This method takes a `Predicate` and iterates internally over the collection, removing any elements that satisfy the predicate object.

`Map::forEach`
: The single argument to this method is a lambda expression that takes two arguments (one of the key's type and one of the value's type) and returns `void`. This is converted to an instance of `BiConsumer` and applied to each key/value pair in the map.

`Map::computeIfAbsent`
: This takes a key and a lambda expression that maps the key type to the value type. If the specified key (first parameter) is not present in the map, then it computes a default value by using the lambda expression and puts it in the map.

(See also `Map::computeIfPresent`, `Map::compute`, and `Map::merge`.)



## Summary

In this chapter, we've met the Java Collections libraries and seen how to start working with Java's implementations of fundamental and classic data structures. We've met the general `Collection` interface, as well as `List`, `Set`, and `Map`. We've seen the original, iterative way of handling collections and introduced the new Java Streams style, based on ideas from fundamental programming. In the Streams API, we've seen how the new approach is more general and can express more subtle programming concepts than the classic approach.

We've only scratched the surface—the Streams API is a fundamental shift in how Java code is written and architected. There are inherent design limitations in how far the ideals of functional programming can be implemented in Java. Having said that, the possibility that Streams represents "just enough functional programming" is compelling.

Let's move on. In the next chapter, we'll continue looking at data, and common tasks like text processing, handling numeric data, and Java 8's new date and time libraries.

# 9
# Handling Common Data Formats

Most of programming is handling data in various formats. In this chapter, we will introduce Java's support for handling two big classes of data—text and numbers. The second half of the chapter will focus on handling date and time information. This is of particular interest, as Java 8 shipped a completely new API for handling date and time. We cover this interface in some depth before finishing the chapter by briefly discussing Java's original date and time API.

Many applications are still using the legacy APIs, so developers need to be aware of the old way of doing things, but the new APIs are so much better that we recommend converting as soon as possible. Before we get to those more complex formats, let's get under way by talking about textual data and strings.

## Text

We have already met Java's strings on many occasions. They consist of sequences of Unicode characters and are represented as instances of the `String` class. Strings are one of the most common types of data that Java programs process (a claim you can investigate for yourself by using the `jmap` tool that we'll meet in Chapter 13).

In this section, we'll meet the `String` class in some more depth and understand why it is in a rather unique position within the Java language. Later in the section, we'll introduce regular expressions, a very common abstraction for searching text for patterns (and a classic tool in the programmer's arsenal, regardless of language).

### Special Syntax for Strings

The `String` class is handled in a somewhat special way by the Java language. This is because, despite not being a primitive type, strings are so common that it makes sense for Java to have a number of special syntax features designed to make handling strings easy. Let's look at some examples of special syntax features for strings that Java provides.

### String literals

As we saw in Chapter 2, Java allows a sequence of characters to be placed in double quotes to create a literal string object. Like this:

```
String pet = "Cat";
```

Without this special syntax, we would have to write acres of horrible code like this:

```
char[] pullingTeeth = {'C', 'a', 't'};
String pet = new String(pullingTeeth);
```

This would get tedious extremely quickly, so it's no surprise that Java, like all modern programming languages, provides a simple string literal syntax. The string literals are perfectly sound objects, so code like this is completely legal:

```
System.out.println("Dog".length());
```

Strings using basic double quotes cannot span multiple lines, but recent versions of Java have included multiline text blocks with the `"""` syntax. The resulting string objects are created at compile-time and are no different than a `"` quoted string, just easier to express:

```
String lyrics = """
  This is the song that never ends
  This song goes on and one my friend
  ...""";
```

See "String literals" on page 84 for complete coverage of string literals in Java.

### toString()

This method is defined on `Object` and is designed to allow easy conversion of any object to a string. This makes it easy to print out any object, by using the method `System.out.println()`. This method is actually `PrintStream::println` because `System.out` is a static field of type `PrintStream`. Let's see how this method is defined:

```
    public void println(Object x) {
        String s = String.valueOf(x);
        synchronized (this) {
            print(s);
            newLine();
        }
    }
```

This creates a new string by using the static method `String::valueOf()`:

```
    public static String valueOf(Object obj) {
        return (obj == null) ? "null" : obj.toString();
    }
```

> The static `valueOf()` method is used instead of `toString()` directly, to avoid a `NullPointerException` in the case where `obj` is `null`.

This construction means that `toString()` is always available for any object, and this comes in very handy for another major syntax feature that Java provides: string concatenation.

### String concatenation

Java allows us to create new strings by "adding" the characters from one string onto the end of another. This is called *string concatenation* and uses the operator `+`. In versions of Java up to and including Java 8, it works by first creating a "working area" in the form of a `StringBuilder` object that contains the same sequence of characters as the original string.

> Java 9 introduced a new mechanism that uses the `invokedynamic` instruction instead of `StringBuilder` directly. This is an advanced piece of functionality and out of scope for this discussion, but it doesn't change the behavior visible to the Java developer.

The builder object is then updated and the characters from the additional string are added onto the end. Finally, `toString()` is called on the `StringBuilder` object (which now contains the characters from both strings). This gives us a new string with all the characters in it. All of this code is created automatically by `javac` whenever we use the `+` operator to concatenate strings.

The concatenation process returns a completely new `String` object, as we can see in this example:

```
String s1 = "AB";
String s2 = "CD";

String s3 = s1;
System.out.println(s1 == s3); // Same object? Yes.

s3 = s1 + s2;
System.out.println(s1 == s3); // Still same? Nope!
System.out.println(s1);
System.out.println(s3);
```

The concatenation example directly shows that the `+` operator is not altering (or *mutating*) `s1` in place. This is an example of a more general principle: Java's strings are immutable. This means that once the characters that make up the string have been chosen and the `String` object has been created, the `String` cannot be changed.

This is an important language principle in Java, so let's look at it in a little more depth.

## String Immutability

To "change" a string, as we saw when we discussed string concatenation, we actually need to create an intermediate `StringBuilder` object to act as a temporary scratch area, and then call `toString()` on it, to bake it into a new instance of `String`. Let's see how this works in code:

```
String pet = "Cat";
StringBuilder sb = new StringBuilder(pet);
sb.append("amaran");
String boat = sb.toString();
System.out.println(boat);
```

Code like this behaves equivalently to the following, although in Java 9 and above the actual bytecode sequences will differ:

```
String pet = "Cat";
String boat = pet + "amaran";
System.out.println(boat);
```

Of course, as well as being used under the hood by `javac`, the `StringBuilder` class can also be used directly in application code, as we've seen.

> Along with `StringBuilder`, Java also has a `StringBuffer` class. This comes from the oldest versions of Java and should not be used for new development—use `StringBuilder` instead, unless you really need to share the construction of a new string between multiple threads.

String immutability is an extremely useful language feature. For example, suppose the `+` changed a string instead of creating a new one; then, whenever any thread concatenated two strings, all other threads would also see the change. This is unlikely to be a useful behavior for most programs, and so immutability makes good sense.

### Hash codes and effective immutability

We have already met the `hashCode()` method in Chapter 5, where we described the contract that the method must satisfy. Let's take a look at the JDK source code and see how the method `String::hashCode()` is defined:

```
public int hashCode() {
    int h = hash;
    if (h == 0 && value.length > 0) {
        char val[] = value;

        for (int i = 0; i < value.length; i++) {
```

```
                h = 31 * h + val[i];
            }
            hash = h;
        }
        return h;
    }
```

The field `hash` holds the hash code of the string, and the field `value` is a `char[]` that holds the characters that actually make up the string. As we can see from the code, Java computes the hash by looping over all the characters of the string. It therefore takes a number of machine instructions proportional to the number of characters in the string. For very large strings, this could take a bit of time. Rather than precompute the hash value, Java calculates it only when it is needed.

When the method runs, the hash is computed by stepping through the array of characters. At the end of the array, we exit the `for` loop and write the computed hash back into the field `hash`. Now, when this method is called again, the value has already been computed, so we can just use the cached value and subsequent calls to `hashCode()` return immediately.

> The computation of a string's hash code is an example of a *benign data race*. In a program with multiple threads, they could race to compute the hash code. However, they would all eventually arrive at exactly the same answer—hence the term *benign*.

All of the fields of the `String` class are final, except for `hash`. So Java's strings are not, strictly speaking, immutable. However, because the `hash` field is just a cache of a value that is deterministically computed from the other fields, which are all immutable then, provided `String` has been coded correctly, it will behave as if it were immutable. Classes that have this property are called *effectively immutable*—they are quite rare in practice, and working programmers can usually ignore the distinction between truly immutable and effectively immutable data.

## String Formatting

In "String concatenation" on page 321, we saw how Java supports building strings from smaller strings by joining them. While this works, it can often be tedious and error prone when constructing more elaborate output strings. Java provides a number of other methods and classes for doing richer string formatting.

The static method `format` on the `String` class allows us to specify a template and then dynamically plug in various values:

```
// Result is the string "The 1 pet is a cat: true?"
var s = String.format("The %d pet is a %s: %b?%n", 1, "cat", true);

// Same result, but called on string instance instead of statically
s = "The %d pet is a %s: %b?%n".formatted(1, "cat", true);
```

Placeholders in the format string where values will be introduced start with the % character. In this example, we substitute an integer with %d, a string with %s, a boolean with %b, and finally end the string with a newline via %n.

Those with a background in C or similar languages will recognize this format from the venerable printf function. Java supports many, though not all, of the same formats with a wide variety of options. Java's printf also provides more sophisticated date and time formatting as seen in C's strftime function. See the Java documentation on java.util.Formatter for the full list of options available.

Java also improves on the experience using these format strings by throwing exceptions on invalid conditions such as mismatched numbers of placeholders to values, or unrecognized % values.

String.format() provides powerful tools for constructing complex strings but, particularly when making output correct across countries, more assistance is needed. NumberFormat is an example of classes Java provides to support more complex, locale-aware formatting of values. Other formatters are also available under java.text:

```
// Some common locales are available as constants
// A much longer list can be accessed at runtime
var locale = Locale.US;

NumberFormat.getNumberInstance(locale).format(1_000_000_000L)
// 1,000,000,000

NumberFormat.getCurrencyInstance(locale).format(1_000_000_000L)
// $1,000,000,000.00

NumberFormat.getPercentInstance(locale).format(0.1)
// 10%

NumberFormat.getCompactNumberInstance(locale , NumberFormat.Style.LONG)
            .format(1_000_000_000L)
// 1 billion

NumberFormat.getCompactNumberInstance(locale, NumberFormat.Style.SHORT)
            .format(1_000_000_000L)
// 1B
```

## Regular Expressions

Java has support for *regular expressions* (often shortened to *regex* or *regexp*). These are a representation of a search pattern used to scan and match text. A regex is a sequence of characters that we want to search for. They can be very simple—for example, abc means that we're looking for *a*, followed immediately by *b*, followed immediately by *c*, anywhere within the text we're searching. Note that a search pattern may match an input text in zero, one, or more places.

The simplest regexes are just sequences of literal characters, like `abc`. However, the language of regexes can express more complex and subtle ideas than just literal sequences. For example, a regex can represent patterns to match like:

- A numeric digit
- Any letter
- Any number of letters, which must all be in the range *a* to *j* but can be upper- or lowercase
- *a* followed by any four characters, followed by *b*

The syntax we use to write regular expressions is simple, but because we can build complex patterns, it is often possible to write an expression that does not implement precisely what we wanted. When using regexes, it is very important to always test them fully. This should include both test cases that should pass and cases that should fail.

To express these more complex patterns, regexes use *metacharacters*. These are special characters that indicate special processing is required. This can be thought of as similar to the use of the `*` character in operating system shells. In those circumstances, it is understood that the `*` is not to be interpreted literally but instead means "anything." If we wanted to list all the Java source files in the current directory on Unix, we would issue the command:

```
ls *.java
```

The metacharacters of regexes are similar, but there are far more of them, and they are far more flexible than the set available in shells. They also have different meanings than they do in shell scripts, so don't get confused.

> Many different flavors of regular expression patterns exist in the world. Java's is PCRE-compatible, supporting a common set of metacharacters popularized by the Perl programming language. Be aware though that a random regex found online may or may not actually work, whatever regex libraries you are using.

Let's meet a couple of examples. Suppose we want to have a spell-checking program that is relaxed about the difference in spelling between British and American English. This means that *honor* and *honour* should both be accepted as valid spelling choices. This is easy to do with regular expressions.

Java uses a class called `Pattern` (from the package `java.util.regex`) to represent a regex. This class can't be directly instantiated, however. Instead, new instances are created by using a static factory method, `compile()`. From a pattern, we then derive a `Matcher` for a particular input string that we can use to explore the input string. For example, let's examine a bit of Shakespeare from the play *Julius Caesar*:

```java
Pattern p = Pattern.compile("honou?r");

String caesarUK = "For Brutus is an honourable man";
Matcher mUK = p.matcher(caesarUK);

String caesarUS = "For Brutus is an honorable man";
Matcher mUS = p.matcher(caesarUS);

System.out.println("Matches UK spelling? " + mUK.find());
System.out.println("Matches US spelling? " + mUS.find());
```

Be careful when using `Matcher`, as it has a method called `matches()`. However, this method indicates whether the pattern can cover the entire input string. It will return `false` if the pattern starts matching only in the middle of the string.

The last example introduces our first regex metacharacter `?`, in the pattern `honou?r`. This means "the preceding character is optional"—so both `honour` and `honor` will match. Let's look at another example. Suppose we want to match both *minimize* and *minimise* (the latter spelling is more common in British English). We can use square brackets to indicate that any character from a set (but only one alternative) `[]` can be used—like this:

```java
Pattern p = Pattern.compile("minimi[sz]e");
```

Table 9-1 provides an expanded list of metacharacters available for Java regexes.

*Table 9-1. Regex metacharacters*

| Metacharacter | Meaning | Notes |
|---|---|---|
| `?` | Optional character—zero or one instance | |
| `*` | Zero or more of preceding character | |
| `+` | One or more of preceding character | |
| `{M,N}` | Between `M` and `N` instances of preceding character | |
| `\d` | A digit | |
| `\D` | A nondigit character | |
| `\w` | A word character | Digits, letters, and _ |
| `\W` | A nonword character | |

| Metacharacter | Meaning | Notes |
|---|---|---|
| `\s` | A whitespace character | |
| `\S` | A nonwhitespace character | |
| `\n` | Newline character | |
| `\t` | Tab character | |
| `.` | Any single character | Does not include newline in Java |
| `[ ]` | Any character contained with the brackets | Called a character class |
| `[^ ]` | Any character not contained with the brackets | Called a negated character class |
| `( )` | Build up a group of pattern elements | Called a group (or capturing group) |
| `\|` | Define alternative possibilities | Implements logical OR |
| `^` | Start of string | |
| `$` | End of string | |
| `\\` | Literal escape (\) char | |

There are a few more, but this is the basic list. The `java.util.regex.Pattern` Java documentation is a good source for all the details. From this, we can construct more complex expressions for matching such as the examples given earlier in this section:

```
String text = "Apollo 13";

// A numeric digit. Note we must use \\ because we need a literal \
// and Java uses a single \ as an escape character, as per the table
Pattern p = Pattern.compile("\\d");
Matcher m = p.matcher(text);
System.out.print(p + " matches " + text + "? " + m.find());
System.out.println(" ; match: " + m.group());

// A single letter
p = Pattern.compile("[a-zA-Z]");
m = p.matcher(text);
System.out.print(p + " matches " + text + "? " + m.find());
System.out.println(" ; match: " + m.group());

// Any number of letters, which must all be in the range 'a' to 'j'
// but can be upper- or lowercase
p = Pattern.compile("([a-jA-J]*)");
```

```java
m = p.matcher(text);
System.out.print(p + " matches " + text + "? " + m.find());
System.out.println(" ; match: " + m.group());

// 'a' followed by any four characters, followed by 'b'
text = "abacab";
p = Pattern.compile("a....b");
m = p.matcher(text);
System.out.print(p + " matches " + text + "? " + m.find());
System.out.println(" ; match: " + m.group());
```

Regexes are extremely useful for determining when a string matches a given pattern, but they also allow for extracting bits and pieces from the strings as well. This is done through the *group* mechanism, which is represented in the patterns by `()`:

```java
String text = "Apollo 13";

Pattern p = Pattern.compile("Apollo (\\d*)");
Matcher m = p.matcher(text);
System.out.print(p + " matches " + text + "? " + m.find());
System.out.println("; mission: " + m.group(1));
```

The call to `Matcher.group(1)` returns the text that the regex matched in the `(\\d*)` of our pattern. Multiple groups are allowed, along with syntax for naming groups rather than using them by position. See the Java documentation for full details.

A common difficulty working with regular expressions is the need to use escape characters for both the Java string and the regular expression. Where text blocks have less escaping—such as quote characters—they can provide for less cluttered expressions:

```java
// Detect if there are any double-quoted passages in string
// Note standard string literal requires escaping quotations
Pattern oldQuoted = Pattern.compile(".*\".*\".*");

Pattern newQuoted = Pattern.compile("""
                                    .*".*".*""");
```

Let's conclude our quick tour of regular expressions by meeting a new method that was added to `Pattern` as part of Java 8: `asPredicate()`. This method is present to allow us to easily bridge from regular expressions to the Java Collections and their new support for lambda expressions.

For example, suppose we have a regex and a collection of strings. It's very natural to ask the question: "Which strings match against the regex?" We do this by using the filter idiom and by converting the regex to a `Predicate` using the helper method, like this:

```java
// Contains a numeric digit
Pattern p = Pattern.compile("\\d");

List<String> ls = List.of("Cat", "Dog", "Ice-9", "99 Luftballoons");
List<String> containDigits = ls.stream()
```

```
            .filter(p.asPredicate())
            .toList();

    System.out.println(containDigits);
```

Java's built-in support for text processing is more than adequate for the majority of text-processing tasks that business applications normally require. More advanced tasks, such as the search and processing of very large data sets, or complex parsing (including formal grammars), are outside the scope of this book, but Java has a large ecosystem of helpful libraries and bindings to specialized technologies for text processing and analysis.

# Numbers and Math

In this section, we will discuss Java's support for numeric types in some more detail. In particular, we'll discuss the two's complement representation of integral types that Java uses. We'll introduce floating-point representations and touch on some of the problems they can cause. We'll also work through examples that use some of Java's library functions for standard mathematical operations.

## How Java Represents Integer Types

Java's integer types are all signed, as we first mentioned in "Primitive Data Types" on page 25. This means that all integer types can represent both positive and negative numbers. As computers work with binary, this means that the only really logical way to represent this is to split the possible bit patterns and use half of them to represent negative numbers.

Let's work with Java's `byte` type to investigate how Java represents integers. This has 8 bits so can represent 256 different numbers (i.e., 128 negative and 128 nonnegative numbers). It's logical to use the pattern `0b0000_0000` to represent zero (recall that Java has the syntax `0b<binary digits>` to represent numbers as binary), and then it's easy to figure out the bit patterns for the positive numbers:

```
    byte b = 0b0000_0001;
    System.out.println(b); // 1

    b = 0b0000_0010;
    System.out.println(b); // 2

    b = 0b0000_0011;
    System.out.println(b); // 3

    // ...

    b = 0b0111_1111;
    System.out.println(b); // 127
```

When we set the first bit of the byte, the sign should change (as we have now used up all of the bit patterns that we've set aside for nonnegative numbers). So the pattern `0b1000_0000` should represent some negative number—but which one?

> As a consequence of how we've defined things, in this representation we have a very simple way to identify whether a bit pattern corresponds to a negative number: if the high-end bit of a bit pattern is a `1`, then the number being represented is negative.

Consider the bit pattern consisting of all set bits: `0b1111_1111`. If we add `1` to this number, then the result will overflow the 8 bits of storage that a `byte` has, resulting in `0b1_0000_0000`. If we want to constrain this to fit within the `byte` data type, then we should ignore the overflow, so this becomes `0b0000_0000`, otherwise known as zero. It is therefore natural to adopt the representation that "all set bits represent `-1`." This allows for natural arithmetic behavior, like this:

```
b = (byte) 0b1111_1111; // -1
System.out.println(b);
b++;
System.out.println(b);

b = (byte) 0b1111_1110; // -2
System.out.println(b);
b++;
System.out.println(b);
```

Finally, let's look at the number that `0b1000_0000` represents. It's the most negative number that the type can represent, so for `byte`:

```
b = (byte) 0b1000_0000;
System.out.println(b); // -128
```

This representation, called *two's complement*, is the most common representation for signed integers. To use it effectively, you need to remember only two points:

- A bit pattern of all 1's is the representation for –1.
- If the high bit is set, the number is negative.

Java's other integer types (`short`, `int`, and `long`) behave in very similar ways but with more bits in their representation. The `char` data type is different because it represents a Unicode character, but in some ways it behaves as an unsigned 16-bit numeric type. It is not normally regarded as an integer type by Java programmers.

## Java and Floating-Point Numbers

Computers represent numbers using binary. We've seen how Java uses the two's complement representation for integers. But what about fractions or decimals? Java, like almost all modern programming languages, represents them using *floating-point arithmetic*. Let's take a look at how this works, first in base-10 (regular decimal) and then in binary. Java defines the two most important mathematical constants, `e` and `π` (pi), as constants in `java.lang.Math` like this:

```
public static final double E = 2.7182818284590452354;
public static final double PI = 3.14159265358979323846;
```

Of course, these constants are actually *irrational numbers* and cannot be precisely expressed as a fraction, or by any finite decimal number.[1] This means that whenever we try to represent them in a computer, there is always rounding error. Let's suppose we only want to deal with eight digits of π, and we want to represent the digits as a whole number. We can use a representation like this:

$314159265 \bullet 10^{-8}$

This starts to suggest the basis of how floating-point numbers work. We use some of the bits to represent the significant digits (`314159265`, in our example) of the number and some bits to represent the *exponent* of the base (`-8`, in our example). The collection of significant digits is called the *significand* and the exponent describes whether we need to shift the significand up or down to get to the desired number.

Of course, in the examples we've met until now, we've been working in base-10. Computers use binary, so we need to use this as the base in our floating-point examples. This introduces some additional complications.

> The number `0.1` cannot be expressed as a finite sequence of binary digits. This means that virtually all calculations that humans care about will lose precision when performed in floating point, and rounding error is essentially inevitable.

Let's look at an example that shows the rounding problem:

```
double d = 0.3;
System.out.println(d); // Special-cased to avoid ugly representation

double d2 = 0.2;
// Should be -0.1 but prints -0.09999999999999998
System.out.println(d2 - d);
```

The official standard that describes floating-point arithmetic is IEEE-754, and Java's support for floating point is based on that standard. The standard uses 24 binary digits for standard precision and 53 binary digits for double precision.

As we mentioned briefly in Chapter 2, Java previously allowed deviation from this standard, resulting in greater precision when some hardware features were used to accelerate calculations. As of Java 17, this is no longer allowed, and all floating-point operations comply with the IEEE-754 standard.

1 In fact, they are actually two of the known examples of *transcendental numbers*.

### BigDecimal

Rounding error is a constant source of headaches for programmers who work with floating-point numbers. In response, Java has a class `java.math.BigDecimal` that provides arbitrary precision arithmetic, in a decimal representation. This works around the problem of `0.1` not having a finite representation in binary, but there are still some edge conditions when converting to or from Java's primitive types, as you can see:

```
double d = 0.3;
System.out.println(d);

BigDecimal bd = new BigDecimal(d);
System.out.println(bd);

bd = new BigDecimal("0.3");
System.out.println(bd);
```

However, even with all arithmetic performed in base-10, there are still numbers, such as `1/3`, that do not have a terminating decimal representation. Let's see what happens when we try to represent such numbers using `BigDecimal`:

```
bd = new BigDecimal(BigInteger.ONE);
bd.divide(new BigDecimal(3.0));
System.out.println(bd); // Should be 1/3
```

As `BigDecimal` can't represent `1/3` precisely, the call to `divide()` blows up with `ArithmeticException`. When you are working with `BigDecimal`, it is therefore necessary to be acutely aware of exactly which operations could result in a non-terminating decimal result. To make matters worse, `ArithmeticException` is an unchecked, runtime exception and so the Java compiler does not even warn about possible exceptions of this type.

As a final note on floating-point numbers, the paper "What Every Computer Scientist Should Know About Floating-Point Arithmetic" by David Goldberg should be considered essential further reading for all professional programmers. It is easily and freely obtainable on the internet.

## Java's Standard Library of Mathematical Functions

To conclude this look at Java's support for numeric data and math, let's take a quick tour of the standard library of functions that Java ships with. These are mostly static helper methods that are located on the class `java.lang.Math` and include functions like:

`abs()`
: Returns the absolute value of a number. Has overloaded forms for various primitive types.

*Trigonometric functions*
: Basic functions for computing the sine, cosine, tangent, and so on. Java also includes hyperbolic versions and the inverse functions (such as arc sine).

`max()`, `min()`
: Overloaded functions to return the greater and smaller of two arguments (both of the same numeric type).

`ceil()`, `floor()`
: Used for rounding to integers. `floor()` returns the largest integer smaller than the argument (which is a double). `ceil()` returns the smallest integer larger than the argument.

`pow()`, `exp()`, `log()`
: Functions for raising one number to the power of another and for computing exponentials and natural logarithms. `log10()` provides logarithms to base-10, rather than the natural base.

Let's look at some simple examples of how to use these functions:

```
System.out.println(Math.abs(2));
System.out.println(Math.abs(-2));

double cosp3 = Math.cos(0.3);
double sinp3 = Math.sin(0.3);
System.out.println((cosp3 * cosp3 + sinp3 * sinp3)); // Always 1.0

System.out.println(Math.max(0.3, 0.7));
System.out.println(Math.max(0.3, -0.3));
System.out.println(Math.max(-0.3, -0.7));

System.out.println(Math.min(0.3, 0.7));
System.out.println(Math.min(0.3, -0.3));
System.out.println(Math.min(-0.3, -0.7));

System.out.println(Math.floor(1.3));
System.out.println(Math.ceil(1.3));
System.out.println(Math.floor(7.5));
System.out.println(Math.ceil(7.5));

System.out.println(Math.round(1.3)); // Returns long
System.out.println(Math.round(7.5)); // Returns long

System.out.println(Math.pow(2.0, 10.0));
System.out.println(Math.exp(1));
System.out.println(Math.exp(2));
System.out.println(Math.log(2.718281828459045));
System.out.println(Math.log10(100_000));
System.out.println(Math.log10(Integer.MAX_VALUE));

System.out.println(Math.random());
```

```java
System.out.println("Let's toss a coin: ");
if (Math.random() > 0.5) {
    System.out.println("It's heads");
} else {
    System.out.println("It's tails");
}
```

To conclude this section, let's briefly discuss Java's `random()` function. When this is first called, it sets up a new instance of `java.util.Random`. This is a *pseudorandom number generator* (PRNG)—a deterministic piece of code that produces numbers that *look* random but are actually produced by a mathematical formula.[2] In Java's case, the formula used for the PRNG is pretty simple, for example:

```java
// From java.util.Random
public double nextDouble() {
    return (((long)(next(26)) << 27) + next(27)) * DOUBLE_UNIT;
}
```

If the sequence of pseudorandom numbers always starts at the same place, then exactly the same stream of numbers will be produced. To get around this problem, the PRNG is seeded by a value that should contain as much true randomness as possible. For this source of randomness for the seed value, Java uses a CPU counter value that is normally used for high-precision timing.

> While Java's built-in pseudorandom numbers are fine for most general applications, some specialist applications (notably cryptography and some types of simulations) have much more stringent requirements. If you are working on an application of that sort, seek expert advice from programmers who are already working in the area.

Now that we've looked at text and numeric data, let's move on to look at another of the most frequently encountered kinds of data: date and time information.

## Date and Time

Almost all business software applications have some notion of date and time. When modeling real-world events or interactions, collecting a point at which the event occurred is critical for future reporting or comparison of domain objects. Java 8 brought a complete overhaul to the way that developers work with date and time. This section introduces those concepts. In earlier versions, the only support is via classes such as `java.util.Date` that do not model the concepts. Code that uses the older APIs should move as soon as possible.

2 It is very difficult to get computers to produce true random numbers, and in the rare cases where this is done, specialized hardware is usually necessary.

## Introducing the Java 8 Date and Time API

Java 8 introduced the new package `java.time`, which contains the core classes that most developers work with. It also contains four subpackages:

`java.time.chrono`
: Alternative chronologies that developers using calendaring systems that do not follow the ISO standard will interact with. An example would be a Japanese calendaring system.

`java.time.format`
: Contains the `DateTimeFormatter` used for converting date and time objects into a `String` and also for parsing strings into the data and time objects.

`java.time.temporal`
: Contains the interfaces required by the core date and time classes and also abstractions (such as queries and adjusters) for advanced operations with dates.

`java.time.zone`
: Classes used for the underlying time zone rules; most developers won't require this package.

One of the most important concepts when representing time is the idea of an instantaneous point on the timeline of some entity. While this concept is well defined within, for example, Special Relativity, representing it within a computer requires us to make some assumptions. In Java, we represent a single point in time as an `Instant`, which has these key assumptions:

- We cannot represent more seconds than can fit into a `long`.
- We cannot represent time more precisely than nanosecond precision.

This means that we are restricting ourselves to modeling time in a manner that is consistent with the capabilities of current computer systems. However, another fundamental concept should also be introduced.

An `Instant` is about a single event in space-time. However, it is far from uncommon for programmers to have to deal with intervals between two events, and so Java also contains the `java.time.Duration` class. This class ignores calendar effects that might arise (e.g., from daylight saving time). With this basic conception of instants and durations between events, let's move on to unpack the possible ways of thinking about an instant.

### The parts of a timestamp

In Figure 9-1, we show the breakdown of the different parts of a timestamp in a number of possible ways.

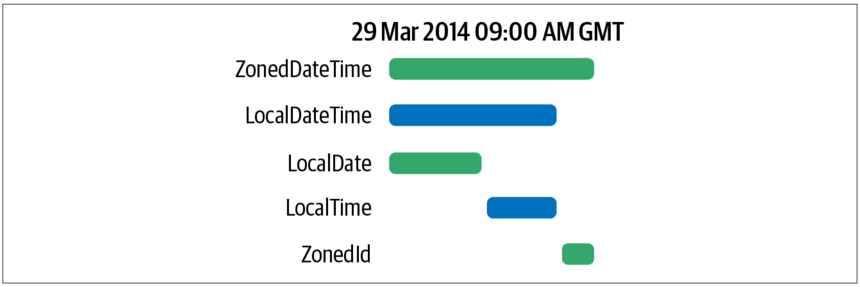


*Figure 9-1. Breaking apart a timestamp*

The key concept here is that a number of different abstractions might be appropriate at different times. For example, there are applications where a `LocalDate` is key to business processing, where the needed granularity is a business day. Alternatively, some applications require subsecond, or even millisecond, precision. Developers should be aware of their domain and use a suitable representation within their application.

## Example

The date and time API can be a lot to take in at first glance, so let's start by looking at an example and discussing a diary class that keeps track of birthdays. If you happen to be very forgetful about birthdays, then a class like this (and especially methods like `getBirthdaysInNextMonth()`) might be very helpful:

```
public class BirthdayDiary {
    private Map<String, LocalDate> birthdays;

    public BirthdayDiary() {
        birthdays = new HashMap<>();
    }

    public LocalDate addBirthday(String name, int day, int month,
                                 int year) {
        LocalDate birthday = LocalDate.of(year, month, day);
        birthdays.put(name, birthday);
        return birthday;
    }

    public LocalDate getBirthdayFor(String name) {
        return birthdays.get(name);
    }
```

```
    public int getAgeInYear(String name, int year) {
        Period period = Period.between(
              birthdays.get(name),
              birthdays.get(name).withYear(year));

        return period.getYears();
    }

    public Set<String> getFriendsOfAgeIn(int age, int year) {
        return birthdays.keySet().stream()
                .filter(p -> getAgeInYear(p, year) == age)
                .collect(Collectors.toSet());
    }

    public int getDaysUntilBirthday(String name) {
        Period period = Period.between(
              LocalDate.now(),
              birthdays.get(name));

        return period.getDays();
    }

    public Set<String> getBirthdaysIn(Month month) {
        return birthdays.entrySet().stream()
                .filter(p -> p.getValue().getMonth() == month)
                .map(p -> p.getKey())
                .collect(Collectors.toSet());
    }

    public Set<String> getBirthdaysInCurrentMonth() {
        return getBirthdaysIn(LocalDate.now().getMonth());
    }

    public int getTotalAgeInYears() {
        return birthdays.keySet().stream()
                .mapToInt(p -> getAgeInYear(p,
                      LocalDate.now().getYear()))
                .sum();
    }
}
```

This class shows how to use the low-level API to build up useful functionality. It also uses innovations such as the Java Streams API and demonstrates how to use `LocalDate` as an immutable class and how dates should be treated as values.

## Queries

Under a wide variety of circumstances, we may find ourselves wanting to answer a question about a particular temporal object. Some example questions we may want answers to are:

- Is the date before March 1st?
- Is the date in a leap year?
- How many days is it from today until my next birthday?

This is achieved by the use of the `TemporalQuery` interface, which is defined like this:

```
public interface TemporalQuery<R> {
    R queryFrom(TemporalAccessor temporal);
}
```

The parameter to `queryFrom()` should not be `null`, but if the result indicates that a value was not found, `null` could be used as a return value.

> The `Predicate` interface can be thought of as a query that can only represent answers to yes-or-no questions. Temporal queries are more general and can return a value of "How many?" or "Which?" instead of just "yes" or "no."

Let's look at an example of a query in action, by considering a query that answers the following question: "Which quarter of the year is this date in?" Java does not support the concept of a quarter directly. Instead, code like this is used:

```
LocalDate today = LocalDate.now();
Month currentMonth = today.getMonth();
Month firstMonthofQuarter = currentMonth.firstMonthOfQuarter();
```

This still doesn't give quarter as a separate abstraction and instead special case code is still needed. So let's slightly extend the JDK support by defining this enum type:

```
public enum Quarter {
    FIRST, SECOND, THIRD, FOURTH;
}
```

Now, the query can be written as:

```
public class QuarterOfYearQuery implements TemporalQuery<Quarter> {
    @Override
    public Quarter queryFrom(TemporalAccessor temporal) {
        LocalDate now = LocalDate.from(temporal);

        if(now.isBefore(now.with(Month.APRIL).withDayOfMonth(1))) {
            return Quarter.FIRST;
        } else if(now.isBefore(now.with(Month.JULY)
                                .withDayOfMonth(1))) {
            return Quarter.SECOND;
        } else if(now.isBefore(now.with(Month.NOVEMBER)
                                .withDayOfMonth(1))) {
            return Quarter.THIRD;
        } else {
```

```
                return Quarter.FOURTH;
            }
        }
    }
```

`TemporalQuery` objects can be used directly or indirectly. Let's look at an example of each:

```
QuarterOfYearQuery q = new QuarterOfYearQuery();

// Direct
Quarter quarter = q.queryFrom(LocalDate.now());
System.out.println(quarter);

// Indirect
quarter = LocalDate.now().query(q);
System.out.println(quarter);
```

Under most circumstances, it is better to use the indirect approach, where the query object is passed as a parameter to `query()`. This is because it is normally a lot clearer to read in code.

## Adjusters

Adjusters modify date and time objects. Suppose, for example, that we want to return the first day of a quarter that contains a particular timestamp:

```
public class FirstDayOfQuarter implements TemporalAdjuster {
    @Override
    public Temporal adjustInto(Temporal temporal) {
        final int currentQuarter = YearMonth.from(temporal)
                .get(IsoFields.QUARTER_OF_YEAR);

        final Month firstMonthOfQuarter = switch (currentQuarter) {
            case 1 -> Month.JANUARY;
            case 2 -> Month.APRIL;
            case 3 -> Month.JULY;
            case 4 -> Month.OCTOBER;
            default -> throw new IllegalArgumentException("Impossible");
        };

        return LocalDate.from(temporal)
                .withMonth(firstMonthOfQuarter.getValue())
                .with(TemporalAdjusters.firstDayOfMonth());
    }
}
```

Let's look at an example of how to use an adjuster:

```
LocalDate now = LocalDate.now();
Temporal fdoq = now.with(new FirstDayOfQuarter());
System.out.println(fdoq);
```

The key here is the `with()` method, and the code should be read as taking in one `Temporal` object and returning another object that has been modified. This is completely normal for APIs that work with immutable objects.

## Timezones

If you work with code that cares about dates, you will almost certainly encounter complications from timezones. Beyond the simple problems of presenting information clearly to users, timezones cause problems because they change. Whether from daylight savings moves or governments reassigning the zone for a given territory, the definition of timezones today isn't guaranteed to be the same next month.

The JVM brings its own copy of the standard IANA timezone data, so getting timezone updates typically requires a JDK upgrade. For those who need changes more frequently, Oracle publishes a `tzupdater` tool that can be used to modify a JDK installation in-place with newer data.

## Legacy Date and Time

Unfortunately, many applications are not yet converted to use the superior date and time libraries that shipped with Java 8. So, for completeness, we briefly mention the legacy date and time support (which is based on `java.util.Date`).

> The legacy date and time classes, especially `java.util.Date`, should *not* be used in modern Java environments. Consider refactoring or rewriting any code that still uses the legacy classes.

In older versions of Java, `java.time` is not available. Instead, programmers rely upon the legacy and rudimentary support provided by `java.util.Date`. Historically, this was the only way to represent timestamps, and although named `Date` this class actually consisted of both a date and a time component—and this led to a lot of confusion for many programmers.

There are many problems with the legacy support provided by `Date`, for example:

- The `Date` class is incorrectly factored. It doesn't actually refer to a date and instead is more like a timestamp. It turns out that we need different representations for a date, versus a date and time, versus an instantaneous timestamp.
- `Date` is mutable. We can obtain a reference to a date and then change when it refers to.
- The `Date` class doesn't actually accept ISO-8601, the universal ISO date standard, as being a valid date.
- `Date` has a very large number of deprecated methods.

The current JDK uses two constructors for `Date`—the `void` constructor that is intended to be the "now constructor," and a constructor that takes a number of milliseconds since epoch.

If you cannot avoid `java.util.Date`, you can still take advantage of the newer APIs by converting with code like the following example:

```
// Defaults to timestamp when called
var oldDate = new java.util.Date();

// Note both forms require specifying timezone -
// part of the failing in the old API
var newDate = LocalDate.ofInstant(
                  oldDate.toInstant(),
                  ZoneId.systemDefault());

var newTime = LocalDateTime.ofInstant(
                  oldDate.toInstant(),
                  ZoneId.systemDefault());
```

## Summary

In this chapter, we've met several different classes of data. Textual and numeric data are the most obvious examples, but as working programmers we will meet a large number of different sorts of data. Let's move on to look at whole files of data and new ways to work with I/O and networking. Fortunately, Java provides good support for dealing with many of these abstractions.

# 10
# File Handling and I/O

Java has had input/output (I/O) support since the very first version. However, due to Java's strong desire for platform independence, the earlier versions of I/O functionality emphasized portability over functionality. As a result, they were not always easy to work with.

We'll see later in the chapter how the original APIs have been supplemented—they are now rich, fully featured, and very easy to develop with. Let's kick off the chapter by looking at the original, "classic" approach to Java I/O, which the more modern approaches layer on top of.

## Classic Java I/O

The `File` class is the cornerstone of Java's original way to do file I/O. This abstraction can represent both files and directories but in doing so is sometimes a bit cumbersome to deal with, leading to code like this:

```
// Get a file object to represent the user's home directory
var homedir = new File(System.getProperty("user.home"));

// Create an object to represent a config file (should
// already be present in the home directory)
var f = new File(homedir, "app.conf");

// Check the file exists, really is a file, and is readable
if (f.exists() && f.isFile() && f.canRead()) {

  // Create a file object for a new configuration directory
  var configdir = new File(homedir, ".configdir");
  // And create it
  configdir.mkdir();
```

```java
      // Finally, move the config file to its new home
      f.renameTo(new File(configdir, ".config"));
    }
```

This shows some of the flexibility possible with the File class, but it also demonstrates some of the problems with the abstraction. It is very general and thus requires a lot of methods to interrogate a File object in order to determine what it actually represents and its capabilities.

## Files

The File class has a very large number of methods on it, but some basic functionality (notably a way to read the actual contents of a file) is not, and never has been, provided directly. The following is a quick summary of File methods:

```java
// Permissions management
boolean canX = f.canExecute();
boolean canR = f.canRead();
boolean canW = f.canWrite();

boolean ok;
ok = f.setReadOnly();
ok = f.setExecutable(true);
ok = f.setReadable(true);
ok = f.setWritable(false);

// Different views of the file's name
File absF = f.getAbsoluteFile();
File canF = f.getCanonicalFile();
String absName = f.getAbsolutePath();
String canName = f.getCanonicalPath();
String name = f.getName();
String pName = f.getParent();
URI fileURI = f.toURI(); // Create URI for File path

// File metadata
boolean exists = f.exists();
boolean isAbs = f.isAbsolute();
boolean isDir = f.isDirectory();
boolean isFile = f.isFile();
boolean isHidden = f.isHidden();
long modTime = f.lastModified(); // milliseconds since epoch
boolean updateOK = f.setLastModified(updateTime); // milliseconds
long fileLen = f.length();

// File management operations
boolean renamed = f.renameTo(destFile);
boolean deleted = f.delete();

// Create won't overwrite existing file
boolean createdOK = f.createNewFile();
```

```
// Temporary file handling
var tmp = File.createTempFile("my-tmp", ".tmp");
tmp.deleteOnExit();

// Directory handling
boolean createdDir = dir.mkdir(); // Non-recursive create only
String[] fileNames = dir.list();
File[] files = dir.listFiles();
```



The File class also has a few methods on it that aren't a perfect fit for the abstraction. They largely involve interrogating the filesystem (e.g., inquiring about available free space) that the file resides on:

```
long free = f.getFreeSpace();
long total = f.getTotalSpace();
long usable = f.getUsableSpace();

File[] roots = File.listRoots(); // all available Filesystem roots
```

## I/O Streams

The I/O stream abstraction (not to be confused with the streams that are used when dealing with the Java 8 Collection APIs) was present in Java 1.0, as a way of dealing with sequential streams of bytes from disks or other sources.

The core of this API is a pair of abstract classes, `InputStream` and `OutputStream`. These are very widely used, and in fact the "standard" input and output streams, which are called `System.in` and `System.out`, are streams of this type. They are public, static fields of the `System` class, and they are often used in even the simplest programs:

```
System.out.println("Hello World!");
```

Specific subclasses of streams, including `FileInputStream` and `FileOutputStream`, can be used to operate on individual bytes in a file—for example, by counting all the times ASCII 97 (small letter *a*) occurs in a file:

```
try (var is = new FileInputStream("/Users/ben/cluster.txt")) {
  byte[] buf = new byte[4096];
  int len, count = 0;
  while ((len = is.read(buf)) > 0) {
    for (int i = 0; i < len; i = i + 1) {
      if (buf[i] == 97) {
        count = count + 1;
      }
    }
  }
  System.out.println("'a's seen: "+ count);
} catch (IOException e) {
  e.printStackTrace();
}
```

This approach to dealing with on-disk data can lack some flexibility—most developers think in terms of characters, not bytes. To allow for this, the streams are usually combined with the higher-level `Reader` and `Writer` classes, which provide a character-stream level of interaction, rather than the low-level bytestream provided by `InputStream` and `OutputStream` and their subclasses.

## Readers and Writers

By moving to an abstraction that deals in characters, rather than bytes, developers are presented with an API that is much more familiar and that hides many of the issues with character encoding, Unicode, and so on.

The `Reader` and `Writer` classes are intended to overlay the bytestream classes and to remove the need for low-level handling of I/O streams. They have several subclasses that are often used to layer on top of each other, such as:

- `FileReader`
- `BufferedReader`
- `StringReader`
- `InputStreamReader`
- `FileWriter`
- `PrintWriter`
- `BufferedWriter`

To read all lines in from a file and print them out, we use a `BufferedReader` layered on top of a `FileReader`, like this:

```
try (var in = new BufferedReader(new FileReader(filename))) {
  String line;

  while((line = in.readLine()) != null) {
    System.out.println(line);
  }
} catch (IOException e) {
  // Handle FileNotFoundException, etc. here
}
```

If we need to read in lines from the console, rather than a file, we will usually use an `InputStreamReader` applied to `System.in`. Let's look at an example where we want to read in lines of input from the console but treat input lines that start with a special character as special—commands ("metas") to be processed, rather than regular text. This is a common feature of many chat programs, including IRC. We'll use regular expressions from Chapter 9 to help us:

```
// Meta example: "#info username"
var SHELL_META_START = Pattern.compile("^#(\\w+)\\s*(\\w+)?");
```

```java
try (var console =
        new BufferedReader(new InputStreamReader(System.in))) {
    String line;

    while((line = console.readLine()) != null) {
      // Check for special commands ("metas")
      Matcher m = SHELL_META_START.matcher(line);
      if (m.find()) {
        String metaName = m.group(1);
        String arg = m.group(2);
        doMeta(metaName, arg);
      } else {
        System.out.println(line);
      }
    }
} catch (IOException e) {
  // Handle FileNotFoundException, etc. here
}
```

To output text to a file, we can use code like this:

```java
var f = new File(System.getProperty("user.home")
 + File.separator + ".bashrc");
try (var out =
        new PrintWriter(new BufferedWriter(new FileWriter(f)))) {
  out.println("## Automatically generated config file. DO NOT EDIT");
  // ...
} catch (IOException iox) {
  // Handle exceptions
}
```

This older style of Java I/O has a lot of other occasionally useful functionality. For example, to deal with text files, the `FilterInputStream` class is quite often useful. Or for threads that want to communicate in a way similar to the classic "piped" I/O approach, `PipedInputStream`, `PipedReader`, and their write counterparts are provided.

Throughout this chapter so far, we have used the language feature known as "try-with-resources" (TWR). This syntax was briefly introduced in "The try-with-resources Statement" on page 72, but it is in conjunction with operations like I/O that it comes into its fullest potential, and it has granted a new lease on life to the older I/O style.

## try-with-resources Revisited

To make the most of Java's I/O capabilities, it is important to understand how and when to use TWR. It is very easy to understand when code should use TWR—whenever it is possible to do so.

Before TWR, resources had to be closed manually; complex interactions between resources that failed to close led to buggy code that leaked resources.

In fact, Oracle's engineers estimate that 60% of the resource handling code in the initial JDK 6 release was incorrect. So, if even the platform authors can't reliably get manual resource handling right, then all new code should definitely be using TWR.

The key to TWR is a new interface—`AutoCloseable`. This interface is a direct superinterface of `Closeable`. It marks a resource that must be automatically closed, and for which the compiler will insert special exception-handling code.

Inside a TWR resource clause, only declarations of objects that implement `AutoCloseable` objects may appear—but the developer may declare as many as required:

```
try (var in = new BufferedReader(
                           new FileReader("profile"));
     var out = new PrintWriter(
                         new BufferedWriter(
                           new FileWriter("profile.bak")))) {
  String line;
  while((line = in.readLine()) != null) {
    out.println(line);
  }
} catch (IOException e) {
  // Handle FileNotFoundException, etc. here
}
```

The consequences of this are that resources are automatically scoped to the `try` block. The resources (whether readable or writable) are automatically closed in the correct order (the reverse order to the way they were opened), and the compiler inserts exception handling that takes dependencies between resources into account.

TWR is related to similar concepts in other languages and environments, for example, RAII (Resource Acquisition Is Initialization) in C++. However, as discussed in the finalization section, TWR is limited to block scope. This minor limitation is because the feature is implemented by the Java source code compiler—it automatically inserts bytecode that calls the resource's `close()` method when the scope is exited (by whatever means).

As a result, the overall effect of TWR is more similar to C#'s `using` keyword, rather than the C++ version of RAII. For Java developers, the best way to regard TWR is as "finalization done right." As noted in "Finalization" on page 248, new code should never directly use the finalization mechanism and should always use TWR instead. Older code should be refactored to use TWR as soon as is practicable, as it provides real tangible benefits to resource handling code.

## Problems with Classic I/O

Even with the welcome addition of `try`-with-resources, the `File` class and friends have a number of problems that make them less than ideal for extensive use when performing even standard I/O operations. For instance:

- "Missing methods" for common operations

- Does not deal with filenames consistently across platforms
- Fails to have a unified model for file attributes (e.g., modeling read/write access)
- Difficult to traverse unknown directory structures
- No platform- or OS-specific features
- Nonblocking operations for filesystems not supported

To deal with these shortcomings, Java's I/O has evolved over several major releases. With the release of Java 7, this support became truly easy and effective to use.

# Modern Java I/O

Java 7 brought in a brand new I/O API—usually called NIO.2—and it should be considered almost a complete replacement for the original `File` approach to I/O.

The new classes are contained in the `java.nio.file` package and are considerably easier for many use cases. The API has two major parts. The first is a new abstraction called `Path` (which can be thought of as representing a file location, which may or may not actually exist). The second piece is lots of new convenience and utility methods to deal with files and filesystems. These are contained as static methods in the `Files` class.

## Files

For example, when you are using the new `Files` functionality, a basic copy operation is now as simple as:

```
var inputFile = new File("input.txt");
try (var in = new FileInputStream(inputFile)) {
  Files.copy(in, Path.of("output.txt"));
} catch(IOException ex) {
  ex.printStackTrace();
}
```

Let's quickly survey some of the major methods in `Files`—the operation of most of them is pretty self-explanatory. In many cases, the methods have return types. We have omitted handling these, as they are rarely useful except for contrived examples and for duplicating the behavior of the equivalent C code:

```
Path source, target;
Attributes attr;
Charset cs = StandardCharsets.UTF_8;

// Creating files
//
// Example of path --> /home/ben/.profile
// Example of attributes --> rw-rw-rw-
Files.createFile(target, attr);
```

```java
// Deleting files
Files.delete(target);
boolean deleted = Files.deleteIfExists(target);

// Copying/moving files
Files.copy(source, target);
Files.move(source, target);

// Utility methods to retrieve information
long size = Files.size(target);

FileTime fTime = Files.getLastModifiedTime(target);
System.out.println(fTime.to(TimeUnit.SECONDS));

Map<String, ?> attrs = Files.readAttributes(target, "*");
System.out.println(attrs);

// Methods to deal with file types
boolean isDir = Files.isDirectory(target);
boolean isSym = Files.isSymbolicLink(target);

// Methods to deal with reading and writing
List<String> lines = Files.readAllLines(target, cs);
byte[] b = Files.readAllBytes(target);

var br = Files.newBufferedReader(target, cs);
var bwr = Files.newBufferedWriter(target, cs);

var is = Files.newInputStream(target);
var os = Files.newOutputStream(target);
```

Some of the methods on `Files` provide the opportunity to pass optional arguments, to provide additional (possibly implementation-specific) behavior for the operation.

Some of the API choices here produce occasionally annoying behavior. For example, by default, a copy operation will not overwrite an existing file, so we need to specify this behavior as a copy option:

```java
Files.copy(Path.of("input.txt"), Path.of("output.txt"),
           StandardCopyOption.REPLACE_EXISTING);
```

`StandardCopyOption` is an enum that implements an interface called `CopyOption`. This is also implemented by `LinkOption`. So `Files.copy()` can take any number of either `LinkOption` or `StandardCopyOption` arguments. `LinkOption` is used to specify how symbolic links should be handled (provided the underlying OS supports symlinks, of course).

## Path

`Path` is a type that may be used to locate a file in a filesystem. It represents a path that is:

- System dependent
- Hierarchical
- Composed of a sequence of path elements
- Hypothetical (may not exist yet, or may have been deleted)

It is therefore fundamentally different from a `File`. In particular, the system dependency is manifested by `Path` being an interface, not a class, which enables different filesystem providers to each implement the `Path` interface and provide for system-specific features while retaining the overall abstraction.

The elements of a `Path` consist of an optional root component, which identifies the filesystem hierarchy that this instance belongs to. Note that, for example, relative `Path` instances may not have a root component. In addition to the root, all `Path` instances have zero or more directory names and a name element.

The name element is the element farthest from the root of the directory hierarchy and represents the name of the file or directory. The `Path` can be thought of as consisting of the path elements joined by a special separator or delimiter.

`Path` is an abstract concept; it isn't necessarily bound to any physical file path. This allows us to talk easily about the locations of files that don't exist yet. The `Path` interface provides static factory methods for creating `Path` instances.

> When NIO.2 was introduced in Java 7, static methods were not supported on interfaces, so a `Paths` class was introduced to hold the factory methods. With Java 17 the `Path` interface methods are recommended instead, and the `Paths` class may in the future be deprecated.

`Path` provides two `of()` methods for creating `Path` objects. The usual version takes one or more `String` instances and uses the default filesystem provider. The `URI` version takes advantage of the ability of NIO.2 to plug in additional providers of bespoke filesystems. This is an advanced usage, and interested developers should consult the primary documentation. Let's look at some simple examples of how to use `Path`:

```
var p = Path.of("/Users/ben/cluster.txt");
var p2 = Path.of(new URI("file:///Users/ben/cluster.txt"));
System.out.println(p2.equals(p));

File f = p.toFile();
System.out.println(f.isDirectory());

Path p3 = f.toPath();
System.out.println(p3.equals(p));
```

This example also shows the easy interoperation between `Path` and `File` objects. The addition of a `toFile()` method to `Path` and a `toPath()` method to `File` allows the developer to move effortlessly between the two APIs and allows for a straightforward approach to refactoring the internals of code based on `File` to use `Path` instead.

We can also use some helpful "bridge" methods that the `Files` class also provides. These provide convenient access to the older I/O APIs—for example, by providing convenient methods to open `Writer` objects to specified `Path` locations:

```
var logFile = Path.of("/tmp/app.log");
try (var writer =
       Files.newBufferedWriter(logFile, StandardCharsets.UTF_8,
                               StandardOpenOption.WRITE,
                               StandardOpenOption.CREATE)) {
  writer.write("Hello World!");
  // ...
} catch (IOException e) {
  // ...
}
```

We're using the `StandardOpenOption` enum, which provides similar capabilities to the copy options but for the case of opening a new file instead. We provide both `WRITE` and `CREATE`, so if the file doesn't exist it will be created; otherwise, we'll simply open it for additional writing.

In this example use case, we have used the `Path` API to:

- Create a `Path` corresponding to a new file
- Use the `Files` class to create that new file
- Open a `Writer` to that file
- Write to that file
- Automatically close it when done

In our next example, we'll build on this to manipulate a JAR file as a `FileSystem` in its own right, modifying it to add a file directly into the JAR. Recall that JAR files are actually just ZIP files, so this technique will also work for *.zip* archives:

```
var tempJar = Path.of("sample.jar");
try (var workingFS =
      FileSystems.newFileSystem(tempJar)) {

  Path pathForFile = workingFS.getPath("/hello.txt");
  Files.write(pathForFile,
              List.of("Hello World!"),
              Charset.defaultCharset(),
              StandardOpenOption.WRITE, StandardOpenOption.CREATE);
}
```

This shows how we create a `FileSystem` object in order to create the `Path` objects that refer to files inside the jar, via the `getPath()` method. This enables the developer to essentially treat `FileSystem` objects as black boxes: they are automatically created via a service provider interface (SPI) mechanism.



To see which file systems are available on your machine, you can run some code like this:

```
for (FileSystemProvider f : FileSystemProvider.installedProviders()) {
    System.out.println(f.toString());
}
```

The `Files` class also provides methods for handling temporary files and directories, which is a surprisingly common use case (and can be a source of security bugs). For example, let's see how to load a resources file from within the classpath, copy it to a newly created temporary directory, and then safely clean up the temporary files (using a `Reaper` class available in the book resources online):

```
Path tmpdir = Files.createTempDirectory(Path.of("/tmp"), "tmp-test");
try (InputStream in =
      FilesExample.class.getResourceAsStream("/res.txt")) {
    Path copied = tmpdir.resolve("copied-resource.txt");
    Files.copy(in, copied, StandardCopyOption.REPLACE_EXISTING);
    // ... work with the copy
}
// Clean up when done...
Files.walkFileTree(tmpdir, new Reaper());
```

One of the criticisms of Java's original I/O APIs was the lack of support for native and high-performance I/O. A solution was initially added in Java 1.4, the Java New I/O (NIO) API, and it has been refined in later Java versions.

## NIO Channels and Buffers

NIO buffers are a low-level abstraction for high-performance I/O. They provide a container for a linear sequence of elements of a specific primitive type. We'll work with the `ByteBuffer` (the most common case) in our examples.

### ByteBuffer

This is a sequence of bytes and can conceptually be thought of as a performance-critical alternative to working with a `byte[]`. To get the best possible performance, `ByteBuffer` provides support for dealing directly with the native capabilities of the platform the JVM is running on.

This approach is called the *direct buffers* case, and it bypasses the Java heap wherever possible. Direct buffers are allocated in native memory, not on the standard Java heap, and they are not subject to garbage collection in the same way as regular on-heap Java objects.

To obtain a direct `ByteBuffer`, call the `allocateDirect()` factory method. An on-heap version, `allocate()`, is also provided, but in practice this is not often used.

A third way to obtain a byte buffer is to `wrap()` an existing `byte[]`—this will give an on-heap buffer that serves to provide a more object-oriented view of the underlying bytes:

```
var b = ByteBuffer.allocateDirect(65536);
var b2 = ByteBuffer.allocate(4096);

byte[] data = {1, 2, 3};
ByteBuffer b3 = ByteBuffer.wrap(data);
```

Byte buffers are all about low-level access to the bytes. This means that developers have to deal with the details manually—including the need to handle the endianness of the bytes and the signed nature of Java's integral primitives:

```
b.order(ByteOrder.BIG_ENDIAN);

int capacity = b.capacity();
int position = b.position();
int limit = b.limit();
int remaining = b.remaining();
boolean more = b.hasRemaining();
```

To get data into or out of a buffer, we have two types of operation—single value, which reads or writes a single value, and bulk, which takes a `byte[]` or `ByteBuffer` and operates on a (potentially large) number of values as a single operation. It is from the bulk operations that we'd expect to realize performance gains:

```
b.put((byte)42);
b.putChar('x');
b.putInt(0xc001c0de);

b.put(data);
b.put(b2);

double d = b.getDouble();
b.get(data, 0, data.length);
```

The single value form also supports a form used for absolute positioning within the buffer:

```
b.put(0, (byte)9);
```

Buffers are an in-memory abstraction. To affect the outside world (e.g., the file or network), we need to use a `Channel`, from the package `java.nio.channels`. Channels represent connections to entities that can support read or write operations. Files and sockets are the usual examples of channels, but we could consider custom implementations used for low-latency data processing.

Channels are open when they're created and can subsequently be closed. Once closed, they cannot be reopened. Channels are usually either readable or writable, but not both. The key to understanding channels is that:

- Reading from a channel puts bytes into a buffer
- Writing to a channel takes bytes from a buffer

For example, suppose we have a large file that we want to checksum in 16M chunks:

```
FileInputStream fis = getSomeStream();
boolean fileOK = true;

try (FileChannel fchan = fis.getChannel()) {
  var buffy = ByteBuffer.allocateDirect(16 * 1024 * 1024);
  while(fchan.read(buffy) != -1 || buffy.position() > 0 || fileOK) {
    fileOK = computeChecksum(buffy);
    buffy.compact();
  }
} catch (IOException e) {
  System.out.println("Exception in I/O");
}
```

This will use native I/O as far as possible and will avoid a lot of copying of bytes on and off the Java heap. If the `computeChecksum()` method has been well implemented, then this could be a very performant implementation.

## Mapped Byte Buffers

These are a type of direct byte buffer that contains a memory-mapped file (or a region of one). They are created from a `FileChannel` object, but note that the `File` object corresponding to the `MappedByteBuffer` must not be used after the memory-mapped operations or an exception will be thrown. To mitigate this, we again use `try`-with-resources, to scope the objects tightly:

```
try (var raf =
  new RandomAccessFile(new File("input.txt"), "rw");
     FileChannel fc = raf.getChannel();) {

  MappedByteBuffer mbf =
    fc.map(FileChannel.MapMode.READ_WRITE, 0, fc.size());
  var b = new byte[(int)fc.size()];
  mbf.get(b, 0, b.length);
  for (int i = 0; i < fc.size(); i = i + 1) {
    b[i] = 0; // Won't be written back to the file, we're a copy
  }
  mbf.position(0);
  mbf.put(b); // Zeros the file
}
```

Even with buffers, there are limitations of what can be done in Java for large I/O operations (e.g., transferring 10G between filesystems) that perform synchronously on a single thread. Before Java 7, these types of operations would typically be done by writing custom multithreaded code and managing a separate thread for performing a background copy. Let's move on to look at the new asynchronous I/O features that were added with JDK 7.

## Async I/O

The key to the asynchronous functionality is new subclasses of `Channel` that can deal with I/O operations that need to be handed off to a background thread. The same functionality can be applied to large, long-running operations and to several other use cases.

In this section, we'll deal exclusively with `AsynchronousFileChannel` for file I/O, but there are a couple of other asynchronous channels to be aware of. We'll peek at asynchronous sockets at the end of the chapter. We'll look at:

- `AsynchronousFileChannel` for file I/O
- `AsynchronousSocketChannel` for client socket I/O
- `AsynchronousServerSocketChannel` for asynchronous sockets that accept incoming connections

There are two different ways to interact with an asynchronous channel—`Future` style and callback style.

### Future-Based Style

A full discussion of the `Future` interface would take us too far into the details of Java concurrency. However, for the purpose of this chapter, it can be thought of as an ongoing task that may or may not have completed yet. It has two key methods:

`isDone()`
: Returns a Boolean indicating whether the task has finished.

`get()`
: Returns the result. If finished, returns immediately. If not finished, blocks until done.

Let's look at an example of a program that reads a large file (possibly as large as 100 Mb) asynchronously:

```
try (var channel =
         AsynchronousFileChannel.open(Path.of("input.txt"))) {
  var buffer = ByteBuffer.allocateDirect(1024 * 1024 * 100);
  Future<Integer> result = channel.read(buffer, 0);

  while(!result.isDone()) {
    // Do some other useful work....
  }
```

```
    System.out.println("Bytes read: " + result.get());
  }
```

## Callback-Based Style

The callback style for asynchronous I/O is based on a `CompletionHandler`, which defines two methods, `completed()` and `failed()`, that will be called back when the operation either succeeds or fails.

This style is useful if you want immediate notification of events in asynchronous I/O—for example, if there are a large number of I/O operations in flight, but failure of any single operation is not necessarily fatal:

```
byte[] data = {2, 3, 5, 7, 11, 13, 17, 19, 23};
ByteBuffer buffy = ByteBuffer.wrap(data);

CompletionHandler<Integer,Object> h =
  new CompletionHandler<>() {
    public void completed(Integer written, Object o) {
      System.out.println("Bytes written: " + written);
    }

    public void failed(Throwable x, Object o) {
      System.out.println("Asynch write failed: "+ x.getMessage());
    }
  };

try (var channel =
       AsynchronousFileChannel.open(Path.of("primes.txt"),
          StandardOpenOption.CREATE, StandardOpenOption.WRITE)) {

  channel.write(buffy, 0, null, h);

  // Give the CompletionHandler time to run before foreground exit
  Thread.sleep(1000);
}
```

The `AsynchronousFileChannel` object is associated with a background thread pool, so that the I/O operation proceeds, while the original thread can get on with other tasks.

> The `CompletionHandler` interface has two abstract methods, not one, so it cannot be the target type for a lambda expression, unfortunately.

By default, this uses a managed thread pool that is provided by the runtime. If required, it can be created to use a thread pool that is managed by the application (via an overloaded form of `AsynchronousFileChannel.open()`), but this is seldom necessary.

Finally, for completeness, let's touch upon NIO's support for multiplexed I/O. This enables a single thread to manage multiple channels and to examine those channels to see which are ready for reading or writing. The classes to support this are in the `java.nio.channels` package and include `SelectableChannel` and `Selector`.

These nonblocking multiplexed techniques can be extremely useful when you're writing advanced applications that require high scalability, but a full discussion is outside the scope of this book. In general, the nonblocking API should only be used for advanced use cases when high performance or other nonfunctional requirements demand it.

## Watch Services and Directory Searching

The last class of asynchronous services we will consider are those that watch a directory or visit a directory (or a tree). The watch services operate by observing everything that happens within a directory—for example, the creation or modification of files:

```
try {
  var watcher = FileSystems.getDefault().newWatchService();

  var dir = FileSystems.getDefault().getPath("/home/ben");
  dir.register(watcher,
               StandardWatchEventKinds.ENTRY_CREATE,
               StandardWatchEventKinds.ENTRY_MODIFY,
               StandardWatchEventKinds.ENTRY_DELETE);

  while(!shutdown) {
    WatchKey key = watcher.take();
    for (WatchEvent<?> event: key.pollEvents()) {
      Object o = event.context();
      if (o instanceof Path) {
        System.out.println("Path altered: "+ o);
      }
    }
    key.reset();
  }
}
```

By contrast, the directory streams provide a view into all files currently in a single directory. For example, to list all the Java source files and their size in bytes, we can use code like:

```
try(DirectoryStream<Path> stream =
    Files.newDirectoryStream(Path.of("/opt/projects"), "*.java")) {
  for (Path p : stream) {
    System.out.println(p +": "+ Files.size(p));
  }
}
```

One drawback of this API is that it will return only elements that match according to glob syntax, which is sometimes insufficiently flexible. We can go further by using the `Files.find()` and `Files.walk()` methods to address each element obtained by a recursive walk through the directory:

```
var homeDir = Path.of("/Users/ben/projects/");
Files.find(homeDir, 255,
  (p, attrs) -> p.toString().endsWith(".java"))
     .forEach(q -> {System.out.println(q.normalize());});
```

It is possible to go even farther and construct advanced solutions based on the `FileVisitor` interface in `java.nio.file`, but that requires the developer to implement all four methods on the interface, rather than just using a single lambda expression as done here.

In the last section of this chapter, we will discuss Java's networking support and the core JDK classes that enable it.

# Networking

The Java platform provides access to a large number of standard networking protocols, and these make writing simple networked applications quite easy. The core of Java's network support lives in the package `java.net`, with additional extensibility provided by `javax.net` (and in particular, `javax.net.ssl`), all of which is in the module `java.base`.

One of the easiest protocols to use for building applications is HyperText Transmission Protocol (HTTP), the protocol used as the basic communication protocol of the Web.

## HTTP

HTTP is the most common and popular high-level network protocol that Java supports out of the box. It is a very simple protocol, implemented on top of the standard TCP/IP stack. It can run on any network port but is usually found on port 443 when encrypted with TLS (known as HTTPS) or port 80 when running unencrypted. These days, HTTPS should be the default wherever possible.

Java has two separate APIs for handling HTTP—one of which dates back to the earliest days of the platform, and a more modern API that arrived fully in Java 11.

Let's take a quick look at the older API, for the sake of completeness. In this API, `URL` is the key class—it supports URLs of the form `http://`, `ftp://`, `file://`, and `https://` out of the box. It is very easy to use, and the simplest example of Java HTTP support is to download a particular URL:

```
var url = new URL("http://www.google.com/");
try (InputStream in = url.openStream()) {
  Files.copy(in, Path.of("output.txt"));
} catch(IOException ex) {
```

```
    ex.printStackTrace();
}
```

For more low-level control, including metadata about the request and response, we can use URLConnection and achieve something like:

```
try {
  URLConnection conn = url.openConnection();

  String type = conn.getContentType();
  String encoding = conn.getContentEncoding();
  Date lastModified = new Date(conn.getLastModified());
  int len = conn.getContentLength();
  InputStream in = conn.getInputStream();
} catch (IOException e) {
  // Handle exception
}
```

HTTP defines "request methods," which are the operations that a client can make on a remote resource. These methods are called GET, POST, HEAD, PUT, DELETE, OPTIONS, and TRACE.

Each has slightly different usages, for example:

- GET should only be used to retrieve a document and *never* should perform any side effects.
- HEAD is equivalent to GET except the body is not returned—useful if a program wants to quickly check via headers whether a URL has changed.
- POST is used when we want to send data to a server for processing.

By default, Java uses GET, but it does provide a way to use other methods for building more complex applications; however, doing so is a bit involved. In this next example, we're using the echo function provided by Postman to return a view of the data we posted:

```
var url = new URL("https://postman-echo.com/post");
var encodedData = URLEncoder.encode("q=java", "ASCII");
var contentType = "application/x-www-form-urlencoded";

var conn = (HttpURLConnection) url.openConnection();
conn.setInstanceFollowRedirects(false);
conn.setRequestMethod("POST");
conn.setRequestProperty("Content-Type", contentType );
conn.setRequestProperty("Content-Length",
  String.valueOf(encodedData.length()));

conn.setDoOutput(true);
OutputStream os = conn.getOutputStream();
os.write( encodedData.getBytes() );

int response = conn.getResponseCode();
```

```
if (response == HttpURLConnection.HTTP_MOVED_PERM
    || response == HttpURLConnection.HTTP_MOVED_TEMP) {
  System.out.println("Moved to: "+ conn.getHeaderField("Location"));
} else {
  try (InputStream in = conn.getInputStream()) {
    Files.copy(in, Path.of("postman.txt"),
                StandardCopyOption.REPLACE_EXISTING);
  }
}
```

Notice that we needed to send our query parameters in the body of a request and to encode them before sending. We also had to disable following of HTTP redirects and to treat any redirection from the server manually. This is due to a limitation of the `HttpURLConnection` class, which does not deal well with redirection of POST requests.

The older API definitely shows its age, and in fact implements only version 1.0 of the HTTP standard, which is very inefficient and considered archaic. As an alternative, modern Java programs can use the new API, which was added as a result of Java needing to support the new HTTP/2 protocol. It has been available in a fully supported module, `java.net.http`, since Java 11. Let's see a simple example of using the new API:

```
var client = HttpClient.newBuilder().build();
var uri = new URI("https://www.oreilly.com");
var request = HttpRequest.newBuilder(uri).build();

var response = client.send(request,
        ofString(Charset.defaultCharset()));
var body = response.body();
System.out.println(body);
```

Note that this API is designed to be extensible, with interfaces such as `HttpResponse.BodySubscriber` available for implementing custom handling. The interface also seamlessly hides the differences between HTTP/2 and the older HTTP/1.1 protocol, meaning that Java applications will be able to migrate gracefully as web servers adopt the new version.

Let's move on to look at the next layer down the networking stack, the Transmission Control Protocol (TCP).

## TCP

TCP is the basis of reliable network transport over the internet. It ensures that web pages and other internet traffic are delivered in a complete and comprehensible state. From a networking theory standpoint, the protocol properties that allow TCP to function as this "reliability layer" for internet traffic are:

*Connection based*
: Data belongs to a single logical stream (a connection).

*Guaranteed in-order delivery*
: Data packets will be resent until they arrive.

*Error checked*
: Damage caused by network transit will be detected and fixed automatically.

TCP is a two-way (or bidirectional) communication channel and uses a special numbering scheme (TCP sequence numbers) for data chunks to ensure that both sides of a communication stream stay in sync. To support many different services on the same network host, TCP uses port numbers to identify services and ensures that traffic intended for one port does not go to a different one.

In Java, TCP is represented by the classes `Socket` and `ServerSocket`. They are used to provide the capability to be the client side and server side of the connection, respectively—meaning that Java can be used both to connect to network services and as a language for implementing new services.

> Java's original socket support was reimplemented, without API changes, in Java 13. The classic socket APIs now share code with the more modern NIO infrastructure and will continue working well into the future as a result.

As an example, let's consider reimplementing HTTP 1.1. This is a relatively simple, text-based protocol. We'll need to implement both sides of the connection, so let's start with an HTTP client on top of a TCP socket. To accomplish this, we will actually need to implement the details of the HTTP protocol, but we do have the advantage that we have complete control over the TCP socket.

We will need to both read and write from the client socket, and we'll construct the actual request line in accordance with the HTTP standard (which is known as RFC 2616, and uses explicit line-ending syntax). The resulting client code will look something like this:

```
var hostname = "www.example.com";
int port = 80;
var filename = "/index.html";

try (var sock = new Socket(hostname, port);
  var from = new BufferedReader(
      new InputStreamReader(sock.getInputStream()));
  var to = new PrintWriter(
      new OutputStreamWriter(sock.getOutputStream())); ) {

  // The HTTP protocol
  to.print("GET " + filename +
    " HTTP/1.1\r\nHost: "+ hostname +"\r\n\r\n");
```

```java
    to.flush();

    for (String l = null; (l = from.readLine()) != null; )
      System.out.println(l);
  }
```

On the server side, we'll need to receive possibly multiple incoming connections. To handle this, we'll kick off a main server loop, then use `accept()` to take a new connection from the operating system. The new connection is then quickly passed to a separate handler class so that the main server loop can get back to listening for new connections. The code for this is a bit more involved than the client case:

```java
// Handler class
private static class HttpHandler implements Runnable {
  private final Socket sock;
  HttpHandler(Socket client) { this.sock = client; }

  public void run() {
    try (var in =
           new BufferedReader(
             new InputStreamReader(sock.getInputStream()));
         var out =
           new PrintWriter(
             new OutputStreamWriter(sock.getOutputStream())); ) {
      out.print("HTTP/1.0 200\r\nContent-Type: text/plain\r\n\r\n");
      String line;
      while((line = in.readLine()) != null) {
        if (line.length() == 0) break;
        out.println(line);
      }
    } catch(Exception e) {
      // Handle exception
    }
  }
}

// Main server loop
public static void main(String[] args) {
  try {
    var port = Integer.parseInt(args[0]);

    ServerSocket ss = new ServerSocket(port);
    while (true) {
      Socket client = ss.accept();
      var handler = new HTTPHandler(client);
      new Thread(handler).start();
    }
  } catch (Exception e) {
    // Handle exception
  }
}
```

When designing a protocol for applications to communicate over TCP, there's a simple and profound network architecture principle, known as Postel's Law (after Jon Postel, one of the fathers of the internet) that you should always keep in mind. It is sometimes stated as: "Be strict about what you send, and liberal about what you will accept." This simple principle means that communication can remain broadly possible in a network system, even in the event of quite imperfect implementations.

Postel's Law, when combined with the general principle that the protocol should be as simple as possible (sometimes called the KISS principle), will make the developer's job of implementing TCP-based communication much easier than it otherwise would be.

Below TCP is the internet's general-purpose haulage protocol—the Internet Protocol (IP) itself.

## IP

IP, the "lowest common denominator" transport, provides a useful abstraction over the physical network technologies that are used to actually move bytes from A to B.

Unlike TCP, delivery of an IP packet is not guaranteed, and a packet can be dropped by any overloaded system along the path. IP packets do have a destination but usually no routing data—it's the responsibility of the (possibly many different) physical transports along the route to actually deliver the data.

It is possible to create "datagram" services in Java that are based around single IP packets (or those with a UDP header, instead of TCP), but this is not often required except for extremely low-latency applications. Java uses the class `DatagramSocket` to implement this functionality, although few developers should ever need to venture this far down the network stack.

Finally, it's worth noting some changes currently in-flight in the addressing schemes that are used across the internet. The current dominant version of IP in use is IPv4, which has a 32-bit space of possible network addresses. This space is now very badly squeezed and various mitigation techniques have been deployed to handle the depletion.

The next version of IP (IPv6) is being rolled out, but it is not fully accepted and has yet to displace IPv4, although steady progress toward it becoming the standard continues. As of this writing, IPv6 traffic is at about 35% of internet traffic and steadily rising. In the next 10 years, IPv6 is likely to overtake IPv4 in terms of traffic volume, and low-level networking will need to adapt to this radically new version.

However, for Java programmers, the good news is that the language and platform have been working for many years on good support for IPv6 and the changes that it introduces. The transition between IPv4 and IPv6 is likely to be much smoother and less problematic for Java applications than for many other languages.

## Summary

In this chapter we've met the file handling, I/O, and networking capabilities provided in Java's SDK. However, these capabilities are not used equally often. The core file handling classes (especially `Path` and the rest of NIO.2) are used very often by Java developers, with the more advanced capabilities being less frequently encountered.

The story is different for the networking libraries. It's good to be aware of these capabilities, but they are fairly basic. In practice, higher-level libraries provided by third parties are often used instead (e.g., Netty). The one exception: the one low-level JDK networking library that Java developers can expect to encounter relatively often is the new HTTP library in `java.net.http`.

Let's move on to meet some of Java's key dynamic features—classloading and reflection—powerful techniques that allow code to be discovered, loaded, and executed at runtime in ways that were unknown at compile time.

# 11 Classloading, Reflection, and Method Handles

In Chapter 3, we met Java's `Class` objects, a way of representing a live type in a running Java process. In this chapter, we will build on this foundation to discuss how the Java environment loads and makes new types available. In the second half of the chapter, we will introduce Java's introspection capabilities—both the original Reflection API and the newer Method Handles capabilities.

## Class Files, Class Objects, and Metadata

Class files, as we saw in Chapter 1, are the result of compiling Java source files (or, potentially, other languages) into the intermediate form used by the JVM. These are binary files that are not designed to be human readable.

The runtime representation of these class files are the class objects that contain metadata, which represents the Java type that the class file was created from.

### Examples of Class Objects

You can obtain a class object in Java in several ways. The simplest is:

```
Class<?> myClass = getClass();
```

This returns the class object of the instance that it is called from. However, as we know from our survey of the public methods of `Object`, the `getClass()` method on `Object` is public, so we can also obtain the class of an arbitrary object `o`:

```
Class<?> c = o.getClass();
```

Class objects for known types can also be written as "class literals":

```java
// Express a class literal as a type name followed by ".class"
c = String.class; // Same as "a string".getClass()
c = byte[].class; // Type of byte arrays
```

For primitive types and `void`, we also have class objects that are represented as literals:

```java
// Obtain a Class object for primitive types with various
// predefined constants
c = Void.TYPE; // The special "no-return-value" type
c = Byte.TYPE; // Class object that represents a byte
c = Integer.TYPE; // Class object that represents an int
c = Double.TYPE; // etc.; see also Short, Character, Long, Float
```

There is also the possibility of using the `.class` syntax directly on a primitive type, like this:

```java
c = int.class; // Same as Integer.TYPE
```

The relationship between `.class` and `.TYPE` can be seen with some simple tests:

```java
// outputs true
System.out.printf("%b%n", Integer.TYPE == int.class);

// outputs false
System.out.printf("%b%n", Integer.class == int.class);

// outputs false
System.out.printf("%b%n", Integer.class == Integer.TYPE);
```

Note that the wrapper types (`Integer`, etc) have a `.TYPE` property, but in general classes do not. Also, all of this works only for types that are known at compile time; for unknown types, we will have to use more sophisticated methods.

## Class Objects and Metadata

The class objects contain metadata about the given type. This includes the methods, fields, constructors, and the like that are defined on the class in question. This metadata can be accessed by the programmer to investigate the class, even if nothing is known about the class when it is loaded.

For example, we can find all the deprecated methods in the class file (they will be marked with the `@Deprecated` annotation):

```java
Class<?> clz =  ... // Get class from somewhere, e.g. loaded from disk
for (Method m : clz.getMethods()) {
  for (Annotation a : m.getAnnotations()) {
    if (a.annotationType() == Deprecated.class) {
      System.out.println(m.getName());
    }
  }
}
```

We could also find the common ancestor class of a pair of class files. This simple form will work when both classes have been loaded by the same classloader:

```
public static Class<?> commonAncestor(Class<?> cl1, Class<?> cl2) {
  if (cl1 == null || cl2 == null) return null;
  if (cl1.equals(cl2)) return cl1;
  if (cl1.isPrimitive() || cl2.isPrimitive()) return null;

  List<Class<?>> ancestors = new ArrayList<>();
  Class<?> c = cl1;
  while (!c.equals(Object.class)) {
    if (c.equals(cl2)) return c;
    ancestors.add(c);
    c = c.getSuperclass();
  }
  c = cl2;
  while (!c.equals(Object.class)) {
    for (Class<?> k : ancestors) {
      if (c.equals(k)) return c;
    }
    c = c.getSuperclass();
  }

  return Object.class;
}
```

Class files have a very specific layout they must conform to if they are to be legal and loadable by the JVM. The sections of the class file are (in order):

- Magic number (all class files starting with the four bytes `CA FE BA BE` in hexadecimal)
- Version of class file standard in use
- Constant pool for this class
- Access flags (`abstract`, `public`, etc.)
- Name of this class
- Inheritance info (e.g., name of superclass)
- Implemented interfaces
- Fields
- Methods
- Attributes

The class file is a simple binary format, but it is not human readable. Instead, tools like `javap` (see Chapter 13) should be used to comprehend the contents.

One of the most frequently used sections in the class file is the *constant pool*, which contains representations of all the methods, classes, fields, and constants that the class needs to refer to (whether they are in this class or another). It is designed so that bytecodes can simply refer to a constant pool entry by its index number—which saves space in the bytecode representation.

A number of different class file versions are created by various Java versions. However, one of Java's backward compatibility rules is that JVMs (and tools) from newer versions can always use older class files.

Let's look at how the classloading process takes a collection of bytes on disk and turns it into a new class object.

## Phases of Classloading

Classloading is the process by which a new type is added to a running JVM process. This is the only way that new code can enter the system and the only way to turn data into code in the Java platform. There are several phases to the process of classloading, so let's examine them in turn.

### Loading

The classloading process starts with loading a byte array. This is usually read in from a filesystem, but it also can be read from a URL or other location (often represented as a `Path` object).

The `ClassLoader::defineClass()` method is responsible for turning a class file (represented as a byte array) into a class object. It is a protected method and so is not accessible without subclassing.

The first job of `defineClass()` is loading. This produces the skeleton of a class object, corresponding to the class you're attempting to load. By this stage, some basic checks have been performed on the class (e.g., the constants in the constant pool have been checked to ensure that they're self-consistent).

However, loading doesn't produce a complete class object by itself, and the class isn't yet usable. Instead, after loading, the class must be linked. This step breaks down into separate subphases:

- Verification
- Preparation and resolution
- Initialization

### Verification

Verification confirms that the class file conforms to expectations, and that it doesn't try to violate the JVM's security model (see "Secure Programming and Classloading" on page 372 for details).

JVM bytecode is designed so that it can be (mostly) checked statically. This has the effect of slowing down the classloading process but speeding up runtime (as checks can be omitted).

The verification step is designed to prevent the JVM from executing bytecodes that might crash it or put it into an undefined and untested state where it might be vulnerable to other attacks by malicious code. Bytecode verification is a defense against malicious hand-crafted Java bytecodes and untrusted Java compilers that might output invalid bytecodes.

> The default methods mechanism works via classloading. When an implementation of an interface is being loaded, the class file is examined to see if implementations for default methods are present. If they are, classloading continues normally. If some are missing, the implementation is patched to add in the default implementation of the missing methods.

## Preparation and Resolution

After successful verification, the class is prepared for use. Memory is allocated and static variables in the class are readied for initialization.

At this stage, variables aren't initialized, and no bytecode from the new class has been executed. Before we run any code, the JVM checks that every type referred to by the new class file is known to the runtime. If the types aren't known, they may also need to be loaded—which can kick off the classloading process again, as the JVM loads the new types.

This process of loading and discovery can execute iteratively until a stable set of types is reached. This is called the "transitive closure" of the original type that was loaded.[1]

Let's look at a quick example by examining the dependencies of `java.lang.Object`. Figure 11-1 shows a simplified dependency graph for `Object`. It shows only the direct dependencies of `Object` that are visible in the public API of `Object` and the direct, API-visible dependencies of those dependencies. In addition, the dependencies of `Class` on the reflection subsystem, and of `PrintStream` and `PrintWriter` on the I/O subsystems, are shown in very simplified form.

In Figure 11-1, we can see part of the transitive closure of `Object`.

1 As in Chapter 6, we're borrowing the expression *transitive closure* from the branch of mathematics called graph theory.

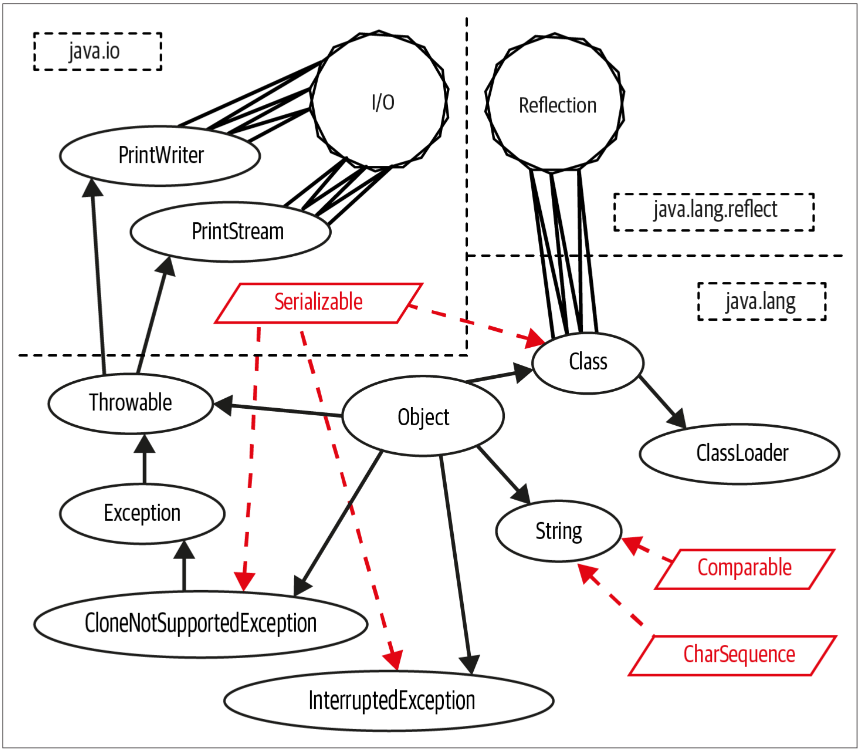


*Figure 11-1. Transitive closure of types*

### Initialization

Once resolved, the JVM can finally initialize the class. Static variables can be initialized and static initialization blocks are run.

This is the first time that the JVM is executing bytecode from the newly loaded class. When the static blocks complete, the class is fully loaded and ready to go.

## Secure Programming and Classloading

Java programs can dynamically load Java classes from a variety of sources, including untrusted sources, such as websites reached across an insecure network. The ability to create and work with such dynamic sources of code is one of the great strengths and features of Java. To make it work successfully, however, Java puts great emphasis on a security architecture that allows untrusted code to run safely, without fear of damage to the host system.

Java's classloading subsystem is where a lot of safety features are implemented. The central idea of the security aspects of the classloading architecture is that there is only one way to get new executable code into the process: a class.

This provides a "pinch point"—the only way to create a new class is to use the functionality provided by `ClassLoader` to load a class from a stream of bytes. By concentrating on making classloading secure, we can constrain the attack surface that needs to be protected.

One extremely helpful aspect of the JVM's design is that the JVM is a stack machine, so all operations are evaluated on a stack, rather than in registers. The stack state can be deduced at every point in a method, and this can be used to ensure that the bytecode doesn't attempt to violate the security model.



Some of the security checks implemented by the JVM are:

- All the bytecode of the class has valid parameters.
- All methods are called with the right number of parameters of the correct static types.
- Bytecode never tries to underflow or overflow the JVM stack.
- Local variables are not used before they are initialized.
- Variables are only assigned suitably typed values.
- Field, method, and class access control modifiers must be respected.
- No unsafe casts (e.g., attempts to convert an `int` to a pointer).
- All branch instructions are to legal points within the same method.

Of fundamental importance is the approach to memory, and pointers. In assembly and C/C++, integers and pointers are interchangeable, so an integer can be used as a memory address. We can write it in assembly like this:

```
mov eax, [STAT] ; Move 4 bytes from addr STAT into eax
```

The lowest level of the Java security architecture involves the design of the Java Virtual Machine and the bytecodes it executes. The JVM does not allow any kind of direct access to individual memory addresses of the underlying system, which prevents Java code from interfering with the native hardware and operating system. These intentional restrictions on the JVM are reflected in the Java language itself, which does not support pointers or pointer arithmetic.

Neither the language nor the JVM allow an integer to be cast to an object reference or vice versa, and there is no way whatsoever to obtain an object's address in memory. Without capabilities like these, malicious code simply cannot gain a foothold.

Recall from Chapter 2 that Java has two types of values—primitives and object references. These are the only things that can be put into variables. Note that "object contents" cannot be put into variables. Java has no equivalent of C's `struct` and always has pass-by-value semantics. For reference types, what is passed is a copy of the reference—which is a value.

References are represented in the JVM as pointers, but they are not directly manipulated by the bytecode. In fact, bytecode does not have opcodes for "access memory at location X."

Instead, all we can do is access fields and methods; bytecode cannot call an arbitrary memory location. This means that the JVM always knows the difference between code and data. In turn, this prevents a whole class of stack overflow and other attacks.

# Applied Classloading

To apply knowledge of classloading, it's important to fully understand `java.lang.ClassLoader`.

This is an abstract class that is fully functional and has no abstract methods. The `abstract` modifier exists only to ensure that users must subclass `ClassLoader` if they want to use it.

In addition to the aforementioned `defineClass()` method, we can load classes via a public `loadClass()` method. This is commonly used by the `URLClassLoader` subclass, which can load classes from a URL or file path.

We can use `URLClassLoader` to load classes from the local disk like this:

```
var current = new File( "." ).getCanonicalPath();
var urls = new URL[] {new URL("file://"+ current + "/")};
try (URLClassLoader loader = new URLClassLoader(urls)) {
  Class<?> clz = loader.loadClass("com.example.DFACaller");
  System.out.println(clz.getName());
}
```

The argument to `loadClass()` is the binary name of the class file. Note that for the `URLClassLoader` to find the classes correctly, they need to be in the expected place on the filesystem. In this example, the class `com.example.DFACaller` would need to be found in the file *com/example/DFACaller.class* relative to the working directory.

Alternatively, `Class` provides `Class.forName()`, a static method that can load classes that are present on the classpath but that haven't been referred to yet.

This method takes a fully qualified class name. For example:

```
Class<?> jdbcClz = Class.forName("oracle.jdbc.driver.OracleDriver");
```

It throws a `ClassNotFoundException` if the class can't be found. As the example indicates, this was commonly used in older versions of Java Database Connectivity (JDBC) to ensure that the correct driver was loaded, while avoiding a direct `import` dependency on the driver classes. With the advent of JDBC 4.0, this initialization step is no longer required.

`Class.forName()` has an alternative, three-argument form, which is sometimes used in conjunction with alternative classloaders:

```
Class.forName(String name, boolean inited, ClassLoader classloader);
```

There are a host of subclasses of `ClassLoader` that deal with individual special cases of classloading—which fit into the classloader hierarchy.

## Classloader Hierarchy



The JVM has a hierarchy of classloaders; each classloader in the system (apart from the initial, "bootstrap" classloader) has a parent that it can delegate to.

> The arrival of modules in Java 9 has affected the details of the way that classloading operates. In particular, the classloaders that load the JRE classes are now *modular classloaders*.

The convention is that a classloader will ask its parent to resolve and load a class, and it will perform the job itself if only the parent classloader is unable to comply. Some common classloaders are shown in Figure 11-2.

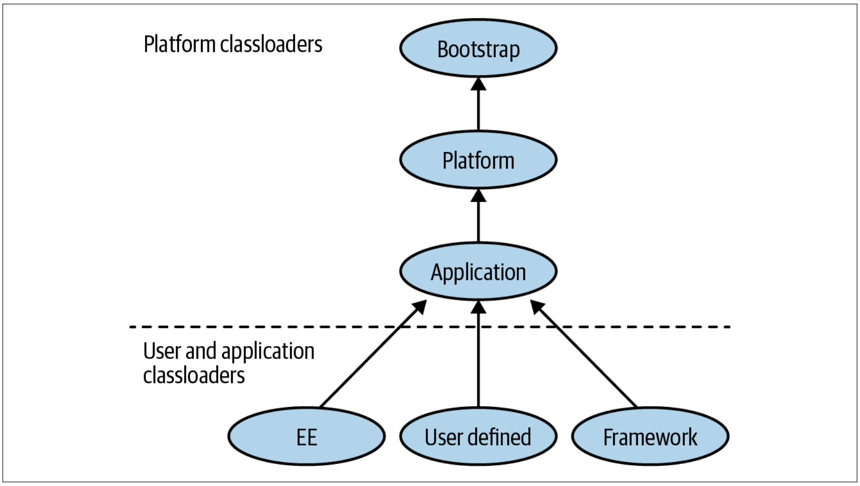


*Figure 11-2. Classloader hierarchy*

### Bootstrap classloader

This is the first classloader to appear in any JVM process and is only used to load the core system classes. In older texts, it is sometimes referred to as the *primordial classloader*, but modern usage favors the bootstrap name.

For performance reasons, the bootstrap classloader does no verification and relies on the boot classpath being secure. Types loaded by the bootstrap classloader are implicitly granted all security permissions, and so this group of modules is kept as restricted as possible.

### Platform classloader

This level of the classloader hierarchy was originally used as the *extension classloader*, but this mechanism has now been removed.

In its new role, this classloader (which has the bootstrap classloader as its parent) is now known as the *platform classloader*. It is available via the method `ClassLoader::getPlatformClassLoader` and appears in (and is required by) the Java specification from version 9 onward. It loads the remaining modules from the base system (the equivalent of the old `rt.jar` used in version 8 and earlier).

In the new modular implementations of Java, far less code is required to bootstrap a Java process; accordingly, as much JDK code (now represented as modules) as possible has been moved out of the scope of the bootstrap loader and into the platform loader instead.

### Application classloader

Historically, this was sometimes called the system classloader, but this is a bad name, as it doesn't load the system (the bootstrap and platform classloaders do). Instead, it is the classloader that loads application code from either the module path or the classpath. It is the most commonly encountered classloader, and it has the platform classloader as its parent.

To perform classloading, the application classloader first searches the named modules on the module path (the modules known to any of the three built-in classloaders). If the requested class is found in a module known to one of these classloaders then that classloader will load the class. If the class is not found in any known named module, the application classloader delegates to its parent (the platform classloader). If the parent fails to find the class, the application classloader searches the classpath. If the class is found on the classpath, it is loaded as a member of the application classloader's unnamed module.

The application classloader is very widely used, but many advanced Java frameworks require functionality that the main classloaders do not supply. Instead, extensions to the standard classloaders are required. This forms the basis of "custom classloading"—which relies on implementing a new subclass of `ClassLoader`.

### Custom classloader

When performing classloading, sooner or later we have to turn data into code. As noted earlier, the `defineClass()` (actually a group of related methods) is responsible for converting a `byte[]` into a class object.

This method is usually called from a subclass—for example, this simple custom classloader that creates a class object from a file on disk:

```
public static class DiskLoader extends ClassLoader {
  public DiskLoader() {
    super(DiskLoader.class.getClassLoader());
  }
```

```
    public Class<?> loadFromDisk(String clzPath) throws IOException {
      byte[] b = Files.readAllBytes(Paths.get(clzPath));

      return defineClass(null, b, 0, b.length);
    }
  }
```



Notice that in the preceding example we didn't need to have the class file in the "correct" location on disk, as we did for the `URLClassLoader` example.

We need to provide a classloader to act as parent for any custom classloader. In this example, we provided the classloader that loaded the `DiskLoader` class (which would usually be the application classloader).

Custom classloading is a very common technique in Java EE and advanced SE environments, and it provides very sophisticated capabilities to the Java platform. We'll see an example of custom classloading later in this chapter.

One drawback of dynamic classloading is that when working with a class object that we loaded dynamically, we typically have little or no information about the class. To work effectively with this class, we will therefore have to use a set of dynamic programming techniques known as reflection.

# Reflection

Reflection is the capability of examining, operating on, and modifying objects at runtime. This includes modifying their structure and behavior—even self-modification.

The Java modules system introduces major changes to how reflection works on the platform. It is important to reread this section after you have gained an understanding of how modules work and how the two capabilities interact. More details on how modules restrict reflection are available in "Open Modules" on page 397.

Reflection is capable of working even when type and method names are not known at compile time. It uses the essential metadata provided by class objects and can discover method or field names from the class object—and then acquire an object representing the method or field.

Instances can also be constructed reflectively (by using `Class::newInstance()` or another constructor). With a reflectively constructed object and a `Method` object, we can call any method on an object of a previously unknown type.

This makes reflection a very powerful technique, so it's important to understand when we should use it, and when it's overkill.

## When to Use Reflection

Many, if not most, Java frameworks use reflection in some capacity. Writing architectures that are flexible enough to cope with code that is unknown until runtime usually requires reflection. For example, plug-in architectures, debuggers, code browsers, and read-evaluate-print loop (REPL)-like environments are usually implemented on top of reflection.

Reflection is also widely used in testing (e.g., by the JUnit and TestNG libraries) and for mock object creation. If you've used any kind of Java framework you have almost certainly been using reflective code, even if you didn't realize it.

To start using the Reflection API in your own code, the most important thing to realize is that it is about accessing objects where virtually no information is known, and that the interactions can be cumbersome because of this.

If some static information is known about dynamically loaded classes (e.g., that the classes loaded all implement a known interface), this can greatly simplify the interaction with the classes and reduce the burden of operating reflectively.

It is a common mistake to try to create a reflective framework that attempts to account for all possible circumstances, instead of dealing only with the cases that are immediately applicable to the problem domain.

## How to Use Reflection

The first step in any reflective operation is to get a `Class` object representing the type to be operated on. From this, other objects, representing fields, methods, or constructors, can be accessed and applied to instances of the unknown type.

If we already have an instance of an unknown type, we can retrieve its class via the `Object::getClass()` method. Alternatively, the static `Class.forName()` method demonstrated in "Applied Classloading" on page 374 for classloading can also perform lookup of a `Class` object by name:

```
var clzForInstance = "Hi".getClass();
var clzForName = Class.forName("java.lang.String");
```

Once we have an instance of a `Class` object, the next reasonable step is calling a method reflectively. The `Method` objects are some of the most commonly used objects provided by the Reflection API. We'll discuss them in detail—the `Constructor` and `Field` objects are similar in many respects.

### Method objects

A class object contains a `Method` object for each method on the class. These are lazily created after classloading, and so they aren't immediately visible in an IDE's debugger.

Methods on `Class` allow us to retrieve (and if necessary lazily initialize) these `Method` objects:

```
var clz = Class.forName("java.lang.String");

// Returns list of all publicly visible methods on clz
var publicMethods = clz.getMethods();

// Returns named method from clz, or throws
var toString = clz.getMethod("toString", new Class[] {});
```

The second parameter to `getMethod()` takes an array of `Class` objects representing the method's parameters to distinguish between method overrides.

The code demonstrated here will only list and find public methods on our `Class` objects. There are alternative methods of the form `getDeclaredMethod` that parallel what we've shown that allow access to protected and private methods. We'll have more to say shortly about using these mechanisms to circumvent Java's access model, though.

Like any good Java object, `Method` provides accessors for all the relevant information about the method. Let's look at the most critical metadata about a method that we can retrieve:

```
var clz = Class.forName("java.lang.String");
var toString = clz.getMethod("toString", new Class[] {});

// The method's name
String name = toString.getName();

// Generic type information for the method
TypeVariable[] typeParams = toString.getTypeParameters();

// List of method annotations with RUNTIME retention
Annotation[] ann = toString.getAnnotations();

// List of checked exception types declared by method
Class[] exceptions = toString.getExceptionTypes();

// List of Parameter objects for callling the method
Parameter[] params = toString.getParameters();

// List of just the `Class` for each parameter to the method
Class[] paramTypes = toString.getParameterTypes();

// Class of the method's return type
Class ret = toString.getReturnType();
```

We can explore the metadata of a `Method` object by calling accessor methods, but by far the single biggest use case for `Method` is reflective invocation.

The methods represented by these objects can be executed by reflection using the `invoke()` method on `Method`.

An example of invoking `hashCode()` on a `String` object follows:

```
Object rcvr = "a";
try {
  Class<?>[] argTypes = new Class[] { };
  Object[] args = null;

  Method meth = rcvr.getClass().getMethod("hashCode", argTypes);
  Object ret = meth.invoke(rcvr, args);
  System.out.println(ret);

} catch (IllegalArgumentException | NoSuchMethodException |
         SecurityException e) {
  e.printStackTrace();
} catch (IllegalAccessException | InvocationTargetException x) {
  x.printStackTrace();
}
```

Note that the static type of `rcvr` was declared to be `Object`. No static type information was used during the reflective invocation. The `invoke()` method also returns `Object`, so the actual return type of `hashCode()` has been autoboxed to `Integer`.

This autoboxing is one of the aspects of Reflection where you can see some of the slight awkwardness of the API—which we'll discuss in an upcoming section.

### Creating instances with Reflection

If you're looking to create new instances of a `Class` object, you'll find that the method lookups don't help. Our constructors don't have names that those APIs are able to find.

In the simplest case of a no-argument constructor, a helper is available via the `Class` object:

```
Class<?> clz = ... // Get some class object
Object rcvr = clz.getDeclaredConstructor().newInstance();
```

For constructors that take arguments, `Class` has methods like `getConstructor` that allow for finding the override you're after. While they return a separate `Constructor` type, using these is very similar to what we've already seen for interacting with `Method` objects.

Let's look at an extended example and see how to combine reflection with custom classloading to inspect a class file on disk for any deprecated methods (these should be marked with `@Deprecated`):

```
public class CustomClassloadingExamples {
    public static class DiskLoader extends ClassLoader {

        public DiskLoader() {
```

```
            super(DiskLoader.class.getClassLoader());
        }

        public Class<?> loadFromDisk(String clzName)
          throws IOException {
            byte[] b = Files.readAllBytes(Paths.get(clzName));

            return defineClass(null, b, 0, b.length);
        }
    }

    public void findDeprecatedMethods(Class<?> clz) {
        for (Method m : clz.getMethods()) {
            for (Annotation a : m.getAnnotations()) {
                if (a.annotationType() == Deprecated.class) {
                    System.out.println(m.getName());
                }
            }
        }
    }

    public static void main(String[] args)
      throws IOException, ClassNotFoundException {
        var rfx = new CustomClassloadingExamples();

        if (args.length > 0) {
            DiskLoader dlr = new DiskLoader();
            Class<?> clzToTest = dlr.loadFromDisk(args[0]);
            rfx.findDeprecatedMethods(clzToTest);
        }
    }
}
```

This showcases some of the power of reflective techniques, but there are also problems that come with using the API.

## Problems with Reflection

Java's Reflection API is often the only way to deal with dynamically loaded code, but a number of annoyances in the API can make it slightly awkward to deal with:

- Heavy use of `Object[]` to represent call arguments and other instances.
- Also uses `Class[]` when talking about types.
- Methods can be overloaded on name, so we need an array of types to distinguish between methods.
- Representing primitive types can be problematic—we have to manually box and unbox.

`void` is a particular problem—there is a `void.class`, but it's not used consistently. Java doesn't really know whether `void` is a type or not, and some methods in the Reflection API use `null` instead.

This is cumbersome, and can be error prone—in particular, the slight verbosity of Java's array syntax can lead to errors.

One further problem is the treatment of non-`public` methods. As mentioned before, instead of using `getMethod()`, we must use `getDeclaredMethod()` to get a reference to a non-`public` method. Additionally, to call non-`public` methods, we must override the Java access control subsystem, calling `setAccessible()` to allow it to be executed:

```
public class MyCache {
  private void flush() {
    // Flush the cache...
  }
}

Class<?> clz = MyCache.class;
try {
  Object rcvr = clz.newInstance();
  Class<?>[] argTypes = new Class[] { };
  Object[] args = null;

  Method meth = clz.getDeclaredMethod("flush", argTypes);
  meth.setAccessible(true);
  meth.invoke(rcvr, args);
} catch (IllegalArgumentException | NoSuchMethodException |
         InstantiationException | SecurityException e) {
  e.printStackTrace();
} catch (IllegalAccessException | InvocationTargetException x) {
  x.printStackTrace();
}
```

Because reflection always involves unknown information, we just have to live with some of this verbosity. It's the price of using the dynamic, runtime power of reflective invocation.

## Dynamic Proxies

One last piece of the Java Reflection story is the creation of dynamic proxies. These are classes (which extend `java.lang.reflect.Proxy`) that implement a number of interfaces. The implementing class is constructed dynamically at runtime and forwards all calls to an invocation handler object:

```
InvocationHandler handler = (proxy, method, args) -> {
    String name = method.getName();
    System.out.println("Called as: "+ name);
    return switch (name) {
        case "isOpen" -> Boolean.TRUE;
        case "close" -> null;
```

```
            default -> null;
        };
    };

    Channel c = (Channel) Proxy.newProxyInstance(
            Channel.class.getClassLoader(),
            new Class[] { Channel.class },
            handler);
    System.out.println("Open? "+ c.isOpen());
    c.close();
```

Proxies can be used as stand-in objects for testing (especially in test mocking approaches).

Another use case is to provide partial implementations of interfaces, or to decorate or otherwise control some aspect of delegation:

```
public class RememberingList implements InvocationHandler {
  private final List<String> proxied = new ArrayList<>();

  @Override
  public Object invoke(Object proxy, Method method, Object[] args)
                             throws Throwable {
    String name = method.getName();
    switch (name) {
      case "clear":
        return null;
      case "remove":
      case "removeAll":
        return false;
    }

    return method.invoke(proxied, args);
  }
}

RememberingList hList = new RememberingList();

var l = (List<String>) Proxy.newProxyInstance(
                                List.class.getClassLoader(),
                                new Class[] { List.class },
                                hList);
l.add("cat");
l.add("bunny");
l.clear();
System.out.println(l);
```

Proxies are an extremely powerful and flexible capability used within many Java frameworks.

# Method Handles

In Java 7, a brand new mechanism for introspection and method access was introduced. This was originally designed for use with dynamic languages, which may need to participate in method dispatch decisions at runtime. To support this at the JVM level, the new `invokedynamic` bytecode was introduced. This bytecode was not used by Java 7 itself, but with the advent of Java 8, it was extensively used in both lambda expressions and the Nashorn JavaScript implementation.

Even without `invokedynamic`, the new Method Handles API is comparable in power to many aspects of the Reflection API—and can be cleaner and conceptually simpler to use, even standalone. It can be thought of as Reflection done in a safer, more modern way.

## MethodType

In Reflection, method signatures are represented as `Class[]`. This is quite cumbersome. By contrast, method handles rely on `MethodType` objects. These are a typesafe and object-oriented way to represent the type signature of a method.

They include the return type and argument types but not the receiver type or name of the method. The name is not present, as this allows any method of the correct signature to be bound to any name (as per the functional interface behavior of lambda expressions).

A type signature for a method is represented as an immutable instance of `MethodType`, as acquired from the factory method `MethodType.methodType()`. The zeroth argument to `methodType()` is the return type of the method, with the types of the method arguments following it.

For example:

```
// Matching method type for toString()
MethodType m2Str = MethodType.methodType(String.class);

// Matching method type for Integer.parseInt()
MethodType mtParseInt =
  MethodType.methodType(Integer.class, String.class);

// Matching method type for defineClass() from ClassLoader
MethodType mtdefClz = MethodType.methodType(Class.class, String.class,
                                            byte[].class, int.class,
                                            int.class);
```

This single piece of the puzzle provides significant gains over Reflection, as it makes method signatures significantly easier to represent and discuss. The next step is to acquire a handle on a method. This is achieved by a lookup process.

## Method Lookup

Method lookup queries are performed on the class where a method is defined and are dependent on the context that they are executed from:

```
// String.toString only has return type with no parameter
MethodType mtToString = MethodType.methodType(String.class);

try {
  Lookup l = MethodHandles.lookup();
  MethodHandle mh = l.findVirtual(String.class, "toString",
                                  mtToString);
  System.out.println(mh);
} catch (NoSuchMethodException | IllegalAccessException e) {
  e.printStackTrace();
}
```

We always need to call `MethodHandles.lookup()`—this gives us a lookup context object based on the currently executing method.

Lookup objects have several methods (which all start with `find`) declared on them for method resolution. These include `findVirtual()`, `findConstructor()`, and `findStatic()`.

One big difference between the Reflection and Method Handles APIs is access control. A `Lookup` object will only return methods that are accessible to the context where the lookup was created—and there is no way to subvert this (no equivalent of Reflection's `setAccessible()` hack).

For example, we can see that when we attempt to look up the protected `ClassLoader::defineClass()` method from a general lookup context, we fail to resolve it with an `IllegalAccessException`, as the protected method is not accessible:

```
public static void lookupDefineClass(Lookup l) {
  MethodType mt = MethodType.methodType(Class.class, String.class,
                                        byte[].class, int.class,
                                        int.class);

  try {
    MethodHandle mh =
      l.findVirtual(ClassLoader.class, "defineClass", mt);
    System.out.println(mh);
  } catch (NoSuchMethodException | IllegalAccessException e) {
    e.printStackTrace();
  }
}

Lookup l = MethodHandles.lookup();
lookupDefineClass(l);
```

Method handles therefore always comply with the security manager, even when the equivalent reflective code does not. They are access-checked at the point where the lookup context is constructed—the lookup object will not return handles to any methods to which it does not have proper access.

The lookup object, or method handles derived from it, can be returned to other contexts, including ones where access to the method would no longer be possible. Under those circumstances, the handle is still executable—access control is checked at lookup time, as we can see in this example:

```
public class SneakyLoader extends ClassLoader {
  public SneakyLoader() {
    super(SneakyLoader.class.getClassLoader());
  }

  public Lookup getLookup() {
    return MethodHandles.lookup();
  }
}

SneakyLoader snLdr = new SneakyLoader();
l = snLdr.getLookup();
lookupDefineClass(l);
```

With a `Lookup` object, we're able to produce method handles to any method we have access to. We can also produce a way of accessing fields that may not have a method that gives access. The `findGetter()` and `findSetter()` methods on `Lookup` produce method handles that can read or update fields as needed.

## Invoking Method Handles

A method handle represents the ability to call a method. They are strongly typed and as typesafe as possible. Instances are all of some subclass of `java.lang.invoke.MethodHandle`, which is a class that needs special treatment from the JVM.

There are two ways to invoke a method handle—`invoke()` and `invokeExact()`. Both of these take the receiver and call arguments as parameters. `invokeExact()` tries to call the method handle directly as is, whereas `invoke()` will massage call arguments if needed.

In general, `invoke()` performs an `asType()` conversion if necessary—this converts arguments according to these rules:

- A primitive argument will be boxed if required.
- A boxed primitive will be unboxed if required.
- Primitives will be widened if necessary.

- A `void` return type will be massaged to 0 or `null`, depending on whether the expected return was primitive or of reference type.
- `null` values are passed through, regardless of static type.

With these potential conversions in place, invocation looks like this:

```
Object rcvr = "a";
try {
  MethodType mt = MethodType.methodType(int.class);
  MethodHandles.Lookup l = MethodHandles.lookup();
  MethodHandle mh = l.findVirtual(rcvr.getClass(), "hashCode", mt);

  int ret;
  try {
    ret = (int)mh.invoke(rcvr);
    System.out.println(ret);
  } catch (Throwable t) {
    t.printStackTrace();
  }
} catch (IllegalArgumentException |
  NoSuchMethodException | SecurityException e) {
  e.printStackTrace();
} catch (IllegalAccessException x) {
  x.printStackTrace();
}
```

Method handles provide a clearer and more coherent way to access the same dynamic programming capabilities as Reflection. In addition, they are designed to work well with the low-level execution model of the JVM and thus hold out the promise of much better performance than Reflection can provide.

# 12 Java Platform Modules

In this chapter, we will provide a basic introduction to the *Java Platform Modules System* (JPMS). However, this is a large, complex subject—interested readers may well require a more in-depth reference, such as *Java 9 Modularity* by Sander Mak and Paul Bakker (O'Reilly).

Modules, a relatively advanced feature, are primarily about packaging and deploying entire applications and their dependencies. They were added to the platform roughly 20 years after the first version of Java and so can be seen as orthogonal to the rest of the language syntax.

Java's strong promotion of backwards compatibility also plays a role here, as non-modular applications must continue to run. This has led the architects and stewards of the Java platform to adopt a pragmatic view of the necessity of teams to adopt modules.

> There is no need to switch to modules.
>
> There has never been a need to switch to modules.
>
> Java 9 and later releases support traditional JAR files on the traditional classpath, via the concept of the unnamed module, and will likely do so until the heat death of the universe.
>
> Whether to start using modules is entirely up to you.
>
> —Mark Reinhold
> https://oreil.ly/4RjDH

Due to the advanced nature of modules, this chapter assumes you are familiar with a modern Java build tool, such as Gradle or Maven.

If you are new to Java, you can safely ignore references to those tools and just read the chapter to get a first, high-level overview of JPMS. It is not necessary for a new

Java programmer to fully understand this topic while still learning how to write Java programs.

# Why Modules?

There were several major motivating reasons for wanting to add modules to the Java platform. These included a desire for:

- Strong encapsulation
- Well-defined interfaces
- Explicit dependencies

These are all language (and application design) level, and they were combined with the promise of new platform-level capabilities as well:

- Scalable development
- Improved performance (especially startup time) and reduced footprint
- Reduced attack surface and better security
- Evolvable internals

The encapsulation point was driven by the fact that the original language specification supports only private, public, protected, and package-private visibility levels. There is no way to control access in a more fine-grained way to express concepts such as:

- Only specified packages are available as an API—others are internal and may not be accessed
- Certain packages can be accessed by this list of packages but no others
- Defining a strict exporting mechanism

The lack of these and related capabilities has been a significant shortcoming when architecting larger Java systems. Not only that, but without a suitable protection mechanism, it would be very difficult to evolve the internals of the JDK—as nothing prevents user applications from directly accessing implementation classes.

The modules system attempts to address all of these concerns at once and to provide a solution that works both for the JDK and for user applications.

## Modularizing the JDK

The monolithic JDK that shipped with Java 8 was the first target for the modules system, and the familiar `rt.jar` was broken up into modules.

> Java 8 had begun the work of modularization, by shipping a feature called *Compact Profiles* that tidied up the code and made it possible to ship a reduced runtime footprint.



`java.base` is the module that represents the minimum that's actually needed for a Java application to start up. It contains core packages, such as:

```
java.io
java.lang
java.math
java.net
java.nio
java.security
java.text
java.time
java.util
javax.crypto
javax.net
javax.security
```

along with some subpackages and nonexported implementation packages such as `sun.text.resources`. Some of the differences in compilation behavior between Java 8 and modular Java can be seen in this simple program, which extends an internal public class contained in `java.base`:

```
import java.util.Arrays;
import sun.text.resources.FormatData;

public final class FormatStealer extends FormatData {
    public static void main(String[] args) {
        FormatStealer fs = new FormatStealer();
        fs.run();
    }

    private void run() {
        String[] s = (String[]) handleGetObject("japanese.Eras");
        System.out.println(Arrays.toString(s));

        Object[][] contents = getContents();
        Object[] eraData = contents[14];
        Object[] eras = (Object[])eraData[1];
        System.out.println(Arrays.toString(eras));
    }
}
```

Attempting to compile the code on Java 11 produces this error message:

```
$ javac javanut8/ch12/FormatStealer.java
javanut8/ch12/FormatStealer.java:4:
        error: package sun.text.resources is not visible
```

```
import sun.text.resources.FormatData;
                              ^
  (package sun.text.resources is declared in module
        java.base, which does not export it to the unnamed module)
javanut8/ch12/FormatStealer.java:14: error: cannot find symbol
        String[] s = (String[]) handleGetObject("japanese.Eras");
                                 ^
  symbol:   method handleGetObject(String)
  location: class FormatStealer
javanut8/ch12/FormatStealer.java:17: error: cannot find symbol
        Object[][] contents = getContents();
                              ^
  symbol:   method getContents()
  location: class FormatStealer
3 errors
```

With a modular Java, even classes that are public cannot be accessed unless they are explicitly exported by the module they are defined in. We can temporarily force the compiler to use the internal package (basically reasserting the old access rules) with the `--add-exports` switch, like this:

```
$ javac --add-exports java.base/sun.text.resources=ALL-UNNAMED \
        javanut8/ch12/FormatStealer.java
javanut8/ch12/FormatStealer.java:5:
        warning: FormatData is internal proprietary API and may be
        removed in a future release
import sun.text.resources.FormatData;
                             ^
javanut8/ch12/FormatStealer.java:7:
        warning: FormatData is internal proprietary API and may be
        removed in a future release
public final class FormatStealer extends FormatData {
                                         ^
2 warnings
```

We need to specify that the export is being granted to the *unnamed module*, as we are compiling our class standalone and not as part of a module. The compiler warns us that we're using an internal API and that this might break with a future release of Java. When compiled and run under Java 11, this produces a list of Japanese eras, like this:

```
[, Meiji, Taisho, Showa, Heisei, Reiwa]
[, Meiji, Taisho, Showa, Heisei, Reiwa]
```

However, if we try to run under Java 17, then we have a different result:

```
$ java javanut8.ch12.FormatStealer

Error: LinkageError occurred while loading main class
        javanut8.ch12.FormatStealer

java.lang.IllegalAccessError: superclass access check failed:
```

```
class javanut8.ch12.FormatStealer (in unnamed module @0x647c3190)
        cannot access class sun.text.resources.FormatData (in module
        java.base) because module java.base does not export
        sun.text.resources to unnamed module @0x647c3190
```

This is because Java 17 now enforces additional checks as part of the tightening up of encapsulation of the internals. To get the program to run, we need to add the `--add-exports` runtime flag as well:

```
$ java --add-exports java.base/sun.text.resources=ALL-UNNAMED \
        javanut8.ch12.FormatStealer
[, Meiji, Taisho, Showa, Heisei, Reiwa]
[, Meiji, Taisho, Showa, Heisei, Reiwa]
```

Although `java.base` is the absolute runtime minimum that an application needs to start up, at compile time we want the visible platform to be as close to the old (Java 8) experience as possible.

This means that we use a much larger set of modules, contained under an *umbrella* module, `java.se`. This module has a dependency graph, shown in Figure 12-1.

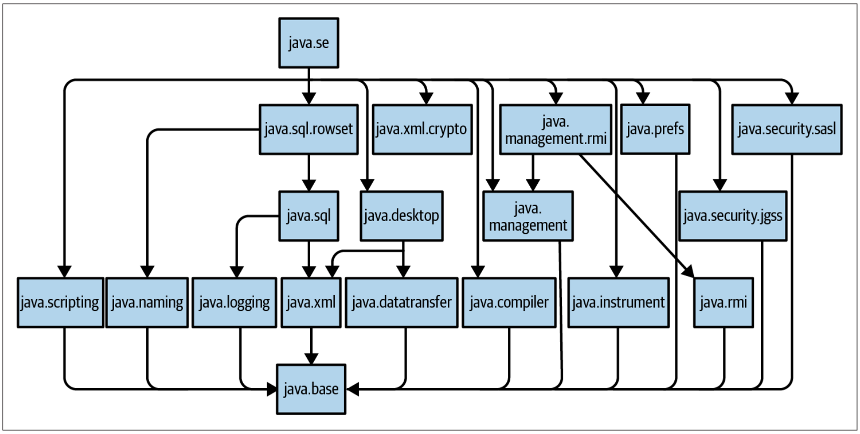


*Figure 12-1. Module dependency graph of java.se*

This brings in almost all of the classes and packages that most Java developers expect to be available.

However, one important exception is that the Java 8 packages defining the CORBA and Java EE APIs (now know as Jakarta EE) have been removed and are not part of `java.se`. This means that any project that depends on those APIs will not compile by default on Java 11 onward and a special build config must be used, to explicitly depend upon external libraries that provide these APIs.

Along with these changes to compilation visibility, due to the modularization of the JDK, the modules system is also intended to allow developers to modularize their own code.

## Writing Your Own Modules

In this section, we will discuss the basic concepts needed to start writing modular Java applications.

### Basic Modules Syntax

The key to modularizing is the new file *module-info.java*, which contains a description of a module. This is referred to as a *module descriptor*.

A module is laid out for compilation correctly on the filesystem in the following way:

- Below the source root of the project (*src*), there needs to be a directory named the same as the module (the *moduledir*).
- Inside the *moduledir* is the *module-info.java*, at the same level as where the packages start from.

The module info is compiled to a binary format, *module-info.class*, which contains the metadata that will be used when a modular runtime attempts to link and run our application. Let's look at a simple example of a *module-info.java*:

```
module httpchecker {
    requires java.net.http;

    exports httpchecker.main;
}
```

This introduces some new syntax: `module`, `exports`, and `requires`—but these are not really full keywords in the accepted sense. As stated in the Java Language Specification SE 11:

> A further ten character sequences are restricted keywords: `open`, `module`, `requires`, `transitive`, `exports`, `opens`, `to`, `uses`, `provides`, and `with`. These character sequences are tokenized as keywords solely where they appear as terminals in the `ModuleDeclaration` and `ModuleDirective` productions.

This means that these restricted keywords can appear only in the module metadata and are compiled into the binary format by `javac`. The meanings of the major restricted keywords are:

`module`
: Starts the module's metadata declaration

`requires`
: Lists a module on which this module depends

`exports`
: Declares which packages are exported as an API

The remaining (module-related) restricted keywords will be introduced throughout the rest of the chapter.

> The concept of *restricted keyword* is considerably expanded in Java 17, and as a result the description is much longer and less clear. We use the older specification here because it refers specifically to the modules system and is more suited to our purposes.

In our example, this means that we're declaring a module `httpchecker` that depends upon the module `java.net.http` that was standardized in Java 11 (as well as an implicit dependency on `java.base`). The module exports a single package, `httpchecker.main`, which is the only package in this module that will be accessible from other modules at compile time.



## Building a Simple Modular Application

As an example, let's build a simple tool that checks whether websites are using HTTP/2 yet, using the API that we met in Chapter 10:

```
import static java.net.http.HttpResponse.BodyHandlers.ofString;

public final class HTTP2Checker {
    public static void main(String[] args) throws Exception {
        if (args.length == 0) {
            System.err.println("Provide URLS to check");
        }
        for (final var location : args) {
            var client = HttpClient.newBuilder().build();
            var uri = new URI(location);
            var req = HttpRequest.newBuilder(uri).build();

            var response = client.send(req,
                    ofString(Charset.defaultCharset()));
            System.out.println(location +": "+ response.version());
        }
    }
}
```

This relies on two modules—`java.net.http` and the ubiquitous `java.base`. The module file for the app is very simple:

```
module http2checker {
    requires java.net.http;
    exports httpchecker.main;
}
```

Assuming a simple, standard module layout, this can be compiled like this:

```
$ javac -d out/httpchecker \
        httpchecker/httpchecker/main/HTTP2Checker.java \
        httpchecker/module-info.java
```

This creates a compiled module in the *out/* directory. For use, it needs to be packaged as a JAR file:

```
$ jar --create --file httpchecker.jar \
        --main-class httpchecker.main.HTTP2Checker \
        -C out/httpchecker .
```

The `--create` switch tells `jar` to create a new jar, which will include the classes contained in the directory. The final `.` at the end of the command is mandatory and signifies that all of the class files (relative to the path specified with `-C`) should be packaged into the jar.

We used the `--main-class` switch to set an *entry point* for the module—that is, a class to be executed when we use the module as an application. Let's see it in action:

```
$ java -jar httpchecker.jar http://www.google.com
http://www.google.com: HTTP_1_1
$ java -jar httpchecker.jar https://www.google.com
https://www.google.com: HTTP_2
```

This shows that, at the time of writing, Google's website was using HTTP/2 to serve its main page over HTTPS but still using HTTP/1.1 for the legacy unencrypted HTTP service.

Now that we have seen how to compile and run a simple modular application, let's meet some more of the core features of modularity that are needed to build and run full-size applications.

## The Module Path

Many Java developers are familiar with the concept of the classpath. When working with modular Java applications, we instead need to work with the *module path*. This is a new concept for modules that replaces the classpath wherever possible.

Modules carry metadata about their exports and dependencies—they are not just a long list of types. This means a graph of module dependencies can be built easily and module resolution can proceed efficiently.

Code that is not yet modularized continues to be placed on the classpath. This code is loaded into the *unnamed module*, which is special and can read all other modules that can be reached from `java.se`. Using the unnamed module happens automatically when classes are placed on the classpath.

This provides a migration path to adopting a modular Java runtime without having to migrate to a fully modular application path. However, it does have two major drawbacks: none of the benefits of modules will be available until the app is fully migrated, and the self-consistency of the classpath must be maintained by hand until modularization is complete.

## Automatic Modules

One of the constraints of the modules system is that we can't reference JARs on the classpath from named modules. This is a safety feature—the designers of the module system wanted the module dependency graph to utilize full metadata and be able to rely on the completeness of that metadata.

However, there may be times when modular code needs to reference packages that have not yet been modularized. The solution for this is to place the unmodified JAR onto the module path directly (and remove it from the classpath). A JAR placed on the module path like this becomes an *automatic module*.

This has the following features:

- Module name derived from JAR name (or read from `MANIFEST.MF`)
- Exports every package
- Requires all other modules (including the unnamed module)

This is another feature designed to mitigate and help with migration, but some safety is still being given up by using automatic modules.

## Open Modules

As noted, simply marking a method `public` no longer guarantees that the element will be accessible everywhere. Instead, accessibility also now depends upon whether the package containing that element is exported by its defining module. Another major issue in the design of modules is the use of reflection to access classes.

Reflection is such a wide-ranging, general-purpose mechanism that it is difficult to see, at first glance, how it can be reconciled with the strong encapsulation goals of JPMS. Worse yet, so many of the Java ecosystem's most important libraries and frameworks rely on reflection (e.g., unit testing, dependency injection, and many more) that not having a solution for reflection would make modules impossible to adopt for any real application.

The solution provided is twofold. First, a module can declare itself an `open` module, like this:

```
open module jin8 {
    exports jin8.api;
}
```

This declaration has the effect that:

- All packages in the module can be accessed via reflection
- Compile-time access is *not* provided for nonexported packages

This means that the configuration behaves like a standard module at compile time. The overall intent is to provide simple compatibility with existing code and frameworks and ease migration pain. With an open module, the previous expectation of being able to reflectively access code is restored. In addition, the `setAccessible()` hack that allows access to `private` and other methods that would not normally permit access is preserved for open modules.

Finer-grained control over reflective access is also provided via the `opens` restricted keyword. This does not create an open module but instead selectively opens specific packages for reflective access by explicitly declaring certain packages to be accessible via reflection:

```
module ojin8 {
    exports ojin8.api;
    opens ojin8.domain;
}
```

This type of usage is likely to be useful when, for example, you are providing a domain model to be used by a module-aware *object-relational mapping* (ORM) system that needs full reflective access to the core domain types of a module.

It is possible to go further and restrict reflective access to specific client packages, using the `to` restricted keyword. Where possible, this can be a good design principle, but of course such a technique will not work well with a general-purpose framework such as an ORM.

> In a similar way, it is possible to restrict the export of a package to only specific external packages. However, this feature was added largely to help with the modularization of the JDK itself, and it has limited applicability to user modules.

Not only that, it is also possible to both export and open a package, but this is not recommended—during migration, access to a package should ideally be either compile-time or reflective but not both.

In the case where reflective access is required to a package now contained in a module, the platform provides some switches to act as band-aids for the transitional period.

In particular, the `java` option `--add-opens module/package=ALL-UNNAMED` can be used to open a specific package of module for reflective access to all code from the classpath, overriding the behavior of the modules system. For code that is already modular, it can also be used to allow reflective access to a specific module.

When you are migrating to modular Java, any code that reflectively accesses internal code of another module should be run with that switch at first, until the situation can be remediated.

Related to this issue of reflective access (and a special case of it) is the issue of widespread use of internal platform APIs by frameworks. This is usually characterized as the "Unsafe problem" and we will encounter it toward the end of the chapter.

## Providing Services

The modules system includes the *services* mechanism, to mitigate another problem with an advanced form of encapsulation. This problem is simply explained by considering a familiar piece of code:

```
import com.example.Service;

Service s = new ServiceImpl();
```

Even if `Service` lives in an exported API package, this line of code still will not compile unless the package containing `ServiceImpl` is also exported. What we need is a mechanism to allow fine-grained access to classes implementing service classes without needing the entire package to be imported. For example, we could write something like:



```
module jin8 {
    exports jin8.api;
    requires othermodule.services;

    provides services.Service with jin8.services.ServiceImpl;
}
```

Now the `ServiceImpl` class is accessible at compile time as an implementation of the `Service` interface. Note that the `services` package must be contained in another module, which is required by the current module for this provision to work.

## Multi-Release JARs

To explain the problem that is solved by multi-release JARs, let's consider a simple example: finding the process ID (PID) of the currently executing process (i.e., the JVM that's executing our code).

> We don't use the HTTP/2 example from earlier on, as Java 8 doesn't have an HTTP/2 API—so we would have had to do a huge amount of work (essentially a full backport!) to provide the equivalent functionality for 8.

This may seem like a simple task, but on Java 8 this requires a surprising amount of boilerplate code:

```
public class GetPID {
    public static long getPid() {
        // This rather clunky call uses JMX to return the name that
        // represents the currently running JVM. This name is in the
        // format <pid>@<hostname>—on OpenJDK and Oracle VMs only—there
        // is no guaranteed portable solution for this on Java 8
        final String jvmName =
            ManagementFactory.getRuntimeMXBean().getName();
        final int index = jvmName.indexOf('@');
```

```
            if (index < 1)
                return -1;

            try {
                return Long.parseLong(jvmName.substring(0, index));
            } catch (NumberFormatException nfe) {
                return -1;
            }
        }
    }
```

As we can see, this is nowhere near as straightforward as we might like. Worse still, it is not supported in a standard way across all Java 8 implementations. Fortunately, from Java 11 onward, we can use the new `ProcessHandle` API, like this:

```
    public class GetPID {
        public static long getPid() {
            // Use new Java 9 Process API...
            ProcessHandle processHandle = ProcessHandle.current();
            return processHandle.getPid();
        }
    }
```

This now utilizes a standard API, but it leads to an essential problem: how can the developer write code that is guaranteed to run on all current Java versions?

What we want is to build and run a project correctly in multiple Java versions. We want to depend on library classes that are only available in later versions but still run on an earlier version by using some code "shims." The end result must be a single JAR, and we do not require the project to switch to a multimodule format—in fact, the JAR must work as an automatic module.

Let's look at an example project that has to run correctly in both Java 8 and Java 11 or higher. The main codebase is built with Java 8, and the Java 11 portion must be built with Java 11. This part of the build must be isolated from the main codebase to prevent compilation failures, although it can depend on the build artifacts of the Java 8 build.

To keep the build configuration simple, this feature is controlled using an entry in `MANIFEST.MF` within the JAR file:

```
    Multi-Release: True
```

The variant code (i.e., that for a later version) is then stored in a special directory in *META-INF*. In our case, this is *META-INF/versions/11*.

For a Java runtime that implements this feature, any classes in the version-specific directory override the versions in the content root. On the other hand, for Java 8 and earlier versions, both the manifest entry and the *versions/* directory are ignored and only the classes in the content root are found.

## Converting to a Multi-Release JAR

To start deploying your software as a multi-release JAR, follow this outline:

1. Isolate code that is JDK-version-specific
2. If possible, place that code into a package or group of packages
3. Get the version 8 project building cleanly
4. Create a new, separate project for the supplementary classes
5. Set up a single dependency for the new project (the version 8 artifact)

For Gradle, you can also use the concept of a *source set* and compile the v11 code using a different (later) compiler. This can then be built into a JAR using a stanza like this:

```
jar {
  into('META-INF/versions/11') {
     from sourceSets.java11.output
  }

  manifest.attributes(
     'Multi-Release': 'true'
  )
}
```

For Maven, the current easiest route is to use the Maven Dependency Plug-in and add the modular classes to the overall JAR as part of the separate `generate-resources` phase.

## Migrating to Modules

Many Java developers are facing the question of whether, and when, they should migrate their applications to use modules.

> Modules should be the default for all greenfield apps, especially those that are architected in a microservices style.

Many applications will not need to be migrated at all. However, modularizing existing code bases can be worthwhile because the better encapsulation and overall architectural benefits do pay off over the longer term—allowing new developers to be brought onto the team faster and providing a clear structure that is easier to understand and maintain.

When considering migration of an existing app (especially a monolithic design), you can use the following roadmap:

1. First upgrade the application runtime to Java 17 (running from the classpath initially)
2. Identify any application dependencies that have been modularized and migrate those dependencies to modules
3. Retain any nonmodularized dependencies as automatic modules
4. Introduce a single *monolithic module* of all application code

At this point, a minimally modularized application should be ready for production deployment. This module will usually be an `open` module at this stage of the process. The next step is architectural refactoring; at this point, applications can be broken out into individual modules as needed.

Once the application code runs in modules, it can make sense to limit reflective access to your code via `opens`. This access can be restricted to specific modules (such as ORM or dependency injection modules) as a first step toward removing any unnecessary access.

For Maven users, it's worth remembering that Maven is not a modules system, but it does have dependencies—and (unlike JPMS dependencies) they are versioned. The Maven tooling is still evolving to fully integrate with JPMS (and many plug-ins have not caught up at the time of this writing). However, some general guidelines for modular Maven projects are emerging, specifically:

- Aim to produce one module per Maven POM
- Don't modularize a Maven project until you are ready (or have an immediate need to)
- Remember that running on a Java 11+ runtime does not require building on a Java 11+ toolchain

The last point indicates that one path for migration of Maven projects is to start by building as a Java 8 project and ensuring that those Maven artifacts can deploy cleanly (as automatic modules) on a Java 11 (or 17) runtime. Only once that first step is working properly should a full modularization be undertaken.

Some good tooling support is available to help with the modularization process. Java 8 and up ships with `jdeps` (see Chapter 13), a tool for determining which packages and modules your code depends upon. This is very helpful for migrations from Java 8 and the use of `jdeps` when rearchitecting is recommended.

## Custom Runtime Images

One of the key goals of JPMS is the possibility that applications may need not every class present in the traditional monolithic runtime of Java 8 and instead can manage with a smaller subset of modules. Such applications can have a much smaller footprint in terms of startup time and memory overhead. This can be taken further: if not all classes are needed, then why not ship an application together with a reduced, custom runtime image that includes only what's necessary?

To demonstrate the idea, let's package the HTTP/2 checker into a standalone tool with a custom runtime. We can use the jlink tool (which has been part of the platform since Java 9) to achieve this:

```
$ jlink --module-path httpchecker.jar:$JAVA_HOME/jmods \
      --add-modules httpchecker,jdk.crypto.ec \
      --launcher http2chk=httpchecker \
      --output http2chk-image
```

Note that this assumes that JAR file *httpchecker.jar* was created with a main class (aka entry point). The result is an output directory, *http2chk-image*, which is about 39M in size, much less than the full image. This also notes that because the tool uses the new HTTP module, it requires the libraries for security, crypto, and so on when connecting using HTTPS.

Modules

From within the custom image directory, we can run the `http2chk` tool directly and see that it works even when the machine does not have the required version of `java`:

```
$ java -version
java version "1.8.0_144"
Java(TM) SE Runtime Environment (build 1.8.0_144-b01)
Java HotSpot(TM) 64-Bit Server VM (build 25.144-b01, mixed mode)
$ ./bin/http2chk https://www.google.com
https://www.google.com: HTTP_2
```

The deployment of custom runtime images is still quite a new tool, but it has great potential to reduce your code footprint and help Java remain competitive in the age of microservices. In the future, `jlink` could even be combined with new approaches to compilation, including an ahead-of-time (AOT) compiler.

# Issues with Modules

The modules system, despite being the flagship feature of Java 9 and having had a large amount of engineering time devoted to it, is not without its problems. This was, perhaps, inevitable—the feature fundamentally changes how Java applications are architected and delivered. It would have been almost impossible for modules to avoid running up against some problems when trying to retrofit over the large, mature ecosystem that is Java.

## Unsafe and Related Problems

`sun.misc.Unsafe` is a class that is both widely used and popular with framework writers and other implementors within the Java world. However, it is an internal implementation class and is not part of the standard API of the Java platform (as the package name clearly indicates). The class name also provides a fairly strong clue that this is not really intended for use by Java applications.

`Unsafe` is an unsupported, internal API and so could be withdrawn or modified by any new Java version, without regard to the effect on user applications. Any code that does use it is technically directly coupled to the HotSpot JVM and is also potentially nonstandard and may not run on other implementations.

Although not an official part of Java SE in any way, `Unsafe` has become a de facto standard and key part of the implementation of basically every major framework in one way or another. Over subsequent versions it has evolved into a kind of dumping ground for nonstandard but necessary features. This admixture of features is a real mixed bag, with varying degrees of safety provided by each capability. Example uses of `Unsafe` include:

- Fast serialization/deserialization
- Threadsafe 64-bit sized native memory access (e.g., offheap)
- Atomic memory operations (e.g., Compare-and-Swap)
- Fast field/memory access
- Multi-operating system replacement for JNI
- Access to array items with volatile semantics (see Chapter 6)

The essential problem is that many frameworks and libraries were unable to move to a modular JDK without replacement for some `Unsafe` features. In turn, this impacts everyone using any libraries from a wide range of frameworks—basically every application in the Java ecosystem.

To fix this problem, Oracle created new, supported APIs for some of the needed functionality and segregated APIs that could not be encapsulated in time into a module, `jdk.unsupported`. This makes it clear this is not a supported API and that developers use it at their own risk. This gives `Unsafe` a temporary pass (which is strictly limited time) while encouraging library and framework developers to move to the new APIs.

An example of a replacement API is VarHandles. These extend the *Method Handles* concept (from Chapter 11) and add new functionality, such as concurrency barrier modes for Java 11. These, along with some modest updates to JMM, are intended to produce a standard API for accessing new low-level processor features without allowing developers full access to dangerous capabilities, as were found in `Unsafe`.

More details about `Unsafe` and related low-level platform techniques can be found in *Optimizing Java* (O'Reilly).

## Lack of Versioning

The JPMS standard as of Java 17 does not include the versioning of dependencies.

> This was a deliberate design decision to reduce the complexity of the delivered system and does not preclude the possibility that modules could include versioned dependencies in the future.



The current situation requires external tools to handle the versioning of module dependencies. In the case of Maven, this will be within the Project Object Model (POM). An advantage to this approach is that the download and management of versions are also handled within the local repository of the build tool.

However it is done, though, the simple fact is that the dependency version information must be stored out of the module and does not form part of the JAR artifact.

There's no getting away from it—this is pretty ugly, but the counterpoint is that the situation is no worse than it was with dependencies being deduced from the classpath.

## Slow Adoption Rates

With the release of Java 9, the Java release model fundamentally changed. Java 8 and 9 used the "keystone release" model—where one keystone (or landmark) feature such as lambdas for Java 8 or modules for Java 9—essentially defined the release and so the ship date was determined by when the feature was complete.

The problem with this model is that it can cause inefficiencies due to uncertainty about when versions will ship. In particular, a small feature that just misses a release will have to wait a long time for the next major release. As a result, from Java 10 onward, a new release model was adopted, which introduces *strict time-based versioning*.

This means:

- Java releases are now classified as *feature* releases, which occur at a regular cadence of once every six months.
- Features are not merged into the platform until they are essentially complete.
- The mainline repo is in a releasable state at all times.

These releases are good for only six months, after which time they are no longer supported. Certain releases are designated by Oracle as *long-term support* (LTS) releases. These have extended, paid-for support available from Oracle.

The release cadence of these LTS releases was initially three years but at time of writing is expected to change to two years. This means that Oracle LTS releases are currently 8 (retrospectively added), 11, and 17; the expected next release will be Java 21 in September 2023.

However, as well as Oracle, builds of OpenJDK are available from other providers including Amazon, Azul, Eclipse Adoptium, IBM, Microsoft, Red Hat, and SAP. These vendors offer various ways to get JDK updates (including security) at zero cost.

There are also new and existing paid support models available from several of the above vendors.

For an in-depth write-up of this topic, please see the guide: "Java Is Still Free" by the Java Champions community, an independent body of Java leaders in the software industry.

Although the Java community is generally positive on the new faster release cycle, adoption rates of Java 9 and above have been much smaller than for previous releases. This may be due to the desire of teams to have longer support cycles, rather than upgrading to each feature release after only six months. In practice, only the LTS releases are seeing widespread adoption, and even that has been slow compared to the rapid uptake of Java 8.

It is also the case that the upgrade from Java 8 to 11 (or 17) is not a drop-in replacement (unlike 7 to 8, and to a lesser extent 6 to 7). The modules subsystem fundamentally changes many aspects of the Java platform, even if end-user applications do not take advantage of modules.

Four years after the release of Java 11, it seems to have finally overtaken Java 8, with more workloads now running on Java 11 than 8. It remains to be seen how quickly Java 17 will be adopted and what the impact of Java 21 will be (assuming that 21 is indeed the next LTS).

# Summary

The modules feature, first introduced in Java 9, aims to solve several problems at once. The aims of shorter startup time, lower footprint, and reduced complexity by denying access to internals have all been met. The longer-term goals of enabling better architecture of applications and starting to think about new approaches for compilation and deployment are still in progress.

However, the plain fact is that, as of the release of Java 17, not many teams and projects have moved wholeheartedly to the modular world. This is to be expected, as modularity is a long-term project that has a slow payoff and relies on network effects within the ecosystem to achieve the full benefit.

New applications should definitely consider building in a modular way from the get-go, but the overall story of platform modularity within the Java ecosystem is still only beginning.

# 13
# Platform Tools

This chapter discusses the tools that ship with the OpenJDK version of the Java platform. The tools covered are all command-line tools. If you are using a different version of Java, you may find different tools as part of your distribution but with similar function.

Later in the chapter, we devote dedicated sections to two tools: `jshell`, which introduced interactive development to the Java platform, and Java Flight Recorder (JFR) tooling for deep profiling of Java applications.

## Command-Line Tools

The command-line tools we cover are the most commonly used tools and those of greatest utility—they are not a complete description of every available tool. In particular, tools concerned with CORBA and the server portion of RMI are not covered, as these modules were removed from the platform with the release of Java 11.

> In some cases, we need to discuss switches that take filesystem paths. As elsewhere in the book, we use Unix conventions for such cases.

Below we'll discuss the following tools, including their basic usage, description, and common switches:

- `javac`
- `java`

- `jar`
- `javadoc`
- `jdeps`
- `jps`
- `jstat`
- `jstatd`
- `jinfo`
- `jstack`
- `jmap`
- `javap`
- `jlink`
- `jmod`
- `jcmd`

> Options described throughout are targeted at Java 17 and may vary in older Java versions. For example, `--class-path` was introduced when `--module-path` became an option but won't work on Java 8 and earlier (which require `-cp` or `--classpath`).

## javac

### Basic usage

`bjavac` *`some`*`/`*`package`*`/MyClass.java`

### Description

`javac` is the Java source code compiler—it produces bytecode (in the form of *.class* files) from *.java* source files.

For modern Java projects, `javac` is not often used directly, as it is rather low-level and unwieldy, especially for larger codebases. Instead, modern integrated development environments (IDEs) either drive `javac` automatically for the developer or have built-in compilers for use while code is being written. For deployment, most projects will use a separate build tool, most commonly Maven or Gradle. Discussion of these tools is outside the scope of this book.

Nevertheless, it is useful for developers to understand how to use `javac`, as there are cases when compiling small codebases by hand is preferable to having to install and manage a production-grade build tool such as Maven.

#### Common switches

`-cp`, `--class-path` *<path>*
: Supply classes we need for compilation.

`-p`, `--module-path` *<path>*
: Supply application modules for compilation. See Chapter 12 for a full discussion of Java modules.

`-d` *some/dir*
: Tell `javac` where to output class files.

`@project.list`
: Load options and source files from the file *project.list*.

`-help`
: Help on options.

`-X`
: Help on nonstandard options.

`-source` *<version>*
: Control the Java version that `javac` will accept.

`-target` *<version>*
: Control the version of class files that `javac` will output.

`-profile` *<profile>*
: Control the profile that `javac` will use when compiling the application.

`-Xlint`
: Enable detail about warnings.

`-Xstdout` *<path>*
: Redirect output of compilation run to a file.

`-g`
: Add debug information to class files.

#### Notes

`javac` has traditionally accepted switches (`-source` and `-target`) that control the version of the source language that the compiler accepts and the version of the class file format used for the outputted class files.

This facility introduces additional compiler complexity (as multiple language syntaxes must be supported internally) for some small developer benefit. In Java 8, this capability was slightly tidied up and placed on a more formal basis.

From JDK 8 onward, `javac` will only accept source and target options from three versions back. That is, only the formats from JDK 5, 6, 7, and 8 will be accepted by `javac` version 8. This does not affect the `java` interpreter—any class file from any Java version will still work on the JVM shipped with Java 8.

C and C++ developers may find that the `-g` switch is less helpful to them than it is in those other languages. This is largely due to the widespread use of IDEs in the Java ecosystem—integrated debugging is simply a lot more useful, and easier to use, than additional debug symbols in class files.

The use of the lint capability remains somewhat controversial among developers. Many Java developers produce code that triggers a large number of compilation warnings, which they then simply ignore. However, experience on larger codebases (especially on the JDK codebase itself) suggests that in a substantial percentage of cases, code that triggers warnings is code in which subtle bugs may lurk. Use of the lint feature, or static analysis tools (such as SpotBugs), is strongly recommended.

## java

### Basic usage

```
bjava some.package.MyClass
java -jar my-packaged.jar
```

### Description

`java` is the executable that starts up a Java Virtual Machine. The initial entry point into the program is the `main()` method that exists on the named class and that has the signature:

```
public static void main(String[] args);
```

This method is run on the single application thread created by the JVM startup. The JVM process will exit once this method returns (and any additional nondaemon application threads that were started have terminated).

If the form takes a JAR file rather than a class (the executable JAR form), the JAR file must contain a piece of metadata that tells the JVM which class to start from.

This bit of metadata is the `Main-Class:` attribute, and it is contained in the *MANIFEST.MF* file in the *META-INF/* directory. See the description of the `jar` tool for more details.

#### Common switches

`-cp`, `--class-path <path>`
: Define the classpath to read from.

`-p`, `--module-path <path>`
: Define the path to find modules.

`--list-modules`
: List modules found with current settings and exits.

`-X`, `-?`, `-help`
: Provide help about the `java` executable and its switches.

`-D<property=value>`
: Set a Java system property that can be retrieved by the Java program. Any number of such properties can be specified this way.

`-jar`
: Run an executable JAR (see the entry for `jar`).

`-Xbootclasspath(/a or /p)`
: Run with an alternative system classpath (very rarely used).

`-client`, `-server`
: Select a HotSpot JIT compiler (see "Notes" for this entry).

`-Xint`, `-Xcomp`, `-Xmixed`
: Control JIT compilation (very rarely used).

`-Xms<size>`
: Set the minimum committed heap size for the JVM.

`-Xmx<size>`
: Set the maximum committed heap size for the JVM.

`-agentlib:<agent>`, `-agentpath:<path to agent>`
: Specify a JVM Tooling Interface (JVMTI) agent to attach to the process being started. Agents are typically used for instrumentation or monitoring.

`-verbose`
: Generate additional output, sometimes useful for debugging.

#### Notes

The HotSpot VM contains two separate JIT compilers—known as the client (or C1) compiler and the server (or C2) compiler. These were designed for different purposes, with the client compiler offering more predictable performance and quicker startup, at the expense of not performing aggressive code optimization.

Traditionally, the JIT compiler that a Java process used was chosen at process startup via the `-client` or `-server` switch. However, as hardware advances have made compilation ever cheaper, a new possibility has become available—to use the client compiler early on, while the Java process is warming up, and then to switch to the high-performance optimizations available in the server compiler when they are available. This scheme is called Tiered Compilation, and it is the default in Java 8. Most processes will no longer need explicit `-client` or `-server` switches.

On the Windows platform, a slightly different version of the `java` executable is often used—`javaw`. This version starts up a Java Virtual Machine, without forcing a Windows console window to appear.

In older Java versions, a number of different legacy interpreters and virtual machine modes were supported. These have now mostly been removed and any remaining should be regarded as vestigial.

Switches that start with `-X` were intended to be nonstandard switches. However, the trend has been to standardize a number of these switches (particularly `-Xms` and `-Xmx`). In parallel, Java versions have introduced an increasing number of `-XX:` switches. These were intended to be experimental and not for production use. However, as the implementations have stabilized, some of these switches are now suitable for some advanced users (even in production deployments).

In general, a full discussion of switches is outside the scope of this book. Configuration of the JVM for production use is a specialist subject, and developers are urged to take care, especially when modifying any switches related to the garbage collection subsystem.

## jar

### Basic usage

`jar cvf my.jar` *`someDir/`*

### Description

The `jar` utility is used to create and manipulate Java Archive (*.jar*) files. These are ZIP format files that contain Java classes, additional resources, and (usually) metadata. The tool has five major modes of operation—Create, Update, Index, List, and Extract—on a JAR file.

These are controlled by passing a command option character (not a switch) to `jar`. Only one command character can be specified, but optional modifier characters can also be used.

#### Command options

- `c`: Create a new archive
- `u`: Update archive
- `i`: Index an archive
- `t`: List an archive
- `x`: Extract an archive

#### Modifiers

- `v`: Verbose mode
- `f`: Operate on a named file, rather than standard input
- `0`: Store, but do not compress, files added to the archive
- `m`: Add the contents of the specified file to the `jar` metadata manifest
- `e`: Make this `jar` executable, with the specified class as the entry point

Platform Tools

#### Notes

The syntax of the `jar` command is intentionally very similar to that of the Unix `tar` command. This similarity is the reason `jar` uses command options, rather than switches (as the other Java platform commands do). More typical explicit switches (e.g. `--create`) are also available and documentation for them can be found via `jar --help`.

When you create a JAR file, the `jar` tool will automatically add a directory called *META-INF* that contains a file called *MANIFEST.MF*—this is metadata in the form of headers paired with values. By default, *MANIFEST.MF* contains just two headers:

```
Manifest-Version: 1.0
Created-By: 17.0.4 (Eclipse Adoptium)
```

Using the `m` option allows additional metadata to be added into *MANIFEST.MF* at JAR creation time. One frequently added piece is the `Main-Class:` attribute, which indicates the entry point into the application contained in the JAR. A JAR with a specified `Main-Class:` can be directly executed by the JVM, via `java -jar`, or double-clicking the JAR in a graphical file browser.

The addition of the `Main-Class:` attribute is so common that `jar` has the `e` option to create it directly in *MANIFEST.MF*, rather than having to create a separate text file for this purpose. Contents of a jar, including the manifest, may be inspected easily using the `--extract` option.

## javadoc

### Basic usage

```
javadoc some.package
```

### Description

`javadoc` produces documentation from Java source files. It does so by reading a special comment format (known as Javadoc comments) and parsing it into a standard documentation format, which can then be output into a variety of document formats (although HTML is by far the most common).

For a full description of Javadoc syntax, refer to Chapter 7.

### Common switches

`-cp`, `--class-path` *<path>*
: Define the classpath to use.

`-p`, `--module-path` *<path>*
: Define the path to find modules.

`-D` *<directory>*
: Tell `javadoc` where to output the generated docs.

`-quiet`
: Suppress output except for errors and warnings.

### Notes

The platform API docs are all written in Javadoc.

`javadoc` is built on top of the same classes as `javac` and uses some of the source compiler infrastructure to implement Javadoc features.

The typical way to use `javadoc` is to run it against a whole package, rather than just a class.

`javadoc` has a very large number of switches and options that can control many aspects of its behavior. Detailed discussion of all the options is outside the scope of this book.

## jdeps

bThe `jdeps` tool is a static analysis tool for analyzing the dependencies of packages or classes. The tool has a number of usages, from identifying developer code that makes calls into the internal, undocumented JDK APIs (such as the `sun.misc` classes) to helping trace transitive dependencies.

`jdeps` can also be used to confirm whether a JAR file can run under a Compact Profile (see later in the chapter for more details on Compact Profiles).

### Basic usage

```
jdeps com.me.MyClass
```

### Description

`jdeps` reports dependency information for the classes it is asked to analyze. The classes can be specified as any class on the classpath, a file path, a directory, or a JAR file.

### Common switches

`-cp`, `--class-path` *`<path>`*
: Define the classpath to use.

`-p`, `--module-path` *`<path>`*
: Define the path to find modules.

`-s`, `-summary`
: Print dependency summary only.

`-m` *`<module-name>`*
: Target a module for analysis

`-v`, `-verbose`
: Print all class-level dependencies.

`-verbose:package`
: Print package-level dependencies, excluding dependencies within the same archive.

`-verbose:class`
: Print class-level dependencies, excluding dependencies within the same archive.

Platform Tools

`-p <pkg name>, -package <pkg name>`
: Find dependencies in the specified package. You can specify this option multiple times for different packages. The `-p` and `-e` options are mutually exclusive.

`-e <regex>, -regex <regex>`
: Find dependencies in packages matching the specified regular expression pattern. The `-p` and `-e` options are mutually exclusive.

`-include <regex>`
: Restrict analysis to classes matching pattern. This option filters the list of classes to be analyzed. It can be used together with `-p` and `-e`.

`-jdkinternals`
: Find class-level dependencies in JDK internal APIs (which may change or disappear in even minor platform releases).

`-apionly`
: Restrict analysis to APIs—for example, dependencies from the signature of public and protected members of public classes including field type, method parameter types, returned type, and checked exception types.

`-R`, `-recursive`
: Recursively traverse all dependencies.

`-h`, `-?`, `--help`
: Print help message for `jdeps`.

### Notes

`jdeps` is a useful tool for making developers aware of their dependencies on the JRE not as a monolithic environment but as something more modular.

## jps

### Basic usage

```
jps
jps <remote URL>
```

### Description

`jps` provides a list of all active JVM processes on the local machine (or a remote machine, if a suitable instance of `jstatd` is running on the remote side). Remote URL support requires RMI; this configuration is explained in more detail in the `jstatd` section.

#### Common switches

`-m`
: Output the arguments passed to the main method.

`-l`
: Output the full package name for the application's main class (or the full path name to the application's JAR file).

`-v`
: Output the arguments passed to the JVM.

#### Notes

This command is not strictly necessary, as the standard Unix `ps` command could suffice. However, it does not use the standard Unix mechanism for interrogating the process, so there are circumstances in which a Java process stops responding (and looks dead to `jps`) but is still listed as alive by the operating system.



## jstat

#### Basic usage

```
jstat -options
jstat <report type such as -class> <PID>
```

#### Description

This command displays some basic statistics about a given Java process. This is usually a local process but can be located on a remote machine, provided the remote side is running a suitable `jstatd` process.

#### Common switches

`-options`
: List report types that `jstat` can produce. Most common options are:

  `-class`
  : Report on classloading activity to date.

  `-compiler`
  : JIT compilation of the process so far.

  `-gcutil`
  : Detailed garbage collection report.

`-printcompilation`
: More detail on compilation.

#### Notes

The general syntax `jstat` uses to identify a process (which may be remote) is:

```
[<protocol>://]<vmid>[@hostname][:port][/servername]
```

This syntax is used to specify a remote process (which is usually connected to via JMX over RMI), but in practice, the more common local syntax simply uses the VM ID, which is the operating system process ID (PID) on mainstream platforms (Linux, Windows, Unix, macOS, etc.).

## jstatd

#### Basic usage

`jstatd <options>`

#### Description

`jstatd` makes information about local JVMs available over the network. It achieves this using RMI and can make these otherwise-local capabilities accessible to JMX clients. This requires special security settings, which differ from the JVM defaults. To start `jstatd`, first we need to create the following file and name it *jstatd.policy*:

```
grant codebase "jrt:/jdk.jstatd" {
   permission java.security.AllPermission;
};

grant codebase "jrt:/jdk.internal.jvmstat" {
   permission java.security.AllPermission;
};
```

This policy file grants all security permissions to any class loaded from the JDK modules that implement `jstatd`. The precise policy requirements changed with the introduction of modules in JDK 9 and may vary in future JDK versions.

To launch `jstatd` with this policy, use this command line:

```
jstatd -J-Djava.security.policy=<path to jstat.policy>
```

#### Common switches

`-p <port>`
: Look for an existing RMI registry on that port and create one if not found.

#### Notes

It is recommended that `jstatd` is always switched on in production environments but not over the public internet. For most corporate and enterprise environments, this is nontrivial to achieve and will require the cooperation of Operations and Network Engineering staff. However, the benefits of having telemetry data from production JVMs, especially during outages, are difficult to overstate.

A full discussion of JMX and monitoring techniques is outside the scope of this book.

---

## jinfo

#### Basic usage

```
jinfo <PID>
jinfo <core file>
```

#### Description

This tool displays the system properties and JVM options for a running Java process (or a core file).

#### Common switches

`-flags`
: Display JVM flags only.

`-sysprops`
: Display system properties only.

#### Notes

In practice, this is very rarely used—although it can occasionally be helpful as a sanity check that the expected program is actually the one that is executing.

---

## jstack

#### Basic usage

```
jstack <PID>
```

#### Description

The `jstack` utility produces a stack trace for each Java thread in the process.

#### Common switches

`-e`
: Extended mode (contains additional information about threads).

`-l`
: Long mode (contains additional information about locks).

#### Notes

Producing the stack trace does not stop or terminate the Java process. The files that `jstack` produces can be very large, and some postprocessing of the file is usually necessary.

## jmap

#### Basic usage

`jmap <output option> <process>`

#### Description

`jmap` provides a view of memory allocation for a running Java process.

#### Common switches

*-dump:<option>,file=<location;>*
: Produce a heap dump from the running process.

*-histo*
: Produce a histogram of the current state of allocated memory.

*-histo:live*
: This version of the histogram displays information only for live objects.

#### Notes

The histogram forms walk the JVMs allocation list. This includes both live and dead (but not yet collected) objects. The histogram is organized by the type of objects using memory and is ordered from greatest to least number of bytes used by a particular type. The standard form does not pause the JVM.

The live form ensures that it is accurate by performing a full, stop-the-world (STW) garbage collection before executing. As a result, it should not be used on a production system at a time when a full GC would appreciably impact users.

For the `-dump` form, note that the production of a heap dump can be a time-consuming process and is STW. The size of the resulting file is proportional to the currently allocated heap and hence may be extremely large for some processes.

## javap

### Basic usage

```
javap <classname>
javap <path/to/ClassFile.class>
```

### Description

`javap` is the Java class disassembler—effectively a tool for peeking inside class files. It can show the bytecode that Java methods have been compiled into, as well as the constant pool information (which contains information similar to that of the symbol table of Unix processes).

By default, `javap` shows signatures of `public`, `protected`, and default methods. The `-p` switch will also show `private` methods.

### Common switches

`-c`
: Decompile bytecode

`-v`
: Verbose mode (include constant pool information)

`-p`
: Include `private` methods

`-cp`, `--class-path`
: Location of classes if loading by class name

`-p`, `--module-path`
: Location of modules if loading by class name

### Notes

The `javap` tool will work with any class file, provided `javap` is from a JDK version the same as (or later than) the one that produced the file.

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> Some Java language features may have surprising implementations in bytecode. For example, as we saw in Chapter 9, Java's String class has effectively immutable instances, and the JVM implements the string concatenation operator + in a different way in Java versions after 8. This difference is clearly visible in the disassembled bytecode shown by javap.

## jlink

### Basic usage

```
jlink [options] --module-path modulepath --add-modules module
```

### Description

jlink is the custom runtime image linker for the Java platform—a tool for linking and packaging Java classes, modules, and their dependencies into a custom runtime image. The image created by the jlink tool will comprise a linked set of modules, along with their transitive dependences.

### Common switches

--add-modules *<module>* [, *module1*]
: Add modules to the root set of modules to be linked

--endian {little|big}
: Specify the endianness of the target architecture

--module-path *<path>*
: Specify the path where the modules for linking can be found

--save-opts *<file>*
: Save the options to the linker in the specified file

--help
: Print help information

@filename
: Read options from filename instead of the command line

### Notes

The jlink tool will work with any class file or module and linking will require the transitive dependencies of the code to be linked.

Custom runtime images don't have any support for automatic updates by default. This means developers are responsible for rebuilding and updating their own applications in the field when necessary. Some Java language features may have restrictions, as the runtime image may not include the full JDK; therefore, reflection and other dynamic techniques may not be fully supported.

## jmod

### Basic usage

`jmod create [options] my-new.jmod`

### Description

`jmod` prepares Java software components for use by the custom linker (`jlink`). The result is a *.jmod* file. This should be considered an intermediate file, not a primary artifact for distribution.



### Basic modes

`create`
: Create a new JMOD file

`extract`
: Extract all files from a JMOD file (explode it)

`list`
: List all files from a JMOD file

`describe`
: Print details about a JMOD file

### Common switches

`--module-path path`
: Specify the module path where the core contents of the module can be found.

`--libs path`
: Specify the path where native libraries for inclusion can be found.

`--help`
: Print help information.

`@filename`
: Read options from filename instead of the command line.

#### Notes

jmod reads and writes the JMOD format, but please note that this is different from the modular JAR format and is not intended as an immediate replacement for it.

> The jmod tool is only currently intended for modules that are to be linked into a runtime image (using the jlink tool). One other possible use case is for packaging modules that have native libraries or other configuration files that must be distributed along with the module.

## jcmd

#### Basic usage

```
jcmd <PID>
jcmd <PID> <command>
```

#### Description

jcmd issues commands to a running Java process. The precise commands may vary between Java versions and may be listed by running jcmd with the process ID and no command.

#### Common switches

-f *<path>*
: Read from commands from a file rather than command-line arguments

-l
: List Java processes (similar to jps)

--help
: Print help information

#### Common commands

GC.heap_dump *<path>*
: Generate a heap dump like jmap. Note the path is relative to the Java process, *not* where jcmd is run!

GC.heap_info
: Display statistics and sizing information about the Java process heap.

JFR.start
: Begin a Java Flight Recorder (JFR) session. JFR is the JVM's built-in performance monitoring and profiling tool.

JFR.stop name=*<name from start>* filename=*<path>*
: Stop named JFR session and record to a file.

`VM.system_properties`
: Output Java process system properties.

#### Notes

> Commands to `jcmd` are grouped by the subsystem they interact with, for instance `GC` or `JFR`. There are many more commands than the examples we've given here. It's worth exploring what's available on your Java installation for help in operating the JVM in production.

## Introduction to JShell



Java is traditionally understood as a language that is class-oriented and has a distinct compile-interpret-evaluate execution model. However, in this section, we will discuss a new technology that extends this programming paradigm by providing a form of interactive/scripting capability.

With the advent of Java 9, the Java runtime and JDK bundles a new tool, JShell. This is an interactive shell for Java, similar to the REPL seen in languages like Python, Scala, or Lisp. The shell is intended for teaching and exploratory use and, due to the nature of the Java language, is not expected to be as much use to the working programmer as similar shells in other languages.

In particular, it is not expected that Java will become an REPL-driven language. Instead, this opens up an opportunity to use JShell for a different style of programming, one that complements the traditional use case but also provides new perspectives, especially for working with a new API.

It is very easy to use JShell to explore simple language features, for instance:

- Primitive data types
- Simple numeric operations
- String manipulation basics
- Object types
- Defining new classes
- Creating new objects
- Calling methods

To start up JShell, we just invoke it from the command line:

```
$ jshell
|  Welcome to JShell -- Version 17.0.4
|  For an introduction type: /help intro

jshell>
```

From here, we can enter small pieces of Java code, which are known as *snippets*:

```
jshell> 2 * 3
$1 ==> 6

jshell> var i = 2 * 3
i ==> 6
```

The shell is designed to be a simple working environment, and so it relaxes some of the rules that working Java programmers may expect. Some of the differences between JShell snippets and regular Java include:

- Semicolons are optional in JShell
- JShell supports a verbose mode
- JShell has a wider set of default imports than a regular Java program
- Methods can be declared at top level (outside of a class)
- Methods can be redefined within snippets
- A snippet may not declare a package or a module—everything is placed in an unnamed package controlled by the shell
- Only public classes may be accessed from JShell
- Due to package restrictions, it's advisable to ignore access control when defining classes and working within JShell

It's simple to create simple class hierarchies (e.g., for exploring Java's inheritance and generics):

```
jshell> class Pet {}
|  created class Pet

jshell> class Cat extends Pet {}
|  created class Cat

jshell> var c = new Cat()
c ==> Cat@2ac273d3
```

Tab completion within the shell is also possible, such as for autocompletion of possible methods:

```
jshell> c.<TAB>
equals(       getClass()    hashCode()    notify()      notifyAll()
toString()    wait(
```

Pressing the tab key twice with certain input will display documentation for a method:

```
jshell> c.hashCode(<TAB>
Signatures:
int Object.hashCode()
```

```
<press tab again to see documentation>
jshell> c.hashCode(<TAB TAB>
int Object.hashCode()
Returns a hash code value for the object. (Full Javadoc follows...)
```

We can also create top-level methods, such as:

```
jshell> int div(int x, int y) {
   ...> return x / y;
   ...> }
|  created method div(int,int)
```

Simple exception backtraces are also supported:

```
jshell> div(3,0)
|  Exception java.lang.ArithmeticException: / by zero
|        at div (#2:2)
|        at (#3:1)
```

We can access classes from the JDK:

```
jshell> var ls = List.of("Alpha", "Beta", "Gamma", "Delta", "Epsilon")
ls ==> [Alpha, Beta, Gamma, Delta, Epsilon]

jshell> ls.get(3)
$11 ==> "Delta"

jshell> ls.forEach(s -> System.out.println(s.charAt(1)))
l
e
a
e
p
```

Or explicitly import classes if necessary:

```
jshell> import java.time.LocalDateTime

jshell> var now = LocalDateTime.now()
now ==> 2018-10-02T14:48:28.139422

jshell> now.plusWeeks(3)
$9 ==> 2018-10-23T14:48:28.139422
```

The environment also allows JShell commands, which start with a `/`. It is useful to be aware of some of the most common basic commands:

- `/help intro` is the introductory help text
- `/help` is a more comprehensive entry point into the help system
- `/vars` shows which variables are in scope
- `/list` shows the shell history
- `/save` outputs accepted snippet source to a file

- `/open` reads a saved file and brings it into the environment
- `/exit` exits the jshell interface

For example, the imports available within JShell include a lot more than just `java.lang`. The whole list is loaded by JShell during startup and can be seen as the *special imports* visible through the `/list -all` command:

```
jshell> /list -all

  s1 : import java.io.*;
  s2 : import java.math.*;
  s3 : import java.net.*;
  s4 : import java.nio.file.*;
  s5 : import java.util.*;
  s6 : import java.util.concurrent.*;
  s7 : import java.util.function.*;
  s8 : import java.util.prefs.*;
  s9 : import java.util.regex.*;
 s10 : import java.util.stream.*;
```

The JShell environment is tab-completed, which greatly adds to the tool's usability. The verbose mode is particularly useful when you are getting to know JShell—it can be activated by passing the `-v` switch at startup as well as via a shell command.

## Introduction to Java Flight Recorder (JFR)

Java Flight Record (JFR) is a powerful, low-latency profiling system built directly into the JVM. It has existed for years but was available only with a commercial license prior to Java 11. Now this rich source of information is available with OpenJDK and worth exploring.

The typical JFR workflow involves starting a profile against a running JVM, downloading the results as a file, and then inspecting that file offline with the JDK Mission Control (JMC) GUI application. While JFR is embedded directly within OpenJDK, JMC isn't distributed with the JDK but can be downloaded from *https://oreil.ly/eq4cg*.

JFR recording can be started either via options at JVM startup or interactively with the `jcmd` tool shown earlier in this chapter. The following `java` invocation starts with JFR recording for two minutes, writing the results to a file when finished:

```
java -XX:StartFlightRecording=duration=120s,filename=flight.jfr \
   Application
```

Options allow for tight control over the volume of data JFR will hold in memory, either by specifying how long a recording to generate or by the size of the file that will be generated. When combined with its low overhead, it is plausible to run JFR persistently in production so data is always ready should you wish to capture it (sometimes referred to as "ring buffer" mode). This opens up a world of possibilities for debugging in amazing detail with the JFR profiles, even minutes to hours after a problem has occurred.

Along with sizing limits, JFR recording can also be configured to gather only specific information of interest. Typical areas (but only a few of the things JFR measures) include:

- Object allocation
- Garbage collection
- Threads and locks
- Method profiling

With Java 17, APIs are available in-process to consume JFR events in a streaming fashion, evolving away from the file-based profiling approaches. This opens the door for monitoring tooling to tap into this rich source of data, without the hassle of logging onto servers to ask for a profile to be dumped.

In the future, we may expect JFR to act as a data source for the new generation of Observability tools that are being adopted by the Java ecosystem, such as OpenTelemetry.



# Summary

Java has changed a huge amount over the last 15+ years, and yet the platform and community remain vibrant. To have achieved this, while retaining a recognizable language and platform, is no small accomplishment.

Ultimately, Java's continued existence and viability depend upon the individual developer. On that basis, the future looks bright, and we look forward to the next wave and beyond.

# A
# Beyond Java 17

This appendix discusses versions of Java beyond Java 17. In previous editions of *Java in a Nutshell*, we have resisted adding forward-looking material, but recent changes in the Java release model (which we discussed in Chapter 1), as well as ongoing and forthcoming Java developments, have prompted a change of tack in this new edition.

In the current model, a new version of Java is released every six months, but only certain releases are LTS. As it stands, Java 11 and 17 are regarded as LTS (with 8 retrospectively added). Note that LTS has a dual meaning: for Oracle customers it means that paid support is available for a multiyear period, while other JDK providers (including Red Hat, Microsoft, Amazon, etc.) have de facto adopted the same versions as those for which backported security and other fixes will be made publicly available—free of charge—as certified OpenJDK binaries.

The industry, as a whole, has not chosen to adopt a six-month Java upgrade cycle for various reasons, and so in practice, the LTS versions are the only ones that are likely to be deployed into production. However, most of the OpenJDK providers do diligently publish binaries for all Java releases, even those that will not be supported beyond the six-month window.

This creates a dichotomy: new features arrive every six months but are not widely deployed by teams until the next LTS, which complicates writing about specific Java versions. This is further complicated by the concept of *Incubating* and *Preview* features, which are used to experiment with new APIs and new language features, respectively, before they are finalized and become a standard part of the language.

The solution we have chosen is to target new editions of this book at LTS versions and include an appendix that covers any new features that have arrived (or are expected to arrive) since the last LTS. We have also chosen to cover only final features in the main part of the book; all discussion of Incubating and Preview features will be confined to appendices.

Let's start by covering how major development efforts are arranged within OpenJDK, then discuss Java 18 and 19, and then conclude with a look at the future beyond that release.

## Long-Term JDK Projects

OpenJDK is organized into projects that cover specific major areas of ongoing work. This includes projects that are centered on the development of future language or JVM features that can take multiyear efforts to deliver.

Four projects currently focus on the delivery of major future aspects of Java. They are usually known by their project codenames:

- Panama
- Loom
- Valhalla
- Amber

Of these, Project Panama provides two major improvements: a modern foreign-function interface for Java and support for vector CPU instructions.

It has been incubating for some time now, but Java 18 contains an interesting milestone iteration of the functionality, and so we will cover the project in the Java 18 section.

Project Loom is a new concurrency model for Java. A first preview of some of Loom's functionality will be available for the first time in Java 19, so we will discuss Loom in that section.

Project Valhalla is the most ambitious, wide-ranging, and highest-impact of all of the projects. It is also the most complex and the farthest from delivery as a shipping product. We discuss it toward the end of the appendix.

Project Amber's remit is incremental language improvements. It is probably the most familiar and easiest-to-understand of the four projects, so we'll discuss it here as our next topic.

### Amber

Amber has been running since Java 9 was delivered. It aims to deliver small chunks of useful language functionality, an approach that fits well with the new delivery schedule for Java releases. The features that have formed part of Amber and delivered so far include:

- Local Variable Type Inference (`var`)
- Switch Expressions
- Enhanced `instanceof`

- Text Blocks
- Records
- Sealed Types
- Pattern Matching

Most of these features have already been completed, but the last of these, Pattern Matching, has not been fully delivered as of Java 17. Only the simplest case, the `instanceof` pattern, has arrived as a final feature so far. Java 17 does have a Preview version of a more advanced form (as we mentioned in Chapter 5) that can be used as part of a switch expression, like this:

```
sealed interface Pet permits Cat, Dog {}
record Cat(String name) implements Pet {}
record Dog(String name) implements Pet {}

boolean isDog(Pet p) {
    return switch (p) {
        case Cat c -> false;
        case Dog d -> true;
    };
}
```

Note the lack of need for a `default` case. All `Pet` objects are either a `Cat` or a `Dog`, because the `Pet` interface is declared as sealed.

Pattern matching will truly come into its full power when further future cases arrive and are standardized as final features. In particular, the combination of pattern matching and *algebraic data types* (one of the names given to the combination of records and sealed types) is especially powerful.

We can see how Amber's approach fits with the model of biannual releases of Java; switch expressions and enhanced `instanceof` are extended and combined into the basics of pattern matching, which is then further enhanced by algebraic data types and further cases of patterns tailored to them.

# Java 18

New Java releases are made up of Java Enhancement Proposals (JEPs): a complete list of current, past, and future JEPs can be found at *https://oreil.ly/BE1r1*.

Java 18 was released in March 2022 and includes the following JEPs:

- 400: UTF-8 by Default
- 408: Simple Web Server
- 413: Code Snippets in Java API Documentation
- 416: Reimplement Core Reflection with Method Handles
- 417: Vector API (Third Incubator)

- 418: Internet-Address Resolution SPI
- 419: Foreign Function & Memory API (Second Incubator)
- 420: Pattern Matching for switch (Second Preview)

Most of these are very minor or internal implementation changes. The two JEPs related to Panama (417 and 419) are significant steps forward for the project, which we'll discuss in detail here.

## Panama

Project Panama aims to provide a modern Foreign (i.e., non-Java) interface for connecting to native code. The codename comes from the isthmus of Panama, a narrow strip connecting two larger "landmasses," understood to be the JVM and native memory (aka "off-heap").

The overall aim is to replace Java Native Interface (JNI), which is well-known to have major problems such as an excess of ceremony, extra artifacts, and a lack of interoperability with libraries written in anything other than C / C++. In fact, even for the C case, JNI does not do anything automatic to map type systems and the portions of Java and C code have to be mapped semimanually.

Panama provides two main components to assist in the interoperation of Java and native code:

- Foreign Memory and Functions API
- Vector API

The Foreign Memory API is concerned with the allocation, manipulation, and freeing of structured foreign memory, and the lifecycle management of foreign resources. This goes beyond the existing capabilities of the `ByteBuffer` class, and for example can address more than 2 GB of memory as a single segment. The issue of how foreign memory is managed is complex, as it is outside the scope of the JVM's garbage collector, and existing mechanisms such as finalization are known to be fatally flawed.

Calling foreign functions is also possible using Panama. A new command-line tool, called `jextract`, creates a Java bridge from a C header file. This bridge is built using method and var handles to provide a set of (static) Java methods that look as close as possible to the original C API.

The runtime support for this is contained in the module `jdk.incubator.foreign`, which is, unsurprisingly, an Incubating API and may well change in future versions before it ships as final. As it stands, C and C++ are the initially supported foreign languages, but other possibilities (notably Rust) are expected to be added as the project develops.

In addition to the Foreign API, Panama also provides support for vector computations by shipping an API that has these main goals:

- Clear and concise API
- Platform agnostic
- Reliable JIT compilation and performance
- Graceful degradation of vector mode back to linear instructions

Panama is initially shipping an implementation for the x64 and AArch64 CPU architectures. However, as expressed in the goals, the API does not—and must not—rule out possible implementations for other CPUs.

# Java 19

Java 19 was released in September 2022 and includes a preview of a new major feature (Loom) as well as the following selection of JEPs:

- 405: Record Patterns (Preview)
- 422: Linux/RISC-V Port
- 424: Foreign Function and Memory API (Preview)
- 426: Vector API (Fourth Incubator)
- 427: Pattern Matching for switch (Third Preview)

These JEPs are mostly continuations of the development of existing preview and incubating features, so rather than spend more time on them, we'll focus on:

- 425: Virtual Threads (Preview)
- 428: Structured Concurrency (Incubator)

These two JEPs provide the basis of the first preview delivery of Project Loom.

## Loom

In Java 17, every executing Java language thread is an OS thread because calling `Thread.start()` triggers a system call that creates an OS thread. This therefore creates a constraint between the number of available Java execution contexts and the limits of the operating system. As programming languages have evolved, this constraint has become more problematic. The OS has data structures (e.g., stack) that it creates for each thread, and it individually schedules execution of each thread.

This naturally leads to the question: how many OS threads can an application start? 1,000? Perhaps 10,000? Regardless of the exact number, there is definitely a hard limit in this approach. Project Loom is a reimagining of Java's concurrency model that is designed to transcend this limitation.

The key is *virtual threads*, a new construct that is not 1-1 with OS threads. From a Java programming perspective, virtual threads look like instances of `Thread`, but they are managed by the JVM, not the OS. This means that no OS-level data structures (e.g., for the thread's stack frames) are created, and all the management metadata is handled by the JVM. This includes the scheduling behavior; rather than the OS scheduler, a Java execution scheduler (a threadpool) is used.

When a virtual thread wants to execute, it does so on an OS *carrier thread* and runs until a blocking call (e.g., I/O) is made. The carrier thread is *yielded* to another virtual thread, and so a virtual thread may execute on several different carriers over its lifetime. The connection to blocking calls means that virtual threads are not suitable for pure CPU-bound tasks, and in general, the use of Loom is very different from approaches such as `async / await` that developers may have used in other languages.

It remains to be seen how much Loom will impact end-user devs, although there is a lot of interest from framework and library authors. An initial version is arriving as a preview in JDK 19, but it is still unclear when it'll arrive as a standard feature. Overall, the expectation in the community is that it will be finalized in the next LTS, which is expected to be Java 21.

# Future Java

Along with the completion of the projects already mentioned, longer-term efforts to evolve Java are underway: Project Valhalla and the rise of Cloud-Native Java.

Let's look at each in turn.

## Valhalla

Project Valhalla is a very ambitious OpenJDK project that has been running since 2014. The goal, "To align JVM memory layout behavior with the cost model of modern hardware," seems simple and innocuous enough.

However, this is deeply deceptive.

For starters, this divides the existing Java objects into two cases: the identity objects we're used to using and a new kind of value object whose main difference is that it doesn't have a unique identity. From these value objects, a further step is taken to allow the reference-ness, or indirection, to be removed and for the value to be directly represented by its bit patterns.

The intended use case for this new data value is small, immutable, final, identity-less types. This allows these new identity-less values to fit with both the existing object reference and primitive worlds, getting the best of each world, and it also alludes to one possible use case as "user-defined primitives."

Users should think of values as objects without identity, and then they will get guaranteed performance benefits from the JIT (such as enhanced *escape analysis*).

Valhalla also provides a mechanism for low-level libraries (such as complex numbers, half-floats for machine learning, etc.) to use the primitive value type directly, but most developers should not need to use this aspect.

The fact that these new data values lack object identity implies that they disrupt the traditional inheritance hierarchy—without identity there is no object monitor, so `wait()`, `notify()`, and `synchronized` are not possible for these types.

In turn, this creates a potentially surprising connection to Java generics because only reference types are permissible as the value for a type parameter. Valhalla therefore proposes to extend generics to allow abstraction over all types including these new data values and even the existing primitives.

In addition to the extensive work to plumb these new forms of data through the JVM, it is also necessary to create a usage model in the Java language that seems natural to Java programmers. Valhalla must also enable existing libraries (including, but not limited to, the JDK) to compatibly evolve as these changes are delivered.

Some new bytecode instructions will be needed, as Valhalla's new types are immutable, so the `putfield` instruction (which modifies object fields) will not work.

Valhalla's new types have been known by several names during the project's history, including *value types*, *inline types*, and *primitive classes*. The JEPs that cover the implementation of Valhalla are not, at the time of writing, targeted at any specific Java version, and it may be some time before most Java programmers encounter them in day-to-day work.

## Cloud-Native Java

One of the ongoing mega trends in the software industry is the transition to workloads that run "in the cloud," which means on time-leased servers owned by infrastructure providers such as Amazon, Microsoft, and Google.

Modern programming environments increasingly need to ensure that they are economic and easy to use in cloud deployments, and Java is no exception. However, Java's design does have certain aspects that are potentially less friendly to cloud applications than we would like. These largely stem from the classloading and JIT compilation aspects of the runtime, which are designed for flexibility and high performance over the lifetime of a single JVM process.

In the cloud, this can have side effects such as:

- Slow application startup time
- Long time to peak performance
- Potentially high memory overhead

In particular, the lifetime of cloud processes (especially for "Serverless" and *Function-as-a-Service* deployments) may be too short for the performance benefits of Java to pay off. This can be seen as the costs required to get the gains not being fully amortized by the time the process exits.

There are ongoing attempts to solve these long-term pain points and ensure that Java remains a competitive and attractive programming environment as Cloud-First becomes the dominant mode of delivery for serverside applications.

One of the major approaches is *native compilation*: the conversion of a Java program from bytecode into compiled machine code. As this compilation occurs before program execution starts (as for languages like Rust and C++), it is known as *ahead-of-time compilation*, or just AOT. This technique is unusual in the Java space, but it aims to provide a faster startup time as programs do not need to be classloaded or JIT compiled. However, it does not generally give better peak performance than the same application would have when running in dynamic VM mode. This is because peak performance isn't the point here. AOT and JIT represent different strategies and different tradeoffs.

The current main effort to support native compiled Java is Oracle's GraalVM. This was developed as a separate research project in Oracle Labs, but as of late 2022, Oracle has announced plans to contribute parts of it to OpenJDK. It is available in two editions, an open-source edition and a proprietary Enterprise Edition, which has a licensing and support cost.

GraalVM contains a compiler called Graal that can operate in either JIT or AOT mode. The AOT mode of Graal is the basis of GraalVM's Native Image technology that can produce a standalone, compiled machine code binary from a Java application. One interesting aspect of the Graal compiler is that it is written in Java, unlike the JIT compilers in OpenJDK, which are implemented in native code.

GraalVM also includes Truffle, an interpreter generating framework for languages on the JVM. Interpreters for supported languages, written on top of Truffle, are themselves Java programs that run on the JVM. Many non-Java languages are already available such as JavaScript, Python, Ruby, and R.

Another of the projects working on improving cloud-native support is Quarkus, a Java microservices framework designed for the Kubernetes cloud orchestration and deployment stack.1411.200 Quarkus attempts to reduce the impact of the cloud-native pain points by extensively using build-time processing. Expensive computations and startup that would normally be handled reflectively during startup are instead performed ahead of time wherever possible.

Quarkus also emphasizes developer experience and provides both reactive and imperative styles of programming microservices.

The framework is open source and production ready, and it has support available from Red Hat, which is the primary maintainer of the project. It also includes support for native compilation, based on the open-source edition of GraalVM.

However, Quarkus can also be run in dynamic VM mode on top of an OpenJDK runtime.

Finally, we should also mention Project Leyden. This is a new (May 2022) OpenJDK project that seeks to introduce *static runtime images* to the Java platform. The project name comes from a "Leyden jar," a device from the 1700s used for storing static electrical charge. A key aspect of this is known as the *closed world* assumption that removes dynamic runtime behavior such as reflection.

The project is still in its early stages but is adopting a different (and more cautious) approach than GraalVM; a key goal of Leyden is to be able to selectively and flexibly constrain and shift dynamism. The intent is to evolve toward similar targets as the AOT-compiled native image binaries created by GraalVM, but as yet there are no indications when these techniques might appear in a production form of Java.

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## Colophon

The animal on the cover of *Java in a Nutshell*, eighth edition, is a Javan tiger (*Panthera tigris sondaica*), a subspecies unique to the island of Java. Although this tiger's genetic isolation once presented an unrivaled opportunity for evolutionary study to biologists and other researchers, the subspecies has all but disappeared in the wake of human encroachment on its habitat: in a worst-case scenario for the tiger, Java developed into the most densely populated island on Earth, and awareness of the Javan tiger's precarious position apparently came too late to secure the animal's survival even in captivity.

The last confirmed sighting of the tiger occurred in 1976, and it was declared extinct by the World Wildlife Fund in 1994. However, reports of sightings around Meru Betiri National Park in East Java and in the Muria mountain range persist. Camera traps have been used as recently as 2012 in efforts to verify the Javan tiger's continued existence.

Many of the animals on O'Reilly covers are endangered; all of them are important to the world.

The cover image is based on a 19th-century engraving from the *Dover Pictorial Archive*. The cover fonts are Gilroy Semibold and Guardian Sans. The text font is Adobe Minion Pro; the heading font is Adobe Myriad Condensed; and the code font is Dalton Maag's Ubuntu Mono.