3RD EDITION

COMPUTING FUNDAMENTALS

WITH C++

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This textbook is dedicated to my publisher and my friend, Jim Leisy (1950–2014).

—R.M.

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PREFACE

Computing Fundamentals with C++, 3rd Edition is written for students in a first course in a Computer Science curriculum using the C++ programming language. It is appropriate for students with no programming experience as well as those with programming experience in another language.

Computing Fundamentals with C++, 3rd Edition emphasizes computing fundamentals while recognizing the relevance and validity of object-oriented programming. This book is the result of decades of reasoning about how best to facilitate student learning in the first course of the computer science curriculum, how best to integrate objects and classes into it, and how best to prepare students for the next course.

FEATURES

Book Resources. Much of the C++ code from this textbook and chapter outlines written as presentations can be found at https://www2.cs.arizona.edu/people/mercer/compfun3/.

Traditional Topics. This textbook recognizes the relevance and validity of object-oriented programming while emphasizing traditional computing fundamentals. It also presents some C++ features that could well become traditional topics, such as templates for generic classes and standard containers with iterators, during the first two courses.

Standard C++. Because the International Standards Organization (ISO) approved the C++ standard document many years ago, students can now study C++ as a language that has an internationally accepted standard. At the time of this writing, not all compilers were completely C++14 compliant. Because of this and the fact that C++14 only added a few things that are beyond the scope of this text book, this textbook only uses elements up through C++11. However, because any newer release would be backwards compatible, you may certainly use C++14 compliant compiler or any newer release.

Gentle Objects-Early Approach. This third edition maintains the objects-early approach of the first and second editions. Students begin by using existing objects such as `string`, `cin`, `cout`, `BankAccount`, and `Grid` for Karel-like (Rich Pattis) programming while honing problem-solving

and program-development skills. Students will then modify, enhance, and ultimately design and implement their own classes of increasing complexity.

Carefully Chosen Subset of Analysis, Design, and C++. Because students using this textbook might have little or no programming or design experience, several C++ features and subtleties are not presented. Students concentrate on a solid subset of this feature-rich language. Some trickier topics are delayed until the later chapters. For example, nested loops with vectors of vectors, pointers, dynamic memory management, and the singly linked data structure are in the final two chapters. Advanced topics such as copy constructors, destructors, and operator overloading have been removed from this third edition.

Not Tied to a Specific System. There is no bias toward a particular operating system or compiler. This textbook presents standard `#includes` and namespaces according to the ISO standard. All material applies to any computer system using standard C++. All code has been tested with Microsoft Visual C++ on Windows, and GNU g++ on Unix.

Algorithmic Patterns. Algorithmic patterns help beginning programmers design algorithms around a set of common algorithm generalities. The first algorithmic pattern, and perhaps one of the oldest—Input/Process/Output (IPO)—is introduced in Chapter 1. It is reused in subsequent chapters. The IPO pattern is especially useful to students with no programming experience and to the lab assistants helping them. Other algorithmic patterns introduced in the appropriate places include Alternative Action and Indeterminate Loop.

Extensively Tested in the Classroom and Lab. This textbook was six years in the making. Students supplied many useful comments and suggestions concerning manuscript clarity, organization, projects, and examples. The tremendous personal contact and testability was made possible with closed lab sections for all students.

PEDAGOGY

This textbook has many pedagogical features that make this introduction to programming, design, and object technology accessible to students.

Self-Check Questions. These short questions and answers allow students to evaluate whether they understand the details and terms presented in the reading. The answers to all self-check questions are included at the end of this textbook.

Exercises. These transitional problems examine the major concepts presented in the chapter. Answers are available only to instructors to encourage students to write down the answers with paper and pencil, as if they were practice test questions.

Programming Tips. Each set of weekly programming projects is preceded by a set of programming tips intended to help students complete programs while warning of potential pitfalls, and promoting good programming habits.

Programming Projects. Many relatively small-scale problems have been extensively lab tested to ensure that projects can be assigned and completed with little or no instructor intervention. The programming projects are strategically positioned to occur every week of lecture to reinforce the concepts just presented.

WHAT'S NEW IN THIS THIRD EDITION?

This third edition contains dramatic improvements in programming projects, making them more interesting and challenging. Included are projects I have developed and class-tested at the University of Arizona, and, in fact, students have rated these "outside" assignments very highly.

This third edition is smaller. We removed chapters on inheritance, object-oriented programming and design, operator overloading, and recursion. Adopters weren't using these chapters and we felt the second edition was too big at 830 pages. The topics in this edition reflect everything used in a traditional CS1 course while adding a few topics from CS2, such as generic collections with templates.

This third edition has been updated to make sure everything works using the current standard, C++14. This edition also incorporates a few appropriate additions to C++, such as the long-overdue literal `nullptr`. Most of the major additions to the C++ programming language, such as threads, are beyond the scope of this textbook.

ACKNOWLEDGMENTS

Critical feedback from students and other instructors is essential to creating a solid textbook. For the first and second editions, I was fortunate enough to have small lecture sizes (20 to 35 students) and to be in all labs with all of my students for 10 years. This enabled me to keep track of their progress and of their problems, which has dramatically helped produce a textbook that is accessible to the intended audience. I acknowledge and thank those Penn State students.

I have been fortunate to encounter many excellent educators and industry people who care and think about the same issues. The debates and new ideas generated in discussions, both live and by email, have allowed me to make the plethora of informed decisions necessary for producing a high-quality textbook. I wish to acknowledge the following people (listed in reverse alphabetical order) with apologies to those whom I have unintentionally left out: Gene Wallingford, Doug Van Weiren, David Teague, Marty Stepp, Dave Richards, Stuart Reges, Margaret Reek, Ken Reek, Rich Pattis, Allison Obourn, Linda Northrop, Zung Nguyen, John McCormick, Carolina McCluskey, Lester McCann, Mary Lynn Manns, Mike Lutz, David Levine, Patrick Homer, Jim Heliotis, Peter Grogono, Adele Goldberg, Michael Feldman, Ed Epp, Robert Duvall

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Though too numerous to mention, I also acknowledge the many authors and presenters who have influenced me during my thirty-year career. In addition, my thanks go to the people at Franklin, Beedle & Associates: the late Jim Leisy, Jaron Ayres, Brenda Jones, and Tom Sumner.

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I would like to thank super-reviewer Kristin Roberts from Grand Rapids Community College. Not only did she provide tremendous feedback, Kristin encouraged me to complete this third edition. There have been several major changes, some reorganization of chapters, many refinements, some updates, and many new programming projects. This textbook is now current, in large part because of Kristin.

CHAPTER ONE

Problem Solving with C++

COMING UP

We begin with a need for a computer-based solution to a problem. The need may be expressed in one or two paragraphs as a problem specification. The progression from understanding a problem specification to achieving a working computer-based implementation is known as problem solving. After studying this chapter, you will understand

- one example of problem solving
- the characteristics of an algorithm
- how algorithmic patterns help in program design
- the relationship between a class and its many objects
- that objects have a name, state, and set of operations
- the categories of errors that occur during the implementation phase of software development

1.1 PROBLEM SOLVING

There are many approaches to problem solving. This chapter begins by examining a strategy with these three steps: analysis, design, and implementation.

Phase	Activity
Analysis:	Understand the problem.
Design:	Design an algorithm that outlines a solution.
Implementation:	Code an executable program.

Our study of computing fundamentals begins with an example of this particular approach to problem solving. Each of these three phases will be exemplified with a case study of one particular problem: computing a course grade.

1.1.1 ANALYSIS (INQUIRY, EXAMINATION, STUDY)

Program development may begin with a study, or analysis, of a problem. Obviously, to determine what a program is to do, you must first understand the problem. If the problem is written down, you can begin the analysis phase by simply reading the problem.

While analyzing the problem, it is helpful to name the data that represents the information. For example, you might be asked to compute the maximum weight allowed for a successful lift-off of a particular airplane from a given runway under certain thrust-affecting weather conditions such as temperature and wind direction. While analyzing the problem specification, you might name the desired information `maximumWeight`. The data required to compute that information could have names such as `temperature` and `windDirection`.

Although such data do not represent the entire solution, they do represent an important piece of the problem. The data names are symbols for what the program will need and what the program will compute. One value needed to compute `maximumWeight` might be 19.0 for `temperature`. Such data values must often be manipulated—or processed—in a variety of ways to produce the desired result. Some values must be obtained from the user, other values must be multiplied or added, and still other values must be displayed on the computer screen.

At some point, these data values will be stored in computer memory. The values in the same memory location can change while the program is running. The values also have a type, such as integers, numbers with decimal points, strings of characters, or types that store several different types of values. These named pieces of memory that store values that change while the program is running are known as *variables*.

You will see that there also are operations for manipulating those values in meaningful ways. It helps to distinguish the data that must be displayed—*output*—from the data required to compute that result—*input*. These variables summarize what the program must do.

Input: Information a user must supply to solve a problem.

Output: Information the computer must display.

A problem can be better understood by answering this question: What would the output be given certain input? Therefore, it is a good idea to provide an example of the problem. Here are two problems with variable names selected to accurately describe the stored values:

Problem	Variable	Input or Output	Sample Problem
Compute a monthly loan payment	`amount`	Input	`12500.00`
	`rate`	Input	`0.08`
	`months`	Input	`48`
	`payment`	Output	`303.14`

Problem	Variable	Input or Output	Sample Problem
Count how often Shakespeare wrote a particular word in a particular play	`theWork`	Input	`Much Ado About Nothing`
	`theWord`	Input	`thee`
	`howOften`	Output	`74`

In summary, problems can be analyzed by:

1. Reading and understanding the problem specification.
2. Deciding what data represent the answer—the output.
3. Deciding what data the user must enter to get the answer—the input.
4. Creating some sample problems (like those above) that summarize.

Textbook problems sometimes provide the variable names and types of values such as strings, integers, or numbers with a decimal point that must be input and output. If not, they are relatively easy to recognize. In real-world problems of significant scale, a great deal of effort is expended in the analysis stage.

SELF-CHECK

1-1 Given the problem of converting British pounds to U.S. dollars, provide a meaningful name for a variable to store the value that must be input by the user. Also give a meaningful name for the variable to store a value that is to be output.

1-2 Given the problem of selecting one CD from a 200-CD player, what variable name would represent all of the CDs? What name would be appropriate to represent one CD selected by the user?

An Example of Analysis

Problem: Using the grade assessment scale to the right, compute a course grade as a weighted average of projects, a midterm, and one final exam.

Item	Weight
Projects	50%
Midterm	20%
Final Exam	30%

Analysis begins by reading the problem specification and establishing the desired output and the required input to solve the problem. Determining and naming the output is a good place to start. The output stores the answer to the problem. It provides insight into what the program must do. Once the need for a data value is discovered and given a meaningful name, the focus can shift to

what must be accomplished. For this particular problem, the desired output is the actual course grade. The name `courseGrade` represents the requested information to be output to the user.

This problem becomes more generalized when the user enters values to produce the result. If the program asks the user for data, the program can be used later to compute course grades for many students with any set of grades. So let's decide on and create names for the values that must be input. To determine `courseGrade`, three values are required: `projects`, `midterm`, and `finalExam`. The first three analysis activities are now complete:

1. Problem understood.
2. Information to be output: `courseGrade`.
3. Data to be input: `projects`, `midterm`, and `finalExam`.

It helps to have a sample problem, a test case. This involves having the input values and the expected output result. For example, when `projects` is 74.0, `midterm` is 79.0, and `finalExam` is 84.0, the weighted average should be 78.0:

```
(0. 50 × projects) + (0.20 × midterm) + (0.30 × finalExam)
   (0.5 × 74.0)    +   (0.2 × 79.0)   +   (0.30 × 84.0)
       37.0        +       15.8       +       25.2
                           78.0
```

The problem has now been analyzed, the input and output variables have been identified, it is understood what the computer-based solution is to do, and one test case exists.

Problem	Variable	Input or Output	Test Case
Compute a course grade	`projects`	Input	74.0
	`midterm`	Input	79.0
	`finalExam`	Input	84.0
	`courseGrade`	Output	78.0

SELF-CHECK

1-3 Complete an analysis for the following problem. You will need a calculator to determine output.

Problem: Show the future value of an investment given its present value, the number of periods (years, perhaps), and the interest rate. Be consistent with the interest rate and the number of periods; if the periods are in years, then the annual interest rate must be supplied (0.085 for 8.5%, for example). If the period is in months, the monthly interest rate must be supplied (0.0075 per month for 9% per year, for example). The formula to compute the future value of money:

$$\text{future value} = \text{present value} * (1 + \text{rate})^{\text{periods}}$$

1.1.2 DESIGN (MODEL, THINK, PLAN, DEVISE, PATTERN, OUTLINE)

Design refers to the set of activities that includes specifying an algorithm for each program component. An *algorithm* is a step-by-step procedure for solving a problem or accomplishing some end, especially by a computer. A good algorithm must

- list the activities that need to be carried out
- list those activities in the proper order

Consider an algorithm to bake a cake taken from directions for carrot cake:

* Preheat oven to 350° F.
* Grease sides and bottom of each pan.
* Blend ingredients in a large bowl.
* Pour batter into the pan and bake immediately. For cupcakes, fill to 2/3 full.
* Bake following the chart below.
* Cake is done when toothpick inserted in center comes out clean.

If the order of the steps is changed, the cook might get a very hot cake pan with raw cake batter in it. If one of these steps is omitted, the cook probably won't get a baked cake—or there might be a fire. An experienced cook may not need such an algorithm. However, cake-mix marketers cannot and do not presume that their customers have this experience. Good algorithms list the proper steps in the proper order and are detailed enough to accomplish the task.

SELF-CHECK

1-4 Cake recipes typically omit a very important activity. Describe an activity that is missing from the algorithm above.

An algorithm often contains a step without much detail. For example, "Blend ingredients in a large bowl" isn't very specific. What are the ingredients? If the problem is to write a recipe algorithm that humans can understand, this step could be refined a bit to instruct the cook on how to blend the ingredients. The refinement to this step could be "Empty the cake mix into the bowl and mix in the milk until smooth," or for scratch bakers:

* Sift the dry ingredients.
* Place the liquid ingredients in the bowl.
* Add the dry ingredients a quarter-cup at a time, whipping until smooth.

Algorithms may be expressed in *pseudocode*—instructions expressed in a language that even nonprogrammers understand. Pseudocode is written for humans, not for computers. Pseudocode algorithms are an aid to program design.

Pseudocode is very expressive. One pseudocode instruction may represent many computer instructions. Pseudocode algorithms are not concerned about issues such as misplaced punctuation marks or the details of a particular computer system. Pseudocode solutions make design easier by allowing details to be deferred. Writing an algorithm can be viewed as planning. A program developer can design with pencil and paper and sometimes in their head.

1.1.3 ALGORITHMIC PATTERNS

Problems often require input from the user in order to compute and display the desired information. This particular flow of activities—input/process/output—occurs so often, in fact, that it can be viewed as a pattern. It is one of several algorithmic patterns you will find helpful in the design of programs.

A *pattern* is anything shaped or designed to serve as a model or a guide in making something else. An algorithmic pattern serves as a guide to help solve problems. For instance, the following Input/Process/Output (IPO) algorithmic pattern can be used to help design our first problem. In fact, this IPO pattern can be used to help design almost all of the programs in the first five chapters of this textbook.

Algorithmic Pattern *Input/Process/Output*

Pattern: Input/Process/Output (IPO)
Problem: The program requires input from the user in order to compute and display the desired information.
Outline:
1. Obtain the input data.
2. Process the data in some meaningful way.
3. Output the results.

Code Example:

```
int n1, n2, n3;
float average;

// Input
cout << "Enter three numbers: ";
cin >> n1 >> n2 >> n3;

// Process
average = (n1 + n2 + n3) / 3.0;

// Output
cout << "Average = " << average;
```

This algorithmic pattern is the first of several. In subsequent chapters, you'll see other algorithmic patterns such as Guarded Action, Alternative Action, and Indeterminate Loop. To use an

algorithmic pattern effectively, you should first become familiar with it. Register this Input/Process/Output algorithmic pattern and look for this pattern while developing programs. This allows you to design programs more easily. For example, if you discover you have no meaningful values for the input data, it may be that you have placed the process step *before* the input step. Or you may have skipped the input step altogether.

Patterns help solve other kinds of problems. Consider this quote from Christopher Alexander's book, *A Pattern Language* [Alexander 77]:

> Each pattern describes a problem which occurs over and over again in our environment, and then describes the core of the solution to that problem, in such a way that you can use this solution a million times over, without ever doing it the same way twice.

Even though Alexander was describing patterns in the design of furniture, gardens, buildings, and towns, his description of a pattern can also be applied to computational problem solving. The IPO pattern frequently pops up during program design. It guides the solution to many problems.

1.1.4 AN EXAMPLE OF ALGORITHM DESIGN

The Input/Process/Output pattern guides the design of the algorithm that relates to our course grade problem.

Three-Step Pattern	Pattern Applied to a Specific Algorithm
1. Input	1. Read in `projects`, `midterm`, and `finalExam`
2. Process	2. Compute `courseGrade`
3. Output	3. Display `courseGrade`

Although algorithm development is usually an iterative process, a pattern provides an outline of the activities necessary to solve this problem.

SELF-CHECK

1-5 Read the three activities of the algorithm above. Do you detect a missing activity?

1-6 Read the three activities of the algorithm above. Do you detect any activity out of order?

1-7 Would this previous algorithm work if the first two activities were switched?

1-8 Is the algorithm detailed enough to compute `courseGrade`?

There currently is not enough detail in the process step of the course grade problem. The algorithm needs further refinement. Specifically, exactly how should the input data be processed to compute the course grade? The algorithm omits the weighted scale described in the problem specification. The process step should be refined a bit more as shown in step 2:

1. Obtain `projects`, `midterm`, and `finalExam` from the user
2. Compute `courseGrade` = (50% `projects`) + (20% `midterm`) + (30% `finalExam`)
3. Display the value of `courseGrade`

It has been said that good artists know when to put down the brush. Deciding when a painting is done is critical for its success. By analogy, a designer must decide when to stop designing. This is a good time to move on to the third phase of problem solving, which is implementation.

In summary, here is what has been accomplished so far:

- The problem is understood
- Variables have been identified
- Expected output of a sample problem is known (`78.0%`)
- An algorithm has been developed

1.1.5 IMPLEMENTATION (FULFILLMENT, OPERATION, USAGE)

A computer is a programmable electronic device that can store, retrieve, and process data. Programmers can simulate an electronic version of an algorithm by following the algorithm and manually performing the activities of storing, retrieving, and processing data using pencil and paper. The following algorithm walkthrough is a human (non-electronic) execution of the algorithm:

1. Retrieve some example values from the user and store them as shown:

```
projects = 80
midterm = 90
finalExam = 100
```

2. Retrieve the values and compute `courseGrade` as follows:

```
courseGrade = (0.5 × projects) + (0.2 × midterm) + (0.3 × finalExam)
               (0.5 × 80.0)    +   (0.2 × 90.0)  +   (0.3 × 100.0)
                    40.0       +       18.0      +        30.0
                           courseGrade = 88.0
```

3. Display the value stored in `courseGrade` to show `88%`

1.1.6 A C++ PROGRAM

The following complete C++ program previews many programming language details presented in the next chapter. You are not expected to understand this C++ source code. For now, just peruse the source code as an implementation of the pseudocode algorithm. The three variables—`projects`, `midterm`, and `finalExam`—represent user input. The output variable is named `courseGrade`. The object `cout`, pronounced "see-out," stands for *common output* and allows a

program to generate output. Input is made possible using the object `cin`, pronounced "see-in," which stands for *common input*.

```
/*
 * This program computes and displays a final course grade as a
 * weighted average after the user enters the appropriate input.
 *
 * File name: CourseGrade.cpp
 */
#include <iostream>  // for cin and cout
#include <string>    // for string
using namespace std; // avoid writing std::cin std::cout std::string

int main() {
  // Explain what this program does.
  cout << "This program computes a weighted course grade." << endl;

  // Read in a string
  cout << "Enter the student's name: ";
  string name;
  cin >> name;

  // I)nput projects, midterm, and finalExam
  double projects, midterm, finalExam;

  cout << "Enter project score: ";
  cin >> projects;

  cout << "Enter midterm: ";
  cin >> midterm;

  cout << "Enter final exam: ";
  cin >> finalExam;

  // P)rocess
  double courseGrade = (0.5 * projects) +
                       (0.2 * midterm) +
                       (0.3 * finalExam);

  // O)utput the results
  cout << name << "'s grade: " << courseGrade << "%" << endl;
}
```

Dialogue

```
This program computes a weighted course grade.
Enter the student's name: Dakota
Enter project score: 80
Enter midterm: 90
Enter final exam: 100
Dakota's grade: 88%
```

1.1.7 TESTING

The important process of testing may, can, and should occur at any phase of problem solving. The actual work can be minimal, and it's worth the effort. However, you may not agree until you have experienced the problems incurred by *not* testing. Testing activities can occur during all phases of program development:

- During analysis, establish test case problems to confirm your understanding of the problem.
- During design, walk through the algorithm to ensure that it has the proper steps in the proper order.
- During testing, run the program several times with different sets of input data. Confirm that the results are correct.
- Review the problem specification. Does the running program do what was requested?

You should have one or more test case problems before the program is coded—not after. Determine the input values and what you expect for output. Using 80, 90, and 100 as input and expecting the output to be 88% is one such test case. When the program finally does generate output, the expected result can then be compared to the output of the running program. Adjustments must be made any time the predicted output does not match the program output. Such a conflict indicates that the problem example, the program output, or perhaps both are incorrect.

Testing with several test cases helps avoid the misconception that a program is correct just because the program runs successfully and generates output. The output could be wrong! Simply executing a program does not make that program correct. Test cases provide confidence that the program does work.

However, even exhaustive testing does not prove a program is correct. E. W. Dijkstra has argued that testing only reveals the presence of errors, not the absence of errors. Even with correct program output, the program is not proven correct. Testing reduces errors and increases confidence that the program works correctly.

SELF-CHECK

1-9 If the programmer predicts `courseGrade` should be `100.0` when all three inputs are `100.0` and the program displays `courseGrade` as `75.0`, what is wrong: the predicted output, the program, or both?

1-10 If the programmer predicts `courseGrade` should be `90.0` when `projects` is `80.0`, `midterm` is `90.0`, and `finalExam` is `100.0` and the program outputs `courseGrade` as `88`, what is wrong: the prediction, the program, or both?

1-11 If the programmer predicts `courseGrade` should be `88` when projects is `80.0`, `midterm` is `90.0`, and `finalExam` is `100.0` and the program outputs `courseGrade` as `90.0`, what is wrong: the prediction, the program, or both?

1.2 OBJECTS, TYPES, AND VARIABLES

To input something that can be used by a program, there must be a place to store it in the memory of the computer. Bjarne Stroustrup, the creator of C++, writes

> We call such a "place" an object. An object is a region of memory with a type that specifies what kind of information can be placed in it. A named object is called a variable. For example, character strings are put into string variables and integers are put into int variables. You can think of an object as a "box" into which you can put a value of the object's type.

For example, the `int` type used in the previous program stores whole numbers, or integers. Some operations on `int` variables include addition, subtraction, multiplication, and division. Note that C++ uses `*` for the multiplication operator (using `x` would be confusing).

```
double courseGrade = 0.5*projects + 0.2*midterm + 0.5*finalExam;
```

The `float` and `double` types (`double` is twice the size of a `float`) store numeric values with a fractional part. The C++ `string` type stores character sequences as `"Firstname I. Lastname"` along with an integer to maintain the number of characters in that `string`.

Objects are entities stored in computer memory. An object is understood by the types of values the object stores—its *attributes*—and the operations that can be applied to that object—its *behavior* [Booch]. Every object has

- a name to store and retrieve the values of that object
- values stored in computer memory, which is known as the object's state
- a set of operations such as addition, input, output, assignment

These three characteristics of objects—name, state, and operations—were all illustrated in the course grade program. It used three numeric objects stored as `projects`, `midterm`, and `finalExam` that were read in from the keyboard. Each of these objects is capable of storing the value of an integer such as 79 or 90. These objects, along with available operations such as input, multiplication, and addition, computed the `courseGrade`. An assignment operation was used to store it as a numeric object. An output operation with `cout <<` was used so the user could see the results of the processing.

Characteristics of Objects in the First Program

Name:	Each of the four numeric objects has its own identity because each has its own name. The first of the four numeric objects was stored as the variable named `projects`.
State:	The value of `projects` was set with an input operation using `cin >>`. The state of `courseGrade` was defined with an assignment operation using the `=` operator. The state of `courseGrade` was retrieved during output with `cout`.
Operations:	Other operations available for the `int` objects included addition (`+`) and multiplication (`*`).

C++ has fundamental types and compound types. The *fundamental* types store one value that corresponds directly to hardware with a fixed size. The type determines what values can be stored into that object and what operations can be performed. With numeric types such as `int` and `double`, the number of bytes, which varies for different computers, determines the range of values that can be stored in it.

Data Type	Size	Typical Range of Values (varies)
short	2 bytes (16 bits)	-32768 to 32767
unsigned short	2 bytes	0 to 65,535
int	4 bytes	-2147483648 to 2147483647
unsigned int	4 bytes	0 to 4294967295
unsigned long	8 bytes	0 to 18446744073709551615
float	4 bytes	3.4E +/- 38 (7 digits)
double	8 bytes	1.7E +/- 308 (15 digits)
char	1 byte	0 to 255
bool	1 byte	true or false

A *compound* type is a type that is defined in terms of another type. C++ has these compound types presented in this textbook: references, functions, classes, arrays, and pointers. For example, `string` is a reference type made up of characters and other data. It has operations to find the length of the sequence of characters and another operation to create a substring from a string given the starting and ending indexes (there are many more operations that will be explored in a later chapter):

```
string aString = "A sequence of characters"; // Output:
cout << aString.length() << endl;            // 24
cout << aString.substr(2, 8) << endl;        // sequence
```

In addition to the `string` type, two other reference types are used immediately. The `istream` type object named `cin` has operations to read from an input source such as the keyboard or a file on disk. The `ostream` type object named `cout` helps generate output.

SELF-CHECK

1-12 Describe the values stored in objects of type `double`.

1-13 Name two operations for `double` objects.

1-14 Describe the values stored in objects of the `int` type.

1-15 Name two operations for `int` objects.

1-16 Describe the values stored in `string` objects.

1-17 Which of the types above store precisely one value?

CHAPTER SUMMARY

This chapter presented a three-step problem-solving strategy of analysis, design, and implementation. The table below shows some of the activities performed during each of these three phases. The maintenance phase has been added to show how the three steps fit into the complete program life cycle. The maintenance phase actually requires the majority of the time, energy, and money of the program's life cycle.

Phase	Activities You Might Perform
Analysis	Read and understand the problem statement.
	Determine the input and output objects.
	Solve a few sample problems.
Design	Look for patterns to guide algorithm development.
	Write an algorithm—steps needed to solve the problem.
	Refine the steps in the algorithm and walk through it.
Implementation	Translate the design into a programming language.
	Fix errors.
	Create an executable program.
	Test the program.
Maintenance	Update the program to keep up with a changing world.
	Enhance it.
	Correct bugs as they are found.

- Some analysis and design tools were introduced:
  - naming the objects that help solve a problem
  - developing algorithms
  - refining one or more steps of an algorithm
  - using the Input/Process/Output pattern
- The sample program we presented previews the details to be discussed in the next chapter. C++ types were previewed: fundamental and compound.
- Testing is important, but it does not prove the absence of errors. Testing can and does detect errors, but it can only build confidence that the program appears to work.

EXERCISES

1. What activities can be performed when analyzing problems?
2. What are the characteristics of a good algorithm?
3. What is the difference between objects used to store output values and objects that store the values input by the user?
4. List the three characteristics of objects.
5. What activities can be performed when designing programs?
6. What is one "deliverable" of design?
7. What type of object would you use to store the number of students registered in a course?
8. What type of object would you use to store π?
9. What type of object would you use to store the words of a Shakespeare play?
10. What is the deliverable from the implementation phase of program development?
11. Does a program that runs work correctly? Justify your answer.
12. Write an algorithm that describes how to get to where you live.
13. Write an algorithm for finding any phone number in the phone book. Will the search always be successful?
14. Write an algorithm that instructs someone to arrive at your home on foot.
15. Obtain the instructions necessary to create, compile, link, and execute a C++ program on your system. You may need to seek out a login procedure and/or basic editing commands and compiling commands. After this, write a complete algorithm that provides all necessary steps to successfully guide a novice to complete a program through testing. Your

algorithm may contain steps such as "Compare example output to program output," "Create a new file," and "Compile the program."

PROBLEM SOLVING: WRITING ALGORITHMS

1A SIMPLE AVERAGE

Write an algorithm that will compute the average of three test scores of equal weight.

1B WEIGHTED AVERAGE

Write an algorithm that will compute the course grade using this weighted scale:

Assessment	Weight
Quiz average	20%
Midterm	20%
Lab grade	35%
Final exam	25%

1C WHOLESALE COST

You happen to know that a store has a 25% markup on compact disc (CD) players. If the retail price (what you pay) of a CD player is $189.98, how much did the store pay for that item (the wholesale price)? In general, what is the wholesale price for any item given its retail price and markup? Analyze the problem and design an algorithm that computes the wholesale price for any given retail price and any given markup. Use this formula and a little algebra to solve for wholesale price: retail price = wholesale price * (1 + markup).

1D TIME DIFFERENCES

Write an algorithm that takes two different train departure times (where 0 is midnight, 0700 is 7:00 a.m., 1314 is 14 minutes past 1:00 p.m., and 2200 is 10 p.m.) and prints the difference between the two times in hours and minutes. Assume both times are on the same date and that both times are valid. For example, 1099 is not a valid time because the last two digits are minutes, which should be in the range of 00 through 59. 2401 is not valid because the hours (the first two digits) must be in the range of 0 through 23 inclusive. For example, if train A departs at 1255 and train B departs at 1305, the difference would be 0 hours and 10 minutes.

CHAPTER TWO

C++ Fundamentals

SUMMING UP

The first chapter introduced a real-world program development strategy of analysis, design, and implementation. You were encouraged to do some analysis and design before writing C++ code. However, many problems encountered in this textbook will not require much effort to analyze and design. Analysis may simply be "Read the problem." Design might end up as "I can picture an algorithm in my head."

COMING UP

In this chapter, the emphasis will be on translating algorithms into programs using the C++ programming language. The resulting source code you type is the input to the compiler. The compiler translates the source code into machine code that your particular computer understands. However, the compiler expects source code to follow the precise rules of the programming language. Understanding how to translate a pseudocode algorithm into its programming language equivalent requires understanding the smallest pieces of a program and how to correctly gather them together to create statements. This chapter also examines operations that can be performed on many objects. After studying this chapter, you will be able to

- understand how to include existing source code in your programs
- obtain data from the user and display information to the user
- evaluate and create arithmetic expressions
- understand that these common operations are available to many objects such as initialization, input, assignment, and output
- solve problems using the C++ programming language

2.1 THE PIECES OF A C++ PROGRAM

A C++ program begins as a sequence of characters stored in a file. The name of the file holding a C++ program typically ends with either `.cc`, `.c`, `.cp`, or `.cpp` (`first.cc`, `first.C`, or `first.cpp`, for example). Some programming environments require or assume certain file-naming conventions.

Therefore, when you create a file to translate an algorithm into its C++ programming language equivalent, create the file with the extension you should—or must—use.

The text contained in the file is introduced as the *general form* of a C++ program (below). A general form describes the *syntax*—the correct language—necessary to write legal programming language constructs. This general form, like all others in this textbook, follows these conventions:

1. Elements written in *monospace* are used exactly as shown. This includes certain words such as `int main`, `cout`, `cin`, and symbols such as `<< >> ;`.
2. The portions of a general form written in *italic* must be supplied by the programmer—for example, *expression* means you must supply a valid expression.
3. An item in italic is defined somewhere else.

General Form 2.1 *Standard C++ Program*

```
// A comment
#include-directives
using namespace std;
int main() {
    statements
   return 0;
}
```

The parts of a general form in boldface must be written exactly as shown. The statements part refers to a collection of different statements. A statement is the smallest standalone element that expresses some action to be carried out. Semicolons terminate statements. A few statements are described in this chapter. Although not necessary with standard C++, the last statement in the C++ programs of this textbook will be `return 0;`. The curly braces { and } mark the extent of the main function. A function is a construct that allows all of the code to be treated as one entity.

Before getting into the details, here is a syntactically correct standard C++ program. To run code as a program, it must have a function named main. (*Note:* `std` is an abbreviation for standard.)

```
// This program prompts for a name and prints a friendly message
#include <iostream>   // For cout, cin, and endl
#include <string>     // for the string type

using namespace std;  // Allow programmers to write cin and cout
                      // rather than std::cin and std::cout
int main() {
  string name;
  cout << "What is your name: ";
  cin >> name;

  cout << "Hello " << name;
```

```
    cout<< ", I hope you're feeling well." << endl;

    return 0;
}
```

Dialogue

What is your name: ***Casey***
Hello Casey, I hope you're feeling well.

This source code represents input to the compiler. The compiler translates source code like this into machine code. Along the way, the compiler may generate error and warning messages. The errors are detected as the compiler scans the source code of the program and any `#include` files that represent additional source code. For example, the file named iostream precedes the code beginning at `int main()` and so the source code in the file becomes part of the program. The `#include` directive is conceptually replaced by the text contained in the `#included` file.

Every C++ program uses more than one file to take advantage of the code produced by other programmers. In fact, C++ compilers are delivered with a large number of files. Below is the general form that adds source code from other files to your program.

General Form 2.2 *Include Directive*

```
#include < include-file >

        - or -

#include " include-file "
```

The `#include` and angle brackets `< >` or double quote marks `" "` must be written exactly as shown. The include-file is the name of an existing file. For example, the previous program contains the following `#include` directive in order to furnish `cout`, `cin`, and `endl`:

```
#include <iostream>
```

However, this `#include` directive actually provides `std::cout`, `std::cin`, and `std::endl`. The C++ standard library, of which `iostream` is a part, is defined in a namespace called `std`. So to avoid repetitiously writing `std::`, this line should accompany `#include <iostream>` and other `#includes` seen later:

```
using namespace std; // Can now write cout instead of std::cout
```

Care should be taken to avoid any blank spaces between the `< >` or `" "`.

```
#include <iostream >       // ERROR, space at end
#include " BankAccount.h"  // ERROR, space up front
```

Any included file with angle brackets < > must be part of the system. Your system should be able to find those files automatically. However, the file names included within double quote marks " " may need to be stored in the same directory as the program that includes them.

2.1.1 TOKENS: THE SMALLEST PIECES OF A PROGRAM

Before looking at the general forms for object initializations and statements, consider the smallest pieces of the programming language that make up the larger constructs. This should help you

- more easily code syntactically correct statements
- better understand how to fix errors detected by the compiler
- understand general forms

As the C++ compiler reads the source code, it identifies individual *tokens*. A token is the smallest recognizable component of a program. Tokens fall into four categories:

Category	Examples
Special symbols	`;  ( )  <<  >>`
Keywords	`return  double  int`
Identifiers	`main  test2  firstName`
Literals	`"Hello"  507 -2.1  true 'c'  nullptr`

2.1.2 SPECIAL SYMBOLS

A *special symbol* is a sequence of one or two characters with one or possibly many specific meanings. Some special symbols such as `{`, `;`, and `,` separate other tokens. Other special symbols such as `+`, `-`, and `<<` represent operators in expressions. Here is a partial list of single-character and double-character special symbols frequently seen in C++ programs:

```
( )   .   +   -   /   *   =<   >=   //   { }   ==   ;   <<   >>
```

2.1.3 IDENTIFIERS

Identifiers are names given to a variety of things. They all follow these rules that govern the creation of C++ identifiers.

- Identifiers begin with upper- or lowercase letters `a` through `z` or `A` through `Z`, dollar sign `$`, or the underscore character `_`.
- The first letter may be followed by a number of upper- and lowercase letters, digits (`0` through `9`), and underscore characters.
- Identifiers are case-sensitive. For example, `Ident`, `ident`, and `iDENT` are three different identifiers.

Valid Identifiers

```
main        cin         incomeTax      i    MAX_SIZE
Maine       cout        employeeName   x    all_4_one
miSpelte    string      A1             n    $motion$
```

Invalid Identifiers

`1A`	Begins with a digit
`miles/Hour`	`/` is unacceptable
`first Name`	The blank space is unacceptable
`pre-shrunk`	The `-` operator means subtraction

C++ comes with a large number of standard—must be part of the language—identifiers. For example, `cin` is the name of an object used to obtain input from the keyboard. Another standard identifier, `cout`, is the name of the object used to prompt generate output. Here are a few other standard C++ identifiers. (*Note:* The first identifier, pronounced "end-ell," is used for end line.)

```
endl  sqrt  fabs  pow  string  vector  width  precision  queue
```

Programmer-defined identifiers have meaning for the programmer who created the program, for others who might later use it, and for those who must maintain the program. For example, `test1`, `finalExam`, and `courseGrade` are programmer-defined. When creating your own identifiers, give them meaningful names that reveal their purposes.

C++ is case-sensitive, which means an uppercase letter is different from the same letter in lowercase; "A" is not the same as "a." For example, every complete program must include the identifier `main`. `MAIN` or `Main` won't do. Also note that several conventions may be used for upper and lowercase letters. Some programmers prefer avoiding uppercase letters; others prefer to use uppercase letters for each new word. The convention used in this textbook is the "`camelBack`" style where each word after the first has an uppercase letter. For example, you will see `letterGrade` rather than `lettergrade`, `LetterGrade`, or `letter_grade`. Different programmers use different styles.

2.1.4 KEYWORDS

Keywords are identifiers that have a specific purpose whose meaning is reserved by the standard language definition, such as the keywords `double` and `int`.

C++ Keywords

```
break     do        for       operator  switch
case      double    if        return    typedef
char      else      int       sizeof    void
class     float     long      struct    while
```

The case sensitivity of C++ applies to keywords. For example, there is a difference between `double` (a keyword) and `Double` (not a keyword). C++ keywords are always in lowercase.

2.1.5 COMMENTS

Comments are portions of text that annotate a program. Comments fulfill any or all of the following expectations:

- Provide internal documentation to help one programmer read another's program—assuming those comments clarify the meaning of the program
- Explain certain code fragments or the purpose of an object
- Indicate the programmer's name and the goal of the program
- Describe a wide variety of program elements and other considerations

Comments may be added anywhere throughout a program, including to the right of any C++ statement, on a separate line, or over several lines. They may begin with the two-character special symbol `/*` when closed with `*/`.

```
/*
  A comment may
  extend over
  several lines
*/
```

An alternate form for comments is to use `//` before the text. Such a comment may appear on a line by itself or at the end of a line:

```
// A complete C++ program
int main() {
  return 0;  // This program returns 0 to the operating system
}
```

Within the context of the programs in this textbook, comments are most often written as one-line comments like `// Comment` rather than `/* Comment */`. All code after `/*` is a comment until `*/` is encountered, so a large portion of the program can accidentally be turned into a comment by forgetting `*/` at the end. The one-line comments make it more difficult to accidentally "comment out" large sections of code.

Comments are added to help clarify and document the purpose of the source code. The goal is to make the program more understandable, easier to debug (correct errors), and easier to maintain (change when necessary). Programmers need comments to understand programs that may have been written days, weeks, months, years, or even decades ago.

2.1.6 C++ LITERALS

The C++ compiler recognizes string, integer, Boolean (true/false), and floating-point literals. A *string literal* is zero or more characters enclosed within double quotes and finished on the same line:

```
"Double quotes are used to delimit string constants."
"Hello, World!"
```

Integer constants are numbers without decimal points. *Floating-point constants* are written with decimal points or using exponential notation: 5e3 = 5 * 103 = 5000.0 and 1.23e-4 = 1.23 * 10^{-4} = 0.000123, for example. *Boolean literals* are true and false. Here are some examples of C++ literals and the C++ types used in this textbook to store those literal objects.

Type	Example Literals
int	`0 1 999 -999 -2147483647 2147483647`
char	`'a' '#' '9' '\t'` (tab) `'\n'` (new line)
double	`1.23 0.5 .5 5. 2.3456e9 1e-12`
bool	`true false`
string	`"Double quoted" "Kim's" "\n" ""` (empty string)

```
// Print a few C++ literals
#include <iostream>  // For cout and endl
using namespace std;

int main() {
  cout << 123 << endl;
  cout << 'a' << '\t' << 'm' << endl;
  cout << 1.23 << endl;
  // true prints as 1 and false as 0
  cout << true << " and " << false << endl;
  cout << "Hello \n world" << endl;

  return 0;
}
```

Output

```
123
a m
1.23
1 and 0
Hello
 world
```

SELF-CHECK

2-1 How many special symbols are there in the preceding program?

2-2 List each of the following as a valid identifier or explain why it is not valid.

a. `abc`
b. `123`
c. `ABC`
d. `#include`
e. `my Age`
f. `#define`
g. `Abc!`
h. `identifier`
i. `(identifier)`
j. `Double`
k. `mispellted`
l. `H.P.`
m. `double`
n. `55_mph`
o. `sales Tax`
p. `main`
q. `a`
r. `å)`
s. `___1___`
t. `Mile/Hour`
u. `os`

2-3 List two special symbols that are one character long.

2-4 List two special symbols that are two characters long.

2-5 List two standard identifiers.

2-6 Create two programmer-defined identifiers.

2-7 Given the following tokens:

```
'\n'   false   234   1.0   'H'   "'"   -123   1.0e+03   "H"   true
```

a. Which are valid `string` literals?
b. Which are valid integer literals?
c. Which are valid floating-point literals?
d. Which are valid Boolean literals?
e. Which are valid `char` literals?

2-8 Which of the following are valid C++ comments?

a. `//  Is this a comment?`
b. `/ / Is this a comment?`
c. `/* Is this a comment?`
d. `/* Is this a comment? */`

2.2 STATEMENTS

A *declaration* introduces one or more object names into a program. An *initialization* also introduces object names into a program with the additional feature of setting the initial *value* to whatever the programmer wants. These variable names are used later when the programmer is interested in the current value or needs to change that value. Here are the general forms for declaring or initializing fundamental and compound types of variables:

General Form 2.3 *Declaration (some classes have a default initial state)*

```
type identifier ;
```

General Form 2.4 *Initialization (declare a variable and assign it a value)*

```
type identifier = initial-state ;
```

The type may be `double`—to store numbers with a decimal point—or a compound type class such as `string` to store a collection of characters (many other compound types exist).

The following code declares some variables and initializes others. The semicolons (`;`) are used to terminate statements.

```
int credits;      // credits is some random integer
double points;    // credits is some random floating point number
double GPA = 0.0; // GPA is initialized to 0.0
bool boolOne;          // boolOne could be either true or false
bool boolTwo = true;   // boolOne is true
string firstName;             // firstName is the empty string ""
string middleName = "James";  // middleName.length() is 5
string lastName = "Potter";   // lastName.length() is 6
```

The fundamental types `int`, `double`, and `bool` differ from `string` and other compound types in several ways. When declared, numeric types have an unknown value. However, the default initial value of `string` objects is the empty `string` `""` when it is not explicitly initialized.

The following table summarizes the initial state of these objects where some have an unknown state. Those variables were declared, but not initialized. The value is whatever bits happen to be there when the program runs. These variables can actually have different value during different program runs.

Variable Name	Object's State
`credits`	`unknown`
`points`	`unknown`
`boolOne`	`unknown`
`boolTwo`	`true  (would print as 1)`
`GPA 0.0`	

```
firstName                 ""
middleName                "James"
lastName                  "Potter"
```

2.2.1 OUTPUT WITH cout

Programs communicate with users. Such communication is provided through, but not limited to, keyboard input and screen output. This two-way communication is a critical component of many of the programming projects in this textbook.

General Form 2.5 *The* `cout` *statement*

```
cout << expression-1 << expression-2 , . . . ,  << expression-n  << endl;
```

The object named `cout` (pronounced "see-out" and short for **c**ommon **out**put) represents where the output will go: the console. *expression-1* through *expression-n* may take the form of object names such as `GPA` and `firstName` or constants such as `"Credits: "` and `99.5`. The output operator `<<` indicates the direction in which data are flowing. Finally, a semicolon (`;`) terminates each statement. Here are some legal output statements that use the `endl` identifier (pronounced "end-ell") to generate a new line:

```
cout << 99.5 << endl;
cout << "Show me literally too" << endl;
cout << "First Name: " << firstName << endl;
cout << "Credits: " << credits << endl;
```

When a `cout` statement is encountered, the expressions are inserted into a data stream going toward the computer screen. The expressions are output in the same order as they are encountered in the statement—in a left-to-right order. When the expression `endl` is encountered, a new line is generated, so any subsequent output starts at the beginning of a new line.

```
cout << 'A' << " line " << true << " " << 123 << 4.56 << endl;
```

Output

```
A line 1 1234.56
```

SELF-CHECK

2-9 Initialize two objects that represent numbers with an initial value of -1.5.

2-10 Declare one object named `address` that could store a street address.

2-11 Write a complete C++ program that displays any names you have on separate lines.

2.2.2 ASSIGNMENT AND TYPE CONVERSIONS

Assignment statements set the state of an object. The value of the expression to the right of = replaces whatever value was in the object to the left of =.

General Form 2.6 *The Assignment Statement*

```
object-name = expression;
```

The *expression* must be a value that can be stored by the object to the left of the assignment operator =. For example, an expression that results in a floating-point value can be stored in a numeric object, and a `string` expression (characters between double quotes " ") can be stored in a `string` object. Here are some other examples of assignment statements:

```
double aNumber = -999.9;
string aString = "Initial state";

aNumber = 456.789;
aString = "Modified state";
```

After the four assignment operations execute, the state of both objects is modified and the state of these objects can be shown like this:

Object	State
aNumber	456.789
aString	"Modified State"

The value to the right of = must be assignment-compatible with the variable's type on the left for the assignment to work correctly. For example, a `string` literal cannot be assigned to a numeric variable.

```
aNumber = "Oooooohhhh no, you can't do that";  // ERROR
```

A `double` literal cannot be assigned to a `string` object.

```
aString = 12.34;  // ERROR
```

The compiler will report errors at both attempted assignment statements. However, type conversions happen automatically when an object of one type is used when an object of another type is expected. There are no warnings or reported errors, just unexpected values assigned to the variables.

```
char c = 65;  // c becomes 'A'
bool b = 0;   // b becomes false
b = 42;       // b becomes true, actually 1
int n = b;    // n becomes 1, the integer for true
n = 5.9999;   // n becomes 5 due to truncation
double x = n; // x becomes 5.0, but prints as 5
long l = n;   // l becomes 5, int promotes to long
```

SELF-CHECK

2-12 Given the variables initialized above, write the assigned value or report as an error.

a. `b = -123;`

b. `n = 123.495678;`

c. `x = 123;`

d. `l = x;`

e. `c = 66;`

f. `ui = "abcde";`

Be wary of a meaningless object values. They can cause unpredictable errors. Make sure you define all objects either through initialization, an assignment operation, or keyboard input. Also be wary of type conversions, especially when there will be a conversion error that can result in a different value. This will occur when mixing signed and unsigned types, so don't do that. To properly use objects in a program, all three characteristics must be considered:

- An object must be given a name with a declaration or initialization.
- An object must be declared as an instance of a specific type.
- At some point, an object should be given a meaningful value.

2.2.3 INPUT WITH `cin`

To make programs more general—for example, to find a course grade for any student—the state of objects is often set through keyboard input. This allows the user to enter any data desired. Input happens with the input stream object named `cin` (pronounced "see-in" and short for **c**ommon **in**put) and the stream extraction operator `>>`. For example, the following statements modify the state of two objects with data supplied by the user:

```
cin >> firstName;  // User must input a string
cin >> credits;   // User must input a number
```

Here is the general form of the input statement with `cin`:

General Form 2.7 *The* `cin` *statement*

```
cin >> object-name ;
       - or -
cin >> object-name-1 >> object-name-2 >> object-name-n;
```

The object-name must be an instance of a class whose value can be typed in at the keyboard. This form of input operation is defined for many but not all objects in this textbook. Input with `cin` is defined for the `int`, `double`, and `string` types.

When a `cin` statement is encountered, the program pauses until the user types the proper input value and presses the Enter key. If everything goes okay, the value typed by the user is converted into the proper machine representation and stored as the state of that object.

In addition to the Enter key, input data is also separated by one or more blank spaces. This makes it difficult to read in a `string` with blank spaces, such as a person's full name or address. Given the following code:

```
string name;
cout << "Enter your name: ";
cin >> name;
```

and this dialogue:

```
Enter your name: Kim McPhee
```

`Kim` is stored into name, not `Kim McPhee` as one would hope. The blank space after `Kim` terminates the input value. To get all characters from one line even with spaces, use the `getline` operation:

```
getline(cin, name);
```

You may write the `cin` statement with more than one object for input. If you do, you must assume that the user knows to separate each input from the preceding one with a blank space (press the Spacebar), a new line (press Enter or Return), or a tab (press the Tab key). The following program was run several times to show the various ways input is separated.

```
#include <iostream>
using namespace std;

int main() {
  int a, b, c, d;
  cout << "Enter four integers: ";

  // Just need to separate input by a space, tab, or new line.
  cin >> a >> b >> c >> d;
  cout << a << endl;
  cout << b << endl;
  cout << c << endl;
  cout << d << endl;
  return 0;
}
```

Three Possible Dialogues

```
Enter four integers:
1 2 3 4
1
2
3
4
```

```
Enter four integers:
1 2

3

4
1
2
3
4
```

```
Enter four integers: 1
2
3
4
1
2
3
4
```

A simple alternative would be to use one `cin` statement for each input.

2.3 ARITHMETIC EXPRESSIONS

Many of the problems in this chapter require you to write arithmetic expressions. Arithmetic expressions are made up of two components: operators and operands. An arithmetic *operator* is one of the C++ special symbols +, -, /, or *. The *operands* of an arithmetic expression may be a numeric object name such as `test1` or a numeric constant such as `0.25`. Assuming `x` is an instance of the `double` class, the following expression has operands `x` and `4.5`. The operator is `+`.

```
x + 4.5
```

Together, the operator and operands determine the value of the arithmetic expression.

The simplest arithmetic expression is a numeric constant or numeric object name. Arithmetic expressions may also have two operands with one operator (see the table below).

An Arithmetic Expression May Be	Example
Numeric object	x
Numeric constant	100 *or* 99.5
Expression + *expression*	x + 2.0
Expression - *expression*	x - 2.0
Expression * *expression*	x * 2.0
Expression / *expression*	x / 2.0
(*Expression*)	(x + 2.0)

The previous definition of expression also suggests that more complex arithmetic expressions are possible, such as this:

```
1.5 * ((x - 99.5) * 1.0 / x)
```

Since arithmetic expressions may be written with many constants, numeric object names, and operators, rules are put into force to allow a consistent evaluation of expressions. The fol-

lowing table lists the five C++ arithmetic operators and the order in which they are applied to numeric objects.

Binary Arithmetic Operators

Operators	Precedence Rule
* / %	In the absence of parentheses, multiplication, division, and remainder (%), operators evaluate before addition and subtraction. In other words, *, /, and % (for the int remainder) have precedence over + and -. If more than one of these operators appear in an expression, the leftmost operator evaluates first.
+ -	In the absence of parentheses, + and - evaluate after all *, /, and % operators, with the leftmost evaluating first. Parentheses may override these precedence rules.

The operators of the following expression are applied to the operands in this order: /, +, and lastly -.

```
2.0 + 5.0 - 8.0 / 4.0  // Evaluates to 5.0
```

Parentheses may alter the order in which arithmetic operators are applied to their operands.

```
(2.0 + 5.0 - 8.0) / 4.0  // Evaluates to -0.25
```

With parentheses, the / operator evaluates last, rather than first.

These precedence rules apply to binary operators only. A *binary operator* is one that requires one operand to the left and one operand to the right. A *unary operator* only requires one operand on the right. Consider this expression, which has the binary operator * and the unary minus operator -.

```
3.5 * -2.0  // Evaluates to -7.0
```

The unary operator evaluates before the binary * operator: 3.5 times negative 2.0 (-2.0) results in negative 7.0 (-7.0).

Arithmetic expressions usually have object names as operands. When C++ evaluates an expression with double objects, the object name is replaced with its state. Consider the following code:

```
double x = 1.0;
double y = 2.0;
double z = 3.0;
double answer = x + y * z / 4.0;
```

When the program is running, the values stored in the variables are retrieved to get this equivalent expression:

```
double answer = 1.0 + 2.0 * 3.0 / 4.0; // store 2.5 into answer
```

SELF-CHECK

2-13 Evaluate the following arithmetic expressions:

```
double x = 2.5;
double y = 3.0;
```

a. `x * y + 3.0`

b. `0.5 + x / 2.0`

c. `1 + x * 3.0 / y`

d. `1.5 * (x - y)`

e. `y + -x`

f. `( x - 2) * (y - 1)`

2.3.1 `int` ARITHMETIC

The C++ language provides several numeric types. Perhaps the two most often used are `double` and `int`. An `int` object represents a limited range of whole numbers. There are times when `int` is the correct choice over `double`. An `int` object has operations similar to `double` (`+`, `*`, `-`, `=`, `<<`, `>>`), but some differences do exist. For example, a fractional part cannot be stored in an `int` object. The fractional part is lost during an assignment statement.

```
int anInt = 1.999;  // The state of anInt is 1, not 1.999
```

The `/` operator has different meanings for `int` and `double` operands. Whereas the result of `3.0 / 4.0` is `0.75`, the result of `3 / 4` is `0`. Two integer operands with the `/` operator have an integer result—not a floating-point result. So what happens? An integer divided by an integer results in the integer quotient. For example, the quotient obtained from dividing `3` by `4` is `0`. This implies that the same operator (`/` in this case) has a different meaning when it has two integer operands.

Another difference is that `int` objects have a remainder operation symbolized by the `%` operator. For example, the result of `18 % 4` is the integer remainder after dividing `18` by `4`, which is `2`. These differences are illustrated in the following program, which shows `%` and `/` operating on integer expressions and `/` operating on floating-point operands. In this example, the integer results describe whole hours and whole minutes rather than the fractional equivalent.

```
// This program provides an example of int division with '/' for
// the quotient and '%' for the remainder
#include <iostream>
using namespace std;

int main() {
  // Declare objects that will be given meaningful values later
  int totalMinutes, minutes, hours;
  double fractionalHour;

  // Input
  cout << "Enter total minutes: ";
  cin >> totalMinutes;

  // Process
  fractionalHour = totalMinutes / 60.0;
  hours = totalMinutes / 60;
  minutes = totalMinutes % 60;

  // Output
  cout << totalMinutes << " minutes can be rewritten as "
       << fractionalHour << " hours " << endl;
  cout << "or as " << hours << " hours and "
       << minutes << " minutes" << endl;

  return 0;
}
```

Dialogue

```
Enter total minutes: 254
254 minutes can be rewritten as 4.23333 hours
or as 4 hours and 14 minutes
```

The preceding program indicates that even though `int` objects and `double` objects are similar, there are times when `double` is the more appropriate class than `int`, and vice versa. The `double` class should be specified when you need a numeric object with a decimal component. If you need whole numbers, select the `int` class. Also, once the class is chosen, you should consider the differences in some of the arithmetic operators. For example, although the `+`, `-`, `/`, and `*` operations can be applied to `double` operands, the `%` operator may only be used with two integer operands.

SELF-CHECK

2-14 What value is stored in `nickel`?

```
int change = 97;
int nickel = 0;
nickel = change % 25 % 10 / 5;
```

2-15 What value is stored in `nickel` when `change` is initialized to:

a. 4
b. 5
c. 10
d. 15
e. 49
f. 0

2.3.2 MIXING INTEGER AND FLOATING-POINT OPERANDS

Whenever integer and floating-point values are on opposite sides of an arithmetic operator, the integer operand is promoted to its floating-point equivalent (3 becomes 3.0, for example). The expression then results in a floating-point number. The same rule applies when one operand is an `int` object and the other a `double`.

```
// Display the value of an expression with a mix of operands
#include <iostream>
using namespace std;

int main() {
  int n = 10;
  double sum = 567.9;

  // n will be promoted to a double and use the floating point /
  cout << (sum / n) << endl;

  return 0;
}
```

Output

```
56.79
```

SELF-CHECK

2-16 Evaluate the following expressions:

a. 5 / 9
b. 5.0 / 9
c. 5 / 9.0
d. 2 + 4 * 6 / 3
e. (2 + 4) * 6 / 3
f. 5 / 2

2.3.3 CONSTANT OBJECTS

The state of any object can be, and usually is, altered during program execution. However, it is sometimes convenient to have data with values that cannot be altered during program execution. C++ provides the keyword `const` for this purpose. Constant objects are created by specifying and associating an identifier with a value preceded by the keyword `const`. In essence, this is an object

whose state cannot be changed through assignment or stream extraction operations. The general form used to initialize a constant object is a combination of an initialization preceded by the keyword `const`. `Const` objects are usually written in upper case.

General Form 2.8 *Initializing a constant object*

```
const type IDENTIFIER = expression;
```

For example, the value stored in the constant object `PI` is the floating-point number `3.1415926`, and `TAX_RATE` is `7.51%`.

```
const double PI = 3.1415926;
const double TAX_RATE = 0.0751;
const string PAUSE_MESSAGE = "Press any key to continue . . .";
```

These constant objects represent values that cannot be changed while the program is executing; therefore a statement such as `PI = PI * r * r;` generates an error because `PI` is declared as constant. The value cannot be destroyed with an input statement such as `cin >> PI;`.

2.4 PROMPT THEN INPUT

The output and input operations are often used together to obtain values from the user of the program. The program informs the user what must be entered with an output statement and then performs an input operation to set the state of the object. This happens so often that this activity can be considered to be a pattern. The Prompt then Input algorithmic pattern has two activities:

1. Ask the user to enter a value (prompt).
2. Obtain the value for the object (input).

Algorithmic Pattern *Prompt then Input*

Pattern:	Prompt then Input
Problem:	The user must enter something
Outline:	1. Prompt the user for input 2. Obtain the input
Code Example:	`cout << "Enter your first name: ";` `cin >> firstName;`

Strange things can happen if the prompt is left out. The user will not know what must be entered. So whenever you require user input, make sure you prompt for it first. Write the code that tells the user precisely what you want. First output the prompt, then obtain the user input.

Here is one instance of the Prompt then Input pattern:

```
cout << "Enter test #1: ";
cin >> test1;
```

and another:

```
cout << "Enter credits: ";
cin >> credits;
```

In general, tell the user the value needed, then read it in with `cin`.

```
cout << "the prompt for the_object: ";
cin >> the_object;
```

The following program uses the Prompt then Input pattern four times. It also reviews operations such as object initialization, assignment, input, and output. This program illustrates a more general approach to computing any grade point average. By requesting input data from the user, it can be used over and over again with different sets of input to produce different results. Also notice the presence of the IPO pattern in the implementation.

```
// This program uses input statements to produce a meaningful
// result that can be used in a variety of examples
#include <iostream>  // For input and output
#include <string>    // For the string class
using namespace std;

int main() {
  // 0. Initialize some objects
  double credits = 0.0;
  double points = 0.0;
  double GPA = 0.0;
  string firstName;
  string lastName;

  // 1. Input
  cout << "Enter first name: ";
  cin >> firstName;
  cout << "Enter last name: ";
  cin >> lastName;
  cout << "Enter credits: ";
  cin >> credits;
  cout << "Enter points: ";
  cin >> points;

  // 2. Process
  GPA = points / credits;

  // 3. Output
  cout << "Name    : " << firstName << " " << lastName << endl;
  cout << "Credits : " << credits << endl;
  cout << "Points  : " << points  << endl;
  cout << "GPA     : " << GPA     << endl;
```

```
  return 0;
}
```

Dialogue

```
Enter first name: Pat
Enter last name: McCormick
Enter credits: 97.5
Enter points: 323.75
Name    : Pat McCormick
Credits : 97.5
Points  : 323.75
GPA     : 3.32051
```

Care must be taken when entering numeric data. If you enter a non-digit instead of valid numeric input, the input object `cin` may no longer be in a "good" state and all subsequent `cin` statements will be ignored.

SELF-CHECK

2-17 Write the value for `GPA` given each of the dialogues shown below.

```
// This program uses input statements to produce a
// meaningful result that can be used for a variety of examples
#include <iostream>  // For cin, cout, and endl
#include <string>    // For the string class
using namespace std;

int main() {
  // 0. Initialize some numeric objects
  double c1 = 0.0;
  double c2 = 0.0;
  double g1 = 0.0;
  double g2 = 0.0;
  double GPA = 0.0;
  // 1. Input
  cout << "Credits for course 1: ";
  cin >> c1;
  cout << "  Grade for course 1: ";
  cin >> g1;
  cout << "Credits for course 2: ";
  cin >> c2;
  cout << "  Grade for course 2: ";
  cin >> g2;
  // 2. Process
  GPA = ( (g1*c1) + (g2*c2) ) / (c1 + c2);
  // 3. Output
  cout << "GPA: " << GPA << endl;
  return 0;
}
```

Dialogue 1:

```
Credits for course 1: 2.0
  Grade for course 1: 2.0
Credits for course 2: 3.0
  Grade for course 2: 4.0
```

a. _____ GPA

Dialogue 2:

```
Credits for course 1: 4.0
  Grade for course 1: 1.5
Credits for course 2: 1.0
  Grade for course 2: 3.5
```

b. _____ GPA

Dialogue 3:

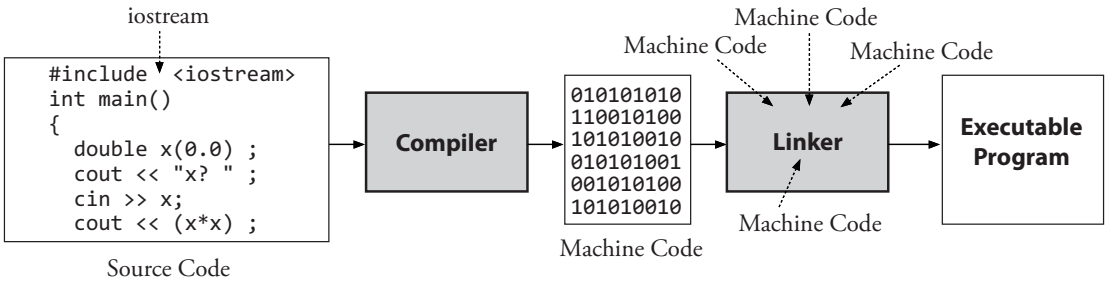
```
Credits for course 1: 1.0
  Grade for course 1: 2.0
Credits for course 2: 4.0
  Grade for course 2: 3.0
```

c. _____ GPA

2.5 IMPLEMENTATION ERRORS AND WARNINGS

There are several types of errors and warnings that occur during the implementation phase of problem solving:

- compile time—errors that occur during compilation
- warnings—code that is risky, suggesting there may be a future error
- linktime—errors that occur when the linker cannot find what it needs
- runtime—errors that occur while the program is executing
- intent—the program does what was entered, not what was intended



2.5.1 ERRORS AND WARNINGS DETECTED AT COMPILE TIME

A programming language requires strict adherence to its own set of formal syntax rules. As you have probably noticed, it is easy to violate these syntax rules while translating algorithms into their programming language equivalents. All it takes is a missing `{` or `;` to really foul things up. As the C++ compiler translates source code into code that can run on the computer, the compiler

- locates and reports as many errors as possible
- warns of potential problems that are syntactically legal, but might cause errors later

A compile time error occurs when the C++ compiler recognizes the violation of a syntax rule. The machine code cannot be created until all compile time errors have been removed from the program. If the machine code is not created, the linker cannot create an executable program. Many strange-looking error messages will be generated by the compiler as it reads the source code. Unfortunately, deciphering these compile time error messages takes practice, patience, and a reasonable knowledge of the C++ programming language. So in an effort to improve this situation, here are some examples of common compile time errors you will soon see and explanations of how they are corrected. (*Note:* Your compiler will generate different error messages.)

Error Detected by a Compiler	Incorrect Code	Corrected Code
Splitting a variable name	`int Total Weight;`	`int totalWeight;`
Misspelling a name	`integer sum = 0 ;`	`int sum;`
Omitting a semicolon	`double x`	`double x;`
Not closing a `string`	`cout << "Hello;`	`cout << "Hello";`
Failing to declare the variable	`cin >> testScore;`	`double testScore;` `cin >> testScore;`
Ignoring case sensitivity	`double X;` `X = 5.0;`	`double x;` `x = 5.0;`
Forgetting an argument	`cout << sqrt;`	`cout << sqrt(x);`
Using wrong type	`cout << sqrt("12");`	`cout << sqrt(12.0);`
Using too many arguments	`cout << sqrt(1.2, 3);`	`cout << sqrt(1.2);`
Forgetting `namespace std;`	`// cout is unknown`	`using namespace std;`

Compilers generate many error messages. However, it is your source code that is the source of these errors. Whenever your compiler appears to be nagging you, remember that the compiler is trying to help you correct your errors as much as possible. The compiler is your friend.

The following code shows several errors the compiler should eventually detect and report. Because error messages generated by compilers vary among systems, the comments here indicate the reason for the error—they are not an attempt to match compile time error messages for any particular compiler (and there are many compilers). Your system will certainly generate quite different error messages.

```
// This attempt at a program contains many errors--over a
// dozen. Add #include <iostream>, and there are only eight.
using namespace std;

int main { // 1. No () after main.
           // 2. Every cin and cout will generate an error
           //    because #include <iostream> is missing.
  int pounds;

  cout << "Begin execution" << endl   // Missing ; after endl
  cout >> "Enter weight in pounds: "; // >> should be <<
  cin << pounds;                      // << should be >>
  cout << "In the U.K., you";         // Extra ;
       << " weigh " << (Pounds / 14)  // Pounds is not declared
       << " stone. " << endl          // Missing ;
  return 0;                           // Missing right brace }
```

Compilers can generate some rather cryptic messages. When the program shown above compiled with one particular compiler, six errors occurred (other compilers found seven and two), all reporting a type name was expected. Other systems generate a different crop of errors. Another Unix compiler generated eight completely different errors. Compile time error messages take some getting used to, so try to be patient and observe the location where the compile time error occurred. The error is usually in the vicinity of the line where the error was detected, although you may have to fix preceding lines. Always remember to fix the first error first. The error not reported until line 23 may be the result of a forgotten semicolon on line 4.

The corrected source code, without error, is given next, followed by an interactive dialogue:

```
// There are no compile time errors in this program
#include <iostream>
using namespace std;

int main() {
  int pounds;

  cout << "Begin execution" << endl;
  cout << "Enter your weight in pounds: ";
  cin >> pounds;
  cout << "In the U.K., "
       << "you weigh "  << (pounds/14.0) << " stone." << endl;

  return 0;
}
```

Dialogue

```
Begin execution
Enter your weight in pounds: 162
In the U.K., you weigh 11.5714 stone.
```

It should also be noted that one small compile time error can result in a cascade of errors. For example, omitting { after `int main()` in an otherwise error-free program caused the Clang C++ compiler to generate 11 compile time errors!

```
#include <iostream>  // For cin and cout
#include <string>    // For the string class
using namespace std;

int main()  // <- Without the left curly brace, there were 11 errors!
  double x;
  string str;
  cout << "Enter a double: ";
  cin >> x;
  cout << "Enter a string: ";
  cin >> str;
  return 0;
}
```

Compile time error messages from one compiler

```
main.cpp:5:11: error: expected ';' after top level declarator
main.cpp:9:3: error: unknown type name 'cout'
main.cpp:9:8: error: expected unqualified-id
main.cpp:10:3: error: unknown type name 'cin'
main.cpp:10:7: error: expected unqualified-id
main.cpp:11:3: error: unknown type name 'cout'
main.cpp:11:8: error: expected unqualified-id
main.cpp:12:3: error: unknown type name 'cin'
main.cpp:12:7: error: expected unqualified-id
main.cpp:13:3: error: expected unqualified-id
main.cpp:14:1: error: expected external declaration
```

The SunOS C++ compiler reported one error, which is more decipherable:

```
"{" expected not double
```

So it is possible that fixing the first error might correct many other errors. It is also true that fixing one error might let the compiler find new ones! Try to concentrate on the first error your compiler reports. The compiler usually, but not always, will be able to approximate the location of the error in your source code. The error may be on the line above, or many lines above.

Also, realize that all statements must be terminated by a semicolon "`;`". Excluding this statement terminator, or putting it in where it doesn't belong, causes compile time errors. Missing semicolon errors are not usually detected until the compiler has already gone past the line with the offense, so look at the statement above the location of the error.

2.5.2 WARNINGS GENERATED AT COMPILE TIME

Compilers also generate warnings, which are messages intended to help programmers avoid errors later on. Consider the following code:

```
#include <iostream>
using namespace std;

int main() {
  double x, y;
  y = 2 * x;
  cout << y << endl;
}
```

SELF-CHECK

2-18 What is the output of the preceding program?

The preceding program has an error, but none that the compiler will catch. The compiler happily translated the source code into machine code and the linker created an executable program. However, the output from two program runs were the rather inexplicable numbers `1.09087e+82` and later `1.39064e-309`. With another compiler, the output was `0`. Fortunately some compilers generate warnings like these:

```
Warning: Possible use of 'x' before definition in main()
Warning: 'x' is used uninitialized in this function
```

The warning states that `x` has been used before it was defined (initialized, actually). This is a good warning that should not be ignored. The program does not initialize `x`. It has an unknown state sometimes referred to as garbage. Unfortunately, not all compilers will warn you of this potential error.

This is not a violation of any C++ rule. It is legal to declare a variable without an initial value. However, this warning should not be ignored. You should read it and make sure `x` has an initialized state before using the object in an arithmetic expression.

This is but one example of a warning. You will see more. You will likely ignore many. However, warnings are hints that something may go wrong and the program will not be correct. If you are getting incorrect results, look to see if there are any warnings—they may be clues to the source of the error.

2.5.3 LINKTIME ERRORS

Computer systems use a linker to combine pieces of machine code to create executable programs. Among other things, the linker must resolve details such as locating the identifier `main` in one of these files. If `main` is not found during the linking process, the linker generates an error that displays `main` is an undefined symbol. If this takes place, verify that your program starts with `int main`.

```
int main() {
  // . . .
}
```

Make sure that `main` is not typed as `mane`, `Main`, or `MAIN`.

Another linktime error occurs when you have two files with the required `int main()`. For example, you may soon try to have two programs in the same folder when completing programming projects. The following linktime error message indicates `initials.cpp` and `average.cpp` both had `int main()` functions in the same directory named `src`:

```
ld: duplicate symbol main ()  in ./src/initials.o and ./src/average.o
```

One solution is to not link both of them. But if you are using an integrated development environment such as Eclipse, Visual Studio, or XCode, make sure you have only one file in your project with the `main` method.

2.5.4 RUNTIME ERRORS

A program may execute after all compile time errors have been removed and the linker has created an executable program. But errors may still occur while the program is running. A runtime error may cause the program to terminate before it should because some event occurs that the computer cannot handle.

For example, when your program is expecting an integer, and the user enters a floating-point number, the input stream `cin` becomes corrupted. Consider the same program run twice, the first time with good input and once with "bad" input; a floating-point number such as `1.2` instead of an integer.

```
#include <iostream>
using namespace std;

int main() {
  int anInt, anotherInt;

  cout << "Enter anInt: ";
  cin >> anInt;
  cout << "anInt: " << anInt << endl;

  cout << "Enter anotherInt: ";
  cin >> anotherInt;
  cout << "anotherInt: " << anotherInt << endl;
  return 0;
}
```

With good input, the user can enter two integers:

```
Enter anInt: 7
anInt is 7
Enter anotherInt: 9
anotherInt is 9
```

With non-integer input, `1.2` cannot be assigned to an `int`, so it is not. Then the second input is not allowed and the user cannot even try to enter a number (the output of `0` will vary since `anotherInt` is undefined):

```
Enter anInt: 1.2
anInt: 1
Enter anotherInt: anotherInt: 0
```

2.5.5 INTENT ERRORS

Even when no compile time errors are found and no runtime errors occur, the program still may not execute properly. A program may run and terminate normally, but it may not be correct. Let's make one small change to an earlier program to get an incorrect program.

```
cout << "Average: " << (n / sum);
```

The interactive dialogue may now look like this:

```
Enter sum: 291
Enter n: 3
Average: 0.010309
```

Such intent errors occur when the program does what was typed, not what was intended. Unfortunately, the compiler does not locate intent errors. The expression `n/sum` is syntactically correct—the compiler just has no way of knowing that this programmer intended to write `sum/n` instead.

Intent errors are the most insidious and usually the most difficult to correct. They may also be difficult to detect—the user, tester, or programmer may not know they even exist.

SELF-CHECK

2-19 Assuming a program is supposed to find an average given the total sum and number of values in a set, then the following dialogue is generated. What clue reveals the presence of an intent error?

```
Enter sum: 100
Number   : 4
Average  : 0.04
```

2-20 Assuming the following code was used to generate the dialogue above, how is the intent error to be corrected?

```
cout << "Enter sum: ";
cin >> n;
cout << "Number   : ";
cin >> sum;
average = sum / n;
cout << "Average  : " << average << endl;
```

2-21 List the type of error (compile time, runtime, linktime, or intent) or warning that exists when the last statement in the preceding program is changed to:

a. `cout << "Average: " << "sum / n";`

b. `cout << "Average: ", sum / n;`

c. `cout << "Average: " << sum / n`

2.5.6 WHEN THE SOFTWARE DOESN'T MATCH THE SPECIFICATION

Even when a process has been automated and delivered to the customer in working order according to the developers, there may still be errors. There have been many instances of software working, but not doing what it was supposed to do. This could be from a failure to meet the problem statement, which occurs when the software developers don't understand the customer's problem statement. Something could have been missed. Something could have been misinterpreted.

A related error occurs when the client specifies the problem incorrectly. This could be the case when the requester isn't sure what they want. A trivial or critical omission in specification may occur, or the request may not be written clearly. Also, the requester may change their mind after problem solving has begun.

For the most part, the end-of-chapter programming projects in this textbook ask you to fulfill the problem specification. If you think there is an omission or there is something you don't understand, don't hesitate to ask questions. It is better to understand the problem and know what it is that you are to trying to solve before getting to the design and implementation phases of problem solving. Although not intended, the problem may be incorrectly or incompletely specified—this does actually happen in the real world!

CHAPTER SUMMARY

- The smallest pieces of a program (tokens) were shown to help you understand general forms and fix errors.
- Objects are entities that have a name, state (`value`), and operations. Output (`cout <<`) and input (`cin >>`) operations are used in concert with double and string objects to set their states. There are at least three techniques for modifying the state of an object:
    - initialization with `double x = 0.0;`
    - input with `cin >>`
    - assignment with `=`
- Knowledge of existing objects aids the program development process. For example, knowing about `cin`, `cout`, `string`, and numeric objects such as `int` and `double` precludes the necessity of implementing many intricate operations such as input, output, addition, and multiplication. Fortunately, other programmers have already built them.
- The objects named `std::cout` and `std::cin` are so frequently used that they are automati-

cally made available for easy screen output and keyboard input with `#include <iostream>`. If you add using `namespace std;` you do not have to precede `cout`, `cin`, and `endl` with `std::` .

- Arithmetic expressions are made up of operators `+`, `-`, `*`, `/`, and `%` (remainder). A binary arithmetic operator requires two operands, which may be numeric constants such as `1` and `2.3`, numeric objects, or other arithmetic expressions.
- Instances of the Prompt then Input pattern will occur in many programming projects. Use it whenever a program needs to get some input from the user.
- When `/` has two integer operands, the result is an integer, so `5 / 2` is `2`.
- When `/` has at least one floating-point operand, the result is a floating-point number, so `5 / 2.0` is `2.5`.
- The `%` operator returns the integer remainder of one integer operand divided by another, so `5 % 2` is `1`.
- The `%` operator cannot have a floating-point argument, so `5 % 2.0` is a compile time error.
- Be careful in choosing `int` and `double`. Always use `double` to store numbers unless it makes sense that the object can only store integers.
- This chapter ended with a discussion of the variety of errors that occur during implementation. You will continue to encounter errors. It is part of the process.
- Errors may be present because the problem statement was incorrect or incomplete.
- Intent errors eventually prove to be the most difficult to fix—they can be difficult to detect.

EXERCISES

1. List three operations that may be applied to numeric types like `double`.
2. Describe the value(s) stored in `string` objects.
3. List three operations that may be applied to any `string` object.
4. List four types of C++ tokens and give two examples of each.
5. Which of the following are valid identifiers?

   a. `a-one`
   b. `R2D2`
   c. `registered_voter`
   d. `BEGIN`
   e. `1Header`
   f. `$money`
   g. `1_2_3`
   h. `A_B_C`
   i. `all right`
   j. `'doubleObject'`
   k. `{Right}`
   l. `Mispelt`

6. Declare `totalPoints` as an object capable of storing a number.

7. Write a statement that sets the state of `totalPoints` to `100.0`.
8. Write the entire dialogue generated by the following program when `5.2` and `6.3` are entered at the prompt. Make sure you write the user-supplied input as well as all program output including the prompt.

```
#include <iostream>
using namespace std;
int main() {
  double x = 0.0;
  double y = 0.0;
  double answer = 0.0;
  cout << "Enter a number: ";
  cin >> x;
  cout << "Enter another number: ";
  cin >> y;
  answer = x * (1.0 + y);
  cout << "Answer: " << answer << endl;
  return 0;
}
```

9. Write C++ code that declares tolerance as a numeric object set to `0.001` that cannot be changed while the program is running.
10. Write a statement that displays the value of a numeric object named `total`.
11. Given these two object initializations, either write the value that is stored in each object or report the attempt as an error.

```
string aString;
double aNumber = 0.0;
```

a. `aString = "4.5";`
b. `aNumber = "4.5";`
c. `aString = 8.9;`
d. `aNumber = 8.9;`

12. With paper and pencil, write an entire C++ program that prompts for a number from `0.0` to `1.0` and stores this input value into the numeric object named `relativeError`. Echo the input (output the input). The dialogue generated by your program should look like this:

```
Enter relativeError [0.0 through 1.0]: 0.341
You entered: 0.341
```

13. Assuming `x` is `5.0` and `y` is `7.0`, evaluate the following expressions:

a. `x / y`
b. `y / y`
c. `2.0 - x * y`
d. `(x*y)/(x+y)`

14. Predict the output generated by these two programs:

a.

```
#include <iostream>
using namespace std;
int main() {
  double x = 1.2;
  double y = 3.4;
  cout << (x + y) << endl;
  cout << (x - y) << endl;
  cout << (x * y) << endl;
  cout << (x / y) << endl;
  return 0;
}
```

b.

```
#include <iostream>
using namespace std;
int main() {
  double x = 0.5;
  double y = 2.3;
  double answer = 0.0;
  answer = x * (1 + y);
  cout << answer << endl;
  answer = x / (1 + y);
  cout << answer << endl;
  return 0;
}
```

15. What is the value of `quarter` when `change` is initialized as follows:

a. `0`

b. `74`

c. `49`

d. `549`

```
int change = (one of the following: 0 , 74, 49, and 549);
int quarter = change % 50 / 25;
```

16. Is this code correct?

```
const double EPSILON = 0.000001;
EPSILON = 999999.9;
```

17. Write C++ code that generates a runtime error and give the reason for the error.

18. At what time will the error in this code be detected?

```
#include <iostream>
using namespace std;
int Main() {
  cout << "Hello world";
  return 0;
}
```

19. Explain how to fix the error in each of these lines:

a. `cout << "Hello world"`

b. `cout >> "Hello world";`

c. `cout "Hello World";`

d. `cout << "Hello World;`

20. Explain the error in this attempt at a program:

```
int main() {
  cout << "Hello world";
```

```
  return 0;
}
```

21. Describe the phrase *intent error*.

22. Does the following code always correctly assign the average of the three `doubles` `x`, `y`, and `z` to average?

```
double average =  x + y + z / 3.0;
```

23. Evaluate the following expressions. Use a decimal point to distinguish integer and floating-point values.

    a. `5 / 2`

    b. `5 / 2.0`

    c. `101 % 2`

    d. `5.0 / 2.0`

    e. `1.0 + 2.0 - 3.0 * 4.0`

    f. `100 % 2`

24. Write the output generated by the following programs:

a.

```
#include <iostream>
using namespace std;
int main() {
  const int MAX = 5;
  cout << (MAX / 2.0) << endl;
  cout << (2.0 / MAX) << endl;
  cout << (2 / MAX) << endl;
  cout << (MAX / 2) << endl;
  return 0;
}
```

b.

```
#include <iostream>
using namespace std;
int main() {
  int j = 14;
  int k = 3;
  cout << "Quotient: "
       << (j / k) << endl;
  cout << "Remainder: "
       << (j % k) << endl;
  return 0;
}
```

c.

```
#include <iostream>
using namespace std;
#include <string>
int main() {
  const string pipe = " ¦ ";
  cout << pipe << (1 + 5.5)
       << pipe << (3 + 3 / 3)
       << pipe << (1 + 2) / (3 + 4)
       << pipe << (1 + 2 * 3 / 4);
   return 0;
}
```

d.

```
#include <iostream>
using namespace std;
int main() {
  int j = 11;
  cout << "  " << (j % 2)
       << "  " << (j / 2)
       << "  " << ((j - j) / 2);
   return 0;
}
```

PROGRAMMING TIPS

1. Semicolons terminate statements. Make sure you terminate statements with `;`. However, do not place semicolons after `#includes` and `int main()`.

```
#include <iostream> ;  // Error found on this line
int main() ;           // Error found on this line
{
```

2. Fix the first error first. When you compile, you may get dozens of errors. Don't panic. Try to fix the very first error first. That may fix several others. Sometimes fixing one error causes others. After fixing one error, the compiler may generate errors that went undetected before.
3. Integer arithmetic behaves unexpectedly for some students. Integer division results in an integer. Therefore `5 / 2` is `2`, not the `2.5` your brain and calculator feel are so right.
4. The `%` arithmetic operator returns an int remainder. Experience shows some students never understand `%`, or at least they still get the wrong answers on the final exam. The expression `a % b` is the integer remainder after dividing `a` by `b`.

```
99 % 50 = 49                    101 % 2 = 1
99 % 50 % 25 = 24               102 % 2 = 0
4 % 99 = 4                      103 % 2 = 1
```

5. If you do not have the line `using namespace std;` you will have to prepend `std::` before every occurrence of the `cin`, `cout`, and `endl`.

```
#include <iostream>     // For cout, cin, and endl
// using namespace std;  Without this, prepend with std::

int main() {
  std::string name;
  std::cin >> name;
  std::cout << "Hello" << std::endl;
  std::cout << name << std::endl;
}
```

PROGRAMMING PROJECTS

2A THE CLASSIC "HELLO WORLD!" PROGRAM

While designing the C language at AT&T, Dennis Ritchie suggested that a first program in any language be one that displays `Hello World!` Many first programs have continued this "Hello World!" tradition. Create a new file called `hello.cpp` and retype the following code as shown. Save this file and use the instructions particular to your setup to compile, link, and run this program.

```
// Programmer: Firstname Lastname
// This programs displays a simple message.
#include <iostream>   // For cout
using namespace std;  // Allow cout instead of std::cout

int main() {
  cout << "Hello World!" << endl;
  return 0;
}
```

2B EXPERIENCE ERRORS GENERATED BY THE COMPILER

One small coding error may cause the report of many errors at compile time—this can be misleading. For example, a missing semicolon may result in dozens of errors throughout a program. Remember to fix the first error first. Start by fixing the earliest discovered error in the source code. You are now asked to observe what happens when a left curly brace is left out of a program. Carefully retype the following program exactly as shown.

```
// Observe how many errors occur when { is missing
#include <iostream>   // For cout
using namespace std;  // To make cout known

int main()  // <- Leave off {
  double x = 2.4;
  double y = 4.5;
  cout << "x: " << x << endl;
  cout << "y: " << y << endl;
  return 0;
}
```

1. Compile your source code and write the number of errors that occur.
2. Add `{` after `int main()` and compile again. Make corrections until you have no errors.
3. Now remove the `#include` directive `#include <iostream>` and compile the program. How many errors do you get?
4. Replace `#include <iostream>` and remove the `()` after `main`. How many errors do you get?
5. Comment out `using namespace std;`. How many errors do you get now?
6. If necessary, edit and compile this program until there are no compile time errors. Link and run the program.

2C BIG INITIALS

Write a C++ program that displays your initials on the screen in large letters. There are no input or process steps, only output. For example, if your initials are E. T. M., the output should look like this generated by five `cout` statements:

```
EEEEE   TTTTTTT     M     M
E          T        M M M M
EEEEE      T        M  M  M
E          T        M     M
EEEEE o    T   o    M     M o
```

2D YODA

Write a C++ program that obtains any three strings from the user and outputs them in reverse order with one space between them. (*Hint:* There is no process step; only input followed by output.)

```
Enter string one: happy
Enter string two: am
Enter string three: I
I am happy
```

2E WEIGHTED AVERAGE

Implement and test a C++ program that will compute the course grade using this weighted scale:

Assessment	Weight
Quiz average	20%
Midterm	20%
Lab grade	35%
Final exam	25%

One dialogue should look like this:

```
Enter Quiz Average: 90.0
Enter Midterm: 90.0
Enter Lab Grade: 90.0
Enter Final Exam: 90.0
Course Average = 90
```

2F SECONDS

Write a program that reads a value in seconds and displays the number of hours, minutes, and seconds represented by the input. Here are two sample dialogues:

```
Enter seconds: 32123
8:55:23
```

```
Enter seconds: 61
0:1:1
```

2G MINIMUM COINS

Write a C++ program that prompts for an integer that represents the amount of change (in cents) to be handed back to a customer in the United States. First, display the minimum number of half dollars, quarters, dimes, nickels, and pennies that will make the correct change. (*Hint*: With increasingly longer expressions, you could use `/` and `%` to evaluate the number of each coin. Or

you could calculate the total number of coins with / and the remaining change with %.) Verify that your program works correctly by running it with a variety of input. Here are two sample dialogues:

```
Enter change [0...99]: 83
Half(ves)  : 1
Quarter(s) : 1
Dime(s)    : 0
Nickel(s)  : 1
Penny(ies) : 3
```

```
Enter change [0...99]: 14
Half(ves)  : 0
Quarter(s) : 0
Dime(s)    : 1
Nickel(s)  : 0
Penny(ies) : 4
```

2H EINSTEIN'S NUMBER

It is said that Albert Einstein used to take great delight in baffling friends with the following puzzle. It could be repeated something like this:

- Write 1089 on a piece of paper, fold it, and hand it to another for safekeeping.
- Ask someone else to write down any three-digit number, emphasizing that the first and last digits must differ: 654 is okay, while 454 and 656 are not allowed.
- Reverse that written down number: if starting with 654, write 456.
- Compute the difference of the written down three digit number and its reverse: use `abs(456-654) = 198`
- Once this is done, reverse the new number: 198 becomes 891.
- Then add the new number to its reverse: 198 + 891 = 1089.

If all goes as planned, observers will be amazed. The number written down at the start, 1089, will always be the same as the end result of this mathematical trick. Replicate this puzzle as a C++ program. Your program dialogue must look like this when the user enters `541`.

```
Enter a 3 digit number (first and last digits must differ): 541

541 -- original
145 -- reversed
396 -- difference
693 -- reverse of the difference
1089 -- difference + reverse of the difference
```

You don't need to error check the three-digit number. Assume input is in the range of `100` to `998` where the first and third digits are not the same. `101`, `252`, or `989` are not expected to generate `1089`. (*Hint:* To find the difference between two numbers, use the absolute value function `abs`. The argument is an expression that subtracts two numbers. You may need to `#include <cstdlib>`.)

```
#include <cstdlib>  // A new include
#include <iostream>
using namespace std;
int main() {
```

```
  // abs is a new function that can return the difference
  // between two numbers by subtracting one from the other.
  cout << abs(541 - 145) << endl;  // 396
  cout << abs(145 - 541) << endl;  // 396
  return 0;
}
```

2I TIME DIFFERENCE

Write a C++ program that takes two different train departure times (where `0` is midnight, `0700` is 7:00 a.m., `1314` is 14 minutes past 1:00 p.m., and `2200` is 10 p.m.) and prints the difference between the two times in hours and minutes. Assume both times are on the same date and that both times are valid. For example, `1099` is not a valid time because the last two digits are minutes, which should be in the range of `00` through `59`. `2401` is not valid because the hours (the first two digits) must be in the range of `0` through `23` inclusive. For example, if train A departs at: `1255` and train B departs at: `1305` the difference would be 0 hours and 10 minutes. One dialogue should look like this, but run your program several times for several test cases.

```
Train A departs at: 1255
Train B departs at: 1305

Difference: 0 hours and 10 minutes
```

CHAPTER THREE

Using Free Functions

SUMMING UP

You should have now gained hands-on experience with your system, the syntax of the language, error messages, and program development—from beginning to end. Most programming projects in the early chapters of this textbook are instances of the IPO algorithmic pattern. You should now be able to put these three steps in the proper order and understand the ramifications of omitting one or mixing up the order.

COMING UP

Software developers often use existing software, a practice that saves time and money. This chapter introduces one way to reuse existing software. Programmers begin with a substantial base of tested software. You will learn how to use existing functions by reading function headings and to determine what the functions do by reading their pre- and postconditions—the contracts for using those functions. The chapter ends with a review of the categories of errors you will probably have encountered. After studying this chapter, you will be able to

- evaluate some mathematical and trigonometric functions
- use arguments in function calls
- appreciate why programmers divide software into functions
- read function headings so you can use existing functions

3.1 cmath FUNCTIONS

C++ defines a large collection of mathematical and trigonometric functions that may be used with `doubles`. Here are two:

```
sqrt(x)  // Return the square root of x
pow(x,y) // Return x to the yth power
```

These functions are *called* by specifying the name of the function, followed by the appropriate number and type of *arguments* within the parentheses. Here is one general form to call certain functions.

General Form 3.1 *Function call*

```
function-name(arguments)
```

The *function-name* is a previously declared identifier representing a function name. The *arguments* represent a set of zero or more expressions separated by commas. In the following function call, the function name is `sqrt` (square root) and the argument is `81.0`:

```
sqrt(81.0)  // An example of a function call
```

Functions may have zero, one, or even more arguments. Although most math functions require exactly one argument, the `pow` function requires exactly two arguments. In the following function call, the function name is `pow` (for power), the arguments are `base` and `power`, and the function call `pow(base, power)` is replaced with $base^{power}$:

```
double base = 2.0;
double power = 3.0;
cout << pow(base, power);  // Output: 8.0
```

Any argument used in a function call must be an expression from an acceptable class. For example, the function call `sqrt("Bobbie")` results in an error because the argument is not one of the numeric classes.

The function must also be supplied with reasonable arguments. For example, the function call `sqrt(-4.0)` could be a problem because `-4.0` is not in the domain of `sqrt`. The square root function is not defined for negative numeric values. The `sqrt` function operates correctly only if certain conditions are met. For `sqrt`, the argument must be greater than or equal to `0.0`. Here are some mathematical and trigonometric functions available when you include `the cmath` function library.

A Partial List of `cmath` Functions. *Note:* `double` *before the function name is the return type*

Function	What it Returns	Example Call	Result
`double ceil(double x)`	Smallest integer ≥ `x`	`ceil(2.1)`	`3.0`
`double cos(double x)`	Cosine of `x` radians	`cos(1.0)`	`0.5403`
`double fabs(double x)`	Absolute value of `x`	`fabs(-1.5)`	`1.5`
`double floor(double x)`	Largest integer ≤ `x`	`floor(2.9)`	`2.0`
`double pow(double x, double y)`	x^y	`pow(2, 4)`	`16.0`
`double sin(double x)`	Sine of `x` radians	`sin(1.0)`	`0.84147`
`double sqrt(double x)`	Square root of `x`	`sqrt(4.0)`	`2.0`

With `#include <cmath>` at the "top" of the program near `#include <iostream>`, the programmer can successfully compile a program with calls to the functions declared in `cmath`. This means that the following program compiles successfully:

```
// Show some mathematical functions available from cmath

#include <cmath>     // For fabs, ceil, floor, and pow
#include <iostream>  // For cout
using namespace std;

int main() {
  double x = -2.1;
  cout << "fabs(-2.1): " <<  fabs(x) << endl
       << "ceil(-2.1): " <<  ceil(x) << endl
       << "floor(-2.1): " <<  floor(x) << endl
       << "pow(-2.1, 2.0): " <<  pow(x, 2.0) << endl;
  return 0;
}
```

Output

```
fabs(-2.1): 2.1
ceil(-2.1): -2
floor(-2.1): -3
pow(-2.1, 2.0): 4.41
```

It should be noted that integer expressions may also be used as arguments to `cmath` functions. As with assignment, the integer value will be promoted to a `double`. So `sqrt(4)` returns the same result as `sqrt(4.0)` without error.

SELF-CHECK

3-1 Evaluate `pow(4.0, 3.0)`

3-2 Evaluate `pow(3.0, 4.0)`

3-3 Evaluate `floor(1.6 + 0.5)`

3-4 Evaluate `ceil(1.6 - 0.5)`

3-5 Evaluate `fabs(1.6 - 2.6)`

3-6 Evaluate `sqrt(16.0)`

3.2 PROBLEM SOLVING WITH `cmath` FUNCTIONS

Problem: Write a program that rounds a number to a specific number of decimal places. For example, `3.4589` rounded to two decimal places should be `3.46` and `3.4589` rounded to one decimal place should be `3.5`.

3.2.1 ANALYSIS

The analysis/design/implementation software development strategy begins with these analysis activities:

1. Read and understand the problem.
2. Decide what object(s) represent the answer—the output.
3. Decide what object(s) the user must enter to get the answer—the input.
4. Write test cases (two were given above).

3.2.2 DESIGN

The deliverable from this design phase is the algorithm. A pseudocode algorithm can be developed with the help of the Input/Process/Output pattern. That pattern is repeated here for your convenience:

Pattern: Input/Process/Output (IPO)
Problem: The program requires input from the user in order to compute and display the desired information.
Outline: 1. Obtain the input data.
2. Process the data in some meaningful way.
3. Output the results.
Example: See the problem of rounding x to n decimals that follows.

The Input/Process/Output pattern helps guide placement of the appropriate activities in the proper order. The algorithm represents the general design—an outline of the solution. Adding two usages of the Prompt then Input pattern and a more detailed algorithm might now look like this:

1. Prompt for the number to round (call it x).
2. Input x.
3. Prompt for the number of decimal places (call it n).
4. Input n.
5. Round x to n decimals.
6. Display the modified state of x.

Steps 1, 2, 3, 4, and 6 have straightforward C++ implementations. They can be implemented as input and/or output statements. However, the details of step 5, "Round x to n decimals," are not present. Step 5 needs refinement. With the rest of the problem out of the way, you can focus on the more difficult process of rounding x to n decimals. A solution is a bit tricky, so one method is provided.

To round a number x to n decimal places, first multiply x by 10^n. Then add 0.5 to the new state of x. Then store floor(x) in x. Finally, divide x by 10^n. The refined algorithm adds this four-step refinement:

1. Prompt for x, the number to round.
2. Input x.
3. Prompt for n, which is the number of decimal places.
4. Input n.
5. Round x to n decimals like this:
   a. Let x become x * 10^n.
   b. Add 0.5 to x.
   c. Let x become floor(x).
   d. Let x become x divided by 10^n.
6. Display the modified state of x.

The following trace of program execution simulates what will happen to x when it starts at 3.4567 and is rounded to two decimal places.

Round 3.4567 to Two Decimal Places

```
x = x * 10^n   =   3.4567 * 10^2      =   345.67
x = x + 0.5    =   345.67 + 0.5       =   346.17
x = floor(x)   =   floor(346.17)      =   346
x = x / 10^n   =   346.17 / 100.0     =   3.46
```

SELF-CHECK

3-7 Trace the same algorithm with the different example problem of rounding 9.99 to one decimal place. What is the result? Write the new value for x in the space provided (x changes state four times after being input).

Algorithm

		x	n
1.	Prompt for the number to round (call it x).	?	?
2.	Input x.	9.99	?
3.	Prompt for the number of decimal places (call it n).	9.99	?
4.	Input n.	9.99	1
5.	Let x become x * 10^n.	_____	1
6.	Add 0.5 to x.	_____	1
7.	Let x become floor(x).	_____	1
8.	Let x become x divided by 10^n.	_____	1
9.	Display the modified state of x.	_____	1

3.2.3 IMPLEMENTATION

The complete C++ source code version is a translation of the previous algorithm. Notice that the algorithm steps are embedded as comments in the source code to show how each was translated into C++.

```
// Round a given number to a specific number of decimal places

#include <iostream>  // For cin and cout
#include <cmath>     // For pow(10, n) and floor(x)
using namespace std;

int main() {
  // Declare objects identified during analysis
  double x = 0.0;
  double n = 0.0;
                                                    //  Algorithm step number:
  // Input
  cout << "Enter number to round : ";              //  1.
  cin >> x;                                        //  2.
  cout << "Enter number of decimal places : " ;    //  3.
  cin >> n;                                        //  4.

  // Process (Round x to n decimals)
  x = x * pow(10, n);                              //  5a.
  x = x + 0.5;                                     //  b.
  x = floor(x);                                    //  c.
  x = x / pow(10, n);                              //  d.

  // Output (Display the modified state of x)
  cout << "Rounded number : " << x << endl;        //  6.
  return 0;
}
```

Dialogue

```
Enter number to round : 3.4567
Enter number of decimal places : 2
Rounded number : 3.46
```

SELF-CHECK

3-8 List three more test cases for the rounding program above.

3-9 What is the final state of `x` after the user enters `3.15` for `x` and `1` for `n`?

3-10 Given the table "A Partial List of `cmath` Functions" on p. 56, find a slightly different algorithm that accomplishes the same task where `3.15` rounded to one decimal place would be `3.1` instead of `3.2`. (*Hint*: Consider subtracting `0.5` rather than adding it.)

3-11 What values are returned with these function calls?

a. `pow(2.0, 4.0)`
b. `sqrt(16.0)`
c. `ceil(-1.7)`
d. `floor(1.0)`
e. `fabs(-23.4)`
f. `pow(4.0, 2.0)`

3.3 CALLS TO DOCUMENTED FUNCTIONS

All functions must first be declared with a function heading so the compiler can determine whether the function calls are correct. These function headings also help the programmer properly call those functions. If you peruse the file `cmath`, you will see many such function headings.

This section concentrates on how to read these function headings and how to use other documentation describing what a particular function expects and what that function will do. These are called the function's preconditions and postconditions, respectively.

3.3.1 PRECONDITIONS AND POSTCONDITIONS

For a function to behave properly, certain conditions are presumed. Consider the `sqrt` function, which presumes that the argument is greater than or equal to 0.0. The *preconditions* of a function state assumptions made about arguments to the function. If the preconditions are not met, all bets are off—the function's behavior is undefined. Some systems cause program termination with an arithmetic overflow error. Other systems may return values such as `-1.#IND` or `nan`, which represents the value "Not a Number." The function call must satisfy the preconditions in order to have predictable results.

The other part of the contract is the *postconditions*—the statements that describe what the function does if the preconditions were met. The pre- and postconditions are often written as part of the function documentation. For example, here is the `sqrt` function documented with preconditions and postconditions:

```
double sqrt(double x)
// precondition:  x is not negative (x >= 0)
// postcondition: Square root of x replaces the function call
```

The comments indicate the argument must be greater than or equal to 0.0. If this precondition is met, the square root of that argument is returned to the *client*—the code that called the function. If the precondition is not met, the result is undefined.

Function Call	Return Result
`sqrt(4.0)`	The precondition was met: `2.0` is returned.
`sqrt(-1.0)`	The precondition was not met. This function call may return `nan` (not a number)

Another implied precondition to calling a function and getting predictable results is this: the client code must supply a proper type of argument. For example, the `ceil` function takes one `double` argument. This implies the argument must be convertible to a `double`, which includes `short`, `int`, `float`, and even `char`. For example, `ceil` will not accept a `string` argument. This could be stated as an obvious precondition like this:

```
double ceil(double x)
// precondition:  Argument must be convertible to a double
// postcondition: Return the smallest integer >= x
```

However, this information is implied in the parameter declaration. The compiler detects improper argument. From now on, such function preconditions will not be written.

The compiler does not detect preconditions. For example, it is syntactically correct to have a program with this:

```
cout << sqrt(-1.0);  // Return depends on the system in use
```

From now on, the label for preconditions will be abbreviated as `pre:` and for postconditions as `post:`. The same function (`ceil`) may now be documented as follows:

```
double ceil(double x)
// post: Return the smallest integer >= x
```

It should be noted that the use of `pre:` and `post:` after the function headings is not required. Different people document functions in their own ways. This documentation is particular to this textbook.

3.3.2 FUNCTION HEADINGS

Pre- and postconditions help programmers determine the proper use of functions. If provided as documentation, they are usually listed after the function heading. The function heading also provides very important usage information such as the type of value returned and the number of arguments required by the function. Here is the general form of a function heading:

General Form 3.2 *Function Heading*

```
return-type function-name (parameter-1, parameter-2, parameter-n)
```

The *return-type* may be any valid C++ class or the keyword `void`. A `void` function does not return anything. The parameters between `(` and `)` may either be value parameters, reference parameters, or `const` reference parameters. Value parameters are up first.

A function may require one or more arguments. Values are passed to functions by adding value parameters of this form:

General Form 3.3 *Value Parameter*

```
class-name identifier
```

Examples of Standard C++ Function Headings:

```
int isapha(int c)
int tolower(int c);
double round (double x);
double remainder(double numerator, double denom);
```

Function headings specify the type of value returned by the function, the function name, and the number of arguments the programmer must supply. The class of arguments required is specified as the *class-name* of each parameter between the parentheses. For example, because the parameters in `pow` below, `x` and `y`, are declared as `double`, one can ascertain that the type of each argument in calls to `pow` must be `double`, or at least convertible to `double`—an integer for example.

```
double pow(double x, double y)
// pre:  When y has a fractional part, x must be positive
//       When y is an integer, x may be negative
// post: Returns x to the yth power
```

Also note that the function name is `pow` and its return type is `double`.

Although the complete implementation of the `pow` function is not present, the information supplied by the preconditions, the postconditions and the function heading are enough to effectively utilize the function.

To summarize, a function heading with pre- and postconditions provides the following information:

1. the *return-type* that provides the type of value returned by the function
2. the *function-name* that begins a valid function call
3. the *parameter-list* that provides the number and class of arguments required in the function call
4. `pre:`, which describes what must be true before calling this function
5. `post:`, which describes what the function does if the preconditions are met

In addition to revealing information to programmers, function headings supply information to the compiler to verify the validity of every attempt to call that function. The compiler informs you if a function is not called properly. Consider the `floor` function heading:

```
double floor(double x)
// post: Returns the largest integer <= x
```

The return type is `double`. This means that a `double` replaces any valid call to `floor`. Therefore, the function call can be used wherever a `double` value is legal—in an arithmetic expression, for instance. Also present is the function name `floor`—very important information for effectively calling this or any particular function. The parameter list shows one `double` parameter named `x`. So the client code must supply exactly one numeric argument to properly call `floor`. For example, the following is a valid call to `double` and it is used in a proper spot in the code:

```
double x;
x = floor(5.55555);  // This assignment is okay
```

However, these function calls are invalid:

```
string s;
s = floor(5.5555);  // Error: floor doesn't return a string
cout << floor(1.0, 2.0);      // Error: too many arguments
cout << floor("wrong type");  // Error: wrong type argument
cout << floor();              // Error: too few arguments
```

SELF-CHECK

3-12 Given the following function heading, write "valid" for each correct function call or explain why it is not valid.

```
double ceil(double x)
```

a. `ceil(1.1)`
b. `floor(2.9)`
c. `ceil(1.2, 3.0)`
d. `ceil("Ceila")`
e. `ceil -0.1`
f. `ceil(-3)`

3-13 Describe the error in each of the following attempts at function headings:

a. `double f ( x )`
b. `int smaller(int n1 int n2)`
c. `toUpper(string s)`
d. `myClass g()`
e. `int twoStrings(string s1, string s2,)`
f. `unknownType initialize("filename.dat")`

Use the following documentation for the questions that follow:

```
double floor(double x)
// post: The floor function returns a floating-point value
//       representing the largest integer that is less than or
//       equal to x
```

3-14 Write four function calls (with different arguments) that would help explain how floor works to someone who has never seen it before.

3-15 Write the values returned from each of the four function calls in your answer to the preceding question.

3.3.3 ARGUMENT / PARAMETER ASSOCIATIONS

A function heading may list zero, one, two, and sometimes more parameters. If there is more than one, the parameters must be separated by commas. The next function heading has two parameters—`str` and `x`.

```
double twoParameters(string str, double x)
```

Exactly one argument of an acceptable class is required for each parameter listed in a function heading. Therefore, precisely two arguments must be present in every call to `twoParameters`. The compiler will report an error if you call this particular function with any other number of arguments than two. Additionally, the type and position of the arguments must match the type and position of the parameters. For example, a `double` argument cannot be associated with a `string` parameter. Here are some examples of correct calls of `twoParameters`:

Valid Calls to the `twoParameters` Function

```
twoParameters("abc", 1.2);
twoParameters("another string", 15);
twoParameters("$", 3.4);
```

The following attempts to call `twoParameters` result in compile time errors:

Error	Reason for Error
`twoParameters("a");`	Needs two arguments.
`twoParameters("1.1", "2.2");`	The string "`2.2`" can't be assigned to a `double`.
`twoParameters(1.1, 1.1);`	The number `1.1` can't be assigned to a `string`.
`twoParameters("a", 2.2, 3.3);`	One too many arguments.
`twoParameters;`	Generate a warning. Statement has no effect.

Arguments associate with parameters by position—first argument to the first parameter, second argument to the second parameter, and so on. For example, when `twoParameters` is called, the first parameter is assigned the value of the first argument and the second argument to the

function is copied into the second parameter `x`. When `twoParameters` is called with arguments `"abc"` and `1.2`, like this:

```
int twoParameters(string str, double x)
                              ↑         ↑
result4 = twoParameters ("abc",    1.2);
```

it's as if these two assignment operations occur:

```
str = "abc";
x = 1.2;
```

Whatever happens inside `twoParameters` now depends on the values of these two parameters. The parameters are used inside the function to produce the return result.

SELF-CHECK

3-16 What value is sent to parameter `str` with `twoParameters("1st", 1.2)`?

3-17 What value is sent to parameter `x` with `twoParameters("2nd", 3.4)`?

Much can be deduced from a function heading when it is accompanied by the function pre- and postconditions. As review, here is the `sin` function heading complete with pre- and postconditions:

```
double sin(double x)
// post: Returns the sine of x radians
```

The following information is ascertained:

- What happens: returns the sine of `x` radians
- Return type: `double`
- Function name: `sin`
- Number of arguments: one
- Type of argument: `double` (or an expression convertible to `double`)

The return results can now be determined (with the help of a scientific calculator in radian mode).

Function Call	Return Result
`sin(3.1415926/2.0)`	`1.0`
`sin(1.0)`	`0.8421  // Approximately`
`sin(3.1415926)`	`5.35898e-08 // close to 0.0`

SELF-CHECK

3-18 Given the following `pow` function from `cmath`, complete with precondition and postcondition documentation, determine the information below:

```
double pow(double x, double y)
// pre:  When y has a fractional part, x must be positive.
//       When y is an integer, x may be negative.
// post: Returns x to the yth power
```

a. return type
b. function name
c. number of arguments
d. class of first argument
e. class of second argument
f. class of third argument

3-19 Write one proper function call to `pow`.

3-20 Is `pow(-81.0, 0.5)` a valid function call? What is the return value?

3-21 Is `pow(-10.0, 2)` a valid function call? What is the return value?

3-22 Is `pow(2, 5)` a valid function call? What is the return value?

3-23 Is `pow(4.0, 0.5)` a valid function call? What is the return value?

3-24 Is `pow(5.0)` a valid function call? What is the return value?

3-25 Write a function heading that returns the fractional component of the first number divided by the second number. Write appropriate pre- and postconditions. For example, `remainder(5.0, 2.0)` must return `0.5` and `remainder(1, 3)` must return `0.3333333`.

3.3.4 A FEW FUNCTIONS FOR `int`, `char`, AND `bool`

Some free functions work with the other primitive types. For example, the standard C++ library has free functions that can be used in an end-of-chapter programming project: `min`, `max`, and `abs`.

```
#include <iostream>
using namespace std;

int main() {
  cout << min(5, 7)     << endl;
  cout << min(5.5, 7.7) << endl;

  cout << max(5, 7)     << endl;
  cout << max(5.5, 7.7) << endl;

  cout << abs(5 - 7)    << endl;

  return 0;
}
```

Output

```
5
5.5
7
7.7
2
```

The `min` and `max` functions are defined in such a way that the same function name can be used with different types. They can take either two `int` arguments or two `double` arguments, but not a mix.

C++ also has some methods that sound Boolean in nature because of names like `islower` and `isdigit`. Other functions seem as though they should have `char` parameters and return types because they convert characters to their upper or lower case equivalents. Consider the function heading for the free function `islower` when you `#include<cctype>` to have access to its set of functions to classify and transform individual characters.

```
int islower(int c);
```

This function checks whether `c` is a lowercase letter. It would seem that the parameter should be `char` and the return type `bool` like this:

```
bool islower(char ch);  // This is not the function heading
```

However, C++ allows an `int` to be assigned to a `char` and vice versa. Arithmetic operations can have a mix of integers and character operands.

```
#include <iostream>
using namespace std;

int main() {
  int anInt = 'A';   // 'A' equals 65
  char aChar = 67;   // 67 equals 'C'

  cout << "anInt: " << anInt << endl;
  cout << "aChar: " << aChar << endl;
  cout << "aChar + anInt: "  << (aChar + anInt)     << endl;
  cout << "anInt % aChar: "  << (anInt % aChar - 2) << endl;

  return 0;
}
```

Output

```
anInt: 65
aChar: C
aChar + anInt: 132
aChar % anInt: 63
```

More confusion may occur because C++ considers true to be 1 and false to be 0.

```
#include <iostream>
using namespace std;

int main() {
  bool aBool = 1;          // C++ allows assignment of int to bool
  int anotherBool = false; // and a bool literal to an int

  cout << aBool << " " << anotherBool << endl;

  return 0;
}
```

Output

```
1 0
```

The output shows `true` prints as `1` and `false` as `0`.

If you need to classify if a `char` is an alphabetic letter like "`A`" or "`a`", or a digit such as "`9`" or "`3`", you can use one of the free functions from `<cctype>`. This program shows three more `cctype` functions:

```
#include <iostream>
#include <cctype>    // For isalpha isblank isdigit
using namespace std;

int main() {
  char ch = 'a';
  cout << "isalpha('" << ch << "')? " << isalpha(ch) << endl;
  ch = '?';
  cout << "isalpha('" << ch << "')? " << isalpha(ch) << endl;

  ch = ' ';
  cout << "isblank('" << ch << "')? " << isblank(ch) << endl;
  ch = 'N';
  cout << "isblank('" << ch << "')? " << isblank(ch) << endl;

  ch = 'P'; // Oh, not zero
  cout << "isdigit('" << ch << "')? " << isdigit(ch) << endl;
  ch = '5';
  cout << "isdigit('" << ch << "')? " << isdigit(ch) << endl;

  return 0;
}
```

Output

```
isalpha('a')? 1
isalpha('?')? 0
isblank(' ')? 1
isblank('N')? 0
isdigit('P')? 0
isdigit('5')? 1
```

The `toupper` and `tolower` functions convert a character to its lowercase or uppercase equivalent. Because the return type for both is `int` instead of `char`, the functions are cast to `char` with the code `(char)`. Otherwise the output from this program would have been `88 97`.

```
#include <iostream>
#include <cctype>    // For toupper and tolower
using namespace std;

int main() {
  char lower = 't';
  char upper = 'A';

  // (char) makes sure we the character, not the int
  cout << (char)toupper(lower) << endl; // Cast required
  cout << (char)tolower(upper) << endl; // to see chars

  return 0;
}
```

Output

```
T
a
```

CHAPTER SUMMARY

- You have been confronted with a large variety of details concerning the C++ programming language, expressions, program development, function calls, and the types of errors that occur during program development. This can be somewhat overwhelming at first, especially if you have never programmed before. However, most of these details are necessary for implementation of even the simplest program.
- `#include<cmath>` provides access to many mathematical and trigonometric functions. `#include<cctype>` provides access to a set of functions that classify and transform individual characters.

- Functions that have a return type of `double` can be used wherever a `double` (or floating-point expression) can be used. Many of the `cmath` functions return `double`.
- Most `cmath` functions require one numeric argument; `pow` requires two.
- Preconditions and postconditions represent a contract between the function and the client code that calls the function. This documentation and other forms of documentation are intended to help someone understand what the function does.
- The function heading itself provides vital usage information such as the return type, the function name, and the number of parameters so the programmer knows how many arguments to include in the call.
- Arguments are associated with parameters by position. It doesn't matter what names are used. The first argument is associated with the first parameter, the second argument with the second parameter, and so on.
- Arguments passed to parameters are like assignment statements. The argument must be compatible with the parameter (the same type). Passing a `double` to an `int` results in loss of value.

EXERCISES

1. Write the return result for each function call or explain the error.

   a. `pow(3.0, 2.0)`
   b. `pow(-2, 5)`
   c. `ceil(1.001)`
   d. `ceil(-1.2)`
   e. `pow(16.0, 0.5)`
   f. `pow(-16.0, 2)`
   g. `fabs(-123.4)`
   h. `sqrt(-1.0)`
   i. `sqrt(sqrt(16.0))`
   j. `ceil 1.1`
   k. `floor()`
   l. `sqrt(0)`

2. Use these initializations to evaluate the expressions that follow:

```
double x = 5.0;
double y = 7.5;
```

   a. `sqrt(x - 1.0)`
   b. `ceil(y - 0.5)`
   c. `sqrt(y - x + 2.0)`
   d. `pow(10, 2)`
   e. `floor(y + 0.5)`
   f. `pow(x, 3.0)`
   g. `fabs(y - x)`
   h. `pow(10, 3)`

3. What is the value of `pow(4, pow(2, 3))`?
4. Write an algorithm that shows the range of a projectile. The formula is

$$range = \sin(2 * angle) * velocity^2 / gravity$$

where *angle* is the angle of the projectile's takeoff (in radians), *velocity* is the initial velocity of the projectile (in meters per second), and *gravity* is acceleration due to gravity at 9.8 meters per second.

5. What happens if the client program does not satisfy the preconditions of a called function?
6. What information do postconditions provide?
7. Which of the following represent valid function headings?

   a. `int large(int a, int b)`
   b. `double(double a, double b)`
   c. `int f(int a; int b;)`
   d. `int f(a, int b)`
   e. `double f()`
   f. `string c(string a)`

8. Name three possible return types from a C++ function (there are many).
9. Given the following function heading with pre- and postconditions, write six function calls (with different arguments) that would adequately test `fmod` and would also help explain how `fmod` works to someone who has never seen it before.

```
double fmod(double x, double y)
// post: Calculates the floating-point remainder.
//       fmod returns the floating-point remainder of x / y.
//       If the value of y is 0.0, fmod returns Not a Number.
// Header required: <cmath>
```

10. Write the values returned from each of the six function calls in your answer to the preceding question.

PROGRAMMING TIPS

1. When calling existing functions, supply the correct number and type of arguments. The function heading and documentation, if present, provide this information. Count the number of parameters between (and). Make sure each associated argument is the same type, or convertible to that type. An `int` can be assigned to a `float`, a `float` to a `double`, an `int` to a `long`, for example.
2. Don't mix arguments types with `min` and `max` functions. `max(2, 3.0)` and `min(1.0, 4)` are compile time errors.
3. Three C++ types appear to be the same. C++ allows integer literals to be treated as character literals and vice versa. Also, underneath, `false` is `0` and `true` is `1`. The reason there is no output here is because `aChar` is storing the non-printable `char` value of `1`.

```
char aChar = true;  // assign 1
cout << ">" << aChar << "<" << endl;   // Output: ><
```

4. If you do not have the line using `namespace std`; you will have to prepend `std::` before every occurrence of the `cmath` function you use.

```
#include <iostream>   // For cout
#include <cmath>      // for ceil and floor
// using namespace std;  Without this, prepend with std::

int main() {
  std::cout << std::ceil(5.99)  << std::endl;  // 6
  std::cout << std::floor(5.99) << std::endl;  // 5
}
```

PROGRAMMING PROJECTS

3A `cmath` FUNCTIONS

Write a program that allows the user to enter any number. After an appropriate label, show the return value from each of the following functions (assume `x` represents the number input by the user):

1. the square root of `x`
2. `x` to the `2.5` power
3. the ceiling of `x`
4. the floor of `x`
5. the absolute value of `x`

Your dialogue should look like this:

```
Enter a number for x: 2.5
sqrt(x)     : 1.5814
pow(x, 2.5) : 6.25
ceil(x)     : 3
floor(x)    : 2
fabs(x)     : 2.5
```

3B CIRCLE

Write a C++ program that inputs a value for the radius of a circle (`r`) from the keyboard and then outputs the diameter, circumference, and area of the circle. Use the `pow` function to compute the area.

- *diameter* = 2 * *radius*
- *circumference* = *pi* * *diameter*
- *area* = *pi* * *radius*^{2}

Initialize `PI` as a constant object with the value of `3.14159`. Your dialogue should look like this (*Note:* Output of floating-point numbers varies among C++ compilers, so your output might be slightly different—especially in the number of decimal places shown for `Circumference` and `Area`):

```
Enter Radius: 1.0
Diameter: 2.0
Circumference: 6.28318
Area: 3.14159
```

Run your program with radius = `1.0`. Verify that your values for `circumference` and `area` match the preceding dialogue. After this, run your program with the input radii of `2.0` and `2.5` and verify that the output is what you expect.

3C MORE ROUNDING

Write a program that asks the user for a number and displays that number rounded to zero, one, two, and three decimal places. Your dialogue should look like this:

```
Enter the number to round: 3.4567
3.4567 rounded to 0 decimals = 3
3.4567 rounded to 1 decimal  = 3.5
3.4567 rounded to 2 decimals = 3.46
3.4567 rounded to 3 decimals = 3.457
```

3D RANGE

Write a program that determines the *range* of a projectile using this formula:

range = sin(2 * *angle*) * *velocity*^{2} / *gravity*

where *angle* is the angle of the projectile's path (in radians), *velocity* is the initial velocity of the projectile (in meters per second), and *gravity* is acceleration at 9.8 meters per second (a constant).

The takeoff angle must be input in degrees. Therefore you must convert this angle to its radian equivalent. This is necessary because the trigonometric function `sin(x)` assumes the argument (`x`) is an angle expressed in radians. An angle in degrees can be converted to radians by multiplying the number of degrees by $\pi/180$ where $\pi \approx 3.14159$. For example, 45° = 45 * 3.14159/180, or 0.7853975 radians. The velocity is presumed to be input in meters per second. Make your interactive dialogue look like this:

```
Takeoff angle (in degrees)? 45.0
Initial velocity (meters per second)? 100.0
Range = 1020.41 meters
```

3E TIME TRAVEL

For astronauts approaching the speed of light in a spaceship, time passes more slowly. Also, the weight of their spaceship increases. The Lorentz factor indicates this change in time and weight depends on the spaceship velocity v

$$factor = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

where v is velocity and c is the speed of light (299,792,458 meters/second). The *factor* can be used to compute how much perceived time is decreased for the astronauts and by how much the weight of their spaceship is increased. For example, at 74948114.5 meters per second (1/4 the speed of light) the factor is 1.038. Time's passage is reduced by the factor and the weight is increased by that factor.

Write a program that reads the weight of the spaceship on earth (90,000 kilograms), the fraction of the speed of light (0.25, less than 1.0), and the distance to travel in light years (Alpha Centauri is about 4.35 light years away).

Dialog 1:

```
Weight of spaceship on earth in kilograms? 90000
Velocity as a fraction of the speed of light 0.0 to 1.0? 0.25
Distance to travel in light years? 4.35

             Travel time: 4.35 light years
          Perceived time: 4.21187 years
Earth weight of spaceship: 90000 kg
      Weight of spaceship: 92951.6 kg traveling at 7.49481e+07 m/s
```

Dialog 2:

```
Weight of spaceship on earth in kilograms? 90000
Velocity as a fraction of the speed of light 0.0 to 1.0? 0.9
Distance to travel in light years? 4.35

              Travel time: 4.35 light years
           Perceived time: 1.89612 years
Earth weight of spaceship: 90000 kg
      Weight of spaceship: 206474 kg traveling at 2.69813e+08 m/s
```

CHAPTER FOUR

Implementing Free Functions

SUMMING UP

C++ has many free functions that any programmer can reuse. These documented functions can be found at **http://www.cplusplus.com/reference**. It is considered good practice to compose code into well-defined functions, test them, and then call them from our programs. This makes for more readable programs. However, C++ does not provide all functions needed by everyone in all situations.

COMING UP

This chapter shows how to write your own functions. After studying this chapter, you will be able to

- implement free functions
- pass values to your functions as input
- return values from your functions as output
- test your new functions
- begin to understand the scope of objects and functions

4.1 IMPLEMENTING YOUR OWN FUNCTIONS

Functions, such as those presented in the previous chapter like `min`, `max`, `abs`, `round`, and `sqrt`, are defined as a function heading followed by a block.

General Form 4.1 *Free Function*

```
function-heading
block
```

A block begins with `{` and ends with `}`. It contains components such as variable declarations and executable statements.

General Form 4.2 *Block*

```
{
  object-initializations
  statements
}
```

Functions get their input via the arguments in the function call. The function uses these input values to compute a result, which is then returned to the caller. You have seen how arguments are associated with parameters to get input into the function. Functions communicate values to the calling code through the return statement.

General Form 4.3 *Return Statement*

```
return expression ;
```

Example of returning a value back to the calling code:

```
int minOf3(int a, int b, int c) {
  // post: Return the smallest value amongst the 3 arguments
  return min(a, min(b, c));
}
```

When the `return` statement is encountered, the expression that follows `return` replaces the function call in the client code as program control returns to the place where the function was called. The following function named `f` implements the function $f(x) = 2x^2 - 1$. Notice that the function must be coded before it can be called—the entire function `f` is located before the call to it from `main`.

```
#include <iostream>  // For cout
#include <cmath>     // For pow
using namespace std;

double f(double x) { // post: Return 2 * x * x - 1
  double result;
  result = 2 * pow(x, 2) - 1.0;
  return result;
}

int main() {
  double x, y;
  cout << "Input x: ";
  cin >> x;
  // Call function f:
  y = f(x);
  cout << "f(" << x << ") = " << y << endl;
  return 0;
}
```

Dialogue

```
Input x: 1.01
f(1.01) = 1.0402
```

SELF-CHECK

4-1 What value is returned for each of these function calls? If there is an error, explain it. Use $f(x) = 2x^2 - 1$ from the previous example.

a. `f(0.0)`

b. `f(-2.0)`

c. `f(3)`

d. `f(1, 2)`

e. `f()`

f. `f(5.8)`

In the next example, the function `serviceCharge` is declared with the `double` return type. The call to `serviceCharge` is replaced by a `double` value that depends on the values of the arguments.

```
// Call serviceCharge to determine a bank debit
#include <iostream>
using namespace std;

const double MONTHLY_FEE = 5.00;

double serviceCharge(int checks, int ATMs) {
  // pre:  checks >= 0 and ATM >= 0
  // post: Return a banking fee based on local rules
  double result;

  result = 0.25 * checks + 0.10 * ATMs + MONTHLY_FEE;
  return result;
}

int main() {
  // 0. Initialize objects
  int checks;
  int ATMs;
  double fee;  // Stores the function return result

  // 1. Input
  cout << "Checks this month? ";
  cin >> checks;
  cout << "ATMs this month? ";
  cin >> ATMs;

  // 2. Process
  fee = serviceCharge(checks, ATMs);  //Call to serviceCharge
```

```
  // 3. Output
  cout << "Fee: " << fee << endl;

  return 0;
}
```

Dialogue

```
Checks this month? 17
ATMs this month? 9
Fee: 10.15
```

Here is what happens when the preceding program runs:

1. The user is asked to supply input for the number of checks and ATM transactions.
2. The values of the arguments (`17` and `9`) are assigned to the parameters of `serviceCharge (checks = 17 and ATMs = 9)`. These particular values will be used by the function to return the proper monthly bank fee.
3. The statements in `serviceCharge` execute.
4. The return is encountered in `serviceCharge`.
5. The function call `serviceCharge(checks, ATMs)` in `main` is replaced by the returned value of 10.15.
6. The function's return value is assigned to `fee`.
7. The fee is displayed.

4.1.1 TEST DRIVERS

When a function requires arguments, it is not unusual to have the same variable name declared in two different places. Consider the previous program that declares `checks` and `ATMs` in `main` and also as parameters within the function `serviceCharge`. The objects declared in `main` are used to obtain user input. The parameters declared in `serviceCharge` obtain input from `main`. Although they have the same names, they are different variables.

Sometimes the duplication of parameter names in `main` is not required. In the next program, you'll see there is no user input, so the duplicated objects are not necessary. Instead, the arguments used to test the function are constants. Rather than being assigned to another object, the program simply displays the return results. The only purpose of this program is to test the function—to verify that the return values are what was expected. This is a good thing to do before the function becomes incorporated into a larger program. In fact, many of the programming problems ask you to carry out this form of testing.

```
// The main function makes several calls to test a new function

#include <iostream>
using namespace std;

const double MONTHLY_FEE = 5.00;

double serviceCharge(int checks, int ATMs) {
  // pre:  checks >= 0 and ATM >= 0
  // post: Return a banking fee based on local rules
  double result;
  result = 0.25 * checks + 0.10 * ATMs + MONTHLY_FEE;
  return result;
}

int main() {
  // Test drive serviceCharge           // Sample problems:
  cout << serviceCharge(0, 0) << endl;  //  5.0
  cout << serviceCharge(1, 0) << endl;  //  5.25
  cout << serviceCharge(0, 1) << endl;  //  5.1
  cout << serviceCharge(1, 1) << endl;  //  5.35
  return 0;
}
```

Output

```
5
5.25
5.1
5.35
```

This version of `main` is called a test driver. A *test driver* is a program with the sole purpose of testing a new function. Functions like `serviceCharge`, `sqrt`, and `pow` are intended to be small parts of much bigger programs. Therefore all functions should be thoroughly tested before they are reused. The four sample problems shown above were predicted and documented in comments. This has been a successful test of the `serviceCharge` function.

4.1.2 FUNCTIONS WITH ONLY A RETURN STATEMENT

Some functions are so simple, they may contain only a `return` statement.

```
double serviceCharge(int checks, int ATMs) {
  // pre:  checks >= 0 and ATM >= 0
  // post: Return a banking fee based on local rules
  return 0.25 * checks + 0.10 * ATMs + MONTHLY_FEE;
}
```

However, this textbook will often use the following convention in addition to the above shortcut (one return statement):

1. Declare a local variable named `result` to be the same type as the function's return type.
2. Store the desired value in `result`.
3. Return `result`.

This is extra work for simple functions. However, this pattern will help when the processing gets more complex, beginning in Chapter 7, "Selection."

Also, the extra two lines of code are likely to prevent you from making a very common mistake. Perhaps because other languages use this technique to return values or perhaps because it simply appears to be the right thing to do, it is common to try to assign a value to the function name. This is a compile time error. You can only assign values to variables.

```
double serviceCharge(int checks, int ATMs) {
  //  You cannot assign a value to a function name
  serviceCharge = 0.25 * checks + 0.10 * ATMs + 5.00;  // ERROR
  return serviceCharge; // ERROR, attempt to return function
}
```

If you do make this common mistake, the compiler will tell you. Fix the error by placing an expression of the correct type, `double`, after the `return`.

SELF-CHECK

4-2 Given the following function `f1`, what value is returned with `f1(9.0)`?

```
double f1(double x) {
  // pre:  x is zero or positive, but not 1.0
  // post: Return f(x) = (square root of x) / ( x - 1.0 )
  return sqrt(x)/(x - 1.0);
}
```

4-3 Does the function call `f1(-1.5)` satisfy the previous function's precondition? What happens during a call to `f1` with a negative number for an argument?

4-4 Describe how to fix the error in each function.

a.
```
double f1(int j);{
  return 2.5 * j;
}
```

b.
```
double f2(int) {
  return 2.5 * j;
}
```

c.
```
double f3(int x) {
  return 2.5 * j;
}
```

d.
```
double f4(double x){
  f4 = 2.5 * x;
}
```

e.
```
double f5(double x) {
  return double;
}
```

f.
```
int f6(string s) {
  return s;
}
```

4-5 Write a function `times3` that returns a value that is three times greater than the argument (`times3(2.0)` should return `6.0`).

4.2 ANALYSIS, DESIGN, AND IMPLEMENTATION

Rather than writing a program, consider a problem that implements a function that may be a very small part of a large program. It may represent just one step of an algorithm, but it is frequently called.

Problem: Compute the distance between two points.

4.2.1 ANALYSIS

Recall that the analysis phase of program development involves determining input and output. Also recall that while developing computer-based solutions to problems involving the IPO algorithmic pattern, the developer determines the output that must be sent to the user and also determines the input required from the user. Replace the word *user* with *client* in the preceding sentence, and the IPO pattern can be applied again to assist the design of functions. Except now the output from the function is expressed in the return statement and the input is expressed in terms of the argument/parameter associations. Here is a generalized IPO algorithm as it relates to functions instead of programs.

IPO Pattern Applied to Functions

Input: Input values to the function via argument/parameter associations.

Process: Compute the result to be returned.

Output: Return the result.

Sample problems are a good way to confirm understanding of a problem. Sample problems also provide expected results that can be compared to program output during program testing. It is a good idea to develop sample problems for new functions. This will help you decide what the function needs as input and, therefore, the number and class of parameters to write in the function heading. The sample problems also provide the expected output of the test driver.

Four `double`s are required to compute the distance between two points (x_1, y_1) and (x_2, y_2) using this formula:

$$distance = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$$

Here are some predicted outputs for a few sets of values for x_1, y_1, x_2, and y_2.

Sample Problems

x_1	y_1	x_2	y_2	Distance
1.0	1.0	2.0	2.0	1.414
0.0	0.0	3.0	4.0	5
-5.7	2.5	3.3	-4.7	11.5256
0.0	0.0	0.0	0.0	0.0

The IPO pattern is now applied to functions as follows:

Input: Input two points at the function call (x_1, y_1) and (x_2, y_2)
Process: Evaluate $\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$
Output: Return the result

4.2.2 DESIGN

The designer must decide how many and what class of parameters are required for a function. In this example, four values are needed to represent the two input points (`x1`, `y1`, `x2`, and `y2`). The best class of parameters is `double` to allow points such as 5.62 and -9.864. The best return type is `double`. With the square root function involved, `double` helps return precise answers. A good function name is `distance`—it describes what the function does. This leads to a function heading with a return type of `double`, a function name of `distance`, and four descriptively named `double` parameters.

```
double distance(double x1, double y1, double x2, double y2)
// post: Return distance between two points (x1, y1) and (x2, y2)
```

Now, within the body of the function (the block), the parameters `x1`, `y1`, `x2`, and `y2` can be used in the distance formula to compute the result.

```
result = sqrt(pow((x1 - x2), 2) + pow((y1 - y2), 2));
```

4.2.3 IMPLEMENTATION

The following program puts this all together with a `main` function written exclusively to test the function (a test driver):

```
// Call distance four times
#include <iostream>  // For cout
#include <cmath>     // For sqrt and pow
using namespace std;

double distance(double x1, double y1, double x2, double y2) {
  // post: Return the distance between any two points
  double result;
  result = sqrt(pow((x1 - x2), 2) + pow((y1 - y2), 2));
```

```
  return result;
}

int main() {
  // Test drive the distance function
  cout << "(1.0, 1.0) (2.0, 2.0): "
       << distance(1.0, 1.0, 2.0, 2.0) << endl;
  cout << "(0.0, 0.0) (3.0, 4.0): "
       << distance(0.0, 0.0, 3.0, 4.0) << endl;
  cout << "(-5.7,2.5) (3.3,-4.7): "
       << distance(-5.7,2.5, 3.3,-4.7) << endl;
  cout << "(0.0, 0.0) (0.0, 0.0): "
       << distance(0.0, 0.0, 0.0, 0.0) << endl;
  return 0;
}
```

Output

```
(1.0, 1.0) (2.0, 2.0): 1.41421
(0.0, 0.0) (3.0, 4.0): 5
(-5.7,2.5) (3.3,-4.7): 11.5256
(0.0, 0.0) (0.0, 0.0): 0
```

Argument/parameter associations are analogous to program input. For example, in the second call to `distance`, the four values are first copied as input to the function `distance`.

```
double distance(x1,  y1,  x2,  y2)
                ↑    ↑    ↑    ↑
       distance(0.0, 0.0, 3.0, 4.0)
```

Control then transfers to the function where the parameters are used to compute the distance between the two points represented by those arguments. Here is the step-by-step computation:

```
sqrt(pow((x1 - x2), 2) + pow((y1 - y2), 2))
sqrt(pow((0.0-3.0), 2) + pow((0.0-4.0), 2))
sqrt(pow(( -3.0  ), 2) + pow(( -4.0  ), 2))
sqrt(          9.0     +          16.0    )
sqrt(                25.0                 )
                      5.0
```

The four arguments become input to the function as the system copies the value of each argument to its associated parameter. This particular mode of argument parameter association is known as *pass by value* because the values are passed to the function. When a function requires input of small objects such as `double` or `int`, write the function heading with value parameters of this form:

```
class-name identifier
```

4.2.4 TESTING

It is a good idea to test functions individually. The previous program did just that. It didn't do anything else. The only purpose for this particular program was to call `distance` with different sets of arguments and display the return results. Notice the similarity of the four calls to `distance` and the sample problems. The arguments are the input to the function. The return result should match the expected results.

It is recommended that you test new functions with a test driver.

4.2.5 SCOPE OF IDENTIFIERS

The *scope* of an identifier is the part of a program from which an identifier can be referenced. The scope of an identifier extends from the point of the identifier's declaration to the end of the block in which it is declared. Recall that a block is delimited by the left and right braces, `{` and `}`. For example, the scope of `local` in the following program is the function `one`. This `local`, declared in `one`, cannot be referenced from outside the block in which it was declared, including `main`.

```
// Illustrate the scope of an object
#include <iostream>
using namespace std;

const int maxValue = 9999;

void one() {
  int local = -1;
  // The scope of local is this function
  cout << local << endl;
  // maxValue is known after its declaration including here:
  cout << maxValue << endl;
}

int main() {
  // The scope of local is limited to one() so this is an error:
  local = 5;
  // Function one() is known everywhere after its declaration
  one();
  // maxValue is known everywhere after its declaration
  cout << maxValue << endl;
  return 0;
}
```

When a variable is declared outside of a block—as in the case of `maxValue`—its scope begins at the point of declaration and extends to the end of the file. Identifiers declared in a block can be referenced only from within that block. These are *local* identifiers. Identifiers declared outside of a block (such as `maxValue`) are said to be global. *Global identifiers* may be referenced from any subsequent part of the file after its declaration, unless that identifier is declared again (redeclared) within another block. In this case, the identifier that was declared first becomes hidden from the block in which it is redeclared. Since many blocks often exist within one program, determining the scope of an object can be somewhat complicated. For example, try to predict the output of

the following program, which includes three different declarations of the `int` variable `identifier`:

```
// This program is a tedious test of your ability to
// determine which of the three int variables named
// identifier are being referenced at any given point.
#include <iostream>
using namespace std;

const int identifier = 1;  // Global variable

void one() {
  // This is a reference to the global identifier
  cout << "identifier in one(): " << identifier << endl;
}

void two() {
  int identifier = 2;  // local to two()
  cout << "identifier in two(): " << identifier << endl;
}

int main() {
  int identifier = 3;   // local to main()
  one();
  two();
  cout << "identifier in main(): " << identifier << endl;
  return 0;
}
```

Output

```
identifier in one(): 1
identifier in two(): 2
identifier in main(): 3
```

When the function `one` is called, the global `const int identifier = 1` is referenced. This global `identifier` can be referenced from within any function that does not declare another identifier named `identifier`. Therefore, the `identifier` that was declared first and initialized to `1` is known (can be referenced) from `one` even though it was not declared inside `one`. But when a reference is made to `identifier` in function `two`, the global `identifier` is hidden because of the local `identifier`. To this point in program execution, `one` has caused the output `0`, and `two` has caused `2` to be displayed. The final statement in `main` references the `identifier` local to `main`—this `identifier` is initialized as `3`.

Typically, a function will have one or more variables declared at the beginning of the block. These variables are said to be local to the function because they may be referenced only from within the function. The same protection applies to the parameters of a function. Parameters are local variable declarations declared inside (and), rather than inside the function block. Parameters are assigned values passed to the function. Parameters can only be used inside the func-

tion block. The restriction provides safekeeping for the local objects so they are not accidentally altered from some other portion of a program.

```
void f1(double x) {
  int local = 0;
  str = "A";  // Error attempting to reference main's local str
}

int main() {
  string str; // str is local to main
  x = 5.0;    // Error attempting to reference f1's parameter x
  local = 1;  // Error attempting to reference f1's local
  return 0;
}
```

SELF-CHECK

4-6 Use the partial program shown below to determine the functions from which each of the following identifiers may be referenced. `cin` and `cout` are initialized in `iostream` so they are known after `#include <iostream>`.

```
// cout   b   cin   MAX   c   f1   a   d  f2  main   e

#include <iostream>
using namespace std;

const int MAX = 999;

void f1(int a) {
  int b;
}

void f2(double c) {
  double d;
}

int main() {
  int e;
  return 0;
}
```

4-7 Name two things that may be declared local to a function.

4-8 If a variable is declared outside of a function, from where may it be referenced?

4.2.6 SCOPE OF FUNCTION NAMES

Now what about function names? After all, they too are identifiers. What is their scope? Like `cin` and `cout`, the scope of functions in an included file like `cmath` also extends to the end of their own file and any file with `#include<cmath>`. So functions such as `sqrt`, `pow`, `ceil`, and `fabs` may be called from within any block unless the function name is re-declared to be something else.

4.2.7 GLOBAL IDENTIFIERS

The problems presented so far are not relatively complex. They are certainly not large. You have probably been working pretty much on your own. However, when programs get large with a team, practice caution with scope.

Global identifiers are known everywhere after they are declared. This opens them up for accidental alteration from anywhere in a very large program. It is difficult to ensure that no one will accidentally modify an object at the wrong time. So try to get in the habit of using local objects everywhere possible. This means you use parameters between `(` and `)` and objects between `{` and `}`. For example, `main` declares `localX` and `localY` locally.

```
int main() {
  double localX, localY;
  // . . .
}
```

If you need to move data between functions, pass them as arguments. This means you must declare parameters rather than having some global `x`.

```
double f(double x) {  // x is local to f
  double result;      // result is local to f
  // Do something with x . . .
}
```

If you need a value in many places throughout a program, make it `const`.

```
#include <iostream>
using namespace std;

const int MAXIMUM_ENTRIES = 100;

// ... a large program with many functions may follow
```

On the other hand, C++ often uses global identifiers. Consider the fact that after including `<iostream>`, `cout` is known everywhere, assuming `using namespace std;` is written before `cout` is referenced (left column following) or `cout` is qualified with `std::` (right column).

```
#include <iostream>
using namespace std;

void f() {
  cout << "In f\n";
}

void g() {
  cout << "In g\n";
}

int main() {
  f();
  g();
  cout << "In main\n";
  return 0;
}
```

```
#include <iostream>
// Equivalent code with std::
void f() {
  std::cout << "In f\n";
}

void g() {
  std::cout << "In g\n";
}

int main() {
  f();
  g();
  std::cout << "In main\n";
  return 0;
}
```

In effect, `using namespace std;` makes `cout` a global identifier. Is this okay? Well, a lot of computer scientists believe so. There is usually only one console, so any output to `cout` will go to the same console, no matter which function sends output to it.

4.3 `void` FUNCTIONS & REFERENCE PARAMETERS

The keyword `void` is used as the return type of functions that do not return anything. Instead of returning values back to the client, `void` functions are often employed to modify the state of the object(s) passed to them. This section shows a `void` function called `swap`, which modifies two arguments. A function must use a reference parameter—with `&` added—to modify the state of the object(s) in the function call. Here is the general form.

General Form 4.4 *Reference Parameter*

```
class-name & identifier
```

Examples of reference parameters in function headings

```
void swap(double & parameterOne, double & parameterTwo)
void changeFormat(ostream & cout)
```

A change to a reference parameter (with `&`) also modifies the associated argument. The parameter name is a reference to—memory location of—the associated argument.

Although parameters typically obtain input from the caller, they can sometimes establish a stronger connection between argument and parameter. In this first example of reference parameter usage, the `swap` function must modify two objects. Since only one value can be returned

through a return statement, the function requires something besides the return statement to communicate more than one value back to the caller. This is accomplished when the special symbol `&` is placed before the parameter name in the function heading. Instead of receiving a copy of the argument, the function receives the memory location or reference to that argument.

When a change is made to a reference parameter, it will change the same object referenced by the argument. This is because the parameter and the argument are pointing to the same object in memory. For example, in the following program, when the `swap` function alters the parameters `parmOne` and `parmTwo`, the arguments `argOne` and `argTwo` are also pointing to that same modified object:

```
// Notice the reference symbol & is in front of parmOne
// and parmTwo. Now a change to parmOne or parmTwo alters
// the associated object that is the argument's value.
#include <iostream>
using namespace std;

// Swap the values of any two int arguments.
// The & lets any change to the parameter alter it argument
void swap(int & parmOne, int & parmTwo) {
  int temp = parmOne;
  parmOne = parmTwo;  // Change argument argOne in main
  parmTwo = temp;     // Change argument argTwo in main
}

int main() {
  int argOne = 89;                              // argOne   argTwo
  int  argTwo = 76;
  cout << argOne << "    " << argTwo << endl; // 89       76

  swap(argOne, argTwo);

  cout << argOne << "    " << argTwo << endl; // 76       89

  return 0;
}
```

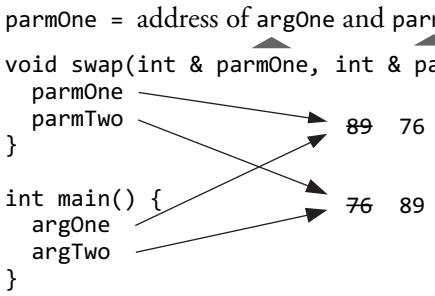
Output

```
89    76
76    89
```

If the ampersands (`&`) are removed from the program above, no change is made to the arguments in `main`. In this case, the values of `argOne` and `argTwo` would be passed by value, not by reference. Without the reference symbol `&`, the values of `parmOne` and `parmTwo` are changed locally, within `swap` only. The values of the associated arguments in `main` are unaffected because they are different objects.

The following figures illustrate the difference between reference and value parameters.

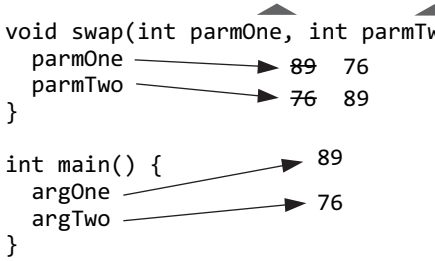
Reference parameters: *argument and parameter reference the same object*



parmOne points to the memory location of argOne and then changes contents from 89 to 76 in swap. This affects the same object pointed to by argOne.

parmTwo points to the memory location of argTwo and then changes contents from 76 to 89 in swap. This affects the same object pointed to by argTwo.

Value parameters: *a change to the parameter does not change the associated argument*



Since values are passed to the swap function, when the swap occurs locally, it does not affect the variables in a different function.

Values in main are not affected when their values are "passed by value".

Because a change to a reference parameter changes the argument, the argument must be a variable. Using a literal value or larger expression results in a compile time error.

```
swap(89, 76);   // Error: Argument must be a variable
```

SELF-CHECK

4-9 Write the values of arg1 and arg2 at the moment when return 0; executes.

a.
```
#include <iostream>
using namespace std;
void changeOr(int a, int b) {
  a = a * 2 + 1;
  b = 123;
}
int main() {
  int arg1 = 5;
```

```
  int arg2 = 5;
  changeOr(arg1, arg2); // arg1 ____   arg2 _____
  return 0;
}
```

b.
```
#include <iostream>
using namespace std;
void changeOr(int & a, int & b) {
  a = a * 2 + 1;
  b = 123;
}

int main() {
  int arg1 = 5;
  int arg2 = 5;
  changeOr(arg1, arg2); // arg1 ____   arg2 ____
  return 0;
}
```

4.4 CONST REFERENCE PARAMETERS

You have now seen two of the three parameter passing modes in C++:

1. value parameters—for passing the values of small objects such as `int`
2. reference parameters—to allow a function to modify the state of one or more arguments
3. `const &` (reference) parameters—for safety and efficiency

A `const` reference parameter is typically used to pass a "big" object that is not to be modified by the function. A big object is one that requires a lot of memory, a very large `string` for example. To understand why programmers pass large objects by `const` reference, consider what happens when arguments are passed into functions.

When passed by value, the entire object is copied into another variable of the same size in the function, which requires twice the memory. For reference parameters, the address of the object is copied to the function, which is only four bytes of memory. In this case, the argument and the parameter reference the same object. For `const &` parameters, the address of the object is copied to the function, again only four extra bytes of memory needed. With `const`, any attempt to modify the parameter in the function will be flagged as an error by the compiler. The `const` prevents accidental changes to the argument. The programmer adds `const` to avoid the bug of unknown modification of an object in a different scope.

Pass by Value `int f1(int j)`	**Pass by Reference** `int f2(string & b)`	**Pass by `const` Reference** `void f3(const int & n)`
Grab enough memory to store the entire object and copy all bytes to the function. A change to the parameter has no effect on the argument.	Use four bytes of memory to store the address of the object and copy that address to the function. Use this when you need to modify the argument. It's efficient too.	`const` means the argument cannot be changed. Any attempt to change `n` results in a compile time error. Use this for efficiency and safety.
`f1` ***cannot*** modify the argument's state.	`f2` ***can*** modify the argument's state.	`f3` function ***cannot*** modify the argument's state. This is efficient.

There are two reasons to use `const` reference parameters. The first is efficiency—the program executes more quickly. The other consideration is better memory utilization—less memory is required to store the large object in the function. For example, passing a small object such as `int` by value only requires the function to allocate and then copy four bytes of memory. By contrast, one large object passed by value could require thousands of bytes. The program might exhaust available memory.

Additionally, every single byte of an argument passed by value will be copied to the function. The computer has to do a lot of unnecessary work. The program might run noticeably slower. Here are two alternatives to make any program more efficient in terms of space (saves memory) and time (runs faster):

1. Pass big objects by reference—efficient but somewhat dangerous.
2. Pass big objects by `const` reference—efficient *and* safe.

The second option is recommended. The program now has much less work to do. When passed by values, the program must then wait until every single byte is copied from the caller to the function. If passed by `const &` reference, only four bytes are required while the safety of value parameters (cannot change the state of the argument) remains intact. Of course, if you are passing an argument to a function in order to modify the state, you must pass it by reference with `&`. Attempts to modify objects passed by `const` reference result in compile time errors.

Using `const` is an antibugging technique that will let the compiler tell us about accidental attempts to modify the `const` parameter. Any function that does not modify the object may still be called—`string`'s `length` function, discussed in the next chapter, for example. However, the compiler will flag any attempt to call functions such as `string`'s `insert` function because as the name implies, `insert` adds things to a `string` to modify the state of the `string` object. You cannot assign a new value to a `const` parameter either.

```
void addSomeStuff(const string & str) {
  cout << str.length() << endl; // Okay
  str.insert(5, "xtra"); // ERROR: can not modify a const parameter
  str = "new string"; // ERROR: Can not assign to a const parameter
}
```

However, when using value parameters only, you get no such error message. The argument's object simply does not change.

Changing `x` in `f` does not change `y` in the main function

```
#include <iostream>
using namespace std;

double f(double x) {
  double result;
  // This does not modify y
  x = x - 1.5;
  result = 2 * x;
  return result;
}

int main() {            // Output:
                        // 8
  double y = 5.0;       // y: 5
  cout << f(y) << endl;
  cout << "y: " << y << endl;
  return 0;
}
```

This code results in a compile time error such as "`cannot modify a const object`"

```
#include <iostream>
using namespace std;

double f(const double & x) {
  double result;
  // An error. Good!
  x = x - 1.5;
  result = 2 * x;
  return result;
}

int main() {
  double y = 5.0;
  cout << f(y) << endl;
  cout << "y: " << y << endl;
  return 0;
}
```

It should be noted that only a few objects will be passed by `const` reference until later. So you will only occasionally see a big object passed by `const` reference in the next several chapters. Also, value parameters will be more common than reference parameters.

CHAPTER SUMMARY

- Functions perform some well-defined services and can have two-way communication through argument/parameter associations and the return statement. The client code supplies input values to the function as arguments. The result is returned via the return statement.
- There are several new implementation issues related to functions such as the scope of identifiers:
  - All identifiers must be declared before they can be referenced.
  - The scope of an object is limited to the block where it is declared.
  - Some identifiers are not declared within a block. In this case, they are global identifiers. Examples of global identifiers include function `sqrt` after `#include <cmath>`, and the global object `std::cout` after `#include <iostream>`.

  - The scope of a parameter is limited to its function.
  - The scope of a function begins at the function heading and continues to the end of its file, or the end of the file that included the function.

- There are many details to remember when using argument/parameter associations.
  - The number of arguments used in a function call must match the number of parameters declared in the function heading.
  - The `void` return type precedes the function name when no value is to be returned. You cannot return anything from a `void` function.
  - When one value is to be returned from a function, a non-`void` return type must begin the function heading. The `return` statement must also be included in the function block. The expression in the return statement should be the same class as the return type.
  - Sometimes a function needs input—that is what parameters are for. Sometimes a function must return something—that is what the return statement is for. Sometimes a function needs to modify objects in the client code—that's what reference parameters are for.
  - The argument used in a function call should usually be the same class as its associated parameter. There are exceptions; for example, an `int` argument may be assigned to a `double` parameter with type conversion.
  - Parameters intended only to receive copies of the argument values (input parameters) should be declared as value parameters without `&`.
  - Reference parameters (with `&`) must be used if the intention is to modify the associated argument—a change to a reference parameter alters the object reference by the argument. A change to a value parameter does not.
  - `const` reference parameters are used to pass large objects. Instead of consuming extra bytes of memory and copying that memory, the address is copied—because of `&`. However, the safety of value parameters is ensured by making the parameter `const`.

EXERCISES

1. How many statements may be written in a block delimited by `{ }`?
2. Which function is called first when a C++ program executes?
3. May a function be called more than once?
4. Write the output generated by the following program:

```
#include <iostream>
using namespace std;
```

```
double f2(double x, double y) {
  return 2 * x - y;
}

int main() {
  cout << f2(1, 2.5) << endl;
  cout << f2(-4.5, -3) << endl;
  cout << f2(5, -2) << endl;
  return 0;
}
```

5. Write the output generated by the following function:

```
#include <iostream>
#include <cmath>
using namespace std;

double mystery(double p) {
  return pow(p, 3) - 1;
}

int main() {
  double a = 3.0;
  cout << mystery(  a) << endl;
  cout << mystery(4.0) << endl;
  cout << mystery( -2) << endl;
  return 0;
}
```

6. Write a function double `sumOf3` that returns the sum of any three doubles. For example, `sumOf3(1.5, 2.2, 3.7)` should return `7.4`.

7. Write a function `int maxOf4` that returns the largest of the four integer arguments. For example, `maxOf4(99, 2, 99, -4)` should return `99`.

8. What is the scope of these identifiers being referenced in the following code?

   a. `std`
   b. `cin`
   c. `MAX`
   d. `aaa`
   e. `string`
   f. `f`
   g. `result`
   h. `s`
   i. `cout`

```
#include <iostream>
#include <cmath>
using namespace std;

const double MAX = 2.0;
```

```
double f(double aaa) {
  double result;
  result = pow(3.0, aaa);
  return result;
}

int main() {
  string s = "a string";
  cout << f(MAX);
  return 0;
}
```

9. Will a change to a value parameter modify the associated argument?
10. Will a change to a reference parameter modify the associated argument?
11. Write the output generated by this program:

```
#include <iostream>
using namespace std;

void changeArgs(double & x, double & y) {
  x = x - 1.1;
  y = y + 2.2;
}

int main() {
  double a = 3.3;
  double b = 4.4;

  cout << a << " " << b << endl;
  changeArgs(a, b);
  cout << a << " " << b << endl;
  changeArgs(a, b);
  cout << a << " " << b << endl;
  return 0;
}
```

PROGRAMMING TIPS

1. Here are some common mistakes made when writing functions:
   - Placing the semicolon at the end of a function heading:

```
string move(int n) ;  // ERROR
{  // many errors flagged here. Remove ; from line above
}
```

- Assigning a value to the function name:

```
double f(double x) {
  f = 2 * x;    // ERROR: Can not assign value to function
  return f;     // ERROR: Can not return a function name
}
```

The solution: Declare a local object, assign it the value, and return it. Or, in the case of simple functions, simply return the expression:

```
double f(double x) {
  return 2 * x;
}

or do this when there is more going on inside the function:

double f(double x) {
  double result;
  result = 2 * x;
  return result;
}
```

- Failing to return a value from a non-`void` function:

```
double f2(double x) {
  double result;
  result = 2 * x;
  // ERROR: f2 must return a number
}
```

- Returning a value from a `void` function:

```
void foo(double x) {
  return 2 * x;   // ERROR
}
```

2. There are several ways that functions communicate with each other:
   - The caller can send values and objects to a function by value.
   - The caller sends objects as arguments to a function by reference when the function is designed to change the arguments.
   - The caller sends objects as arguments to a function by `const` reference to save time and memory when the function is not supposed to change the arguments.
   - The caller gets values back from a function via the return statement.
   - The caller gets values back from a function by having the function change arguments associated with reference parameters changed in the function.
3. If you want two or more values back from a function, use reference parameters. The return statement returns only one thing. If you need more than one thing back from a function, use one or more reference parameters in addition to a return statement.

PROGRAMMING PROJECTS

4A SUM THREE

Write the function `sumThree` that returns the sum of three `double` arguments.

```
// Test drive sumThree
int main() {
  cout << sumThree(1.1, 2.2, 3.3) << endl;   // 6.6
  cout << sumThree(-1, -2, 3) << endl;       // 0
  return 0;
}
```

4B ROUNDING TO n DECIMAL PLACES

Write a function named `round` that returns the value of its `double` argument rounded to the number of decimal places specified as the second argument.

```
// Test drive round
int main() {
  // Arguments: number to round (-2.9), decimal places (0)
  cout << round(-2.9, 0)     << endl;  // -3
  cout << round(-2.59, 1)    << endl;  // -2.6
  cout << round(0.0059, 2)   << endl;  // 0.01
  cout << round(1.23467, 3)  << endl;  // 1.235
  cout << round(9.999999, 4) << endl;  // 10
  return 0;
}
```

4C PAYMENT

The payment on a loan is a function of the interest rate, the number of payments (periods), and the amount borrowed. Pass these three values as arguments to a function payment that returns the loan payment. The function heading is provided for you along with a test driver. Round your answer to two decimal places (see Section 3.2). See if your answers match an online mortgage calculator.

```
#include <iostream>  // For the cout object
#include <cmath>     // For pow, which you definitely need here
using namespace std;

double payment(double amtBorrowed, double interestRate, int numPeriods) {
   // TODO: Complete this function
}

int main() { // Test drive payment

  // 6.0 needs to be divided by 100 and then by 12 to become a monthly
  // interest rate, The number of years (30) also needs to multiplied
```

```
  // by 12. The following test cases represent a monthly payment.
  cout << payment(185000.00, 6.0/100.0/12, 30*12) << endl;
  cout << payment(185000.00, 5.0/100.0/12, 30*12) << endl;
  cout << payment(185000.00, 4.0/100.0/12, 30*12) << endl;

  return 0;
}
```

Here is the formula used to calculate payments on a loan given the amount borrowed, interest rate for one period, and the number of periods:

$$Payment = Amount \times Rate \times \frac{(Rate + 1)^{Months}}{(Rate + 1)^{Months} - 1}$$

4D POPULATION GROWTH PREDICTION

According to **http://www.census.gov/popclock/**, at the time of this writing the population growth in the United States can be predicted as follows:

One birth every *8 seconds*
One death every *13 seconds*
One international migrant (net) every *40 seconds*

Write a function that predicts the population for any number of days into the future when also given the current population. The following test driver must compile and generate the output shown in comments:

```
int main() {
  cout << populationPrediction (320000000, 0) << endl; // 320000000

  // One and two day growth:
  cout << populationPrediction(320000000, 1) << endl;  // 320006314
  cout << populationPrediction(320000000, 2) << endl;  // 320012628

  // One and two year growth
  cout << populationPrediction(320000000, 365) << endl;   // 322304554
  cout << populationPrediction(320000000, 2*365) << endl; // 324609108

  return 0;
}
```

Once the function has been tested, write a complete program that prompts the user for the current population and the days into the future using a dialog that looks just like this:

```
Predict population growth given the current population
and days into the future

Current population? 320000000
Day into the future? 365
```

```
In 365 days, the population should grow by 2304554
to become 322304554
```

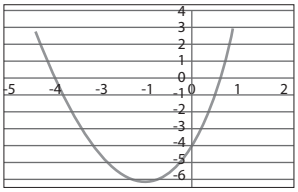
4E QUADRATIC FORMULA

The quadratic formula (below) uses the *a*, *b*, and *c* from quadratic equations of the form $ax^2 + bx + c$ to find both roots.

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

For example, the two real roots of $x^2 + 3x - 4$ are 1 and –4 as indicated by this dialog and the plotting of this function:

```
Enter a b and c coefficients of a quadratic equation: 1 3 -4

roots: 1 and -4

1x^2 + 3x + -4 when x is 1 should be 0
This should be 0 or very close? 0

1x^2 + 3x + -4 when x is -4 should be 0
This should be 0 or very close? 0
```



You are asked to complete and test these three functions as described in the comments:

```
// Given the 3 coefficients, compute the two roots that
// are made accessible as reference parameters. Assignment to
// root1 and root2 also change the associated arguments.
void findBothRoots(double a, double b, double c,
                        double & root1, double & root2)

// Evaluate any quadratic equation given the 3 coefficients
// and the root in question. This function should return 0.0,
// but something close to 0.0 like -6.66134e-16 is okay.
// This function could return nan if b^2 – 4ac < 0 or a is 0.
double evaluate(double a, double b, double c, double root)

// Generate the requested dialog using the two functions above.
int main()
```

To avoid the roots being not a number (`nan`) when there is a negative square root, complex numbers could be used. However, if the roots are not real, the return result is allowed to be `nan`

(or `-1.#IND` in Visual Studio as of this writing). The quadratic equation $3x^2 + 4x + 2$ has no real roots. This program run indicates there are no real roots since `nan` is returned with `3`, `4`, and `2` input for `a`, `b`, and `c` respectively:

```
Enter a b and c coefficients of a quadratic equation: 3 4 2

roots: nan and nan

3x^2 + 4x + 2 when x is nan should be 0
This should be 0 or very close? nan

3x^2 + 4x + 2 when x is nan should be 0
This should be 0 or very close? nan
```

CHAPTER FIVE

Sending Messages

SUMMING UP

You have now used and implemented free (non-member) functions. These functions represent only a small portion of available non-member functions. These free functions—those that are not part of a specific class—continue to play a role in the C++ language. You can use new functions by reading the function headings and associated documentation.

COMING UP

This chapter introduces sending messages to existing objects with a syntax that differs from calling free functions. This chapter explores some of the standard member functions of the classes `string`, `ostream`, and `istream` and two author-supplied classes `BankAccount` and `Grid`. This will help you develop problem-solving skills while encouraging you to contemplate the increasing importance of classes that encapsulate data members and the member functions that use that state. After studying this chapter, you will be able to

- send messages to objects
- use `string` and `ostream` messages and understand their effects
- problem solve with `string`, `Grid` and `BankAccount` objects
- appreciate why programmers partition software into classes, which are collections of member functions combined with their related data members.

5.1 MODELING THE REAL WORLD

The C++ programming language has primitive types to store Booleans, characters, and numbers. C++ also has many types implemented with the C++ class construct. For example, `string` (which is implemented as a C++ class) stores a collection of characters along with other information such as the number of characters in that `string`. `string` type objects represent names, addresses—all sorts of data. Other classes allow programmers to store large collections of data. Even then, these hundreds of C++ classes do not supply everything that every programmer will ever need. There are many times when programmers discover they need their own types to model things in their applications. Consider the following system from the domain of banking:

The Bank Teller Specification

> Implement a bank teller application to allow bank customers to access bank accounts through unique identification. A customer, with the help of the teller, may complete any of the following transactions: withdraw money, deposit money, query account balances, and see the ten most recent transactions. The system must maintain the correct balances for all accounts. The system must be able to process one or more transactions for any number of customers.

You are not asked to implement this system now. However, you should be able to pick out some types that are relevant to this system. One simple tool for finding the types of objects that model a solution is to write down the nouns in the problem statement. Then consider each as a candidate type that might eventually represent part of the system. The types used to build the system come from sources such as

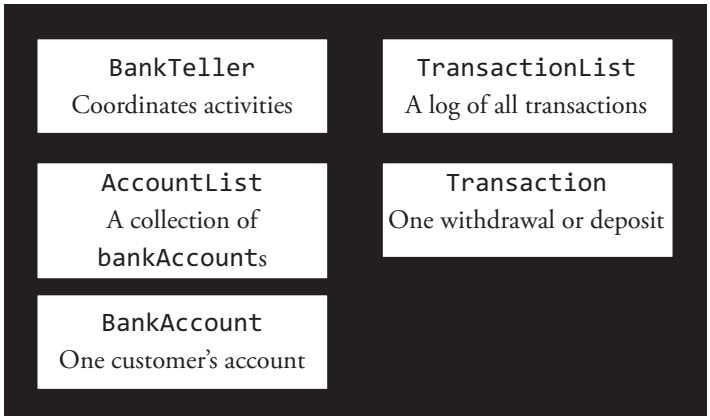
- the problem specification
- an understanding of the problem domain
- the types that come with the programming language

The types should model the real world if possible. Here are some candidates:

Candidate Objects to Model a Solution

bank teller	transaction
customers	10 most recent transactions
bank account	balance

Here is a picture to give an impression of the major types in the bank teller system. The `BankTeller` will accomplish this by getting help from many other objects.



This problem specification shows that programs usually consist of many different types. Instead of implementing the entire system and adding a user interface, only one type of object will be used here as an example — `BankAccount`.

5.1.1 BankAccount OBJECTS

Implementing a `BankAccount` type as a C++ class (in the chapter that follows) provides the ability to have many `BankAccount` objects. Each instance of `BankAccount` represents an account at a bank. Using your knowledge of the concept of a bank account, you might recognize that each `BankAccount` object should have its own account number and its own account balance. Other values could be part of every `BankAccount` object: a transaction list, a personal identification number (PIN), and a mother's maiden name, for example. You might visualize other banking operations, such as creating a new account, making deposits, making withdrawals, and accessing the current balance. There could also be many other banking messages—`generateMonthlyStatementAsPDF`, for example.

As a preview to a class as a collection of operations and values, here is a definition for the `BankAccount` type in the file `BankAccount.h` (`h` stands for header). The details for implementing new types as C++ classes will be presented in the next chapter.

```
#include <string>

class BankAccount {
  public:
    BankAccount(std::string initName, double initBalance);
    // post: Construct call with two arguments:
    //       BankAccount anAcct("Hall", 100.00);

    void deposit(double depositAmount);
    // post: Credit depositAmount to the balance

    void withdraw(double withdrawalAmount);
    // post: Debit withdrawalAmount from the balance

    double getBalance() const;
    // post: Return this account's current balance

    std::string getName() const;
    // post: Return this account's name

  private:
    std::string name;
    double balance;

};
```

Consider this class `BankAccount` definition as a blueprint used by C++ to construct many `BankAccount` objects. Each `BankAccount` object will have its own data member's name and `currentBalance`. Each `BankAccount` object will understand the same five member functions: `BankAccount`, `deposit`, `withdraw`, `getName`, and `getBalance`. While the definition is in a file

named `BankAccount.h`, the actual implementation of this C++ class will be in another file named `BankAccount.cpp`.

It should be noted here that the C++ community uses the term *data member* for a function that is part of a class. They also use the term *data member* for the variables that store the state of the objects. Other object-oriented programming languages use the term *method* rather than *member function* and the term *instance variable* rather than *data member*. This textbook will use the C++ terms.

`BankAccount` objects are constructed with two arguments to initialize the object's state:

- A `string` to represent the account identifier, a name for example
- A floating-point number to represent the initial account balance

General Form 5.1 *Constructing objects (initial values are optional)*

```
class-name object-name(initial-value(s));
```

Example object constructions:

```
BankAccount anAccount("Chris", 125.50);
string str("A string")
string str2() // default value is an empty string ""
```

Every object has

- a name: a variable that references the entire object
- state: the values that the object currently has
- messages: the operations each object can do

Every object will have a variable to provide access to the state of that object. Every object has its own unique state. Every object will understand the same set of messages. For example, given this object construction,

```
BankAccount anotherAccount("Dakota", 60.00);
```

we can derive the following information:

- a name to access the object: `anotherAccount`
- state: an account name of "`Dakota`" and a balance of `60.00`
- messages: understands messages like `withdraw`, `deposit`, `getBalance`

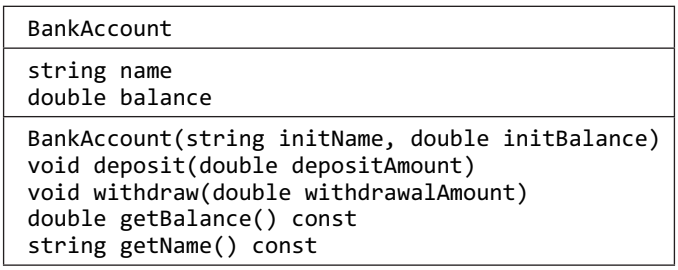
Other instances of `BankAccount` will understand the same set of messages. However, they will have their own separate state. For example, after another `BankAccount` construction,

```
BankAccount newAccount("Kim", 1000.00);
```

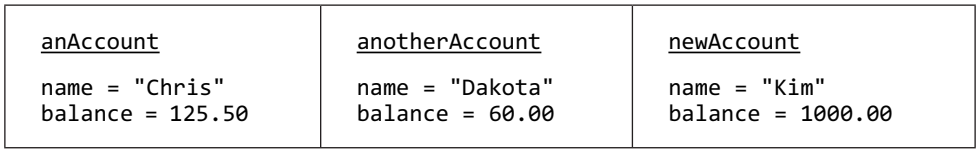
`newAccount` has its own name "Kim" and its own balance of `1000.00`.

5.1.2 CLASS AND OBJECT DIAGRAMS

The three characteristics of objects can be summarized with a class diagram:



A class diagram lists the class name in the topmost compartment. The instance variables appear in the compartment below it. The bottom compartment captures the methods. Objects can also be viewed as instance diagrams where the name of the object is underlined and values are shown:



These three object diagrams describe the current state of three different `BankAccount` objects. One class can be used to construct many objects, each with its own separate state (set of values).

5.2 SENDING MESSAGES

Objects such as `cin`, `cout` and any `string` object have class member functions. Using them is a bit different from using the free functions such as those declared in `cmath`. A different syntax is required. This different type of function call is even distinguished with a different name—*message*—when using a member function. Some messages return the object's state. Other messages tell an object to do something.

- A message that asks the object to return its state: `anAccount.getBalance();`
- A message that tells the object to do something: `anAccount.withdraw(25.00);`

The state of objects is made accessible through certain operations such as `getName` and `getBalance`. Other class member functions exist so programmers can modify the state of the object: `withdraw` and `deposit`, for example. Here is the general form used to send messages to objects:

General Form 5.2 *Sending a message to an object*

object-name.function-name(argument-list)

Example `BankAccount` messages:

```
anAccount.deposit(237.42);
anAccount.withdraw(5);
anAccount.getBalance();
```

The following are incorrect:

```
anAccount.deposit();          // Missing the amount to deposit
deposit();                    // missing the object-name and .
anAccount.getBalance;         // missing ()
anAccount.withdraw("10");     // wrong class of argument
anAccount;                    // missing member function name
anAccount.withdrawal(10);     // BankAccount has no function withdrawal
```

Fortunately, failure to supply the object name, the dot, and the operation name in the proper order usually generates an error message at compile time. Also, as with any function, the compiler complains if the client code does not supply the proper arguments between parentheses.

The `BankAccount` class (and therefore all `BankAccount` objects) has two member functions to access the state of the object: `getName` and `getBalance`. The `BankAccount` class has two member functions that modify the state—`withdraw` and `deposit`. These operations are exemplified in the following program that constructs two `BankAccount` objects and sends messages to both of those objects. Those messages result in the following actions:

- deposit `133.33` to the object named `ba1`
- withdraw `250.00` from the object named `ba2`
- display the names and modified balances of both objects

```
// Initialize two BankAccount objects and send some messages
#include <iostream>  // for cout
using namespace std;
#include "BankAccount.h"  // for class BankAccount

int main() {
  BankAccount ba1("Miller", 100.00);
  BankAccount ba2("Barber", 987.65);

  ba1.deposit(133.33);
  ba2.withdraw(250.00);

  cout << ba1.getName() << ": " << ba1.getBalance() << endl;
  cout << ba2.getName() << ": " << ba2.getBalance() << endl;

  return 0;
}
```

Output

```
Miller: 233.33
Barber: 737.65
```

Objects store varying amounts of data depending on the class to which they belong. The state of an object may require many values—and these values also may be of different classes. For example, a `BankAccount` object stores a `string` object to represent the account name, and at the same time stores a number to represent the balance. A `weeklyEmployee` object might store several `strings` such as name, address, social security number, and several numbers such as pay rate and hours worked. A `robot` object may store a current position, a map, and the state of its arm mechanism.

SELF-CHECK

5-1 Each of the lettered lines has an error. Explain why.

```
#include <iostream>      // For cout
#include "BankAccount.h" // For class BankAccount
using namespace std;

int main() {
  BankAccount b1("Sam");       // -a
  BankAccount b2(500.00);      // -b
  BankAccount b3("Jo", 200.00);// -c
  b1.deposit();  // -d
  b1.deposit; // -e
  b1.deposit("100.00"); // -f
  B1.deposit(100.00);   // -g
  b1.Deposit(100.00);   // -h
  withdraw(100); // -i
  cout << b4.getName() << endl;// -j
  cout << b1.getName << endl;  // -k
  cout << b1.getName(100.00) << endl;  // -l
  return 0;
}
```

5-2 Write the output generated by the following program:

```
#include <iostream>  // For cout
using namespace std;
#include "BankAccount.h"  // For the BankAccount class
int main() {
  BankAccount b1("Chris", 0.00);
  BankAccount b2("Kim", 500.00);
  b1.deposit(222.22);
  b1.withdraw(20.00);
  b2.deposit(55.55);
  b2.withdraw(10.00);
```

```
    cout << b1.getName() << ": " << b1.getBalance() << endl;
    cout << b2.getName() << ": " << b2.getBalance() << endl;
    return 0;
}
```

5.3 string OBJECTS

Like `bankAcount`, the `string` type is implemented as a C++ class. Although each `string` object stores a collection of characters, a programmer may sometimes be interested in one single character. At other times the programmer may require several characters or the current length of a `string` (number of characters stored). It is sometimes necessary to discover if a certain substring exists in a `string`. For example, is the substring `", "` included in the string `"Last, First"` and if so, at what index does `", "` begin? The C++ `string` type provides a large number of member functions to help with problems requiring knowledge of `string` values. You will use `string` objects in many programs.

Each `string` object stores a collection of zero or more characters. `string` objects can be constructed in two ways.

General Form 5.3 *Constructing string objects in two different ways*

```
string identifier(string-literal);
string identifier = string-literal;
```

Examples

```
string stringReference("A String Object");
string anotherStringReference = "Another";
```

As with most classes, `string` has member functions that modify the state of `string` objects—`insert`, `replace`, `erase`—and member functions that return something about the state—`length`, `find`, and `substr`. The `string` class has operations that allow access to the elements, or individual characters `at`, `[]`, `front`, and `back`. There are also a number of operators that can be applied to `string` objects such as `+`, `[]`, `<<`, and `>>`.

5.3.1 ACCESSING METHODS

string::length()

A `length` message sent to a `string` object returns the number of characters currently in the `string`.

```
string stringReference("A String Object");
string anotherStringReference = "Another";
stringReference.length();         // returns 15
anotherStringReference.length();  // returns 7
```

string::at

An `at` message returns the character located at the index passed as an `int` argument. Notice that `string` objects have zero-based indexing. The first character is located at index 0, and the second character is located at index 1, or as the message `at(1)`.

```
string str("A string object");
str.at(0); // returns 'A'
str.at(1); // returns ' '
str.at(2); // returns 's'
str.at(str.length()-1);  // returns 't', the last character
```

string::find and string::rfind

A `find` message returns the index of the first character where the entire `string` argument is found. If the `string` argument does not exist, `find` returns `string::npos` (no position), which is a very large integer that may be different from the integer shown below. `rfind` returns the starting index of the *last* occurrence of the `string` argument.

```
string str("there is the other the");
str.find("the");          // returns 0, the first "the"
cout << str.rfind("the"); // returns 19, the last "the"
cout << str.find(" is "); // returns 5
cout << str.find("not here"); // returns string::npos which
                              // may be 18446744073709551615
```

string::substr

A `substr` message returns the part of a `string` starting at the index specified as the first argument. The second argument represents the total number of characters to the end of the `string`.

```
string str("Smiles a Lot");
str.substr(1, 4);  // returns "mile"
str.substr(9, 1);  // returns "L"
str.substr(9, 2);  // returns "Lo"
str.substr(9, 55); // returns "Lot"
```

str::front and str::back

The `front` and `back` member functions provide access to the first and last characters in the `string` object.

```
string str("abc");
// front and back are part of C++11.  With some C++ compilers,
// this code may generate compile time errors because their
// string class may does not yet have these member functions.
str.front(); // returns 'a'
str.back();  // returns 'c'
```

5.3.2 MODIFYING METHODS

str::insert

An `insert` message adds additional characters into the `string` object right before the character indexed by the first argument. The second argument can be a `string` literal or another `string` object.

```
string quick("quick");
string all("the  brown jumped  dog");

all.insert(4, quick); // all.length() increased
all.insert(23, "over the lazy");

cout << all; // prints: the quick brown jumped over the lazy dog
```

str::replace

The `replace` member function changes the portion of the `string` that begins at the index of the first argument and spans the number of characters specified as the second argument.

```
string quick("quick");
string all("the  brown jumped  dog");
all.replace(4, 14, quick);
cout << all; // prints: the quick dog
```

str::erase

An `erase` message erases the part of the `string` indicated by the indexes specified in the arguments.

```
string all("the quick brown fox");
all.erase(4, 12);
cout << all << endl;  // prints: the fox
cout << all.length(); // prints 7
```

5.3.3 OPERATORS DEFINED FOR `string` OBJECTS

+ OPERATOR

Programmers often make one `string` object from two separate `strings` with the + operator that concatenates (connects) two or more `strings` into one `string`.

```
string firstName("Kim");
string lastName("Potter");

string fullName = lastName + ", " + firstName;
cout <<  fullName; // prints Potter, Kim
```

Characters can also be concatenated with `strings`.

```
fullName =  '>' + fullName + '<';
cout <<  fullName; // prints >Potter, Kim<
```

<< AND >> OPERATORS

The << and >> operators are overloaded for the `string` class to allow input and output of `string`s, just like numbers.

```
string firstName;
cout << "Enter first name: ";
cin >> firstName;              // If the user enters Kim
cout << "Hello " + firstName;  // output would be:  Hello Kim
```

[ ] OPERATOR

The `[]` is like the `at` member function. Using square brackets, individual characters can be accessed or changed.

```
string str("abcde");

str[0];  // returns 'a'
str[1];  // returns 'b'
str[4];  // returns 'e'

str[2] = 'X';
str[3] = 'O';
cout << str; // prints abXOe
```

Other operators for comparing `string`s, such as <= and ==, will be presented in a later chapter.

SELF-CHECK

5-3 What is the output from the following program?

```
#include <iostream>
#include <string>
using namespace std;  // Allows string instead of std::string

int main() {
  string str("Social Network");
  cout << str.length() << endl;
  cout << str.at(0) << endl;
  cout << str.at(str.length() - 1) << endl;
  cout << str.find("Net") << endl;
  cout << str.find("net") << endl;
  cout << str.substr(7, 3) << endl;
  cout << str.substr(7, 1) << endl;
  cout << str.substr(7, 99) << endl;
  cout << str[1] << endl
  return 0;
}
```

5-4 What is the modified value of each `string` object?

a.
```
string str1("Social");
str1.replace(0, 1, "UnS");
```

b.
```
string str3("Social");
str3.insert(3, "iet");
str3.erase(6, 1);
```

c.
```
string str2("Social");
str2.erase(3, 2);
```

d.
```
string str4("Social");
str4[0] = 'N';
str4[5] = 'X';
str4[2] = 'T';
```

5-5 Write the code to store the middle character of a `string` object into a `char` variable named `mid`. If there is an even number of characters, store the `char` to the right of the middle. For example, the middle character of "`abcd`" is '`c`'.

5-6 For each of the following messages, if there is something wrong, write "error"; otherwise, write the value of the expression.

```
string str("Any String");
```

a. `length(str)`
b. `str.length`
c. `str(length)`
d. `str.find(" ")`
e. `str.substr(2, 5)`
f. `str.substr("tri")`

5.4 `ostream` AND `istream` MEMBER FUNCTIONS

The `istream` and `ostream` classes provide input and output.

`ostream::width`

The member function `width` modifies the state of the `ostream` object named `cout`.

```
#include <iostream>
using namespace std;
int main() {
  cout << 1;
  cout.width(5);
  cout << 2;
  cout << 3;
  return 0;
}
```

Output

```
1    23
```

Normally, the state of cout is set to display the next output in the minimum number of columns—with no leading spaces—which is the default state of cout. The cout.width(5) message temporarily alters the state of cout such that the very next output will be output in a minimum of five columns. After that, the default situation is back in force so the 2 is printed in one column, immediately following the 3.

ostream::precision

To gain control over the appearance of floating-point output, use the ostream member function precision. A precision message tells the ostream object cout to show a specific number of digits in floating-point numbers. Unlike width, the precision remains the same until another precision message is sent to cout.

```
// Send two precision messages to the ostream object named cout
#include <iostream>
using namespace std;

int main() {
   double x = 1.23456;

   cout << x << endl;  // Default (1.23456)
   cout.precision(1);  // Modify the state of cout
   cout << x << endl;  // Show only one significant digit (1)
   cout.precision(4);  // Modify the state of cout
   cout << x << endl;  // Show four digits rounded (1.235)
   cout << x << endl;  // Precision of 4 still in effect

   return 0;
}
```

Output

```
1.23456
1
1.235
1.235
```

istream::good

The member function good of the istream class returns the state of an input object (usually cin). Normally, cin.good() returns 1, which means "true" if cin is still capable of reading. However, if someone enters an improper value, such as input of BAD instead of a number as shown below, the good message returns 0, which means "false."

```
cout << cin.good();  // Returns 1 for good, 0 for bad
```

Whenever cin.good() is false, no more input is allowed from cin unless other steps are taken. So if you enter an invalid number—an easy input mistake to make—strange things may occur.

```
// Demonstrate what happens with bad input
#include <iostream>  // For the cout and cin objects
using namespace std;

int main() {
  int x = 0.0;

  cout << "Is cin good? " << cin.good() << endl;
  cout << "Enter an int: ";
  cin >> x;
  cout << "Is cin still good? " << cin.good() << endl;

  return 0;
}
```

Dialogue: 1 means true	A 2nd Dialogue: 0 means false

`Is cin good? 1`
`Enter an int: 123`
`Is cin still good? 1`
	`Is cin good? 1`
	`Enter an int: NotAnInt`
	`Is cin still good? 0`

5.4.1 CLASS MEMBER FUNCTION HEADINGS

When a function is a member of a class, the function heading is qualified with the class name followed by the scope resolution operator `::`. Using `::` will be necessary to successfully build a C++ class in the next chapter. It also helps the reader determine when the dot notation is required to send a message. Any function heading of the following form identifies the function as a class member function:

General Form 5.4 *Class member function headings*

class-name `::` *function-name*`(`*parameters*`)`

So for example, `int string::length()` indicates that `length` is a member of the `string` class. It is different from the nonmember functions `sqrt` and `pow`. Here is the list of some of class member function headings that have been revealed so far (many more exist):

EXAMPLES OF CLASS MEMBER FUNCTION HEADINGS

Class	Member function heading
`string`	`int string::length() const;` `// Return the number of characters in this string`

```
                int string::find(string subString);
                // Return position of first substring

                string string::substr(int pos, int n) const;
                // Return the n characters to the right of
                // string[pos] or up to this string's length

                string insert (int pos, const string& str);
                 // Inserts additional characters into the string right
                 // before the character indicated by pos.

ostream         int ostream::width(int nCols);
                // Next output to this ostream object will be
                // displayed in nCols. Returns the current value
                // of the date member width.

                int ostream::precision(int nDigits);
                // Show floating-point output with nDigits of digits.
                // Also returns the current precision.

istream         int istream::good();
                // post: Return 1 if istream can read or 0 if corrupt

BankAccount     BankAccount::BankAccount(string aName, double initBalance);
                // post: Construct a BankAccount with two arguments

                void BankAccount::deposit(double amount);
                // pre:  amount >= 0
                // post: amount is credited to this object's balance

                void BankAccount::withdraw(double amount);
                // pre:  amount >= 0 and <= this object's balance
                // post: amount is debited from this object's balance

                double BankAccount::getBalance() const;
                // post: Return this object's current balance

                string BankAccount::getName() const;
                // post: Return this object's name
```

The class name and `::` should help you determine whether you must call a non-member (free) function without the function name first or send a message with the object name followed by a dot.

Free Function Heading	Function Call

`double pow(double base, double power)`
`// post: Return base to the power power`
	`double answer = 0.0;`
	`double x = 1.023102;`
	`answer = pow(x, 360.0);`

Member Function Heading	Message

`string string::substr(int pos, int n)`
`// post: Return n characters of this`
`//  string beginning at index pos`
	`string name("Doe, Jo");`
	`int n = name.find(",");`
	`string last =`
	`name.substr(0, n);`

Additionally, to document a function name as a class member function requiring the dot notation, you will often see member functions referred to without the parameter list and return type such as `string::length`. This is true in the context of this textbook and with most online and book documentation.

SELF-CHECK

5-7 Write the output generated by the following program. Make sure you line up all output in the correct column.

```
#include <iostream>
using namespace std;
int main() {
  cout << "123456789012345" << endl;
  cout.width(3);
  cout << 1;
  cout.width(5);
  cout << 2.3;
  cout.width(6);
  cout << "who" << endl;
  return 0;
}
```

5-8 Write the exact output generated by the following program:

```
#include <iostream>
using namespace std;
int main() {
  cout.precision(3);
  cout << 9.876543 << endl;
  cout.precision(1);
  cout << 1.2 << endl;
  cout.precision(8);
  cout << 1.2 << endl;
  return 0;
}
```

5-9 Write the complete dialogue generated by the following program when:

a. the user enters ***123***

b. the user enters ***XYZ***

```
#include <iostream>
using namespace std;
int main() {
  int anInt(0);
  cout << "Enter an integer: ";
  cin >> anInt;
  cout << "Good? " << cin.good() << endl;
  return 0;
}
```

5-10 What class does each member function belong to?

a. `istream::clear`
b. `Grid::move`
c. `ostream::width`
d. `string::replace`
e. `BankAccount::withdraw`
f. `istream::good`

5.5 ANOTHER NONSTANDARD CLASS: `Grid`

This section presents another nonstandard class that will be used occasionally over the next several chapters to help you think in terms of objects while providing opportunities to improve problem-solving skills.

This section presents a `Grid` type implemented as a C++ class. Before you study this section, please realize that the `Grid` class is meant to be used for teaching and learning purposes only. It will be used occasionally in later chapters to demonstrate new concepts in a visual manner. However, `Grid` objects are not meant to predominate any of those new concepts. The graphical state of `Grid` is meant to help you more readily grasp the access and modification of object state through messages. You will be able to complete a few programming projects comprised only of messages to this object.

The `Grid` class presented here is based on the work of Rich Pattis' *Karel the Robot: A Gentle Introduction to the Art of Programming* and a game seen at Disney World's Epcot Center. The game asked the question, "Could you be a programmer?" The player was invited to guide a pirate ship to a treasure while avoiding obstacles.

A `Grid` object stores a little rectangular map of rows and columns with an object to move. A `Grid` object is initialized with five arguments:

```
Grid Grid-name (rows, cols, mover-row, mover-col, direction);
```

where the first two arguments represent the size of the Grid in rows and columns, the next two arguments are the mover's starting row and column, and the last argument is the mover's starting direction. The direction must be listed either as `north`, `south`, `east`, or `west`.

The following program provides an example initialization with an output message (`Grid::display`) that allows the programmer to inspect the state of the `Grid`. To maintain

consistency with C++, which begins counting at `0`, the first row is referenced as the `0` row. The first column is also referenced as the `0` column and the intersection of the first row, first column location is referenced as `0, 0`.

```
// Initialize and display a Grid object
#include "Grid.h"  // For the Grid class

int main() {
  // Arguments used to initialize a Grid object go like this:
  // #rows, #columns, StartRow, StartColumn, StartDirection

  Grid aGrid(8, 16, 4, 8, east);  // 4 is the fifth and
                                  // 8 is the ninth column
  aGrid.display();
  return 0;
}
```

Output

```
The Grid:
. . . . . . . . . . . . . . . .
. . . . . . . . . . . . . . . .
. . . . . . . . . . . . . . . .
. . . . . . . . . . . . . . . .
. . . . . . . . > . . . . . . .
. . . . . . . . . . . . . . . .
. . . . . . . . . . . . . . . .
. . . . . . . . . . . . . . . .
```

A `Grid` object's state is accessed with class member functions such as these:

- `int Grid::row() const`
- `int Grid::nRows() const`
- `int Grid::nColumns() const`
- `void Grid::display() const`
- `bool Grid::frontIsClear() const`

Although you may not see the need for these operations at this point, they will come in handy if you do any problem solving associated with `Grid` objects.

```
// Access the state of a Grid object with messages
#include <iostream>  // For the cout object
using namespace std;
#include "Grid.h"    // For class Grid

int main() {
  Grid aGrid(7, 14, 5, 8, east);  // Column 8 is the ninth column
  cout << "Current row      : " << aGrid.row()          << endl;
  cout << "Current column   : " << aGrid.column()       << endl;
  cout << "Number of rows   : " << aGrid.nRows()        << endl;
```

```
  cout << "Number of columns: " << aGrid.nColumns()     << endl;
  cout << "Front is clear?  : " << aGrid.frontIsClear() << endl;
  return 0;
}
```

Output

```
Current row      : 5
Current column   : 8
Number of rows   : 7
Number of columns: 14
Front is clear?  : 1
```

The state of any `Grid` object is modified with the messages `Grid::move()`, `Grid::turnLeft()`, and `Grid::turnRight()`.

```
#include "Grid.h"  // For the Grid class

int main() {
  Grid aGrid(7, 9, 1, 3, east);

  aGrid.move();
  aGrid.move();
  aGrid.turnRight();
  aGrid.move();
  aGrid.move();
  aGrid.turnRight();
  aGrid.move();
  aGrid.move();
  aGrid.turnLeft();
  aGrid.move();
  aGrid.move();
  aGrid.display();
  return 0;
}
```

Output

```
The Grid:
. . . . . . . . .
. . .       . . .
. . . . .   . . .
. . .       . . .
. . .   . . . . .
. . . v . . . . .
. . . . . . . . .
```

SELF-CHECK

5-11 Write the output of the following program:

```
#include <iostream>  // For cout
using namespace std;
#include "Grid.h"      // For the Grid class

int main() {
  Grid aGrid(6, 6, 4, 2, east);
  aGrid.move(2);
  aGrid.turnLeft();
  aGrid.move(3);
  aGrid.turnLeft();
  aGrid.move(2);
  aGrid.display();
  cout << "row: " << aGrid.row() << endl;
  cout << "col: " << aGrid.column() << endl;
  return 0;
}
```

5.5.1 OTHER `Grid` OPERATIONS

There are several other `Grid` operations, some of which will be needed in this chapter's programming projects. Completing those projects provides practice at sending messages to objects—calling member functions—and developing algorithms resulting in a more graphical result.

The following class diagram lists all `Grid` member functions. It is not necessary to know the data members to use objects, so the state is omitted here.

`Grid` MEMBER FUNCTIONS

```
// -- Modifiers
  void move();
  void move(int spaces);
  void turnLeft();
  void turnRight();
  void putDown();
  void putDown(int putDownRow, int putDownCol);
  void toggleShowPath();
  void pickUp();
  void block(int blockRow, int blockCol);

// -- Accessors
  bool frontIsClear() const;
  bool rightIsClear() const;
  int row() const;
  int column() const;
  int nRows() const;
  int nColumns() const;
  void display() const;
```

Although this class diagram provides a summary of legal messages, it does not explain the number and class of arguments to use when sending messages to a `Grid` object. For that, the

following subset of the member function headings is provided (all the ones you need to do the programming projects in this chapter) with pre- and postconditions.

SUBSET OF `Grid` MEMBER FUNCTIONS

These help us understand what each function does. A precondition tells us what must be true before a message is sent. A postcondition tells us what will happen if the precondition is met.

```
Grid::Grid(int Rows, int Cols,
           int startRow, int startCol,
           int direction)
// post: Construct a 10-by-10 Grid object with 5 arguments
//       Grid aGrid(10, 10, 0, 0, east);

void Grid::move()
// pre:  The mover has no obstructions in the next space
// post: The mover is 1 space forward

void Grid::move(int spaces)
// pre:  The mover has no obstructions in the next spaces
// post: The mover is spaces forward

void Grid::putDown(int putDownRow, int putDownCol)
// pre:  The intersection (putDownRow, putDownCol) has nothing at
//       it except, perhaps, the mover
// post: There is one thing at the intersection

void Grid::pickUp()
// pre:  There is something to pick up at the mover's location
// post: There is nothing to pick up from the current intersection

void Grid::turnLeft()
// post: The mover is facing 90 degrees counterclockwise

void Grid::block(int blockRow, int blockCol)
// pre:  There is nothing at the intersection (blockRow, blockCol)
// post: The intersection can no longer be visited

void Grid::display() const
// post: The current state of the Grid is displayed on the screen
```

For example, think about a program that blocks three intersections (represented by `#`), instructs a kid to eat two cookies, and moves the kid back to the starting point. A few messages to `Grid::putDown` will place a few "cookies" (or whatever you would like the capital letter "`O`" to represent) on the `Grid`. Then the challenge is sending the proper messages to move the kid to eat the cookies using the `Grid` member functions such as `Grid::move`. If the kid is facing south you will see a `v`, if the kid is facing north you will see `^`, if the kid is facing east you will see `>` and facing west `<`. To "eat" the cookies send messages to `Grid::pickUp`. Here is the program:

```
// This program sets two cookies on the table and instructs a kid
// on how to locate them, "eat" them, and return home
```

```
#include "Grid.h"  // For the Grid class

int main() {
  Grid kid(8, 12, 0, 0, south);
  kid.putDown(4, 0);
  kid.putDown(4, 3);
  kid.block(3, 2);  // Can't move through a block #
  kid.block(4, 2);
  kid.block(5, 2);
  // Show the state of kid
  kid.display();

  // "Eat" two cookies
  kid.move(4);
  kid.pickUp();
  kid.move(2);
  kid.turnLeft();
  kid.move(3);
  kid.turnLeft();
  kid.move(2);
  kid.pickUp();

  // Get the kid back home
  kid.move(4);
  kid.turnLeft();
  kid.move(3);

  // Show the ending state
  kid.display();
  return 0;
}
```

Output

```
The Grid
v . . . . . . . . . .
. . . . . . . . . . .
. . . . . . . . . . .
. . # . . . . . . . .
O . # O . . . . . . .
. . # . . . . . . . .
. . . . . . . . . . .
. . . . . . . . . . .

The Grid
<       . . . . . . .
  . .   . . . . . . .
  . .   . . . . . . .
  . #   . . . . . . .
  . #   . . . . . . .
  . #   . . . . . . .
        . . . . . . .
. . . . . . . . . . .
```

5.5.2 FAILURE TO MEET THE PRECONDITIONS

There are many "illegal" messages you can send to a `Grid` object. For example, you could try sending a `move` message that asks the mover to move through a block (`#`) or off the edge of the `Grid`. All it takes is one incorrect message—moving four rows instead of three, for example.

SELF-CHECK

5-12 If you were designing the operations for a `Grid` object, what would you want to prevent from occurring?

So what should a `Grid` object do when sent a message that makes no sense? Quite frankly, it's a bit awkward. The object could respond by doing nothing. In this case, the state of the object would remain unaltered. Or the object could travel off the end of the `Grid` or move through blocks—but this sounds more like a Superman object. Here's yet another snippy answer: the behavior is *undefined*.

This awkwardness is circumvented by the notion of preconditions. A function's *precondition* is what the function presumes to be true when a function is called or the message is sent. For example, the `void move(int spaces)` operation has the precondition that there is no block or `Grid` edge in the path of the mover. Also, the `Grid::pickUp()` message presumes there is something to pick up.

```
void Grid::move(int spaces)
// pre:  The mover has no obstructions in the next spaces
// post: The mover is spaces forward

void Grid::pickUp()
// pre:  There is something to pick up at the mover's location
// post: There is nothing to pick up from the current intersection
```

So what does happen when you violate one of these preconditions? You'll likely find out if you work on certain `Grid`-related programming projects.

5.5.3 FUNCTIONS WITH NO ARGUMENTS STILL NEED ( )

You have now seen several messages that require no arguments. If a function has no parameters, it requires no arguments. Here are two examples:

```
cout << aString.length() << endl;
cout << aGrid.row() << endl;
```

It should be noted, before you do any of this chapter's programming projects, that even though no values need to be passed as arguments to either `string::length` or `Grid::row`, the parentheses must still be included in the message. The following code will not do what you might expect:

```
cout << aString.length << endl;  // ERROR: Missing () after length
cout << aGrid.row << endl;       // ERROR: Missing () after row
```

The parentheses represent the function call operator. Without `(` and `)`, there is no function call—even when zero arguments are needed by the function.

5.6 WHY FUNCTIONS AND CLASSES?

Abstraction is the process of pulling out and highlighting the relevant features of a complex system. One aspect of abstraction is understanding the computer from the programming-language level without full knowledge of the details at the lower levels. Abstraction is our weapon against complexity.

You can use operations such as `sqrt`, `pow`, `Grid::move`, and any other new function without knowing the implementation details coded by other programmers. Abstraction allows programmers to quickly and easily use `int`, `double`, `string`, `BankAccount`, and `Grid` objects. The characteristics of `int` data (a specific range of integer values) and `int` operations (such as addition, multiplication, assignment, input, and output) can be understood without knowing the details of those operations, or even how those values are stored, or how these operations are implemented in the hardware and software. Abstraction is friendly. Abstraction makes life easier. Abstraction helps keep us sane. Abstraction is that little "black box" programmers are always talking about. When you can't see how a function is implemented, a programmer calls that a "black box." That is abstraction.

Even though C++ is delivered with a large set of abstractions known as functions and classes, additional functions and classes will still be required. New abstractions are built from existing objects, operations, and algorithms. As you begin to create function and class abstractions, set a goal to build these abstractions so they are easy to use and perform a well-defined operation. When the details of implementation are long forgotten, you will still be able to use the abstraction because you know *what* it does. You won't have to remember *how* it does it.

Instead of encapsulating a group of related code statements in a function, you could write all code statements directly in the `main` function. Those statements would then replace the function call. However, as the table below shows, that detailed way is quite extensive in the number of lines required.

The Actions Represented by One Message

Operation	The Object-Oriented Way	The Detailed Way
Construct one `Grid` object	`Grid g(15,15,9,4,east);`	35 lines
Move in current direction	`g.move(2);`	112 lines
Output the `Grid`	`g.display();`	6 lines
Change direction	`g.turnLeft();`	10 lines

The four messages in the middle column represent the abstract equivalent of coding the 163 lines the non-function way, as listed in the right column. Now imagine a six-message program that moves and turns three times. The equivalent non-function way would require approximately 366 detailed lines of code rather than the six messages!

By placing the many lines of detailed code into functions, the programmer may execute that operation with just one message or function call. The same message may be sent over and over again. So whenever you have code that can be used more than once in a program, it is preferable to implement that behavior within the confines of a free (nonmember) function or as one of many member functions available to the objects. Function calls and messages represent many hidden instructions and details. The programmer need not see, nor understand, all implementation details. Encapsulating code in functions also helps avoid code duplication, a sign of poorly-written programs. *Abstraction*, *encapsulation*, and *black box* are all terms used for hiding information.

SELF-CHECK

5-13 Using the previous table, how many lines of code are required to initialize the state of one `Grid` object using the object-oriented way?

5-14 Using the previous table, how many lines of code are required to initialize the state of one `Grid` object when the detailed way is used (right column)?

5-15 Write a paper and pencil program that constructs a `Grid` object and moves it one space in all four directions: `north` `east` `south` `west`.

By partitioning low-level details into one function, the implementation need only be written once. Another advantage of functions is that the same operation can be used over and over again with a one-line message. Rather than one huge `int main() { }`, programs are composed of more manageable calls to nonmember (free) functions (`sqrt` and `pow`) and messages to class member functions (`string::substr` and `Grid::move`). Here are some reasons why C++ programmers use existing functions and objects to better manage the complexity of software development:

- to reuse existing code rather than write it from scratch
- to concentrate on the bigger issues at hand
- to reduce errors by writing the function only once and testing it thoroughly

In the early days of programming, programs were written as one big `main` program. As programs became bigger, *structured programming* techniques became popular. One major feature of structured programming was to partition programs into functions for more manageable code. Programmers found this helped people understand the program better. It is easier to maintain programs that place related processing details in an independent function. It is easier to fix a

20-line function in a program with 100 functions than it is to fix a 2,000-line program. Other reasons for dividing a program into smaller functions include:

- placing details into a function or class makes the code easier to comprehend
- the same actions need to be achieved more than once in a program
- the function or class can be reused in other applications

With free functions, the data are passed around from one nonmember function to another. When the data are available everywhere throughout a large program, they become susceptible to accidental changes.

Now as software has become even more complex, object technology encapsulates collections of functions with the data manipulated by those functions. Developers don't throw the data around between disparate groups of nonmember functions which would leave them open for accidental attack. As you will see in the next chapter, with object-oriented programming, data are encapsulated with the functions—nice and safe.

Historical Progression of How Programs Are Organized into Modules

The Early Days

```
main() {
 // 1
_____________
_____________
_____________
_____________
_____________
_____________
_____________
_____________
_____________
_____________
_____________

 //500
_____________
_____________
_____________
_____________
_____________
_____________
_____________
_____________
_____________
_____________
_____________
_____________
 //1000
}
```

Structured

```
one() {
_____________
_____________
}
two() {
_____________
_____________
}

//...

ninety9() {
_____________
_____________
}
hundred() {
_____________
_____________
}

main() {
_____________
_____________
_____________
_____________
_____________
_____________

}
```

Object-Oriented

```
class ONE {
  one()
  two()
  // ...
  ten()
}

// ...

class NINE {
  eighty1()
  eighty2()
  // ...
  ninety()
}

//...

class TEN {
  ninety1()
  ninety2()
  //...
  hundred()
}

main() {

}
```

SELF-CHECK

5-16 What reason for using functions makes the most sense to you?

5-17 Describe one example of how abstraction helps you get through the day.

CHAPTER SUMMARY

- The `string` class has a large number of operations for manipulating all or part of a `string`. These include `substr`, `find`, `at`, `replace`, and `length`.
- Some messages require the object name and a dot (`.`) before the member function name and arguments. Use `aString.substr(2, 5)` rather than `substr(aString, 2, 5)`.
- Consider using `cout.width(10)` to right-justify numeric output in 10 columns (or `cout.width(9)` for 9 columns, and so on). The new column width starts after the output of the previous value. It does not start at the left margin.
- Class member functions are often written with the class name and the scope resolution operator `::` to indicate the class of objects that would understand the message, so you'll see `ostream::width` rather than simply `width`.
- Class member function headings supply the same usage information as their nonmember cousins (`sqrt`, `pow`, `fmod`). The return type is given, as is the function name and the number and class of arguments that must be used.
- Class member functions additionally are qualified with their class names, for example, `void Grid::move()`.
- Most classes in this textbook are part of the C++ standard. The `BankAccount` and `Grid` classes are available at this textbook's website.
- A class diagram summarizes the names of the messages understood by any instance of a class (object). The programmer needs more information to correctly send a message such as number and class of arguments. That is why some of the class member functions were shown with pre- and postconditions.
- In the 1960s, programs were written as collections of statements. By the 1970s, programs were usually collections of free functions. Starting in the 1990s, more and more programs have been collections of interacting objects, where each object is an instance of a class containing a collection of member functions. Each improvement allows more complex software to be built.
- Abstraction means the programmer can call a function or send a message without knowing the implementation details. The programmer does need to know the function name, the return type, or the number and class of arguments.

EXERCISES

1. Write the output generated by the following program:

```
#include <iostream>
using namespace std;
#include "BankAccount.h"  // For class Grid

int main() {
  BankAccount b1("One", 100.00);
  BankAccount b2("Two", 200.00);
  b1.deposit(50.00);
  b2.deposit(30.00);
  b1.withdraw(20.00);
  cout << b1.getBalance() << endl;
  cout << b2.getBalance() << endl;
  return 0;
}
```

2. Write the complete dialogue of this program when the user enters this input in the order requested: `MyName  100  22.22  44.44`

```
#include <iostream>  // For cout and endl
using namespace std;
#include "BankAccount.h"  // For the BankAccount class
int main() {
  string name;
  double start, amount;
                                  // Input:
  cout << "name: ";               // MyName
  cin >> name;
  cout << "initial balance: ";  // 100
  cin >> start;

  // Construct a BankAccount
  BankAccount one(name, start);

  cout << "deposit? ";           // 22.22
  cin >> amount;
  one.deposit(amount);

  cout << "withdraw? ";          // 44.44
  cin >> amount;
  one.withdraw(amount);

  cout << "balance for " << one.getName() << " is "
                         << one.getBalance() << endl;
  return 0;
}
```

3. Write the output generated by the following program:

```
#include <iostream>  // For the object cout
using namespace std;
```

```
#include "Grid.h"      // For the Grid class
int main() {
  Grid aGrid(6, 6, 1, 1, south);
  aGrid.putDown(2, 3);  // Place thing at a specific intersection
  aGrid.block(0, 0);
  aGrid.block(5, 5);
  aGrid.move(2);
  aGrid.turnLeft();
  aGrid.putDown();      // Place thing where the mover is
  aGrid.move(3);        // located, which appears as &
  aGrid.turnLeft();
  aGrid.putDown();      // Place object where the mover is located
  aGrid.move(1);
  aGrid.turnLeft();
  aGrid.move(1);
  aGrid.display();
  cout << "Mover: row#" << aGrid.row() << " col#" << aGrid.column()
       << endl;
  return 0;
}
```

4. What is the value of `position`?

```
string s("012345678");
// Initialize position to the first occurrence of "3" in s
int position = s.find("3");
```

5. What is the value of `s2`?

```
string s1("012345678");
string s2(s1.substr(3, 2));
// assert: s2 is a substring of s1
```

6. What is the value of `lengthOfString`?

```
string s3("012345678");
int lengthOfString = s3.length();
// assert: lengthOfString stores the number of characters in s3
```

7. Choose the most appropriate classes for each of the following from this set of classes: `double`, `int`, `ostream`, `istream`, `string`, `BankAccount`, or `Grid`.

   a. Represent the number of students in a section.

   b. Represent a student's grade point average.

   c. Represent a student's name.

   d. Represent the number of questions on a test.

   e. Represent a person's savings account.

   f. Simulate a very limited version of the arcade game Pac-Man.

   g. Read input from a user.

   h. Display output.

8. Name two reasons why programmers use or implement functions.
9. Must a programmer understand the implementation of `Grid::move` to use it?
10. Answer the following questions given the member function heading:

```
void Grid::block(int blockRow, int blockCol)
// pre:  The intersection at (blockRow, blockCol) has nothing
//       at all on it, not even the mover
// post: The intersection at (blockRow, blockCol) is blocked. The
//       mover cannot move into this intersection.
```

    a. What is the member function name?
    b. What type does it return?
    c. What class does it belong to?
    d. Write a valid message assuming a `Grid` object named `aGrid` exists.

11. Write a complete C++ program that will initialize a `BankAccount` object with an initial balance of $500.00 and your own name. Make a deposit of $125 and a withdrawal of $20.00. Then show the name and balance. The output should look like this:

```
name: Your Name
balance: 605
```

PROGRAMMING TIPS

1. You will need author-supplied files to complete some programming projects. These are the files included with " and " rather than < and > (`"Grid.h"` and `"BankAccount.h"`, for example). Both files need to be located in the same directory (folder) as the `.cpp` file with the main function that you are writing. You can download the proper files from this textbook's website.
2. Distinguish standard `#include` files from nonstandard (user defined) files. `#include` standard libraries (classes and objects) with `< >` and nonstandard classes with `" "`. Here are some examples:

```
#include <string>    // For the standard string class
#include <iostream>  // For cout and cin
using namespace std; // Required to avoid writing std::cout

#include "BankAccount.h"  // For class BankAccount
#include "Grid.h"         // For class Grid
```

3. Even if no arguments are required, end messages with `()`. Do not forget parentheses in messages that do not require arguments.

```
cout << myAcct.balance;   // Error: This references a memory location
cout << myAcct.balance(); // Good
```

4. C++ begins counting at 0, not 1. The first character in a `string` is referenced with subscript `0`, not `1`.

```
cout << aString[0];  // Return the first character
cout << aString[1];  // Return the second character
```

5. Don't reference `aString[aString.length()]`. This is an attempt to reference a single value that is not in the range of `0` to `aString.length()-1`. In general, do not reference characters in a `string` that do not exist.

```
string aString;
aString = "This string has 29 characters";
cout << aString[-1];  // ERROR: -1 is out of range, only use 0..28
cout << aString[aString.length()];  // ERROR: 29 is also out of range
```

6. Two different kinds of constructions are allowed when only one argument is required (C++11 defines another, but it is not used until later). One with parenthesis and one with the assignment operator:

```
string state1 = "Arizona";
string state2("Minnesota");

int n2 = 0;
int n1(0);

double x2 = 0.0;
double x1(0.0);
```

   However, when two or more values are needed to initialize an object, use parentheses like this:

```
BankAccount anAcct("Skyler", 23.41);
Grid aGrid(12, 12, 0, 0, east);
```

7. The `::` operator indicates the class to which a function belongs. The `::` operator is called the "scope resolution operator." The class name followed by `::` documents a function as a member function. Any instance of that class will understand the message. Therefore, `string::length` documents that any `string` object will understand the `length` message. However, the class name and `::` are not to be used in the message.

```
BankAccount anAcct("Milan", 345.67);

// Need 'object-name.functionName' not 'class-name::functionName'
cout << BankAccount::balance(); // Invalid
cout << anAcct.balance();       // A valid message
```

PROGRAMMING PROJECTS

5A A LITTLE CRYPTOGRAPHY

Write a C++ program that hides a message in five words. Use one of the characters in the five input `string`s to spell out one new word. Make up at least one other message besides these two that requires running the same program twice:

```
Enter five words: cheap energy can cause problems
Enter five integers: 4 2 1 0 5
Secret message: peace

Enter five words: programming is very complex work
Enter five integers: 3 0 0 5 2
Secret message: giver
```

5B LETTER I

Write the code that would go in a `main` function that constructs a 13-by-7 `Grid` object and then instructs the mover to "draw" the letter I exactly as shown (the mover could be left anywhere next to the I).

```
. . . . . .
. . . . . .
. .       . .
. . .   . . .
. . .   . . .
. . .   . . .
. . .   . . .
. . .   . . .
. . .   . . .
. . .   . . .
. .       > .
. . . . . . .
. . . . . . .
```

5C HURDLES

Write a function `void jumpOneHurdle(Grid & g)` that instructs the mover to jump one "hurdle" (the block #). The main function must make five calls to this function and display the current state after each function call to `jumpOneHurdle`.

```
g.display();  // Show initial state, just after construction
jumpOneHurdle(g);  g.display();
jumpOneHurdle(g);  g.display();
jumpOneHurdle(g);  g.display();
jumpOneHurdle(g);  g.display();
jumpOneHurdle(g);  g.display();
```

The first display message should show this state of the `Grid` object:

```
The Grid:
. . . . . . . . . . . . . . . . . . . . . . . .
. . . . . . . . . . . . . . . . . . . . . . . .
> . . # . . . # . . . # . . . # . . . # . . . #
. . . . . . . . . . . . . . . . . . . . . . . .
```

The sixth display message should show the mover has jumped five hurdles:

```
The Grid:
. . . . . . . . . . . . . . . . . . . . . . . .
. .       .       .       .       .       . .
      #       #       #       #       # > . .
. . . . . . . . . . . . . . . . . . . . . . . .
```

5D STAIR CLIMB

Write a function `void climbStair(Grid & g)` that instructs the mover to climb one step and call it enough times to climb to the top of the stairs. You will need six block messages to simulate the stairs below.

Before

```
The Grid:
. . . . . . . . .
. . . . . . . . .
. . . . . # # # .
. . . . # . . . .
. . . # . . . . .
> . # . . . . . .
. . . . . . . . .
```

After

```
The Grid:
. . . . . . . . .
. . . .       . >
. . .     # # # .
. .     # . . . .
.     # . . . . .
    # . . . . . .
. . . . . . . . .
```

5E TEN `String` PROCESSING FUNCTIONS

Write one C++ program that uses this test driver as a `main` function to generate the output shown by calling ten new free functions, which are specified below.

```
// Test drive 10 String processing functions
int main() {
  cout << "    matterAntiMatter(\"LOL\"): " << matterAntiMatter("LOL")     << endl;
  cout << "       removeEnds(\"MarkeR\"): " << removeEnds("Marker")        << endl;
  cout << "             tripleUp(\"on\"): " << tripleUp("on")              << endl;
  cout << " splitString(\"IU\", \"owe\"): " << splitString("IU", "owe")    << endl;
  cout << "   reverse7Chars(\"1234567\"): " << reverse7Chars("1234567")    << endl;
  cout << "       halfAndHalf(\"ABcde\"): " << halfAndHalf("ABcde")        << endl;
  cout << "nameRearranged(\"Li, Kim R\"): " << nameRearranged("Li, Kim R") << endl;
  cout << "      middleThree(\"123456\"): " << middleThree("123456")       << endl;

  // Use reference parameters instead of returning a string
  string str1("abacada");
  remove3(str1, "a");
  cout << "    remove3(\"abacada\", \"a\"): " << str1 << endl;

  string str2("ornoon");
```

```
  replace(str2, 'o', 'X');
  cout << "replace(\"ornoon\", 'o', 'X'): " << str2 << endl;

  return 0;
}
```

Expected Output

```
           matterAntiMatter("LOL"): Anti-LOL
              removeEnds("MarkeR"): arke
                    tripleUp("on"): 1)on 2)on 3)on
           splitString("IU", "owe"): IoweU
           reverse7Chars("1234567"): 7654321
              halfAndHalf("ABcde"): cdeAB
        nameRearranged("Li, Kim R"): Kim R. Li
             middleThree("123456"): 345
            remove3("abacada", "a"): bcda
        replace("ornoon", 'o', 'X'): XrnXXn
```

1. `string antiMatter(string matter)`

   Everyone knows that interplanetary space travel is fueled by letting matter and antimatter mix. With this in mind, write a function `antiMatter` that takes a `string` with the name of some thing or idea. Return a `string` with "`Anti-`" prepended to it. Don't forget the hyphen.

   `matterAntiMatter("Shoes")` returns `"Anti-shoes"`

   `matterAntiMatter("noisy trucks")` returns `""Anti-noisy trucks"`

   `matterAntiMatter("LOL")` returns `"Anti-LOL"`

2. `string removeEnds(string str)`

   Complete method `removeEnds` to return a substring of the supplied `string` that does not have the characters at either end. Precondition: `str` always has at least two characters.

   `removeEnds ("MarkeR")` returns `"arke"`

   `removeEnds ("mom")` returns `"o"`

   `removeEnds ("to")` returns `""`

3. `string tripleUp(string str)`

   Complete method `tripleUp` to return a `string` that has the argument repeated three times with `1)`, `2)`, and `3)` as shown. Precondition: `str.length() ≥ 1`

   `tripleUp("top")` returns `"1)top 2)top 3)top"`

4. `string splitString(string str, string mid)`

   This function takes in a `string` of length 2 or greater, and returns a `string` with a space added into the middle of the `string`. If the `string`'s length is an odd number, the second

half of the `string` will be the longer half.

`splitString("IU", "owe")` returns `"IoweU"`
`splitString("ab", "_ _")` returns `"a_ _b"`

5. `string halfAndHalf(string str)`

Complete method `halfAndHalf` to return a new `string` that has the first half of the argument at the end and the last half of the argument at the beginning. If there are an odd number of letters, consider the last half to have one more character than the first half before the split. Precondition: `str.length() ≥ 2`.

`halfAndHalf("1234abcd")` returns `"abcd1234"`
`halfAndHalf("ABcde")` returns `"cdeAB"`
`halfAndHalf("Hello")` returns `"lloHe"`

6. `string nameRearranged(string name)`

Implement `nameRearranged` that takes a name in the form `lastName`, `", "` `firstName`, and an initial and returns a `string` in the form of `firstName`, `initial`, `". "` and `lastName`.

`nameRearranged("Jones, Kim R")` returns `"Kim R. Jones"`

7. `string middleThree(string str)`

Implement `middleThree` so it returns the middle three characters of any string that has three or more characters. If the length of name is even, favor the right. Precondition: `str.length() ≥ 3`.

`middleThree("Rob")` returns `"Rob"`
`middleThree("Roby")` returns `"oby"`
`middleThree("Robie")` returns `"obi"`
`middleThree("123456")` returns `"345"`

8. `string reverse7Chars(string str)`

Implement `reverse7Chars` so it returns a `string` that is the reverse of the argument. Precondition: The argument `str` is seven characters long.

`reverse7Chars("1234567")` returns `"7654321"`
`reverse7Chars("morning")` returns `"gninrom"`

9. `void remove3(string & str, string sub)`

Implement `remove3` so it modifies the `string` argument `str` such that the first three occurrences of `sub` are removed. Precondition: The argument `sub` exists at least three times in `str`.

```
string str("there is the other the");
```

```
removeThree(str, "he");   // str changes to " tre is t otr the"

string str2("to be or to be or to be");
removeThree(str2, "to "); // str2 changes to " be or  be or  be"
```

10. `void replace(string & str, char oldC, char newC)`

    Implement `replace` to modify the `string` argument `str` so that the first three occurrences of `oldC` are changed to `newC`. Precondition: The argument `oldC` exists at least three times in `str`.

```
string str3("ornoono");
replace(str3, 'o', 'X');  //  str3 changes to XrnXXno
```

CHAPTER SIX

Class Definitions and Member Functions

SUMMING UP

Functions hide details, can be called many times, can be reused in other programs, and help in the design of larger programs. Each function performs a well-defined service.

COMING UP

When a function belongs to a class, it becomes a class member function. Class member functions have a lot in common with their nonmember cousins. Chapter 6 presents an introduction to C++ class definition and member function implementations. You will learn to read and understand classes by their *definitions*—the collection of member function headings (the interface) and data members (the state). In the second part of this chapter, you will learn to implement class member functions. You will also see a few appropriate object-oriented design guidelines that help explain why classes are designed the way they are. After studying this chapter, you will be able to

- read and understand class definitions (interface and state)
- implement class member functions using existing class definitions
- apply some object-oriented design guidelines

6.1 DEFINING A CLASS IN A HEADER FILE

Abstraction refers to the practice of using and understanding something without full knowledge of its implementation. Abstraction allows the programmer using a class to concentrate on the data characteristics and the messages that manipulate the state. For example, a programmer using the `string` class need not know the details of the internal data representation or how those operations are implemented in the hardware and software. The programmer can concentrate on the set of allowable messages—*the interface*.

This chapter presents some implementation issues that so far have been hidden. In the first part of this chapter, the `BankAccount` class will be studied at the implementation-detail level. However, before examining the physical side of class design, let's consider some of the design decisions that were made for this textbook's `BankAccount` class.

All `BankAccount` objects have four allowable operations: `deposit`, `withdraw`, `getBalance`, and `getName`. There could have been more, or there could have been fewer. The member functions for `BankAccount` were chosen to keep the class simple and to provide a collection of operations that are relatively easy to relate to. A compromise was made. The design decisions were influenced by the context—a first example of a C++ class used in a particular domain, the area of banking.

The `BankAccount` member functions that make up the interface are only a subset of the operations named by students who were asked this question: what should we be able to do with bank accounts? The data members are also a subset of the operations named by students who were asked this question: what should bank accounts know about themselves?

Many additional operations that were recognized by students (`transfer`, `applyInterest`, `printMonthlyStatement`) and many additional data members (type of account, record of transactions, address, Social Security number, and mother's maiden name) were not included. The design of these classes was affected by the intention of keeping these objects as simple as possible while retaining some realism. However, a group of object-oriented designers developing large-scale applications in the banking domain would likely retain many of the operations and attributes recognized by students. There is rarely one single design that is correct for all circumstances.

Designing anything requires making decisions in an effort to make the thing "good." Good might mean having a software component that is easily maintainable; it might mean classes that can be reused in other applications; or it might mean a system that is very robust—one that can recover from almost any disastrous event. Good might mean a design that results in something that is easier to use, prettier, etc. There is rarely ever a single perfect design. There are usually trade-offs. Design is an iterative process that evolves with time.

Design is influenced by personal opinion, evolving research, and the domain, which could be banking, information systems, process control, engineering, and so on. Fortunately, there are design guidelines to show the way, a few of which are presented later. Let's now turn to the construct that captures many of these design decisions in object-oriented software development—the *class definition*.

The classes of objects under study—`ostream`, `istream`, `string`, `BankAccount`, and `Grid`—are building blocks of larger programs. However, programs typically require many other classes. They may be standard classes, classes that are bought off the shelf, or other classes that must be designed and implemented by a programming team.

Because it is difficult to have mastery of all classes in a large project, this section provides some general techniques for understanding unfamiliar classes. The knowledge attained here also provides experience with the major component of object-oriented software development—the class.

This process begins with learning to read class definitions. You will also implement member functions and add new operations to existing classes. This approach has the added benefit of making it easier to design and implement new classes of your own.

A class definition lists member functions after the keyword `public:`. This set of operations represents the class interface. The class definition also lists the *data members*—the object declarations after `private:`. This set of data members represents the state of the objects.

A class definition provides a lot of information. A class definition stresses the *what*, not the *how*. It lists the messages understood by the objects. It specifies the number, type, and order of arguments required when sending a message to one of the objects. When documented with preconditions, postconditions, and example messages, a class definition also explains how to use instances of the class. The documentation may provide other pertinent information. All of these things allow the programmer to use objects of the class without knowing the details of the implementation.

General Form 6.1 *Class definition*

```
class  class-name {
public: // MEMBER FUNCTIONS (the interface)

//--constructor
  class-name(parameter-list) ;

//--modifiers
  function-heading;         // Member functions that
  function-heading;         // modifies the state

//--accessors
  function-heading const;    // Member function that access
  function-heading const;    // but can't change state
  . . .

private:  // DATA MEMBERS (the state)
  object-declaration         // Data member
  object-declaration         // Data member
  . . .
};  // Class definitions must end with a semicolon
```

6.1.1 DEFINING `class` BankAccount

Now let's get down to a concrete, familiar example. Recall that the data members in the `private` section represent the state. Every `BankAccount` object stores its own private `name` and `balance` data. The public section has the member functions representing the messages each `BankAccount` understands: `withdraw`, `deposit`, `getBalance`, and `getName`. These are combined in the header file `BankAccount.h` as a class definition.

Class Definition: *BankAccount*

File `BankAccount.h`

```
#include <string>
// Do not place using statements in header files. Use std::

class BankAccount {
public:
  BankAccount(std::string initName, double initBalance);
  // post: Construct with two arguments, example:
  //       BankAccount anAcct("Hall", 100.00);

  void deposit(double depositAmount);
  // post: Credit depositAmount to the balance

  void withdraw(double withdrawalAmount);
  // post: Debit withdrawalAmount from the balance

  double getBalance() const;
  // post: Return this account's current balance

  std::string getName() const;
  // post: Return this account's name

private:
  std::string name;
  double balance;

};   // Don't forget the semicolon
```

Most `BankAccount` member function headings in this `BankAccount` class definition are similar to the nonmember function headings—they usually have return types and parameters. However, one of the member function headings above does not fall into this category. Can you spot something different about the function heading with the name `BankAccount`?

First of all, the `BankAccount::BankAccount` member function has no return type. It also has the same name as the class! These special member functions are referred to as *constructors* because they are used to "build" objects. Specifically, constructors associate the object name with a portion of memory and initialize the data members of the object as in a `BankAccount` object construction. For example, this code constructs a `BankAccount` object with an initial name of `"Pat Barker"` and an initial balance of `507.34`, which can be referenced with the variable named `anAccount`.

```
BankAccount anAccount("Pat Barker", 507.34);
```

When another object is constructed like this:

```
BankAccount another("Skyler Boatwright", 437.05);
```

there exists a separate `BankAccount` object with its own balance of `437.05` and its own name of `"Skyler Boatwright"`. So the return values of these two messages would be `507.34` followed by `437.05`.

```
cout << anAccount.balance() << endl;  // 507.34
cout << another.balance() << endl;    // 437.05
```

SELF-CHECK

Use this class definition to answer the self-check questions that follow:

```
/*
 * Class definition for LibraryBook
 * file:  LibraryBook.h
 */
#include<string>

class LibraryBook {
public:

//--constructor
  LibraryBook(std::string initTitle, std::string initAuthor);
  // post: Initialize a LibraryBook object

//--modifiers
  void borrowBook(std::string borrowersName);
  // post: Records the borrower's name
  // and makes this book not available

  void returnBook();
  // post: The book becomes available

//--accessors
  bool isAvailable() const;
  // post: returns true if this book is not borrowed

  std::string getBorrower() const;
  // post: Return borrower's name if this book is not available

  std::string getBookInfo() const;
  // post: Returns this book's title and author

private:
  std::string author;
  std::string title;
  std::string borrower;
  bool available;
};
```

6-1 What is the name of the class defined above?

6-2 Name all the member functions that modify the state of the objects.

6-3 Name all the member functions that access the state of the objects and cannot change that state.

6-4 Name all data members.

6-5 What type of value is returned by `LibraryBook::getBorrower`?

6-6 What type of value is returned by `LibraryBook::isAvailable`?

6-7 Initialize one `LibraryBook` object using your favorite book and author.

6-8 Send the message that borrows your favorite book. Use your own name as the argument.

6-9 Write the message that returns the borrower's name of the book.

6.2 IMPLEMENTING CLASS MEMBER FUNCTIONS

Class member function implementations are similar to those of their nonmember relatives—with these differences:

1. Class member functions implemented outside of the class definition must be qualified with the class name and the scope resolution operator `::`. This tells the compiler they are member functions of a particular class and as such, they are allowed to directly reference the private data members.
2. The constructors are class member functions with the same name as the class and they do not have a return type. The return type is not needed because constructors return a new object of the type specified in the constructor and class name.

The relatively familiar `BankAccount` class will be used to demonstrate member function implementations. For each `.h` file there will be a `.cpp` file that `#includes` the `.h` (header) file with the class definition. This `.cpp` file implements the member functions.

6.2.1 IMPLEMENTING CONSTRUCTORS

A constructor is a special member function that always has the same name as the class. It never has a return type. Although member functions can be defined within a class definition, this textbook uses the software engineering principle of separating interface from implementation by implementing the member functions in a separate file. In this case, the member functions must begin with `class-name ::`.

The following code implements the two-parameter constructor:

```
// File name: BankAccount.cpp
#include "BankAccount.h"       // Allows for separate compilation

BankAccount::BankAccount(string initName, double initBalance) {
  name = initName;
```

```
  balance = initBalance;
}

// . . .  more member functions need to be implemented . . .
```

This is the function that executes whenever a `BankAccount` is initialized with two arguments: a string followed by a number.

In the following code, the account name `"Corker"` is passed to the parameter `initName`, which in turn is assigned to the private data member `name`. The starting balance of `250.55` is also passed to the parameter named `initBalance`, which in turn is assigned to the private data member `balance`. After an object is constructed, the state of the object is initialized.

```
// Call the two-parameter constructor
BankAccount anInitializedAccount("Corker", 250.55);
                                                    // Output:
cout << anInitializedAccount.getName() << endl;     // Corker
cout << anInitializedAccount.getBalance() << endl;  // 250.55
```

There is a major difference between implementing class member functions and their nonmember cousins. Class member function implementations must be preceded with the class name and the `::` operator. For example, the `BankAccount` constructor is preceded with `BankAccount::` to inform the compiler that it is a member function and as such, has access to the object's private data members. Failure to add `BankAccount::` results in a nonmember function that cannot reference the data members. For example, the compiler will generate error messages at any attempt to access private data members (`name` and `balance`). `BankAccount::` is missing.

```
BankAccount(string initName, double initBalance) {  // <-- WHOOPS
  name = initName;        // ERROR: name is not known
  balance = initBalance;  // ERROR: balance is not known
}
```

Scope Rule for C++ Classes

The scope of private members is limited to the class member functions.

So remember to precede a class member function implementation with the class to which it belongs and the special symbol `::`. This defines the function as a class member function that can access the private data members. A member function can do whatever it has to do with the state.

6.2.2 IMPLEMENTING MODIFYING MEMBER FUNCTIONS

A member function may either modify the state or access the state of an instance of the class. For example, consider `BankAccount::deposit`, which modifies the `private` data member `balance`.

```
void BankAccount::deposit(double depositAmount) {
  balance = balance + depositAmount;
}
```

When the following `deposit` message is sent, the argument `157.42` is copied by value to the parameter `depositAmount`, which is then added to this object's balance:

```
anAcct.deposit(157.42);
```

Notice that the function headings match the class definition. Specifically, the return type of `BankAccount::deposit` is `void` and there is one double argument.

```
// function headings in BankAccount.h//--modifiers
  void deposit(double depositAmount);
  void withdraw(double withdrawalAmount);
  // . . .
```

The `BankAccount::withdraw` function is another modifying member function that changes the state of a `BankAccount` object. Specifically, a `withdraw` message deducts `withdrawalAmount` from `balance`:

```
void BankAccount::withdraw(double withdrawalAmount) {
  balance = balance - withdrawalAmount;
}
```

When the following `withdraw` message is sent, the argument `50.00` is copied by value to the parameter `withdrawalAmount`, which is then subtracted from `balance`:

```
anAcct.withdraw(50.00);
```

As you are implementing class member functions, make sure all function headings match the appropriate function heading in the class definition. Your member function implementations, stored in a different file, must have the same exact return type, function name, number, type, and order of parameters as exist in the class definition. A good idea is to copy all the member functions to your implementation file. That will ensure you keep member function headings the same and you won't miss implementing a member function. Then replace the semicolon at the end of each member function heading with a function body and add the class name:: to the start of each member function name.

It should be noted here that there could be much more processing within the body of a class member function. The member function implementations in this chapter have been kept intentionally simple during this introduction to member function implementations.

6.2.3 IMPLEMENTING ACCESSING MEMBER FUNCTIONS

It is good design to make the data members private and have functions that allow access to that state. Some of these accessing functions simply return the value of a data member.

```
string BankAccount::getName() const {
  return name;
}

double BankAccount::getBalance() const {
  return balance;
}
```

Because these accessing functions in the class definition have the keyword `const`, the implementation of the member function must also include `const` after the function heading and before the block start at `{`. The keyword `const` denotes a member function that does not modify state. If you examine the accessor implementations above, you'll notice no data members get changed in the block. `getName` and `getBalance` simply return the values of those data members. If you pass an object by `const &` reference, these `const` methods can be used in that other function. On the other hand, the modifying functions `withdraw` and `deposit` change the state of the object, `balance` specifically. If you pass an object by `const &` reference, an attempt to use these modifying (non `const`) methods will be the source of a compile time error. The `const` function can be used when passed by `const` reference.

Remember to make sure all member function headings exactly match the headings in the class definitions (without `;`). And remember to type the class name and `::` before the class member function name in the `.cpp` files. To summarize, here is the complete implementation of all of `BankAccount` member functions in the file `BankAccount.cpp`.

Member Function Implementation: *BankAccount*

File `BankAccount.cpp`

```
/*
 * Implement the member functions defined in BankAccount.h
 *
 * File name: BankAccount.cpp
 */
#include "BankAccount.h"
using namespace std;

//--constructor
BankAccount::BankAccount(string initName, double initBalance) {
  name = initName;
  balance = initBalance;
}

//--modifiers
void BankAccount::deposit(double depositAmount) {
  balance = balance + depositAmount;
}

void BankAccount::withdraw(double withdrawalAmount) {
  balance = balance - withdrawalAmount;
}

//--accessors
double BankAccount::getBalance() const {
  return balance;
}

string BankAccount::getName() const {
```

```
  return name;
}
```

SELF-CHECK

6-10 How does a function implementation become a member of a class?

6-11 Can class member functions reference the private data members?

6-12 Can nonmember functions reference private data members?

6-13 Use this implementation of the `LibraryBook` member functions to write the output generated by the program below:

```
/*
 * Implement the member functions defined in LibraryBook.h
 *
 * File name: LibraryBook.cpp
 */
#include <string>
using namespace std;
#include "LibraryBook.h"

const std::string AVAILABLE_MESSAGE = "CAN BORROW";

//--two argument constructor
LibraryBook::LibraryBook(std::string bookTitle,
                         std::string bookAuthor) {
  title = bookTitle;
  author = bookAuthor;
  available = true;
  borrower = AVAILABLE_MESSAGE;
}

// -- modifiers --
void LibraryBook::borrowBook(std::string borrowersName) {
  borrower = borrowersName;
  available = false;
}

void LibraryBook::returnBook() {
  borrower = AVAILABLE_MESSAGE;
  available = true;
}

//--accessors
bool LibraryBook::isAvailable() const {
  return available;
}

std::string LibraryBook::getBorrower() const {
  return borrower;
}
```

```
std::string LibraryBook::getBookInfo() const {
  return  "'" + title + "' by " + author;
}
```

Here is the program that uses this new type `LibraryBook` now implemented as a C++ class.

```
// Send every possible message to a LibraryBook object
#include <iostream>
using namespace std;
#include "LibraryBook.h"  // For class LibraryBook definition

int main() {
  LibraryBook aBook("Tinker Tailor Soldier Spy", "John le Carre");
  cout << aBook.getBookInfo() << endl;
  cout << aBook.getBorrower() << endl;
  cout << aBook.isAvailable() << endl;  // 1 if true, 0 if false
  aBook.borrowBook("Charlie Archer");
  cout << aBook.getBorrower() << endl;
  cout << aBook.isAvailable() << endl;
  aBook.returnBook();
  cout << aBook.isAvailable() << endl;
  cout << aBook.getBorrower() << endl;
  return 0;
}
```

Output

```
'Tinker Tailor Soldier Spy' by John le Carre
CAN BORROW
1
Charlie Archer
0
1
CAN BORROW
```

6.3 DEFAULT CONSTRUCTORS

Every class requires at least one constructor. A class can have more than one, as long as they have a different number, type and/or order of parameters. Consider this simple `class Adder` that has two constructors. The constructor with no parameters is known as the default constructor. The programmer can specify whatever default state seems appropriate in the default constructor, which in this case sets the data member `sum` to `0.0`.

```
// File: Adder.h
#include <string>

class Adder {

public:

  // Default constructors have no parameters.
  // Construct an Adder with sum staring at 0.0
```

```
  Adder();

  // Construct an Adder with sum starting at start
  Adder(double start);

  void add(double number);
  // post: add number to sum

  double getSum() const;
  // post: Return the sum of all added numbers

private:
  double sum;  // total of all scores added
};
```

Because `class Adder` has two constructors, `Adder` objects can be constructed two different ways.

```
  Adder adder1(123.45);  // Call one argument constructor
  Adder adder2;  // New: Call the default constructor, no ()
```

The object referenced by `adder1` gets built using the one argument constructor `Adder::Adder(double start)`. The object referenced by `adder2` gets built using the default constructor `Adder::Adder()`, which initializes `sum` to `0.0` as shown in the class implementation file `Adder.cpp`.

```
#include "Adder.h"
using namespace std;

Adder::Adder() {
  sum = 0.0;
}

Adder::Adder(double start) {
  sum = start;
}

void Adder::add(double number) {
  sum = sum + number;
}

double Adder::getSum() const {
  return sum;
}
```

The following program uses both constructors to show the difference.

```
#include <iostream>
using namespace std;
#include "Adder.h"

int main() {
  Adder adder1(123.45);
  cout << " Initial sum: " << adder1.getSum() << endl;
```

```
  Adder adder2;
  cout << " Default sum: " << adder2.getSum() << endl;

  adder2.add(1.1);
  adder2.add(2.2);
  adder2.add(3.3);
  cout << "After 3 adds: " << adder2.getSum() << endl;

  return 0;
}
```

Output

```
Initial sum: 123.45
Default sum: 0
After 3 adds: 6.6
```

Here are the reasons to have a default constructor in addition to other constructors:

- They are required to have collections of objects (see Chapter 10, "Vectors").
- They guarantee initialization to a specific state. Programmers always know what to expect (more vivid examples are yet to come).
- They define the default values used when another default constructor is called. For example, the default state for `string` is the empty string `""`.

6.3.1 FUNCTION OVERLOADING

You may be wondering how there could be two constructors since they have the same name. Through a technique known as *function overloading*, more than one function with the same name is allowed to exist. However, there has to be something that distinguishes two functions with the same name. One of these distinguishing characteristics is having a different number of parameters. Function overloading allows the programmer to have a default constructor with zero parameters in the same scope as a constructor with one or more parameters. In other words, C++ distinguishes between the two constructor function headings inside the class definition.

Function overloading also occurs when the type of parameters differs, even if there are the same number of parameters. These three functions may exist in the same scope because the types of the one parameter are different.

```
void aFunction(int n);
void aFunction(long n);
void aFunction(string str);
```

These functions may exist in the same scope because the order of parameters is different.

```
void aFunction(int n, string s);
void aFunction(string s, int n);
```

However, functions that differ only in their return type cannot be overloaded.

```
void aFunction(int n);
string aFunction(int n);  // <- Error
```

6.4 THE STATE OBJECT PATTERN

Even though quite different in specific operations and state, `string`, `BankAccount`, and `LibraryBook` objects have the following common characteristics:

- private data members store the state of the object
- constructors initialize the state
- some messages modify the state
- other messages allow access to the current state of the object

These commonalities guide the effective use of these and similar classes of objects. These patterns also help programmers understand how to use new objects. The constructors, modifiers, and accessors in the `public:` section of a class definition are the operations available to all instances of the class.

6.4.1 CONSTRUCTORS

Constructors are present for many reasons, including initializing the state of any instance of the class. As shown earlier, objects are initialized like this:

```
string aString("initial string");  // State is "initial string"

BankAccount anAcct("Xi Grey", 215); // name and balance are set

LibraryBook aBook("Tale of Two Cities", "Charles Dickens");
// Title and author are set and this book is available to borrow
```

6.4.2 MODIFIERS

Modifying methods change the state of an object. Modifiers are part of the State Object pattern for a variety of reasons. Perhaps it's best to simply show some example messages that modify the state of an object:

```
aString.replace(1, 3, "NEW");
// assert: s2 is "iNEWial string"

g.move(5);
// assert: The mover is five spaces forward

anAcct.withdraw(50.00);
// assert: The balance of anAcct is 50.00 less

aBook.borrowBook("Fred Featherstone");
// assert: aBook's borrower has become Fred Featherstone
```

Sending a modifier message results in a change of state. Modifiers are not declared with const after the function heading—accessors are.

6.4.3 ACCESSORS

Accessors are part of the state object pattern simply because programmers often need to access the state of an object. An accessor message returns information related to the state of an object. An accessor may simply return the value of a data member as with `LibraryBook::borrower` and `BankAccount::balance`. Accessors may also need to do some internal processing using the state of an object to return the information (`employee::incomeTax`, for instance). Here are some example messages that access the state of objects:

```
s2.length()          // Return the number of characters in s2
g.row()              // Return the mover's current row
anAcct.getBalance()  // Return the current balance of anAcct
aBook.getBorrower()  // Return the borrower's name of aBook
```

6.4.4 NAMING CONVENTIONS

Modifying operations are typically given a name that indicates the message will change the state of the object. This is easily accomplished if the designer of the class simply gives a descriptive name to the operation. The name should describe—as best as possible—what the operation actually does. Another way to help programmers who use a class to distinguish modifiers from accessors is to give the modifiers names that can be used as verbs such as `withdraw`, `deposit`, `borrowBook`, and `returnBook`, for example. The accessors are given names that often begin with "`get`," such as `getBorrower` and `getBalance`. Considering that the constructor has the same name as the class, some guidelines are established for designing and reading class definitions. These three categories of operations—typical of state objects—can be distinguished by using the following naming conventions.

Operation	Name
Constructor	Same name as the class
Modifier	Identifier name that could be used as a verb
Accessor	Identifier name that begins with "`get`"

Above all, always try to use identifiers that describe what the object is. For example, don't use `x` as the name of the operation to withdraw money from a `BankAccount` or `turnRight` to make the mover turn left.

6.4.5 `public:` OR `private:`

One of the considerations in the design of a class is the placement of member functions and data members under the most appropriate access mode, either `public:` or `private:`. Whereas public

members of a class can be called from another function outside of the class, the scope of private members is limited to the class member functions. For example, the `BankAccount` data member `balance` is only known to the member functions of the `BankAccount` class. On the other hand, any member declared in the `public:` section of a class is known everywhere in the class and also in the block of source code where the object is declared (or globally, if defined outside of a block).

Access Mode	Where Is the Member Known?
`public:`	In all class member functions and in the block of the client code where the object has been declared (in `main`, for instance).
`private:`	Only inside the class member functions. Because these are known everywhere in the class, you do not have to pass or return those values among the class member functions.

Although the data members representing state could have been declared under `public:`, it is highly recommended that all data members be declared under the `private:` access mode. There are several reasons for this.

The consistency helps simplify some design decisions. More importantly, when data members are made `private:`, the state can be modified only through a member function. This prevents client code from indiscriminately changing the state of objects. For example, it's impossible to accidentally make a credit like this from anywhere outside of the class:

```
// An error occurs: attempting to modify private data
myAcct.balance = myAcct.balance + 100000.00;  // <- ERROR
```

or a debit like this:

```
// An error occurs: attempting to modify private data
myAcct.balance = myAcct.balance - 100.00;
```

6.4.6 SEPARATING INTERFACE FROM IMPLEMENTATION

The practice of studying a class through its interface represents a principle in software engineering. It allows one to separate the interface from the implementation—the details of how the operations actually work. In C++, the completed member function implementations are often separated from the class definition by placing them in separate files. Historically, class definitions have been kept in `.h` (header) files with member function implementations in `.cpp` files (file extensions vary). Some programmers implement the member functions directly in the same file as the class definitions.

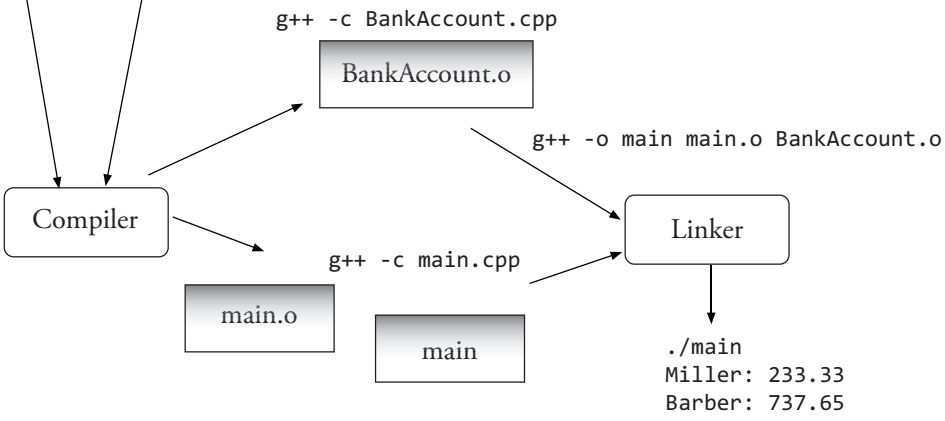
The convention used in this textbook is to separate the class definition from the implementation. This is done by storing the class definition in a `.h` file and the member function implementations in a `.cpp` file. It is often the case that several files are combined together to make an executable program. There are several ways to do this. The following figure illustrates one way to do this with these commands using the GNU compiler:

```
g++ -c BankAccount.cpp
g++ -c main.cpp
g++ -o main main.o BankAccount.o
./main
```

```
/*
 * Implement the member functions
 * defined in BankAccount.h
 *
 * File name: BankAccount.cpp
 */
#include "BankAccount.h"

//--constructor
BankAccount::BankAccount(std::string initName,
                         double initBalance){

  name = initName;
  balance = initBalance;
}
   …
```

```
/*
 *  Define class BankAccount
 *
 *  File name: BankAccount.h
 */
#ifndef BANKACCOUNT_H_
#define BANKACCOUNT_H_

#include <string>

class BankAccount {

public:
  BankAccount(std::string initName,
              double initBalance);
```

```
#include <iostream>
using namespace std;
#include "BankAccount.h"

int main() {
  BankAccount ba1("Miller", 100.00);
  BankAccount ba2("Barber", 987.65);

  ba1.deposit(133.33);
  ba2.withdraw(250.00);
  cout << ba1.getName() << ": " << ba1.getBalance() << endl;
  cout << ba2.getName() << ": " << ba2.getBalance() << endl;

  return 0;
}
```



SELF-CHECK

6-14 What is meant when the `const` keyword is part of the function heading in a class definition?

6-15 Which member functions have the same name as the class?

6-16 What do accessors do?

6-17 What do modifiers do?

6-18 What do constructors do?

6-19 What are the data members for?

6.5 OBJECT-ORIENTED DESIGN GUIDELINES

One particular object-oriented design decision involves determining where to place the data members that store object state. More specifically, since this text uses C++ as the implementation language, the designer has to decide if data member functions go in the `public:` or the `private:` section of a C++ class. The following design guideline states that a good design protects object state from the outside world:

Object-Oriented Design Guideline

All data should be hidden within its class.

Although data members could be `public:`, the convention used in this text—and in any well-designed class—is to hide the data members. C++ data members are easily hidden when declared in the `private:` section of the class definition. This simplifies some design decisions. A `private:` data member can then only be modified or accessed through messages.

This prevents users of the class from indiscriminately changing certain data such as an account balance. The state of an object can be protected from accidental or improper alteration. With data members declared in the `private:` section, the state of any object can only be altered through a message. It becomes impossible to accidentally make a false debit like this:

```
// Compile time error: attempt to modify private data
// If balance is public:, what is the new balance?

myAcct.balance = myAcct.balance - myAcct.balance;
```

However, if `balance` had been declared in the `public:` section, the compiler would not protest. The resulting program would allow you to destroy the state of any object. The hidden balance is more properly modified only when the transaction is allowed according to some policy. What happens, for instance, if a withdrawal amount exceeds the account balance in a withdraw

message? Some accounts allow this by transferring money from a savings account. Other bank accounts may generate loans in increments of $100.00.

With `balance` declared in the `private:` access section, users of the class must instead send a withdraw message. The client code relies on the `BankAccount` to determine if the withdrawal is to be allowed. Perhaps the `BankAccount` object will ask some other object if the withdrawal is to be allowed. Perhaps it delegates authority to some unseen `bankManager` object. Perhaps the `BankAccount` object itself can decide what to do. Although this text's implementation of `BankAccount` doesn't do much, real-world withdrawals do.

By hiding data and other details, all credits and debits must "go through the proper channels." This might be quite complex. For example, each withdrawal or deposit may be recorded in a transaction file to help prepare monthly statements for each `BankAccount`. The withdraw and deposit operations may have additional processing to prevent unauthorized credits and debits. Part of the hidden red tape might include manual verification of a deposit or a check-clearing operation at the host bank; there may be some sort of human or computer intervention before any credit is actually made. Such additional processing and protection within the deposit and withdraw operations help give `BankAccount` a "safer" design. Because all hidden processing and protection is easily circumvented when data members are exposed in the `public:` section, the object designer must enforce proper object use and protection by hiding the data members.

6.5.1 COHESION WITHIN A CLASS

The set of messages described in the class interface should be strongly related. A class stores data, and that data should be strongly related. In fact, all elements of a class should have a persuasive affiliation with each other. These ideas relate to the preference for tight cohesion (solidarity, hanging together, adherence, unity) within a class. For example, don't expect a `BankAccount` object to understand the message `isPreheated`. This may be an appropriate message for an `oven` object, but certainly not for a `BankAccount` object. Here is one guideline related to the desirable attribute of cohesion:

Object-Oriented Design Guideline

Keep related data and behavior in one place.

The `BankAccount` class should hide certain policies such as handling withdrawal requests greater than the balance. The system's design improves when behavior and data combine to accomplish the withdrawal algorithm. This makes for nice clean messages from the client code, like this:

```
anAccount.withdraw(withdrawalAmount);
```

This client code relies on the `BankAccount` object to determine what should happen. The behavior should be built into the object that has the necessary data. Perhaps the algorithm al-

lows a withdrawal amount greater than the balance—with the extra cash coming as a loan or as a transfer from a savings account. Even though the `BankAccount` class of this textbook does very little, a real bank account class might have eight different actions that are triggered for every withdrawal—all behind the scenes.

6.5.2 WHY ARE ACCESSORS `const` AND MODIFIERS NOT?

You may be wondering why `const` is added to function headings intended to access, rather than modify, the object's state. The answer has to do with the three different parameter modes.

When an object is passed by value or by reference to a function, that function can send any and all possible messages to that object inside the other function. However, when the `const` reference parameter mode is utilized, the function promises not to change that object. In fact, it cannot. To illustrate, consider the following function that will not compile—there is a compile time error at the attempt to withdraw from the `const` reference parameter `ba`. This is actually a good thing. The reason for using `const` reference parameters is to avoid accidental modification of the associated argument.

```
// Illustrate connection between member functions tagged as const
// functions and passing objects of that class as const parameter

#include <iostream>  // For cout and endl
using namespace std;
#include "BankAccount.h"  // For the BankAccount class

void display(const BankAccount & ba) {
  // Can send accessing messages--they are declared const
  cout << "{ BankAccount: " << ba.getName()
       << ", $" << ba.getBalance() << " }" << endl;

  // This modifier was not tagged with const. A compile time
  // error will be generated since ba is a const parameter.
  ba.withdraw(234.56);  // <-- ERROR at compile time
}

int main() {
  BankAccount anAcct("Angel Draper", 1234.56);

  display(anAcct);
  return 0;
}
```

This protection works fine for standard classes such as `string`. The same protection will only work with your new classes if care is taken to tag the accessors as `const` and leave the modifiers as non-`const`.

A consistent use of `const` accessors allows the accessing messages to be sent to the `const` parameters. At the same time, by not using `const` with modifiers, a `const` parameter prevents use of a message that will change the object.

Object-Oriented Design Guideline

Only `const` messages are allowed on `const` parameters.

On the other hand, it is okay to send messages that do not modify the object. This safety net is possible only when the programmer diligently tags accessing class member functions with `const` and always remembers not to tag a modifier that way.

```
class BankAccount {

public:
//--modifiers
  void deposit(double depositAmount);  // No const for modifiers
  void withdraw(double withdrawalAmount);

//--accessors
  double getBalance() const;  // Use const on accessors
  string getName() const;
// . . .
```

This leads to another design guideline:

Object-Oriented Design Guideline

Always declare accessor member functions as `const`.

Perhaps the biggest problem with this guideline is in remembering the guideline. It is easily violated. You'll never know the ramifications until an instance of your class is passed as a `const` reference parameter. As another example, consider the `Grid` class modifiers, which are non-`const`, and some accessors, which are declared as `const` functions.

```
class Grid {
public:
  . . .
//--modifiers
  void move(int spaces);
 . . .
//--accessors
  int row() const;
  int column() const;
  . . .
};
```

The presence of `const` tells the compiler to allow the message to be sent even for objects passed by `const` reference (`g` here):

```
void doSomething(const Grid & g) {
  cout << g.row() << endl;       // OKAY
  cout << g.nColumns() << endl;  // OKAY
```

```
  g.display();                  // OKAY
  g.move();                     // Compile time ERROR
  g.pickUp();                   // Compile time ERROR
}
```

On the other hand, the attempt to send non-`const` messages such as `Grid::move` results in a compile time error like these (more cryptic error messages exist) depending on the compiler used:

```
    non-const member function 'Grid::move()' called for const object
```

- or -

```
    attempt to modify a const object
```

- or -

```
    member function 'pickUp' not viable: 'this' argument has type
          'const Grid', but function is not marked const
```

Declaring accessors as `const` functions allows existing objects to be safely passed to a `const` parameter. However, it takes diligence to maintain the same safety net for the new classes that you write. Remember these two class design guidelines:

1. Modifiers should *not* be declared `const` so the compiler can catch attempts to modify `const` objects.
2. Accessors should be declared `const` so objects can be safely passed to `const` parameters and still allow non-modifying messages.

It would be easier to completely ignore these rules, but the only way to get away with it would be to never pass objects to `const` parameters. This textbook uses `const` in a member function because it says something about whether or not a function modifies the state of an object. And this is something object-oriented programmers must know about. The designer of the class must still decide if the message will modify an instance of the class or not.

SELF-CHECK

6-20 Using the class definition of the `BankAccount` class, list the lines that cause errors in a standard C++ compiler (1, 2, 3, and/or 4).

```
#include <iostream>
using namespace std;
#include "BankAccount.h"  // For the BankAccount class

void check(const BankAccount & b, double amount) {
  cout << b.getName() << endl;     // 1
  b.deposit(amount);               // 2
  b.withdraw(amount);              // 3
  cout << b.getBalance() << endl;  // 4
}
```

```
int main() {
  BankAccount myAcct("Me", 12345.00);
  check(myAcct, 50.00);
  return 0;
}
```

CHAPTER SUMMARY

- This chapter showed class definitions with a collection of function headings that represent the class interface. These are the message names that any object of the class will understand.
- A class definition lists:
    - the class member functions with parameters and return types, collectively known as the interface
    - the data members, known collectively as the state
- Each object of a class may store many values, which may be of different classes. For example, each BankAccount object stores string data for the name and numeric data for the balance.
- The state object pattern guides class design when the primary need for the object is to store state and provide adequate access to it. The state object pattern in C++ recommends that the following items be included in a class definition:
    - a constructor to initialize objects with programmer-supplied state
    - modifying functions
    - accessor functions
    - private data members to store the state of every object
- Modifying class member functions changes the state of the object.
- Accessor functions provide access to the state of an object.
- Accessors have the keyword `const` attached at the end of the function heading.
- Ramifications of adhering to Object-Oriented Design Guideline "All data should be hidden within its class" include:
    - Good: can't mess up the state (compiler complains)
    - Bad: need to implement additional accessors (`getBalance`, for example)
- The ramifications of adhering to Design Guideline "Keep related data and behavior in one place" include:
    - Good: results in a more intuitive design
    - Good: easier to maintain
- The ramifications of adhering to Design Guideline "Always declare accessor member functions as `const`" include:
    - Good: helps the user distinguish between modifiers and accessors
    - Good: adheres to the principle that objects passed as const reference parameters cannot be accidentally modified by the function while allowing the function to send const messages

    - Bad: it is easy to forget to use `const` and the error will not show up until the object is passed in the three different modes—the result is more extensive testing to ensure the safety of `const` and the efficiency of `const` reference parameters
- Class member functions are implemented in a manner similar to nonmember functions. However, class member functions must be qualified with the class name and `::` (the scope resolution operator). This gives the function access to the private data members.
- Class definitions have historically been stored in `.h` files.
- Member function implementations have historically been stored in `.cpp` files.
- A class should be designed to exhibit high cohesion:
    - the data should be related to the operations
    - the messages should be related to each other

EXERCISES

1. Does the interface of a class refer to its member functions or its data members?
2. Does the client code need to know the names of data members to use objects of the class?
3. Describe the scope of the public members of a class.
4. Describe the scope of the private members of a class.
5. Give one justification for making the data members of a class private.
6. If the designer of `BankAccount` class changed the name balance to `my_Balance`, would programs using `BankAccount` need to be changed?
7. If a designer changed the name of the `withdraw` message to `withdrawThisAmount` after the class was already in use by dozens of programs, would these dozens of programs need to be changed?
8. What is responsible for deciding if a particular `LibraryBook` is available for lending, the `LibraryBook` or the program using `LibraryBook`?
9. Should a `BankAccount` object understand the message `isThisBrakeLockingUp`?
10. If an object is passed by value, which messages can be sent: modifiers, accessors, or both?
11. If an object is passed by reference (with `&`), which set of messages can be sent: modifiers, accessors, or both?
12. If an object is passed by `const` reference as in (`const Grid & aGrid`), which set of messages can be sent: modifiers, accessors, or both?
13. Given this definition for a `class Counter` class, predict the output from the test driver below:

```
/*
 * Filename: Counter.h
 */
class Counter {
public:
//-- constructor
  Counter(int maxValue);
  // post: Initialize count to 1 and set the maximum count

// modifiers
  void click();
  // post: If count is at maximum, set count to 1, otherwise add 1
  // to the count. This uses the % operator when adding to count.

  void reset();
  // post: Resets the counter to 1

// accessor
  int getCount() const;
  // post: Return the current count

private:
  int count;  // Current count, always start at 1
  int max;    // The largest value count can reach
};
```

TEST DRIVER

```
#include <iostream>
using namespace std;
#include "Counter.h"  // For the counter class definition

int main() { // Test drive counter class
  Counter aCounter(3);
  cout << "a: " << aCounter.getCount() << endl;
  aCounter.click();
  cout << "b: " << aCounter.getCount() << endl;
  aCounter.click();
  cout << "c: " << aCounter.getCount() << endl;
  aCounter.click();
  cout << "d: " << aCounter.getCount() << endl;
  aCounter.click();
  cout << "e: " << aCounter.getCount() << endl;
  aCounter.reset();
  cout << "f: " << aCounter.getCount() << endl;
  return 0;
}
```

14. Write all code that would go into `Counter.cpp` that completely implements all member functions defined in `Counter.h` so that the program above generates the correct output.

PROGRAMMING TIPS

1. Working with three files is more difficult than working with one, but some programming projects will now require that you work with three files, not just one. This takes a little patience as you grow accustomed to working with multiple files. Remember, the `.h` file contains the class definition; the `.cpp` file contains the member function implementations. The third file has the `main` function.
2. There is a variety of ways to make classes available. Even though the convention of having one file include the `.h` and `.cpp` files is atypical, it makes things easier and matches the standard (many `#include` files do not have `.h` anymore). However, someday you may be asked to create object files or project files to compile and link programs using author-supplied classes. Then your program may just include the `.h` file so it can compile. Linking comes later.

```
#include " BankAccount.h "  // Other steps required to link
int main() {
  // . . .
}
```

3. The nonmember function syntax applies to member function headings also. The function heading in the implementation must match the function heading in the class definition in terms of

   • return type (none for constructors)
   • function name
   • number of parameters
   • type of parameters
   • order of parameters
   • use of `const` in both places (or neither)

4. Don't write `using namespace std;` in header files. Once you use a namespace you can't unuse it. While it may not cause any problems in the programs in this textbook, you should get in the habit now to avoid future programming problems.
5. Function headings in the implementation file (`.h`) differ from the function headings in the implementation file (`.cpp`).

   • functions need `className::` to precede the function name
   • the function body `{ }` replaces the semicolon

```
/*
 * File name: CD.h
 */
#include <string>
class CD {
```

```
public:
  CD(std::string initArtist, std::string initTitle);
  std::string getArtist() const;

private:
  std::string artist, title;
};

/*
 * File name: CD.cpp
 */
#include "CD.h"
using namespace std;

CD::CD(string initArtist, string initTitle) {
  // . . .
}

string CD::getArtist() const {
  // . . .
}
```

PROGRAMMING PROJECTS

6A ADD `int getTransactionCount` TO `BankAccount`

Allow `BankAccount` objects to keep track of and report the number of transactions, deposits, and withdrawals made since the initialization of any `BankAccount` object. Name this new function `int getTransactionCount()`. Use this test driver and ensure your output matches and compiles:

```
#include <iostream>
using namespace std;
#include "BankAccount.h"

int main() {
  BankAccount anAcct("Do 3", 3.00);
  cout << "0? " << anAcct.getTransactionCount() << endl;
  anAcct.deposit(10.00);
  anAcct.withdraw(20.00);
  anAcct.deposit(30.00);
  cout << "3? " << anAcct.getTransactionCount() << endl;

  BankAccount another("Do 1", 1.00);
  another.withdraw(25.00);
  cout << "1? " << another.getTransactionCount() << endl;

  return 0;
}
```

Output

```
0? 0
3? 3
1? 1
```

6B ADD turnAround AND turnRight TO class Grid

Add the following operations to the definition of the `Grid` class in the file named `Grid.h`:

```
void turnAround();
// post: The mover is facing the opposite direction

void turnRight();
// post: The mover is facing 90 degrees clockwise
```

Also add both class member functions at the top of the file named `Grid.cpp`. Please try to ignore all the other stuff in that rather large file. You will find it easier to use the existing member function `turnLeft` to implement these two new functions.

```
#include "Grid.h"

int main() {
  Grid g(6, 12, 1, 9, east);
  g.display();
  g.turnAround();
  g.move(5);
  g.turnLeft();
  g.move(2);
  g.turnRight();
  g.move(3);
  g.display();
  return 0;
}
```

```
The grid:
. . . . . .
. . . . . > . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .
The grid:
. . . . . .
. . . .       . .
. . . .   . . . . .
. <       . . . . .
. . . . . .
. . . . . .
```

6C CLASS AVERAGER

Given the following definition of `class Averager` in the file `Averager.h`, implement all member functions in a new file `Averager.cpp`. You should be able to add any number of test or quiz scores and find the average and number of scores added at any time.

```
/*
 * Define class Averager that maintains the average for
 * any number of quiz or test scores.
 *
 * File name: Averager.h (available on this book's website)
 */
class Averager {
```

```
public:
  // Construct an Averager with no scores added.
  Averager();

//-- modifiers
  void addScore(double score);
  // post: Add a score so the count and average are correct.

//--accessors
  double getAverage() const;
  // post: Return the average of all scores entered.

  int getScoresAdded() const;
  // post: Return how many scores were added

private:
  int n;  // number of scores added so far, initially 0
  double sum;  // total of all scores added, initially 0.0
};
```

This test driver should generate the expected output below:

```
#include <iostream>
using namespace std;
#include "Averager.h"

int main() {
  Averager averager;
  cout << "     0? " << averager.getScoresAdded() << endl;

  averager.addScore(90.0);
  cout << "    90? " << averager.getAverage() << endl;
  cout << "     1? " << averager.getScoresAdded() << endl;

  cout << endl;
  averager.addScore(100.0);
  averager.addScore(80.0);
  averager.addScore(70.0);
  averager.addScore(60.0);
  averager.addScore(53.0);
  cout << "Scores Added 6? " << averager.getScoresAdded() << endl;
  cout << "  Average 75.5? " << averager.getAverage() << endl;
  return 0;
}
```

Expected Output

```
 0? 0
90? 90
 1? 1

Scores Added 6? 6
  Average 75.5? 75.5
```

6D class PiggyBank

A `PiggyBank` object encapsulates the contents of a piggy bank with messages associated with real world actions. It knows how many of each coin—pennies, nickels, dimes, and quarters—are in it along with total cash value. A `PiggyBank` object can also be emptied with a `drainTheBank` message, which also returns the amount of money at that moment. Here is the class definition:

```
/*
 * This class models a piggy bank to which pennies, nickels, dimes,
 * and quarters can be added. A PiggyBank object maintains how many
 * of each coin it holds and can tell you the total amount of money
 * in it.
 *
 * File name: PiggyBank.h (available on this book's website)
 */
class PiggyBank {
public:
  PiggyBank();
  // post: An PiggyBank is built with no coins

  void addPennies(int penniesAdded);
  // pre: penniesAdded > 0
  // post: This PiggyBank has penniesAdded more pennies

  void addNickels(int nickelsAdded);
  // pre: nickelsAdded > 0
  // post: This PiggyBank has nickelsAdded more nickels

  void addDimes(int dimesAdded);
  // pre: dimesAdded > 0
  // post: This PiggyBank has dimesAdded more dimes

  void addQuarters(int quartersAdded);
  // pre: quartersAdded > 0
  // post: This PiggyBank has quartersAdded more quarters

  double drainTheBank();
  // post: Remove  all of the coins from this PiggyBank
  // and returns how much there was before it was emptied


//-- Accessors
  int getPennies();
  // post: Return the total number of pennies in this bank

  int getNickels();
  // post: Return the total number of nickels in this bank

  int getDimes();
  // post: Return the total number of dimes in this bank

  int getQuarters();
  // post: Return the total number of quarters in this bank
```

```
  double getTotalCashInBank();
  // post: return the total cash in the bank. Pennies are
  // $0.01, nickels are $0.05, dimes are $0.10, and quarters
  // are $0.25 (no half or one dollar coins).

private:
  int pennies, nickels, dimes, quarters;
};
```

This test driver should generate the expected output below:

```
#include <iostream>
using namespace std;
#include "PiggyBank.h"

int main() {
  PiggyBank pb;
  cout << "   0? " << pb.getTotalCashInBank() << endl;
  pb.addPennies(4);
  pb.addNickels(3);
  pb.addDimes(2);
  pb.addQuarters(1);
  cout << "   4? " << pb.getPennies() << endl;
  cout << "   3? " << pb.getNickels() << endl;
  cout << "   2? " << pb.getDimes() << endl;
  cout << "   1? " << pb.getQuarters() << endl;
  cout << "0.64? " << pb.getTotalCashInBank() << endl;
  cout << "0.64? " << pb.drainTheBank() << endl;
  cout << "   0? " << pb.getTotalCashInBank() << endl;
  return 0;
}
```

Expected Output

```
   0? 0
   4? 4
   3? 3
   2? 2
   1? 1
0.64? 0.64
0.64? 0.64
   0? 0
```

6E class Employee

Note: This type asks for a new member function in Chapter 7: Selection

While programmers at Chrystal Bends, Inc., were designing the payroll system, they realized they needed an `Employee` type. An `Employee` object is responsible for maintaining the information necessary to complete an employee's paycheck for employees who get paid on an hourly basis. This `Employee` object is responsible for computing its own gross and net pay and computing how

much to withhold for Social Security tax (6.2% of the gross pay) and Medicare tax (1.45% of the gross pay) for the week. The Chrystal Bends, Inc. programming team has designed this C++ class definition, which you are asked to use to implement and test the member functions.

```
/*
 * Model a weekly employee who gets paid on an hourly basis.
 * Only two taxes are included so far: Medicare and Social
 * Security. You may be asked to add Federal Income tax later
 *
 * File name: Employee.h  (available on this book's website)
 */
#include <string>
#include <iostream>
#include <cmath>

class Employee {
public:
  // Constants for two taxes. C++11 needed for initialization.
  const double SOCIAL_SECURITY_TAX_RATE = 0.062;
  const double MEDICARE_TAX_RATE = 0.0145;

  // Contructor
  Employee(std::string initName, double hourlyRate);
  // post: A Employee is built with 0.00 hours worked.

  void giveRaise(double raise);
  // pre: raise > 0. The argument 3.5 means a 3.50% raise.
  // post: The hourly rate of pay has changed

  void setHoursWorked(double hoursWorked);
  // pre: hoursWorked >= 0.0
  // post: hours worked for the current week is set.
  //       Gross pay, net pay, and taxes can now be computed.

//--accessors
  std::string getName();
  double getHoursWorked();
  double getHourlyRate();
  double getSocSecurityTax();
  double getMedicareTax();
  double getGrossPay();
  double getNetPay();

private: // data members
  std::string name;
  double rate;
  double hours;
};
```

The following test driver sends all possible messages to one `Employee`. The hours worked per week must be set with a `setHoursWorked` message in order for the gross pay taxes and net pay to be computed. This test driver should generate the expected output below:

```
#include <iostream>
#include "Employee.h"
using namespace std;

// Test Driver
int main() {
  Employee emp1("Ali", 10.00);
  cout << "   Ali? " << emp1.getName()           << endl;
  cout << "    10? " << emp1.getHourlyRate()     << endl;
  cout << "     0? " << emp1.getHoursWorked()    << endl;
  cout << "     0? " << emp1.getGrossPay()       << endl;

  // Record the hours worked in the current week
  emp1.setHoursWorked(40.00);
  cout << "   400? " << emp1.getGrossPay()       << endl;
  cout << "  24.8? " << emp1.getSocSecurityTax() << endl;
  cout << "   5.8? " << emp1.getMedicareTax()    << endl;
  cout << " 369.4? " << emp1.getNetPay()         << endl;
  cout << endl;

  emp1.giveRaise(10);  // 10% raise

  cout << "    11? " << emp1.getHourlyRate()     << endl;
  cout << "   440? " << emp1.getGrossPay()       << endl;
  cout << "406.34? " << emp1.getNetPay()         << endl;
}
```

Expected Output

```
   Ali? Ali
    10? 10
     0? 0
     0? 0
   400? 400
  24.8? 24.8
   5.8? 5.8
 369.4? 369.4

    11? 11
   440? 440
406.34? 406.34
```

CHAPTER SEVEN

Selection

SUMMING UP

Until this point, all programs in this textbook executed all statements in a sequential fashion, in order from the first statement of each block to the last. The function calls and messages executed unseen code that involved other forms of statement control.

COMING UP

Chapter 7 examines statements that select which actions execute. Depending on the current circumstances, an action may execute one time but not the next. The alternatives are made possible with the C++ `if`, `if...else`, and `switch` statements. After studying this chapter you will be able to

- recognize when to use the Guarded Action pattern (do something only under certain conditions)
- implement the Guarded Action pattern with the C++ `if` statement
- use relational operators such as < and >
- create and evaluate expressions with the logical operators
- use `bool` objects
- understand the Alternative Action pattern
- implement the Alternative Action pattern with the C++ `if...else` statement
- implement the Multiple Selection pattern with `if...else` and `switch`
- solve problems using the Multiple Selection pattern

7.1 SELECTIVE CONTROL

Programs must often anticipate a variety of situations. For example, an automated teller machine (ATM) must serve valid bank customers—but it must also reject invalid access. Once validated, a customer may wish to perform a balance query, a cash withdrawal, or a deposit transaction. The code that controls an ATM must permit these different requests. Without selective forms of control—the new statements of this chapter—all bank customers could only perform one particular transaction. Worse yet, invalid PINs could not be rejected!

Before any ATM becomes operational, programmers must implement code that anticipates all possible transactions. The code must turn away customers with invalid PINs. The code must prevent invalid transactions such as cash withdrawal amounts that are not in the proper increment, typically $20.00. The code must be able to deal with customers who attempt to withdraw more than they have. To accomplish these tasks, a new form of control is needed—a statement to permit or prevent execution of certain statements depending on certain inputs.

7.1.1 THE GUARDED ACTION PATTERN

Programs often need actions that do not always execute. At one moment, a particular action must occur. At some other time—the next day or the next millisecond perhaps—the same action must be skipped. For example, one student may have made the dean's list because the student's grade point average (GPA) was 3.5 or higher. That student becomes part of the dean's list. The next student may have a GPA lower than 3.5 and should not become part of the dean's list. The action—adding a student to the dean's list—is guarded. The *Guarded Action pattern* and the C++ means of implementing it are shown next.

Algorithmic Pattern: *The Guarded Action pattern*

Pattern:	Guarded Action
Problem:	Do something only if certain conditions are true
Outline:	`if ( true-or-false-condition is true )` `    execute this action (s)`
Code Example:	`if (GPA >= 3.5)` `  cout << "Made the deans list" << endl;`

7.1.2 THE `if` STATEMENT

This Guarded Action pattern is often implemented with the C++ `if` statement.

General Form 7.1 `if` *statement*

```
if (logical-expression)
      true-part;
```

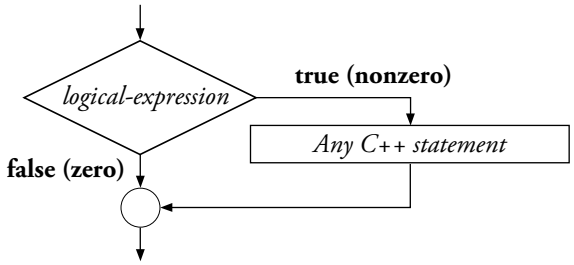
The *logical-expression* is any expression that evaluates to either true or false. The *true-part* may be any valid C++ statement, including a block that uses curly braces `{ }` to treat two or more statements as if they were one statement.

Example: `if` *statements*

```
cin >> hoursStudied;
if (hoursStudied > 4.5)
  cout << "You are ready for the test" << endl;


if (hours > 40.0) {
  regularHours = 40.0;
  overtimeHours = hours - 40.0;
}
```

When an `if` statement is encountered, the logical expression is evaluated to a false (zero) or true (nonzero) value. The true part executes only if the logical expression is true. So in the first example above, the output `"You are ready for the test"` appears only when the user enters something greater than 4.5 hours. When the input is 4.5 or less, the true part is skipped—the action is guarded. Here is a flowchart view of the Guarded Action pattern:

Flowchart view of the `if` statement



The next program illustrates how selection alters the flow of control. Each of the sample dialogues below illustrates that the code performs different actions due to the variety of conditions. More specifically, the `musicAward` function returns a different `string` due to the different arguments in the three function calls from `main`.

```
// Show that the same code can return three different results.
// showAward has three instances of the Guarded Action pattern.

#include <iostream>  // For cout and endl
#include <string>    // For the string class
using namespace std;

string musicAward(long int recordSales) {
  // pre:  Argument < maximum long int (usually 2,147,483,647)
  // post: Return a message appropriate to record sales
  string result;

  if (recordSales < 500000)
```

```
    result = "--Sorry, no certification yet. Try more concerts.";

  if (recordSales >= 500000)
    result = "--Congrats, your music is certified gold.";

  if (recordSales >= 1000000)
     result = result + " It's also gone platinum!";

  return result;
}

int main() {
  // Test drive showAwards three times with different results
  cout <<  123456 << musicAward( 123456) << endl;
  cout <<  504123 << musicAward( 504123) << endl;
  cout << 3402394 << musicAward(3402394) << endl;
  return 0;
}
```

Output

```
123456--Sorry, no certification yet. Try more concerts.
504123--Congrats, your music is certified gold.
3402394--Congrats, your music is certified gold. It's also gone platinum!
```

Through the power of the `if` statement, the same exact code results in three different versions of statement execution. The `if` statement controls execution because the true part executes only when the logical expression is true. The `if` statement also controls statement execution by disregarding statements when the logical expression is false. For example, the platinum message is disregarded when `recordSales` is less than one million.

7.2 RELATIONAL OPERATORS

Two new operators, `<` and `>=`, test the relationship between the value of `recordSales` and the numeric values 500,000 and 1,000,000. They are part of the set of relational operators that create logical expressions—an important part of `if` statements (see table below):

Relational Operator	Meaning
`<`	Less than
`>`	Greater than
`<=`	Less than or equal to
`>=`	Greater than or equal to
`==`	Equal to
`!=`	Not equal to

When a relational operator is applied to two operands that can be compared, the result is one of two values: `true` or `false`. The next table shows some examples of simple logical expressions and their resulting values. Notice that objects such as `double` and `string` can be compared to other objects of the same class. `string` objects are related alphabetically—`"A"` is less than `"B"` and `"D"` is greater than `"C"`, for example.

Logical Expression	Result	Logical Expression	Result
`double x = 4.0;`		`string name = "Bill";`	
`x < 5.0`	`true`	`name == "Sue"`	`false`
`x > 5.0`	`false`	`name != "Sue"`	`true`
`x <= 5.0`	`true`	`name < "Chris"`	`true`
`5.0 == x`	`false`	`"Bobbie" > Bobby"`	`false`
`x != 5.0`	`true`	`"Bob" < "Bobbie"`	`true`

This is a good time to point out an all-too-common and difficult-to-track-down error that can create havoc. All math courses you have ever taken use = for algebraic equality. When you try to do that in C++, you will actually be using the assignment operator = rather than ==, the C++ equality operator. The problem is that the compiler does not detect an error. Consider this `if` statement:

```
int x = 0;
if (x = 3)
  cout << x << " equals 3" << endl;
```

Output

```
3 equals 3
```

First `x` was `0`, then it became `3` while testing the logical expression `x = 3`, which is an assignment.

It turns out that C++ assignment operations evaluate to the value being stored. The expression `x = 3` not only assigns `3` to `x`, it also evaluates to the value actually assigned, which in this case is `3`, or nonzero, or true. If you want to compare `x` to `3`, use == like this:

```
int x = 0;
if (x == 3)
  cout << x << " equals 3" << endl;
```

Output

```
There is no output.
```

SELF-CHECK

7-1 Which expressions evaluate to true assuming `j` and `k` are initialized like this:

```
int j = 4;
int k = 8;
```

a. `(j+4) == k`

b. `0 == j`

c. `j >= k`

d. `j != k`

e. `j < k`

f. `4 == j`

g. `j = 0` *careful*

h. `j = 165` *careful*

7-2 Write the output generated by the following code:

a.
```
string option = "A";
if (option == "A")
  cout << "addRecord";
if (option == "D") {
  cout << "deleteRecord";
}
```

b.
```
string option = "D";
if (option == "A")
  cout << "addRecord";
if (option == "D")
  cout << "deleteRecord";
```

c.
```
string option = "a";
if (option == "A") {
  cout << "addRecord";
}
if (option == "D") {
   cout << "deleteRecord";
}
```

d.
```
int grade = 45;
if (grade >= 70)
  cout << "passing" << endl;
if (grade < 70)
  cout << "dubious" << endl;
if (grade < 60)
  cout << "failing" << endl;
```

e.
```
int grade = 65;
if (grade >= 70)
  cout << "passing" << endl;
if (grade < 70)
  cout << "dubious" << endl;
if (grade < 60)
 cout << "failing" << endl;
```

f.
```
int g = 45;
// Careful!
cout << "g: " << g << endl;
if (g = 70)
  cout << "at cutoff" << endl;
  cout << "g: " << g << endl;
if (g = 1)
  cout << "you get one" << endl;
cout << "g: " << g << endl;
```

7.3 THE ALTERNATIVE ACTION PATTERN

Programs must often select from a variety of actions. For example, one student passes with a final grade of >= 60.0 and the next student fails with a final grade of < 60.0. This is an example of the Alternative Action algorithmic pattern. The program must choose one course of action or an alternative.

Algorithmic Pattern: *The Alternative Action pattern*

Pattern: Alternative Action

Problem: Need to choose one action from two alternatives

Outline:
```
if ( true-or-false-condition is true )
    execute action-1
else
   execute action-2
```

Code Example:
```
if (finalGrade >= 60.0)
  cout << "passing" << endl;
else
  cout << "failing" << endl;
```

7.3.1 THE `if...else` STATEMENT

The Alternative Action pattern is implemented in C++ with the `if...else` statement. This control structure can be used to choose between two different courses of action (and as shown later, to choose between more than two alternatives).

General Form 7.2 `if...else` *statement*

```
if (boolean-expression)
       true-part;
else
      false-part;
```

The `if...else` statement is an `if` statement followed by the alternate path after an `else`. The *true-part* and the *false-part* may be any valid C++ statement, including a block.

```
if (sales <= 20000.00)
  cout << "No bonus this month" << endl;
else
  cout << "Bonus coming" << endl;
```

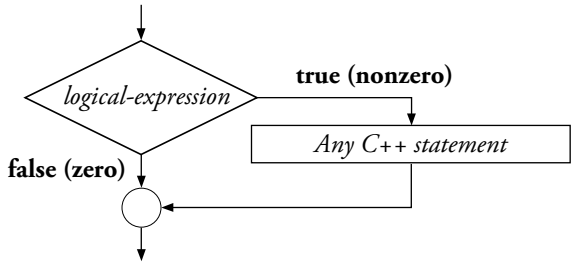
When an `if...else` statement is encountered, the *logical expression* evaluates to either false or true. When true, the true part executes—the false part does not. When the logical expression is

false, only the false part executes.

The next example illustrates how `if...else` works. When `x` has a value less than or equal to zero, the output is `FALSE`. When `x` is positive, the true part executes and `TRUE` is output.

```
double x;
cout << "Enter x: ";
cin >> x;
if (x > 0.0)
  cout << "TRUE" << endl;
else
  cout << "FALSE" << endl;
```

Flowchart view of the Alternative Action pattern



Here is another example of `if...else` demonstrating alternative action that depends on the logical expression (`miles > 900000`). Sometimes the true part executes—when `miles` is greater than `90000`. Otherwise, the false part executes—when `miles` is not greater than `90000`.

```
int miles;
cout << "Enter miles: ";
cin >> miles;
if (miles > 90000) {
  cout << "Tune-up " << (miles-90000) << " miles overdue" << endl;
}
else {
  cout << "Tune-up due in " << (90000-miles) << " miles" << endl;
}
```

When `miles` is input as `96230`, the output is `Tune-up 6230 miles overdue`, but when `miles` is input as `89200`, the false part executes; the output is `Tune-up due in 800 miles`.

SELF-CHECK

7-3 What output occurs when `miles` is `90000`?

The ability to choose is a powerful feature of any programming language. The `if...else` statement provides the means to make a program general enough to generate useful information

appropriate to a variety of data. For example, an employee's gross pay may be calculated as hours times the rate when hours is less than or equal to 40. However, certain employers must pay time-and-a-half to employees who work more than 40 hours per week. Gross pay with overtime can be computed as follows:

```
pay = (40 * rate) + (hours - 40) * 1.5 * rate;
```

With alternative actions, a program can correctly compute gross pay for a variety of values including those less than 40, equal to 40, and more than 40. This instance of the Alternative Action pattern is now placed in the context of a complete program.

```
// Illustrate the flexibility offered by Alternative Action
#include <iostream>
using namespace std;

int main() {
  double pay = 0.0;
  double rate = 0.0;
  double hours = 0.0;

  cout << "Enter hours worked and rate of pay: ";
  cin >> hours >> rate;

  if (hours <= 40.0)
    pay = hours * rate;  // True part
  else
    pay = (40 * rate) + (hours - 40) * 1.5 * rate;  // False part

  cout << "pay: " << pay << endl;

  return 0;
}
```

Dialogue 1:

```
Enter hours worked and rate of pay: 38.0  10.0
pay: 380
```

Dialogue 2:

```
Enter hours worked and rate of pay: 42.0  10.0
pay: 430
```

It should be noted that semicolon (;) placement in `if...else` statements is somewhat confusing at first. If you observe a compile time error near an `if...else` statement, look closely at the placement or lack of semicolons. Also be careful that you don't place a semicolon immediately after the logical expression. This is a common mistake. In this case, the true part is an empty statement where nothing happens and what follows `;` is not part of the `if` statement.

SELF-CHECK

7-4 Given the following code:

```
if (hours >= 40.0)
  hours = 40 + 1.5 * (hours - 40);
```

Determine the final value of `hours` when `hours` starts as:

a. `38`
b. `40`
c. `42`
d. `43.5`

7-5 Write the output generated by each of the following programs given these initializations of `n` and `x`:

```
int n = 8;
double x = -1.5;
```

a.
```
if (x < -1.0)
  cout << "true" << endl;
else
  cout << "false" << endl;
  cout << "after if...else";
```

b.
```
if (n >= 0) {
  cout << "zero or pos";
}
else {
  cout << "neg";
}
```

c.
```
if (x >= n)
  cout << "x is high";
else
  cout << "x is low";
```

d.
```
// true part is another if...else
if (x <= 0.0) {
  if (x < 0.0)
    cout << "neg";
  else
    cout << "zero";
}
else
  cout << "pos";
```

7-6 Write an `if...else` statement that displays your name if `option` has the value `1`, and displays your school if `option` has the value of anything else.

7.4 BLOCKS WITH SELECTION STRUCTURES

The special symbols `{` and `}` have been used to gather a set of statements that are treated as one inside the body of a function. These two special symbols delimit (mark the boundaries of) a block. The block groups together many actions, which can then be treated as one. The block is also useful for combining more than one action as the true or false part of an `if...else` statement.

```
// This program uses blocks for both the true and false parts. The
// block makes it possible to treat many statements as one.
#include <iostream>
using namespace std;
```

```
int main() {
  double GPA = 0.0;
  double margin = 0.0;  // How far from dean's list cut-off

  cout << "Enter GPA: ";
  cin >> GPA;
  if (GPA >= 3.5) {
    // True part contains more than one statement in this block
    cout << "Congratulations, you are on the dean's list." << endl;
    margin = GPA - 3.5;
    cout << "You made it by " << margin << " points." << endl;
  }
  else {
    // False part contains more than one statement in this block
    cout << "Sorry, you are not on the dean's list." << endl;
    margin = 3.5 - GPA;
    cout << "You missed it by " << margin << " points." << endl;
  }
  return 0;
}
```

The block makes it possible to treat several statements as one. When `GPA` is input as `3.7`, `GPA >= 3.5` becomes true and the following dialog is generated:

```
Enter GPA: 3.7
Congratulations, you are on the dean's list.
You made it by 0.2 points.
```

When `GPA` is `2.9`, `GPA >= 3.5` becomes false and this output occurs:

```
Enter GPA: 2.9
Sorry, you are not on the dean's list.
You missed it by 0.6 points.
```

This alternative execution is provided by the two possible evaluations of the logical expression `GPA >= 3.5`. If true, the true part executes; if false, the false part executes.

7.4.1 THE TROUBLE IN FORGETTING { AND }

Neglecting to use the block can cause a variety of errors. Modifying the previous example illustrates what can go wrong if the block is not used when attempting to execute both `cout` statements.

```
if (GPA >= 3.5)
  margin = GPA - 3.5;
  cout << "Congratulations, you are on the dean's list." << endl;
  cout << "You made it by " << margin << " points." << endl;
else  // <- ERROR: Unexpected else
```

With { and } removed there is no block; the two highlighted statements no longer belong to the preceding `if...else`—even though the indentation might make it appear as such. This previous

code represents an `if` statement, followed by two `cout` statements, followed by the reserved word `else`. When `else` is encountered, the C++ compiler complains because there is no statement that begins with an `else`.

Here is another example of what can go wrong when a block is omitted. This time, `{` and `}` are omitted after `else`.

```
else
  margin = 3.5 - GPA;
  cout << "Sorry, you are not on the dean's list." << endl;
  cout << "You missed it by " << margin << " points." << endl;
```

There are no compile time errors here, but the code does contain an intent error. The final two statements always execute! They do not belong to `if...else`. Whenever `GPA >= 3.5` is false, the code does execute as one would expect, but when this logical expression is true, the output is not what is intended. Instead, this rather confusing output shows up:

```
Congratulations, you are on the dean's list.
You made it by 0.152 points.
Sorry, you are not on the dean's list.
You missed it by -0.152 points.
```

Although not necessary, it could help if you always use blocks as the true and false part of `if` and `if...else` statements. The practice can make for more readable code and at the same time prevent intent errors such as the one above. One of the drawbacks is that there are more lines of code and more sets of curly braces to line up. Also, as you'll see in the second part of this chapter with the Multiple Selection pattern, the action is most often only one statement. The block is not required.

7.5 bool OBJECTS

C++ has `bool` objects to store either one of these constants: `true` or `false`. Named after the mathematician George Boole, `bool` objects simplify logical expressions as demonstrated in the following program:

```
// Demonstrates bool initialization and assignment. A standard C++
// compiler has bool, true, and false built in.
#include <iostream>
using namespace std;

int main() {
  // Initialize three bool objects to false
  bool ready, willing, able;
  double credits = 28.5;
  double hours = 9.5;
  // Assign true or false to all three bool objects
  ready = hours >= 8.0;
  willing = credits > 20.0;
  able = credits <= 32.0;
```

```
  // If all three bools are true, the logical expression is true
  if (ready && willing && able)
    cout << "YES" << endl;
  else
    cout << "NO" << endl;

  return 0;
}
```

Output

```
YES
```

Like other objects, `bool` objects can be declared, initialized, and assigned a value. The assigned expression should be a logical expression—one that evaluates to true or false. Two new constants are also added: `true` and `false`. This is shown in the initializations of the three `bool` objects in the previous program.

The `bool` class is often used as the return type in both nonmember and class member functions. For example, the `LibraryBook` class has a member function that returns `true` when a book is available or `false` if it was checked out.

```
bool LibraryBook::isAvailable()
// post: Return true if this book is available, or false if not
```

Here is an example free function that returns `true` if the integer argument is odd:

```
// Demonstrate a simple bool function
#include <iostream>
using namespace std;

bool isOdd(int n) {
  // post: Return true if n is an odd integer
  return (n % 2) != 0;
}

int main() {
  int j = 3;

  // Ensure j is an even number
  if (isOdd(j)) {
    j = j + 1;
  }
  cout << j << endl;

  return 0;
}
```

Output

```
4
```

7.5.1 BOOLEAN OPERATORS

C++ has three Boolean operators, `!` (not), `||` (or), and `&&` (and), to create more complex logical expressions. For example, this logical expression:

```
(test >= 0) && (test <= 100)
```

shows the logical "and" operator (`&&`) applied to two logical operands. Since there are only two logical values, true and false, the following table shows every possible combination of logical values and the logical operators `!`, `||`, and `&&`:

`!` (not)		`||` (or)		`&&` (and)	
Expression	**Result**	**Expression**	**Result**	**Expression**	**Result**
`! false`	`true`	`true || true`	`true`	`true && true`	`true`
`! true`	`false`	`true || false`	`true true`	`true && false`	`false`
		`false || true`	`false`	`false && true`	`false`
		`false || false`		`false && false`	`false`

The next example logical expression uses the Boolean operator `&&` (logical "and") to ensure a test is in the range of 0 through 100 inclusive. The logical expression is true when `test` has a value greater than or equal to 0 (`test >= 0`) and at the same time is less than or equal to 100 (`test <= 100`).

```
if ((test >= 0) && (test <= 100))
  cout << "Test is in range";
else
  cout << "**Warning--Test is out of range";
```

Here is how the `if` statement evaluates its logical expressions when `test` has the value 97 and then 977 (to simulate an attempt to enter `97` when the user accidentally presses `7` twice):

When test is 97	When test is 977
`(test >= 0) && (test <= 100)`	`(test >= 0) && (test <= 100)`
`( 97  >= 0) && ( 97  <= 100)`	`(977  >= 0) && (977  <= 100)`
`true  &&  true`	`true  &&  false`
`true`	`false`

7.5.2 OPERATOR PRECEDENCE RULES

Programming languages have precedence rules governing the order in which operators are applied to the operand(s). For example, in the absence of parentheses, the relational operators `>=` and `<=`

are evaluated before the `&&` operator. Most operators are grouped (evaluated) in a left-to-right order: `a / b / c / d` is equivalent to `(((a / b) / c) / d)`.

However, there is one notable exception. The assignment operator groups in a right-to-left order to allow multiple assignments such as this: `x = y = z = 0.0` is equivalent to `(x = (y = (z = 0.0)))`. The expression `z = 0.0` returns `0.0`, which is then transferred to `y`, which is transferred to `x`.

The following table lists some (though not all) of the C++ operators in order of precedence. The `::` and `()` operators are evaluated first (have the highest precedence), and the assignment operator `=` is evaluated last. Although there are more operators in C++, this table represents all the operators used in this textbook, and they have all been discussed already.

Precedence rules of C++ operators (partial list)

Category	Operators	Descriptions	Grouping
Highest	`::` , `()`	Scope resolution, Function call	Left to right
Unary	`!` , `+` , `-`	Not, Unary plus, Unary minus	Right to left
Multiplicative	`*` , `/` , `%`	Multiplication, Division, Remainder	Left to right
Additive	`+` , `-`	Binary plus, Binary minus	Left to right
Input/Output	`>>` , `<<`	Stream extraction, Stream insertion	Left to right
Relational	`<` , `>`	Less than, Greater than	Left to right
	`<=` , `>=`	Less or equal, Greater or equal	
Equality	`==` , `!=`	Equal, Not equal	Left to right
and	`&&`	Logical and	Left to right
or	`¦¦`	Logical or	Left to right
Assignment	`=`	Assign right value to left value	Right to left

One of the problems with these elaborate precedence rules is simply trying to remember them. When unsure, use parentheses to clarify these precedence rules. Using parentheses makes the code more readable and therefore more understandable.

SELF-CHECK

7-7 Evaluate the following expressions to true or false:

a. `(false ¦¦ true)`

b. `(true && false)`

c. `(1 * 3 == 4 - 1)`

d. `(false ¦¦ (true && false))`

e. `(3 < 4 && 3 != 4)`

f. `(! false && ! true)`

g. `((5 + 2) > 3 && (11 < 12))`

h. `! ((false && true) ¦¦ false)`

7-8 Write an expression that is true only when the `int` object named `score` is in the range of 1 through 10 inclusive.

7-9 Write an expression that is true if `test` is outside the range of 0 through 100 inclusive.

7-10 Write the output generated by the following code (be careful):

```
double GPA = 1.03;
if (GPA = 4.0)
  cout << "President's list";
```

7.5.3 THE BOOLEAN "OR" ¦¦ WITH A `grid` OBJECT

The next sample logical expression uses the operator ¦¦ (logical "or") to determine if the mover in a `grid` object is on one of the four edges. The logical expression is true when the mover is in row number 0, column number 0, the last row, or the last column.

```
   (g.row() == 0)
¦¦ (g.row() == g.nRows()-1)
¦¦ (g.column() == 0)
¦¦ (g.column() == g.nColumns()-1)
```

This logical expression evaluates like this when the mover is in row 1, column 5 of a 6-by-6 `grid` object (the ¦¦ operator evaluates in a left-to-right order):

```
The grid:
. . . . . .
. . . . . >
. . . . . .
. . . . . .
. . . . . .
. . . . . .

g.row()==0 ¦¦ g.row()==g.nRows()-1 ¦¦ g.column()==0 ¦¦ g.column()==g.nColumns()-1
      1==0 ¦¦       1==5           ¦¦          5==0 ¦¦          5==5
     false ¦¦       false          ¦¦          5==0 ¦¦          5==5
          false                    ¦¦         false ¦¦          5==5
                                   false            ¦¦          true
                                                    true
```

The only time this expression is false is when all four subexpressions are false. If any one of them is true, the expression evaluates to true, in fact, more quickly than you might think (see short circuit Boolean evaluation below). Now here is the same expression put into the context of a function that determines if the mover is on the edge of *any* `grid` object:

```
// Show a more complex logical expression inside a bool function

#include <iostream>  // For cout
using namespace std;
#include "Grid.h"    // For class Grid

bool moverOnEdge(const Grid & g) {
```

```
  // post: Return true if the mover is on an edge or false if not
  bool result;

  result =    (g.row() == 0)                  // On north edge?
           || (g.row() == g.nRows()-1)        // On south edge?
           || (g.column() == 0)               // On west edge?
           || (g.column() == g.nColumns()-1); // On east edge?

  return result;
}

int main() {
  // Test drive moverOnEdge
  Grid tarpit(6, 6, 2, 5, east);

  if (moverOnEdge(tarpit)) {
     cout << "On edge" << endl;
  }
  else {
     cout << "Not on edge" << endl;
  }

  return 0;
}
```

Output

```
On edge
```

SELF-CHECK

7-11 Many tests are necessary for the `moverOnEdge` function. Write the output from the preceding program when the mover is at each of the following intersections:

Row	Column	Output—on edge or not?
3	4	
4	3	
2	2	
0	2	
2	0	

7.5.4 SHORT CIRCUIT BOOLEAN EVALUATION

In the logical expression (`E1 && E2`), `E1` is evaluated first and if it is false, `E2` is not evaluated. This is called *short circuit evaluation*. It is satisfactory because `false && false` is `false`. So is `false && true`. Evaluating the second expression `E2` is not necessary. This is the way C++ evaluates logical expressions—stopping as soon as possible. Short circuit evaluation is also possible

with the "or" operator ¦¦. In the expression (E1 ¦¦ E2), E1 is evaluated first and if E1 is true, E2 is not evaluated. A programmer can actually get away with code like this:

```
if ((x >= 0.0) && (sqrt(x) <= 4.0))
```

When x is negative, the second expression with sqrt(x) is never evaluated. By checking for x >= 0.0 first, the square root of a negative number never occurs. Switch the order of statements and a runtime error occurs when x < 0.0.

Also consider the previous example of Boolean evaluation in the bool function moverOnEdge. When the mover was in row 2 and column 5, the first three Boolean subexpressions were false. Therefore, the evaluation had to carry on until the fourth (and final) subexpression. This entire expression would also be evaluated whenever the mover was not on an edge—all four subexpressions would be false. However, consider the same expression if the mover had been in row 0:

```
The grid:
. . . . . >
. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .

   g.row()==0                          true
¦¦ g.row()==g.nRows()-1                not evaluated
¦¦ g.column()==0                       not evaluated
¦¦ g.column()==g.nColumns()-1not evaluated
```

As soon as g.row()==0 evaluates to true, the following three subexpressions do not need to be evaluated. true ¦¦ anything is true. Short circuit Boolean evaluation is part of C++ because it improves runtime efficiency. Imagine evaluating one or two fewer subexpressions millions of times.

SELF-CHECK

7-12 Evaluate the following expressions after each set of assignments to x and y:

```
((fabs(x - y) >= 0.001) && (x >= 0.0) && (sqrt(x) < 6.5))
```

a.
```
x = 1.0
y = 2.0
```

b.
```
x = 56.77779
y = 56.77777
```

c.
```
x = -1.0
y = 2.0
```

d.
```
x = -1.0
y = 1.0
```

7-13 How many subexpressions evaluate when the mover is in row 5, column 3, assuming a 6-by-6 grid?

```
   g.row()==0
¦¦ g.row()==g.nRows()-1
¦¦ g.column()==0
¦¦ g.column()==g.nColumns()-1
```

7.6 A bool MEMBER FUNCTION

The class definition of `BankAccount` has a `void` withdraw member function with the precondition that the withdrawal amount must not be greater than the balance. This implementation currently allows the balance to go negative when the preconditions are not met by the client code (the following member function is from `BankAccount.cpp`).

```
void BankAccount::withdraw(double withdrawalAmount) {
  // pre: withdrawalAmount <= balance
  balance = balance - withdrawalAmount;
}
```

A better design would be to disallow negative balances. Then the client code would not have to worry about satisfying the precondition. The withdraw message could avoid negative balances. The return type could also become `bool` so the client code has the chance to determine if the withdraw message was successful or not. First, the class definition would have to be changed. `void` is changed to `bool` in the file `BankAccount.h`:

```
bool withdraw(double withdrawalAmount);
// post: If withdrawalAmount <= balance && withdrawalAmount > 0.0,
//       debit withdrawalAmount from this balance and return true.
//       Otherwise don't change anything--just return false.
```

Then the implementation is changed in `BankAccount`. The Alternative Action pattern chooses between debiting the account and returning true or returning false when the balance is not large enough.

```
bool BankAccount::withdraw(double withdrawalAmount) {
  bool result = true;
  if ((withdrawalAmount > balance) || (withdrawalAmount <= 0.00))
    result = false;
  else
    balance = balance - withdrawalAmount;

  return result;
}
```

The following program test drives this new behavior. Because withdraw returns either true or false, the message can be used as a test expression.

```
// Test drive the "safe" BankAccount::withdraw
#include <iostream>
using namespace std;
#include "BankAccount.h"  // A modified "safe" BankAccount

int main() {
  BankAccount aSafeAccount("Charlie", 50.00);
  double withdrawalAmount;

  cout << "Enter amount to withdraw: ";
```

```
  cin >> withdrawalAmount;
  if (aSafeAccount.withdraw(withdrawalAmount)) {
    cout << "Balance = $" << aSafeAccount.getBalance() << endl;
  }
  else {
    cout << "Could not withdraw " << withdrawalAmount << endl;
  }

  // Can ignore return result
  aSafeAccount.withdraw(10000);
  return 0;
}
```

Dialogue 1

```
Enter amount to withdraw: 75.00
Could not withdraw 75.00
```

Dialogue 2

```
Enter amount to withdraw: 20.00
Balance = $30
```

In C++, any function return result can be ignored. This new version of `withdraw` could be used as it was before—as a stand-alone statement rather than as part of an `if` statement. This is done at the attempt to withdraw $1,000.00 as the last statement in `main`, just before `return 0`.

SELF-CHECK

7-14 Using this new safe version of the `BankAccount::withdraw` function, write the output generated by the program given below for each value of `wAmount`:

a. `double wAmount = 100.00;`

b. `double wAmount = -100.00;`

c. `double wAmount = 112.50;`

d. `double wAmount = 200.00;`

```
#include <iostream>      // For cout
using namespace std;
#include "BankAccount.h" // For the BankAccount class

int main() {
  BankAccount b("Kilroy", 112.50);
  double wAmount = -100.00;  // Substitute new values here
  if (b.withdraw(wAmount)) {
    cout << "okay" << endl;
  }
```

```
  else {
    cout << "failed" << endl;
  }
  return 0;
}
```

7.7 MULTIPLE SELECTION

Multiple Selection refers to the times when the programmer needs to select one action from many possible actions. This is something that occurs quite often when programming. The pattern that solves this problem can be implemented as an `if...else` statement that has other `if...else`s nested inside their false parts. The more actions there are to choose from, the more nesting occurs. This pattern is summarized as follows:

Algorithmic Pattern: *The Multiple Selection pattern*

Pattern: Multiple Selection

Problem: Must execute one set of actions from three or more alternatives

Outline:

```
if ( condition 1  is true )
  execute action 1
else if ( condition 2 is true )
  execute action 2
// ...
else if ( condition n-1 is true )
  execute action n-1
else
  execute action n
```

Code Example:

```
if (grade < 60.0)
  result = "F";
else if (grade < 70)
  result = "D";
else if (grade < 80)
  result = "C";
else if (grade < 90)
  result = "B";
else
  result = "A";
```

The following program contains an instance of the Multiple Selection pattern to select from one of the three possible actions:

```
// Multiple selection where exactly one cout statement executes.
// The output is dependent on the input value for GPA.

#include <iostream>
using namespace std;

int main() {
  double GPA;
  cout << "Enter your GPA: ";
  cin >> GPA;

  if (GPA < 3.5) {
    cout << "Try harder" << endl;
  }
  else {
    // Execute this multiple selection statement
    if (GPA < 4.0)
      cout << "You made the dean's list" << endl;
    else
      cout << "You made the president's list" << endl;
  }
  return 0;
}
```

Notice that the false part of the first `if...else` statement is another `if...else` statement. If `GPA` is less than `3.5`, `Try harder` is output and the program skips over the nested `if...else`. However, if the logical expression is false (when `GPA` is greater than or equal to `3.5`), the second `if...else` statement determines if `GPA` is high enough to qualify for either the dean's list or the president's list. Here one alternative selection is nested inside another alternative selection.

When implementing the Multiple Selection pattern, it is important to use proper indentation so the code will execute as its written appearance suggests. The readability realized by good indentation habits can save you time during program implementation, which includes testing. To illustrate the flexibility in formatting, the previous multiple selection may be rewritten in the following preferred manner to line up the three paths through this control structure:

```
if (GPA < 3.5)
  cout << "Try harder" << endl;
else if (GPA < 4.0)
  cout << "You made the dean's list" << endl;
else
  cout << "You made the president's list" << endl;
```

The previous formatting represents the preferred method of this textbook. However, you could also use blocks to make multiple selection look like this:

```
if (GPA < 3.5) {
  cout << "Try harder" << endl;
}
```

```
else if (GPA < 4.0) {
  cout << "You made the dean's list" << endl;
}
else {
  cout << "You made the president's list" << endl;
}
```

7.7.1 ANOTHER EXAMPLE: DETERMINING LETTER GRADES

Some instructors use a scale like the following to determine the proper letter grade to assign to a student. The letter grade is based on a percentage representing a weighted average of all work for the term.

Value of Percentage (should be in the range 0 through 100 inclusive)	**Assigned Grade**
90.0 ≤ percentage	A
80.0 ≤ percentage < 90.0	B
70.0 ≤ percentage < 80.0	C
60.0 ≤ percentage < 70.0	D
percentage < 60.0	F

A function could be implemented with `if` statements that begin like this:

```
if ( percentage >= 90.0)
  result = "A";

if ( percentage >= 80.0 && percentage < 90 )  // Not necessary
  result = "B";

if ( percentage >= 70.0 && percentage < 80 )  // Not necessary
// . . .
```

However, when given the problem of choosing from among five different actions, try to remember that the choice is Multiple Selection, not Guarded Action. The preferred Multiple Selection is also more efficient at runtime. The Multiple Selection pattern is also less prone to intent errors.

```
string letterGrade(double percentage) {
  // pre: percentage >= 0.0 && percentage <= 100.0
  // post: Return letter grade according to external documentation
  string result;
  // Determine the proper result . . .

  if (percentage >= 90.0)
    result = "A";
  else if (percentage >= 80.0)
    result = "B";
  else if (percentage >= 70.0)
    result = "C";
```

```
  else if (percentage >= 60.0)
    result = "D";
  else
    result = "F";

  return result;
}
```

Here, the output depends on the value of `percentage`. If `percentage` is greater than or equal to 90.0, then the statement `result = "A";` executes. The program skips over all other statements after the first `else`. If `percentage == 50.0`, then all logical expressions are false and the program executes the action after the final `else: result = "F";`.

When `percentage` has a value between 60.0 and 90.0, logical expressions evaluate until the first one that is true. When `percentage >= 90.0` is false, the opposite logical expression, `percentage < 90.0`, must be true. The second logical expression, `percentage >= 80.0`, evaluates when the first expression is false. When the first true logical expression is finally encountered, the very next true part executes and the program skips over the remaining alternative(s).

This function could be improved by ensuring that letter grades are returned only when `percentage` is within the range of 0.0 through 100.0 inclusive. There is a possibility, for example, that an argument will be passed as 777 instead of an intended input of 77. Since 777 >= 90.0 is true, the function improperly returns `"A"` when `"C"` would have been the correct result. `letterGrade` could be modified to contain a test for out-of-range input. This first logical expression now checks to see if `percentage` is either less than 0.0 or greater than 100.0.

```
if ((percentage < 0.0) ¦¦ (percentage > 100.0))
  result = "**Error--Percentage is not in range [0...100]";
else if (percentage >= 90)
  result = "A";
```

If `percentage` is out of range, the result becomes an error message and the program skips over the remainder of the nested `if...else` structure. Rather than returning an incorrect letter grade for percentages less than 0 or greater than 100, this string is returned instead for the argument 777:

```
**Error--Percentage is not in range [0...100]
```

7.7.2 MULTIPLE RETURNS

The previous implementation of `letterGrade` shows that the proper letter grade is first assigned to the local object named `result`. Another implementation option uses multiple return statements. The first time any return statement executes, the function terminates. Therefore, a function could be written with many return statements:

```
string letterGrade(double percentage) {
  if (percentage >= 90)
    return "A";
```

```
  if (percentage >= 80)
    return "B";
  if (percentage >= 70)
    return "C";
  if (percentage >= 60)
    return "D";
  if (percentage >= 0)
    return "F";  // ERROR: runtime error when percentage < 0
}
```

If you do use the technique of multiple returns, ensure that something is always returned. For example, the previous code will not return anything for arguments that are less than `0.0`. This code might cause a warning or a compile time error. Worse, some systems will wait until it is too late and generate a runtime error. The problem goes away when the block ends like this instead:

```
  // . . .
  if (percentage >= 0)
    return "F";

  return "Error: argument to letterGrade < 0";
}
```

And while you're at it, consider returning an error message when `percentage > 100` if that would in fact be an error.

7.8 TESTING MULTIPLE SELECTION

Consider how many function calls should be made to test the `letterGrade` function with Multiple Selection—or for that matter, any function or segment of code containing Multiple Selection. To test this particular example to ensure that Multiple Selection is correct for all possible percentage arguments, the function could be called with all numbers in the range from `-1.0` through `101.0`. However, this would require a virtually infinite number of function calls. This is unnecessary!

First consider a set of test data that executes every possible branch through the nested `if...else`. Branch coverage testing occurs by observing what happens when each and every statement (the true or false part) of a nested `if...else` executes once. These three things are necessary to correctly perform branch coverage testing:

- Establish a set of data that executes all branches of the Multiple Selection.
- Execute the portion of the program containing the Multiple Selection for all selected data values. This can be done with a test driver.
- Observe that the program segment behaves correctly for all data values.
- For example, the following data set executes all branches of `letterGrade`:

```
-1.0  55.0  65.0  75.0  85.0  95.0  101.0
```

A test driver could start like this:

```
int main() {
  cout << "-1.0 = " << letterGrade(-1.0) << endl;
  cout << "55.0 = " << letterGrade(55.0) << endl;
  cout << "65.0 = " << letterGrade(65.0) << endl;
  // . . .
```

and then the program output must be examined to indicate that every function call returned the proper value:

```
-1.0 = **Error--Percentage is not in range [0...100]
55.0 = F
65.0 = D
     . . .
```

7.8.1 BOUNDARY TESTING

Boundary testing occurs by observing what happens for each cut-off (boundary) value. This extra effort could go a long way. For example, boundary testing avoids situations where students with `90` are accidentally shown to have a letter grade of `B` rather than `A`. This would occur when the logical expression `(percentage >= 90)` is accidentally coded as `(percentage > 90)`. The arguments of `60`, `70`, `80`, and `90` complete boundary testing of the code above.

Perhaps the best testing strategy is to select test values that combine branch and boundary testing at the same time. For example, a `percentage` of `90.0` should return `A`. The value of `90` not only checks the path for all; it also tests the boundary—`90.0` is the cut-off. Counting down by tens to `60` checks all boundaries. But it misses one path: the one that sets result to `F`. Adding `59.9` completes the test driver.

```
int main() {
  // A test driver for string letterGrade(double percentage)
  cout << "90.0? " << letterGrade(90.0) << endl;  // 90.0? A
  cout << "80.0? " << letterGrade(80.0) << endl;  // 80.0? B
  cout << "70.0? " << letterGrade(70.0) << endl;  // 70.0? C
  cout << "60.0? " << letterGrade(60.0) << endl;  // 60.0? D
  cout << "59.9? " << letterGrade(59.9) << endl;  // 59.9? F
  return 0;
}
```

7.9 THE ASSERT FUNCTION

So far testing has been done by printing things with `cout`. This requires a careful inspection of the `cout` statements and the associated output. Placing the expected output on the same line, as is done above with `letterGrade`, can help. The expected and actual values are right next to each other. If they do not match, then either the expected value is incorrect, the return value is incorrect, or perhaps both. The C++ `assert` function can also be used to test where the expected value is next to the function call or message.

The `assert` function takes a `bool` argument. If the argument is `false`, C++ will inform you with a line of output that begins with `Assertion failed`. In this case, `assert` will terminate the program.

If all expressions in all calls to the function are true, there is *no* output. So if you write your tests with `assert` functions, you only have to look at output when something has gone wrong. The following `main` function represents a test of `letterGrade` that is equivalent to the version above with five `cout` statements. Getting no output means the assertions all passed—there were no detected errors when comparing the expected values like `"A"` with the actual return values like `letterGrade(90.0)`.

```
/*
 * Test letterGrade using assert
 *
 * File name: main.cpp
 */
#include <cassert> // Required for the assert function
#include <string>
using namespace std;

string letterGrade(double percentage) {
  // pre:  percentage >= 0.0 && percentage <= 100.0
  // post: Return letter grade according to external documentation
  string result;
  if (percentage >= 90.0)
    result = "A";
  else if (percentage >= 80.0)
    result = "B";
  else if (percentage >= 70.0)
    result = "C";
  else if (percentage >= 60.0)
    result = "D";
  else
    result = "F";
  return result;
}

int main() {
  assert("A" == letterGrade(90.0));
  assert("B" == letterGrade(80.0));
  assert("C" == letterGrade(70.0));
  assert("D" == letterGrade(60.0));
  assert("F" == letterGrade(59.9));
}
```

The preceding code will have no output. Changing the `"C"` to a `"D"` will make the expression false in this call to the `assert` function:

```
assert("D" == letterGrade(70.0));
```

Now we get this output from `assert` indicating the assertion failed. You even get the line number and the file name where the assertion failed:

Output

```
Assertion failed: ("D" == letterGrade(70.0)), function main, file main.cpp, line 32.
```

This method of testing is suggested for the programming projects at the end of this chapter. There are several functions that have many branches. The `assert` function makes testing easier.

SELF-CHECK

7-15 Which value of `percentage` would detect the intent error in the following code?

```
if (percentage >= 90)
  result = "A";
else if (percentage >= 80)
  result = "B";
else if (percentage > 70)
  result = "C";
else if (percentage >= 60)
  result = "D";
else
  result = "F";
```

7-16 What `string` is incorrectly assigned to `letterGrade` for the value of `percentage` you answered above?

7-17 Would you be happy with the result if your grade were computed with this argument?

7-18 Using the nested structure below, write the return value for each of these six different arguments for weather: `-40  20  -1  42  15  31`

```
string weather(int temp) {
  if (temp <= -40)
    return "extremely frigid";
  else if (temp < 0)
    return "below freezing";
  else if (temp < 20)
    return "freezing to mild";
  else if (temp < 30)
    return "warm";
  else if (temp < 40)
    return "very hot";
  else
    return "toast";
}
```

7-19 List the range of integers that would cause the previous program to display `warm`.

7-20 List the range of integers that would cause the previous program to display `below freezing`.

7-21 Write a test for weather that uses the `assert` function to completely test this free function.

7.10 THE `switch` STATEMENT

The C++ `switch` statement also implements the Multiple Selection pattern. Although nested `if...else` statements can do anything the `switch` statement does, it is included here because you will see it in other C++ programs and because some programmers prefer this implementation of Multiple Selection.

General Form 7.3 *The C++* `switch` *statement*

```
switch (switch-expression) {
  case constant-value-1:
       statement(s)-1;
    break ;
  case constant-value-2:
       statement(s)-2;
     break ;
          ...
  case constant-value-n:
      statement(s)-n;
      break ;
  default :
    default-statement(s);
}
```

When a `switch` statement is encountered, the switch-expression is compared to *`constant-value-1`*, *`constant-value-2`*, through *`constant-value-n`* until a match is found. When the switch expression matches one of these values, the statements following the colon execute. If no match is made, the statement(s) after `default` execute.

The keyword `default` needs to be present only if some processing is desired whenever the `switch` expression cannot match any of the case values. With no `default`, it is possible that no statements will execute inside the `switch` statement. Sometimes that is the appropriate design.

The following `switch` statement chooses one of three paths based on the input value of `option`. If the user enters `1`, the first case section of code is executed. The first `break` terminates the `switch` statement.

```
int option = 0;
cout << "Enter option 1, 2, or 3: ";
cin >> option;

switch(option) {
  case 1:
```

```
    cout << "option 1 selected" << endl;
      break;
    case 2:
      cout << "option 2 selected" << endl;
      break;
    case 3:
      cout << "option 3 selected" << endl;
      break;
    default:
      cout << "option < 1 or option > 3" << endl;
  } // End switch
```

If neither `1`, `2`, nor `3` are entered, the statement(s) after `default:` execute.

The switch expression (`option` above) and each constant value (`1`, `2`, and `3` above) after `case` must be compatible. In fact, the constants must be one of the C++ integral types, which consist of the integer types (`int`, `long`, and so on) or `char`—the class discussed in the next section.

The `break` statement—a new reserved word—causes an exit from the control structure the program is executing. The `break` statement at the end of each `case` section causes a jump out of the `switch` statement. In fact, the `switch` statement typically requires many `break` statements. They avoid unintentional execution of the remaining portions of the `switch` statement.

7.10.1 char OBJECTS

The `char` class of objects is an integral type often used as the constant value in `switch` statements. A `char` object stores one character constant—a character between single quotes (apostrophes):

```
'A'   'b'    '?'    '8'    ' '     ','
```

There are several special escape sequences—a backward slash (\) followed by one of a select few characters that have special meaning (see the following table).

Escape Sequence	Meaning
`'\n'`	new line
`'\"'`	double quote in a `char`
`'\''`	single quote in a `char`
`'\\'`	one backward slash
`'\t'`	tab

`char` objects are declared, initialized, assigned values, and displayed in the same way as the other fundamental types like `int`.

```
// Use some char objects
#include <iostream>
using namespace std;
```

```
int main() {
  // Declare and initialize some char objects
  char one, two;
  char letterGrade = 'A';
  char newLine = '\n';

  // Assignment is possible with character expressions
  one = 'T';
  two = 'o';

  // Output some char objects, char constants, and escape sequences
  cout << "letterGrade is " << letterGrade << endl;
  cout << one << two << newLine << one << '\t' << two << endl;
  cout << '\"' << 'A' << ' ' << '\\' << ' ' << 'S' << 't'
       << 'r'  << 'i' << 'n' << 'g' << '?' << '\'' << endl;

  return 0;
}
```

Output

```
letterGrade is A
To
T       o
"A \ String?'
```

The `char` type has its own set of nonmember functions included in `cctype`. For example, the `toupper` function returns 68, which is the ASCII (numeric) code for the uppercase equivalent of its argument. If you want to see the actual character, typecast with `char()` to see the 'D':

```
cout << toupper('d') << endl;        // Output: 68
cout << char(toupper('d')) << endl;  // Output: D
```

Here is a `switch` statement that uses characters as the constant expressions. It chooses one of five paths based on the value of the `char` object `option`:

```
// Illustrate another switch statement
#include <iostream>  // For cout <<
using namespace std;
#include <cctype>  // For toupper(char) returns uppercase char

int main() {
  char option;
  cout << "B)alance  W)ithdraw  D)eposit  Q)uit: ";
  cin >> option;
  switch(toupper(option)) {
    case 'B':
      cout << "Balance selected" << endl;
      break;
    case 'W':
      cout << "Withdraw selected" << endl;
      break;
    case 'D':
```

```
      cout << "Deposit selected" << endl;
      break;
    case 'Q':
      cout << "Quit selected" << endl;
      break;
    default:
      cout << "Invalid choice" << endl;
  } // End switch

  return 0;
}
```

One Possible Dialogue

```
B)alance  W)ithdraw  D)eposit  Q)uit: D
Deposit selected
```

If the value extracted for option is `B`, the message `Balance selected` is output and `break` is executed to exit the `switch` control structure. If `Q` or `q` is input, `Quit selected` is output and another `break` is executed. In this example, each case is evaluated until `option` is matched to one of the four `char` values following `case`. If `option` is any other value, the message `Invalid choice` is displayed.

One final comment on the `switch` statement: don't forget to include the optional `break` statements in the `case` portions of `switch`. Failure to break out of the `switch` causes all remaining statements to execute. Although this may be what you want in some unusual circumstance, it is usually not a good idea to forget the `break`s. For example, imagine the preceding `switch` with all `break` statements removed:

```
switch(toupper(option)) {
  case 'B':
    cout << "Balance selected" << endl;
  case 'W':
    cout << "Withdraw selected" << endl;
  case 'D':
    cout << "Deposit selected" << endl;
  case 'Q':
    cout << "Quit selected" << endl;
  default:
    cout << "Invalid choice" << endl;
} // End switch
```

Now when `B` is input, every statement executes—including the default!

```
B)alance  W)ithdraw  D)eposit  Q)uit: B
Balance selected
Withdraw selected
Deposit selected
Quit selected
Invalid choice
```

SELF-CHECK

7-22 Write the output produced by this `switch` statement:

```
char option = 'A';
switch(option) {
  case 'A':
    cout << "AAA";
    break;
  case 'B':
    cout << "BBB";
    break;
  default:
    cout << "Invalid";
    }
```

7-23 What is the output from the code above when `option` is `B`?

7-24 What is the output from the code above when `option` is `C`?

7-25 What is the output from the code above when `option` is `D`?

7-26 Write a `switch` statement that displays your favorite music if the `int` object `choice` is `1`, your favorite food if `choice` is `2`, and your favorite instructor if `choice` is `3`. If the option is anything else, display `Error`. Don't forget the `break` statements.

CHAPTER SUMMARY

- Selection requires logical expressions that evaluate to true or false. The logical expressions usually have one or more of the following relational, equality, or logical operators:

  `<` `>` `<=` `>=` `!=` `==` `!` `||` `&&`

- The Guarded Action pattern is implemented with the `if` statement that either executes a collection of statements or skips them depending on the circumstances.
- The Alternative Action pattern, implemented with the C++ `if...else` statement, is used to choose one action or its alternative—two choices.
- Multiple Selection can be implemented with nested `if...else` statements or with the `switch` statement. Multiple Selection should be used whenever there are three or more actions to select from.
- Selection control allows the program to respond to a variety of situations in an appropriate manner.
- The `bool` class and the `bool` constants `true` and `false` are sometimes used as the return type of a function to conveniently return information about the state of an object. Is the book available? Was the withdraw message successful or not? Are there real roots to this equation?
- Several examples of Multiple Selection showed the need for thorough testing.

- When implementing the Multiple Selection pattern, be sure to thoroughly test the code with the Multiple Selection. Establish a set of data that executes all branches and tests all cut-off (boundary) values.
- Without thorough testing, a program may only appear to work when in fact there is perhaps one value among thousands that does not work.

EXERCISES

1. True or False: When an `if` statement is encountered, the *true-part* always executes.
2. True or False: When an `if` or `if...else` statement is encountered, valid logical expressions are evaluated to either true, false, or maybe.
3. Proper indentation and spacing improve readability. The next code segment is an example of poor indentation; try to predict the output.

```
        int j=123;if (j>=0)if (0==j)cout<<"one";else cout<<"two";else
   cout<<"three";
```

4. Write the output from the following code fragments:

a.
```
double x = 4.0;
if (10.0 == x)
  cout << "is 10";
else
  cout << "not 10";
```

b.
```
string s1 = "Ab";
string s2 = "Bc";
if (s1 == s2)
cout << "equal";
if (s1 != s2)
cout << "not";
```

c.
```
int j = 0, k = 1;
if (j != k) cout << "abc";
if (j == k) cout << "def";
(j <= k) cout << "ghi";
if (j >= k) cout << "klm";
```

d.
```
double x = -123.4,  y = 999.9;
if (x < y)  cout << "less ";
if (x > y)  cout << "greater ";
if (x == y) cout << "equal ";
if (x != y) cout << "not eq. ";
```

5. Write the output from the following code fragments:

a.
```
string name = "Parker";
if (name >= "A" && name <= "F")
  cout << "A..F";
if (name >= "G" && name <= "N")
  cout << "G..N";
if (name >= "O" && name <= "T")
  cout << "O..T";
if (name >= "U" && name <= "Z")
  cout << "U..Z";
```

b.
```
int t1 = 87, t2 = 76, larger = 0;
if (t1 > t2)
  larger = t1;
else
  larger = t2;
cout << "larger: " << larger;
```

c.
```
double x1 = 2.89;
double x2 = 3.12;
if (fabs(x1 - x2) < 1)
  cout << "true";
else
  cout << "false";
```

6. Write the output generated from the following program fragments, assuming `j` and `k` are `int` objects with the values `25` and `50`, respectively.

```
int j = 25;
int k = 50;
```

a.
```
if (j == k)
  cout << j;
cout << k;
```

b.
```
if (j <= k && j >= 0)
  cout << "ONE" <<
else
  cout << "TWO";
```

c.
```
if (j > k || k < 100)
  cout << "THREE";
else
  cout << "FOUR";
```

d.
```
if (j >= 0 && j <=100)
  cout << "FIVE";
else
  cout << "SIX";
```

7. Write a statement that displays `YES` if `intObject` is positive, `NO` if `intObject` is negative, or `NEUTRAL` if `intObject` is zero.
8. Write a statement that will add `1` to the `int` object `j` only when the `int` object counter has a value less than the `int` object `n`.
9. Write a statement that displays `Hello` if the `int` object `hours` has a value less than 8, or `Goodbye` if `hours` has any other value.
10. Write a program fragment that guarantees that the `int` object `amount` is even. If `amount` is odd, increment `amount` by `1`.
11. Write a program segment that adds `1` to the `int` object `amount` if `amount` is less than `10`. In this case, also display `Less than 10`. If `amount` is greater than `10`, subtract `1` from `amount` and display `Greater than 10`. If `amount` is `10`, just display `Equal to 10`.
12. Write an expression that is true if and only if the mover in the `Grid` object `myGrid` is on one of the four corners of the `Grid`.
13. Write function `inc3` that increments all three arguments associated with the parameters by `1.0`. The following function call must change the objects as shown.

```
double x = 0.0, y = 0.0, z = 0.0;
inc3(x, y, z);
// assert x, y, and z all equal 1.0.
```

14. Implement function `bool turnTillClear(Grid & grid)` that faces the mover in the first direction that has a clear front (like the mover in the left column below). In this case, return `true`. Return `false` when the mover is surrounded as shown with the `Grid` on the right.

```
The grid:
. . . . . . . . . . .
. . . # < . . . . . .
. # # # # # # # # # .

mover turns left twice

The grid:
. . . . . . . . . . .
. . . # > . . . . . .
. # # # # # . . . . .
```

```
The grid:
. . . # # # . . . .
. . . # < # . . . .
. # # # # # # # # .

mover is trapped

The grid:
. . . # # # . . . .
. . . # ^ # . . . .
. # # # # # # # # .
```

15. Write the output from the following program when:

a. `choice = 3`

b. `choice = 1`

c. `choice = 2`

d. `choice = 0`

```
#include <iostream>
using namespace std;
int main() {
  int choice = 3;  // Change 3 to 1, 2, and then 0
  switch(choice) {
    case 1:
      cout << "1 selected" << endl;
      break;
    case 2:
      cout << "2 selected" << endl;
      break;
    case 3:
      cout << "3 selected" << endl;
      break;
    default:
      cout << "Invalid choice" << endl;
  } // End switch
  return 0;
}
```

PROGRAMMING TIPS

1. Take notice of the difference between = and ==. = assigns and == compares. It is very easy, even natural, to write = instead of ==. The following code will always execute the true part because `grade = 100` returns `100`, which is nonzero, which is true.

```
if (grade = 100)
 cout << "another perfect score" << endl;
else
cout << "this never ever executes" << endl;
```

Perhaps this is the most famous C++ "gotcha": using = instead of == in an `if` statement.

2. Test drivers help protect against errors. Use test drivers with many calls to the function containing the Multiple Selection. Send arguments that check all boundary values. Send arguments that ensure that each branch executes at least once.

3. The compound statement may be used even if it is not required. Consider always using curly braces to mark the beginning and end of the true part and the false part of an `if...else`. You *must* use the block to treat several statements as one. You *may* use the block for readability and to help avoid bugs.

4. The way a mathematician writes an expression does not always work in C++. It is easy, even natural, to write the following code that checks to see if a value is in a certain range:

```
int x = 2222;
if ( 0 <= x <= 100 ) {
 cout << x << " is in the range of 0 through 100" << endl;
}
```

If you're lucky, you will get a warning on a compiler. However, in either case, the code compiles and runs. Then when `x` is `2222`, you get this output indicating an intent error:

```
2222 is in the range of 0 through 100  // Wrong
```

That's because the logical expression evaluates like this:

```
if ( 0 <=  x  <= 100 )
 0 <= 222 <= 100
   true    <= 100  // True is like 1 and 1 <= 100 is true
     true
```

5. Short circuit evaluation makes programs more efficient and comes in handy sometimes. Short circuit Boolean evaluation is always in effect to make programs run more quickly, especially when millions of comparisons are made. You might find that fact useful occasionally. One particular algorithm in a later chapter uses short circuit evaluation to avoid runtime errors.

6. Don't forget to use the `break` statement to terminate `switch` statements. C++ executes all code to the bottom of the `switch` or until the first `break` is encountered. The following code works correctly when `option == 'W'`. On the other hand, when `option == 'B'`, both options execute as shown in the accompanying output.

```
switch(option) {
  case 'B':
  cout << "Balance selected" << endl;
  case 'W':
   cout << "Withdraw selected" << endl;
}
```

Output (when `option == 'B'`)

```
Balance selected
Withdraw selected
```

PROGRAMMING PROJECTS

7A A HALF-DOZEN SELECTION METHODS

Write one C++ program where your main method is a test driver of your own design that tests six new free functions implemented in the same file. You may write your own tests with `assert` functions.

```
/*
 * A test driver like this may be used to test the functions
 *
 * File name: TestSelectionFunctions (on the book's website)
 */
int main() {
  // Test isEven
  assert(isEven(-2));
  assert(isEven(0));
  assert(isEven(2));
  assert( ! isEven(-1));
  assert( ! isEven(1));
  // . . . many more asserts are available
```

1. `bool isEven(int number)`

Complete the free function `isEven` to return true if the integer argument is an even number.

```
isEven(-2) returns true
isEven(0) returns true
isEven(2) returns true
isEven(-1) returns false
isEven(1) returns false
```

2. `int largest(int a, int b, int c)`

Complete the free function `largest` to return the largest of three integers.

```
largest(2, 4, 6) returns 6
largest(1, 2, 2) returns 2
largest(-5, -2, -7) returns -2
```

3. `string firstOf3Strings(string a, string b, string c)`

Complete the free function `firstOf3Strings` to return a reference to the `string` that is not "greater than" the other two. This is the `string` that alphabetically precedes, or is equal to, the other two arguments. Use the relational operator to compare strings. Note: `"abc" < "abc "` and `"A" < "a"`.

```
firstOf3Strings("c", "b", "a") returns "a"
firstOf3Strings("B", "B", "a") returns "B"
firstOf3Strings("ma", "Ma", "ma") returns "Ma"
firstOf3Strings("x     ", "x   ", "x ") returns "x "
```

4. `string letterGrade(double numericGrade)`

Complete the free function `letterGrade` that returns the proper letter grade as a `string` for a plus/minus system with the following scale:

Percentage	Grade
93.0 ≤ percentage	A
90.0 ≤ percentage < 93.0	A-
87.0 ≤ percentage < 90.0	B+
83.0 ≤ percentage < 87.0	B
80.0 ≤ percentage < 83.0	B-
77.0 ≤ percentage < 80.0	C+
70.0 ≤ percentage < 77.0	C
60.0 ≤ percentage < 70.0	D
percentage < 60.0	F

After implementing the function, perform branch and boundary testing. If the argument is a value outside the range of `0.0` through `100.0`, return `"Unkown"` as the `string` letter grade.

5. `double salary(double sales)`

Complete the free function `salary` that returns a salesperson's salary for the month according to the following policy:

Sales Over	But Not Over	Monthly Salary
0	$10,000	Base salary
$10,000	$20,000	Base salary plus 5% of sales over $10,000
$20,000	$30,000	Base salary plus $500.00 plus 8% of sales over $20,000
$30,000		Base salary plus $1300.00 plus 12% of sales over $30,000

The base salary is $1,500.00, which means salary returns a value that is never less than `1500.00`. When sales are over $10,000, commission is added to the base salary. For example, when `sales`

equals `10001`, the monthly salary is $1,500.00 + 5% of $1.00 for a total of $1,500.05, and when `sales` is `20001`, the monthly salary is $1,500.00 + $500.00 + 8% of $1.00 for a total of $2,000.08.

6. `int romanNumeral(char numeral)`

Complete the free function `romanNumeral` that returns the numeric equivalent of an upper- or lowercase Roman numeral, which is actually a `char`. Roman numerals and their decimal equivalents are 'I' (or 'i') = 1, 'V' (or 'v') = 5, 'X' (or 'x') = 10, 'L' (or 'l') = 50, 'C' (or 'c') = 100, 'D' (or 'd') = 500, and 'M' (or 'm') = 1,000. If the input is not a valid Roman numeral, return `-1`.

```
romanNumeral('i') returns 1
romanNumeral('I') returns 1
romanNumeral('v') returns 5
romanNumeral('X') returns 10
romanNumeral('L') returns 50
romanNumeral('c') returns 100
romanNumeral('D') returns 500
romanNumeral('m') returns 1000
```

7B A HALF DOZEN CALENDAR FUNCTIONS

Write one C++ program where your main method is a test driver of your own design that tests six new free functions implemented in the same file. You may write your own tests using output statements or asserts.

```
/*
 * A test driver like this may be used to test the functions
 *
 * File name: TestCalendarFunctions (on the book's website)
 */
int main() {
  // Test isLeapYear
  assert(isLeapYear(2016));
  assert(isLeapYear(2020));
  assert( ! isLeapYear(2019));
  assert( ! isLeapYear(2100));
```

1. `bool isLeapYear(int year)`

Complete the free function `isLeapYear` that returns `true` if the integer argument represents a leap year in which February has 29 days instead of 28 days. This is done because there are actually close to 365.25 days in a year. A leap year is a year after 1582 that is evenly divisible (no remainder after division) by four unless it is the end of a century. In this case—where the year is also evenly divisible by 100—`year` must also be divisible by 400. For example, 2000 and 2400 are leap years but 1900 and 2100 are not. Let `leapYear` return `true` if the argument represents a leap year or `false` if it does not.

```
isLeapYear(1580) returns false
isLeapYear(1584) returns true
isLeapYear(2020) returns true
isLeapYear(-2020) returns false
isLeapYear(2100) returns false
```

2. `string day(int dayOfWeek)`

Complete the free function `dayOfWeek` that returns the `string` `"Monday"` if the `int` argument passed to the parameter `dayOfWeek` is 1, returns `"Tuesday"` for the argument `2`, and so on up through returning `"Sunday"` if the argument is `7`. Return `"Unknown"` if the argument is not in the range of `1` through `7`.

```
dayOfWeek(0) returns "Unknown"
dayOfWeek(3) returns "Wednesday"
dayOfWeek(4) returns "Thursday"
dayOfWeek(6) returns "Saturday"
dayOfWeek(8) returns "Unknown"
```

3. `int daysInMonth(int month, int year)`

Complete the free function `daysInMonth` that returns the number of days in a month for the given year. There are 30 days in the months September, April, June, and November, or months 9, 4, 6, and 11. February has 28 days unless it is a leap year, when it has 29. All other months—1, 3, 5, 7, 8, 10, and 12 (December)—have 31 days. Assume the year is always >= 1582. You may use your own existing method `isLeapYear`. Return `-1` if `month` is not in the range of `1` through `12`.

```
daysInMonth(1, 2020) returns 31
daysInMonth(2, 2020) returns 29
daysInMonth(2, 2019) returns 28
daysInMonth(0, 2019) returns -1
daysInMonth(13, 2019) returns -1
```

4. `int thanksDate(int firstDay)`

In the U.S., Thanksgiving falls on the fourth Thursday of each November. Complete method `thanksDate` that determines the day of the month upon which Thanksgiving falls, no matter which day November begins on. November can begin on any day where `1` represents Monday, through `7`, which represents Sunday. A valid call would be `thanksDate(2)` to indicate the first day of November is Tuesday. `thanksDate` should then return the day of the month upon which Thanksgiving falls, which is 24 (as shown in the calendar below). Arguments can only be `1` (for Monday) through `7` (for Sunday). If the argument is out of the range of `1` through `7`, return `-1`.

```
thanksDate(2) returns 24 // 1-Nov is Tue
thanksDate(5) returns 28 // 1-Nov is Fri
thanksDate(7) returns 26 // 1-Nov is Sun
```

November						
Su	Mo	Tu	We	Th	Fr	Sa
		1	2	3	4	5
6	7	8	9	10	11	12
13	14	15	16	17	18	19
20	21	22	23	24	25	26
27	28	29	30			

5. `bool validDate(string date)`

Write free function `validDate` to return `true` if the `string` argument is a valid calendar date. The arguments always take the form of month, day, and year as positive integers separated by / as in `"mm/dd/yyyy"`. If the `string` argument does not express a proper date, return `false`. You will need the free function `std::stoi(string possibleInt)` (**s**tring **to i**nteger) that returns the integer value of the `string` argument with the precondition that the `string` argument is a valid integer. For example, `str("08")` returns `8` and `str("2021")` returns `2021`.

```
validDate("01/31/2016") returns true
validDate("12/31/2017") returns true
validDate("06/15/2018") returns true
validDate("02/28/2019") returns true
validDate("02/29/2019") returns false
validDate("2019/06/06") returns false
```

6. `int dayNumber(string date)`

Write free function `dayNumber` to return how many days a valid date is into the year. If the `string` argument is not a valid date, return `-1`.

```
dayNumber("01/03/2016") returns 3
dayNumber("12/31/2017") returns 365
dayNumber("12/31/2020") returns 366
dayNumber("13/11/2020") returns -1
```

7C CLASS STUDENT

Given header file `Student.h` below, implement the member functions in a new file named `Student.cpp` for `class Student` such that they satisfy all postconditions in the class definition (shown below). Use this table to satisfy the postconditions of `Student::standing`:

Credits Completed	`string` Return Value
Less than 30 credits	`"Freshman"`
30 credits to less than 60 credits	`"Sophomore"`
60 credits to less than 90 credits	`"Junior"`
90 credits or more	`"Senior"`

```
/*
 * Define a Student type that knows its GPA and class standing.
 *
 * File name: Student.h
 */
#include <string>

class Student {
public:

  Student(std::string initName,
          double initCredits,
          double initQualityPoints);
  // post: Initialize a student with a 3 argument constructor
  // Student s("Ryan", 30.0, 120.0); // Straight A sophomore.

  void completedCourse(double credits,
                       double numericGrade);
  // post: Record a completed course by adding credits to credits
  // and incrementing the qualityPoints by credits*numericGrade.
  // aStudent.completedCourse(4.0, 3.67) is a 4 credit A-

  double getGPA() const;
  // post: return the current grade point average.

  std::string getStanding() const;
  // post: use selection to return the current standing as either
  // Freshman, Sophomore, Junior, or Senior.

  std::string getName() const;
  // post: return the student's name

private:
  std::string name;
  double credits;  // Total credits completed
  double qualityPoints; // sum of credits multiplied by grades
};
```

Implement the methods in `Student.cpp` along with your own test driver. Construct at least four students at the cutoffs for the standings. Make sure you send every possible message to one or more objects.

7D EMPLOYEE OVERTIME PAY AND FEDERAL INCOME TAX

To complete this project, first complete `class Employee` from the Chapter 6 programming projects. This project asks you to make these three changes to the specification in the previous chapter.

1. Now that Chrystal Bends, Inc. has interstate commerce, employees are entitled to 1.5 times their rate of pay for any hours worked over 40.00 in the week. For example, someone working 42 hours a week at $10.00 per hour would have a gross pay of `40 * 10.00 + 2 * 15.00 = 430.00`. Change `getGrossPay` method to allow overtime pay.
2. Add method `getIncomeTax` to compute how much to withhold for this tax on the paycheck.
3. Add two data members, one to store marital status as either `"S"` for single or `"M"` for married and another data member to store the number of withholding allowances such as 1 through 99. Modify the constructor to take in these two new arguments. This code must compile:

```
Employee we("Peyton", 9.70, "S", 2);
cout << we.getIncomeTax() << endl;
```

Fully test your two new methods, especially `getIncomeTax`. No one should be withholding too much from an employee's paycheck. Perhaps more importantly, no one should withhold too little federal income tax per week. Employees might have to pay fines or even go to jail for withholding too little each week. You will need many `getIncomeTax` messages with a lot of categories for both single and married employees. There are 14 total income tax withholding categories for a weekly payroll period, and you are required to use the Percentage Method Tables of IRS Publication 15 (Circular E) Employer's Tax Guide to determine these categories. The percentage method from the IRS Employer's Tax Guide is summarized in the following section:

THE PERCENTAGE METHOD FROM THE IRS EMPLOYER'S TAX GUIDE

Under the percentage method, you will use "TABLE 1—Weekly Payroll Period" for the weekly employee payroll period based on the number of withholding allowances claimed on the Form W-4 and the amount of wages; find the amount of tax to withhold. Use these steps to deterimine the income tax to withhold under the percentage method:

1. Multiply one withholding allowance for your payroll period by the number of allowances the employee claims. One Withholding Allowance = $76.00.
2. Subtract that amount from the employee's gross pay.
3. Determine the amount to withhold from the appropriate table (see table below).

Example: An unmarried employee is paid $600 this week. This employee has a Form W-4 claiming two withholding allowances. Using the percentage method, figure the income tax to withhold as follows:

1.	Total wage payment	$600.00
2.	One allowance	$76.90 (changes year to year)
3.	Allowances claimed on Form W-4	2
4.	Multiply line 2 by line 3	$153.80
5.	Amount subject to withholding (subtract line 4 from line 1)	$446.20
6.	Tax to be withheld on from Table: (2nd row under (a) SINGLE person)	$17.80 + 0.15 × ($446.20 – $222) = $51.43

Note: The table below has the details for amounts to withhold for 2015. For other years, find the IRS Publication 15 for the year in question, (Circular E), Employer's Tax Guide.

TABLE 1—WEEKLY Payroll Period

(a) SINGLE person (including head of household)—				**(b) MARRIED person—**			
If the amount of wages (after subtracting withholding allowances) is:		The amount of income tax to withhold is:		If the amount of wages (after subtracting withholding allowances) is:		The amount of income tax to withhold is:	
Not over $44		$0		Not over $165		$0	
Over—	**But not over—**		**of excess over—**	**Over—**	**But not over—**		**of excess over—**
$44	—$222	$0.00 plus 10%	—$44	$165	—$520	$0.00 plus 10%	—$165
$222	—$764	$17.80 plus 15%	—$222	$520	—$1,606	$35.50 plus 15%	—$520
$764	—$1,789	$99.10 plus 25%	—$764	$1,606	—$3,073	$198.40 plus 25%	—$1,606
$1,789	—$3,685	$355.35 plus 28%	—$1,789	$3,073	—$4,597	$565.15 plus 28%	—$3,073
$3,685	—$7,958	$886.23 plus 33%	—$3,685	$4,597	—$8,079	$991.87 plus 33%	—$4,597
$7,958	—$7,990	$2,296.32 plus 35%	—$7,958	$8,079	—$9,105	$2,140.93 plus 35%	—$8,079
$7,990		$2,307.52 plus 39.6%	—$7,990	$9,105		$2,500.03 plus 39.6%	—$9,105

CHAPTER EIGHT

Repetition

SUMMING UP

Two important control structures have now been discussed—sequence and selection. Sequential control refers to the time when every statement executes—one after another. One of those statements could be a selection statement; in that case, one or more statements may be skipped. Selection executes different actions under different circumstances. Of course, it is your responsibility as a programmer to ensure that the proper actions always occur under the proper circumstances.

COMING UP

Chapter 8 begins a study of repetitive control, the third major control structure. Repetition is discussed within the context of two major algorithmic patterns—the Determinate Loop pattern and the Indeterminate Loop pattern. These two patterns may be implemented with the C++ `for` and `while` statements, respectively. A repetitive control structure executes some actions a specified, predetermined number of times or until some event terminates the loop. After studying this chapter, you will be able to

- recognize and use the Determinate Loop pattern to execute a set of statements a predetermined number of times
- implement determinate loops with the C++ `for` statement
- recognize and use the Indeterminate Loop pattern to execute a set of statements until some event occurs to stop it (no more data, for example)
- implement indeterminate loops with the C++ `while` statement

8.1 REPETITIVE CONTROL

Repetition refers to the repeated execution of a set of statements. Repetition occurs naturally in non-computer algorithms such as these:

- For every name on the attendance roster, call the name. Mark "0" if absent or a checkmark if present.

- Practice the fundamentals of a sport.
- Add the flour ¼ cup at a time, whipping until smooth.

Repetition is also used to express algorithms intended for computer implementation. If something can be done once, it can be done repeatedly. These examples have computer-based applications:

- Process any number of customers at an automated teller machine (ATM).
- Continuously accept reservations.
- While there are more fast food items, sum each item.
- Compute the course grade for every student in a class.
- Microwave the food until either the timer reaches 0, the Cancel button is pressed, or the oven door is opened.

This chapter examines repetitive algorithmic patterns and the C++ statements that implement them. It begins with a statement that executes a collection of actions a fixed, predetermined number of times.

8.1.1 WHY IS REPETITION NEEDED?

Many jobs once performed by hand are now accomplished by computers at a much faster rate. Think of a payroll department with the job of producing employee paychecks. With only a few employees, this task could certainly be done by hand. However, with several thousand employees, a very large payroll department would be necessary to hand compute and generate that many paychecks in a timely fashion. Other situations requiring repetition include, but are certainly not limited to: finding an average, searching through a collection of objects for a particular item, alphabetizing a list of names, and processing all the data in a file. Let's start with the following code that finds the average of exactly three numbers. No repetitive control is present yet.

```
double sum = 0, average, number;
cout << "Enter number: ";  // <- Repeat
cin >> number;             // <- these
sum = sum + number;        // <- statements

cout << "Enter number: ";
cin >> number;
sum = sum + number;

cout << "Enter number: ";
cin >> number;
sum = sum + number;

average = sum / 3.0;
cout << "average = " << average;
```

There is a drawback to this brute-force approach to repetition. Any time a larger or smaller set of numbers needs averaging, the program itself must be modified. It is not general enough to handle input sets of various sizes. Using the previous approach, the three statements would need

to be repeated for every number. This means averaging 100 numbers would require an additional 97 copies of these three statements. Also, the constant `3.0` in `average = sum / 3.0;` would have to be changed to `100.0`. A situation like this is improved with a structure that can execute these three statements over and over again.

8.2 ALGORITHMIC PATTERN: THE DETERMINATE LOOP

Without the selection control structures of the preceding chapter, computers are little more than nonprogrammable calculators. Selection control makes computers more adaptable to varying situations. However, what makes computers even more powerful is their ability to repeat the same actions accurately and very quickly. Two algorithmic patterns emerge. The first involves performing some action a specific, predetermined (known in advance) number of times. For example, to find the average of 142 test grades, repeat some process exactly 142 times. To pay 89 employees, repeat some process 89 times. To produce grade reports for 32,675 students, repeat some process 32,675 times. There is a pattern here.

In each of these examples, the program requires that somehow the exact number of repetitions be predetermined. In these situations, the number of times to repeat the process must be pre-established and constant. One too many or one too few repetitions results in an incorrect algorithm. This pattern of predetermining the number of repetitions and then executing a set of statements precisely that number of times is called the Determinate Loop pattern.

The Determinate Loop Pattern

Pattern: Determinate Loop

Problem: Do something exactly *n* times, where *n* is known in advance.

Algorithm:

```
determine n
repeat the following n times {
    perform these actions
}
```

Code Example:

```
double sum = 0.0;
int n;
double number;

cout << "Enter n: ";
cin >> n;
// do something n times
for (int count = 1; count <= n; count = count + 1) {
  cout << "Enter number: ";  // <- Repeat these
  cin >> number;             // <- statements
  sum = sum + number;        // <- n times
}
```

The Determinate Loop pattern uses an integer—named `n` here—to represent the number of

times the process must repeat. However, other appropriately-named objects certainly are allowed, such as `numberOfEmployees`. So the first thing to do in the Determinate Loop pattern is to determine `n` somehow.

```
n = number of repetitions
```

The number of repetitions may come from keyboard input as in `cin >> n;`. Or `n` may be defined at compile time, `int n = 124;`. Or `n` may be passed as an argument to a function as in `pow(x, n)`. Once `n` is defined, another object—named `count` here—controls the loop iterations. Other appropriately-named objects could be used, `counter` for example. The Determinate Loop pattern is shown next in the context of a small program. It is implemented with the C++ `for` statement.

```
// Determine the average of n inputs. The user must supply n.

#include <iostream>  // For cout, cin, and endl
using namespace std;

int main() {
  int n = 0;         // The number of inputs--supplied by user
  double sum = 0.0;  // Keep running sum
  double number;     // Temporarily store each input
  double average;    // Holds the average for potential future use

  cout << "How many numbers do you need to average? ";
  cin >> n;
  for (int count = 1; count <= n; count = count + 1) {
    cout << "Enter number: ";
    cin >> number;
    sum = sum + number;
  }

  average = sum / n;
  cout << "Average of " << n << " numbers is " << average;

  return 0;
}
```

Dialogue

```
How many numbers do you need to average? 4
Enter number: 70
Enter number: 80
Enter number: 90
Enter number: 100
Average of 4 numbers is 85
```

C++ has several structures for implementing the Determinate Loop pattern. The `for` statement is most frequently used because it combines everything needed after `n` is determined.

8.2.1 THE for STATEMENT

The following `for` statement shows the three components that maintain the Determinate Loop pattern with the C++ `for` statement.

```
int n = 5;  // Predetermined number of iterations
for (int count = 1; count <= n; count = count + 1) {
  // Execute this block n times
}
```

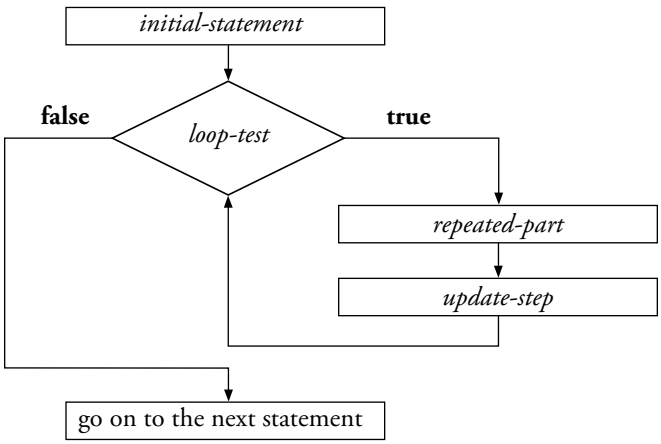
In the preceding `for` loop, `count` is declared and initialized with the value of `1`. Next, `count <= n (1 <= 5)` evaluates to `true` and so the block executes. When the statements inside the block are done, `count` increments by `1 (count = count + 1)`. These three components ensure that the block executes `n` times:

```
count = 1      // Declare and initialize counter
count <= n     // Loop test
count = count + 1  // Update counter
```

General Form 8.1 `for` *statement*

```
for (initial-statement; loop-test; update-step) {
  repeated-statements(s);
}
```

When a `for` loop is encountered, the *initial-statement* is executed first—and only once. The *loop-test* is then checked before each execution of the *repeated-statement(s)*. The *update-step* executes after each iteration of the repeated part. This process continues until the loop test is false. This generalized behavior of a `for` loop is summarized in this flowchart view:



The following `for` statement simply displays the value of the loop counter named `count` as it ranges from `1` through `5` inclusive:

```
int n = 5;
for (int count = 1; count <= n; count = count + 1) {
  cout << count << " ";
}
```

Output

```
1 2 3 4 5
```

Although a block is not necessary to repeat one statement, consider always using a block (`{ }`) with the `for` loop. This practice helps avoid difficult-to-detect intent errors later if you get into the habit of using `{` and `}`.

8.2.2 OTHER INCREMENT AND ASSIGNMENT OPERATORS

Assignment operations alter computer memory even when the object on the left of `=` is also involved in the expression to the right of `=`. For example, the `int` object `count` is updated by +1 with this assignment operation:

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

This type of update—incrementing an object—is used so frequently that C++ offers other, additional incrementing operators. The `++` and `--` operators increment and decrement an object by 1, respectively. For example, the expression `count++;` adds 1 to the value of `count`. The expression `x--` reduces `x` by 1. The `++` and `--` unary operators alter the numeric object that they follow (see the table below).

Statement	State of `count`
`int count = 0;`	`0`
`count++;`	`1`
`count++;`	`2`
`count--;`	`1`

So, within the context of the counting `for` loop, the update step can be written as `count++` rather than `count = count + 1`. The `for` loop

```
for (int count = 1; count <= n; count = count + 1)
  // . . .
```

may now be written as this equivalent loop with the `++` operator used in the update step:

```
for (int count = 1; count <= n; count++)
  // . . .
```

These new assignment operators are shown because they provide a convenient method for accomplishing incrementing and decrementing operations in the `for` loop. Another reason has to do with the fact that most C and C++ programs use the `++` operator in `for` loops.

C++ also has several assignment operators in addition to `=`. Two of them are used to add and subtract value from an object.

Operator	Equivalent Meaning
`+=`	Increment object on left by value on right.
`-=`	Decrement object on left by value on right.

These two new operators alter the numeric object that they follow (see the table below).

Statement	State of `count`
`int count = 0;`	`0`
`count += 3;`	`3`
`count += 4;`	`7`
`count -= 2;`	`5`

Whereas the operators `++` and `--` increment and decrement the object by one, respectively, the operators `+=` and `-=` increment and decrement the object by any amount. The `+=` operator is most often used to accumulate values inside a loop. For example, the following code sums all input by the user:

```
// Demonstrate the summing pattern
#include <iostream>
using namespace std;

int main() {
  int n;
  double aNum;
  double sum = 0.0;  // Maintains running sum, so start at 0.0

  cout << "How many numbers are there to sum? ";
  cin >> n;
  cout << "Enter " << n << " numbers now: ";
  for (int count = 1; count <= n; count++) {
    cin >> aNum;
    sum += aNum;  // Equivalent to sum = sum + aNum;
  }
  cout << "Sum: "  << sum << endl;

  return 0;
}
```

Dialogue

```
How many numbers are there to sum? 4
Enter 4 numbers now: 7.5  3.0  1.5  2.0
```

`for` Loop Iteration	State of `count`	State of `aNum`	State of `sum`
0	0	0.0	0.0
1	1	7.5	7.5
2	2	3.0	10.5
3	3	1.5	12.0
4	4	2.0	14.0

The `+=` and `-=` operators also increment and decrement for the loop counters by values other than 1:

```
for (int count = 0; count <= 10; count += 2) {  // Count by twos
  cout << count << "  ";
}
// Output: 0  2  4  6  8  10
```

SELF-CHECK

8-1 Does a `for` loop evaluate the loop test first?

8-2 Must a `for` loop update step increment the loop counter by + 1?

8-3 Do all `for` loops always execute the repeated part at least once?

8-4 Describe a situation when the loop test `count <= n` of a `for` loop never becomes false.

8-5 Write the output from the following program segments.

a.
```
for (int c = 1; c < 5; c = c + 1) {
  cout << c << " ";
}
```

b.
```
int n = 5;
for (int c = 1; c <= n; c++) {
  cout << c << " ";
}
```

c.
```
int n = 3;
for (int c = -3; c <= n; c += 2) {
  cout << c << " ";
}
```

d.
```
for (int c = 0; c < 5; c++) {
  cout << c << " ";
}
```

e.
```
for (int c = 5; c >= 1; c --) {
  cout << c << " ";
}
```

f.
```
cout << "before" << endl;
int n = 0;
for (int c = 1; c <= n; c++) {
  cout << c << " ";
}
cout << "after" << endl;
```

8-6 Write a `for` loop that displays all the integers from 1 to 100 on separate lines.

8-7 Write a `for` loop that displays all the integers from 10 down to 1.

8.2.3 DETERMINATE LOOPS WITH `Grid` OBJECTS

A `Grid` object has row numbers that range from `0` to `aGrid.nRows()-1` inclusive. The column numbers range from `0` to `aGrid.nColumns()-1` inclusive. Using these facts and the Determinate Loop pattern allows us to manipulate `Grid` objects more compactly. For example, the `blockBorder` function (below) has two `for` loops that block all intersections on all four edges of any `Grid` object.

```
// Use for loops to set blocks around a Grid of any size
#include <iostream>
using namespace std;
#include "Grid.h"  // For the Grid class

void setBorder(Grid & g) {  // Changing g changes the argument
  // pre:  The mover is not on an edge
  // post: The entire outside border is blocked
  int r, c;

  // It is useful that objects know things about themselves--number
  // of rows and columns for example, which vary from Grid to Grid
  for (r = 0; r < g.nRows(); r++) {
    g.block(r, 0);               // Block west edge
    g.block(r, g.nColumns()-1);  // Block east edge
  }

  // The first and last columns are blocked already so block
  // column #1 up to 1 less than the last column
  for (c = 1; c < g.nColumns() - 1; c++) {
    g.block(0, c);            // Block most of the north edge
    g.block(g.nRows()-1, c);  // Block most of the south edge
  }
}

int main() {
  Grid aGrid(8, 10, 1, 1, east);
  Grid anotherGrid(3, 30, 1, 28, west);

  setBorder(aGrid);
  aGrid.display();

  cout << endl;

  setBorder(anotherGrid);
  anotherGrid.display();
  return 0;
}
```

Output

```
The Grid
# # # # # # # # # #
# > . . . . . . . #
# . . . . . . . . #
# . . . . . . . . #
# . . . . . . . . #
# . . . . . . . . #
# . . . . . . . . #
# # # # # # # # # #

The Grid
# # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # #
# . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . < #
# # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # #
```

The `for` loops—applied in yet another instance of the Determinate Loop pattern—reduce the number of instructions. For example, a 20-by-20 `Grid` would require exactly 76 `block` messages. More importantly, such a brute-force approach would allow the function to work only on a 20-by-20 `Grid`. The accessor functions `Grid::nColumns` and `Grid::nRows` and the determinate `for` loop pattern allow the function to work properly for any sized `Grid`. This is because every `Grid` object knows its own size.

SELF-CHECK

8-8 What difference occurs when the first `for` loop in `setBorder` is changed to `for (r = 0; r <= g.nRows(); r++)`?

8-9 What difference occurs when the second `for` loop in `setBorder` is changed to `for (c = 1; c < g.nColumns(); c++)`?

8-10 What difference would occur when the function heading is changed to `void setBorder(Grid g)`?

8.3 APPLICATION OF THE DETERMINATE LOOP PATTERN

Problem: Write a program that determines a range of temperature readings. Range is defined as the difference between the highest and lowest. The user must supply the number of temperature readings first.

In this application, the user is required to enter the total number of temperature readings before entering the actual temperatures. The output must be labeled as `Range` followed by the range of temperatures (23–11 or 12 with this dialogue). The dialogue must look like this:

Dialogue

```
Enter number of temperature readings: 6

Enter temperatures:
11
15
19
23
20
16
Range: 12
```

8.3.1 ANALYSIS

The number of temperature readings will first be obtained from the user. An integer named `n` will serve nicely. Another numeric object is required to hold the individual temperature readings as they are processed. This object could be appropriately named `aTemp`. The range of temperature readings is the difference between the highest and lowest temperature readings in the list, so two more objects are needed to store the highest and lowest.

To find the range without the aid of a computer (easier with a small number of temperature readings), one could glance at the list of numbers and simply keep track of the highest and lowest while scanning the list from top to bottom:

aTemp	highest	lowest
-5	-5	-5
8	8	-5
22	22	-5
-7	22	-7
15	22	-7

For this set of data, the `range = highest - lowest =  22 - (-7) = 29` as shown in this sample problem.

Problem Description	Object Name	Sample Values	Input/Output
Compute the range of temperature readings	`n`	`5`	Input
	`aTemp`	`-5, 8, 22, -7, 15`	Input
	`highest`	`22`	Process
	`lowest`	`-7`	Process
	`range`	`29`	Output

8.3.2 DESIGN

For a large list—an approach more suited to a computer—the algorithm mimics the repetition of the hand-operated version just suggested. It uses a determinate loop to compare every temperature reading in the list to the highest and lowest—updating them if necessary.

Determining the Range Algorithm

```
input the number of temperature readings (n)
for each temperature reading {
    input aTemp from user
    if aTemp is greater than highest so far,
        store it as the highest
    if aTemp is less than lowest so far,
        store it as the lowest
}
range = highest – lowest
```

As usual, it is a good idea to walk through the algorithm to verify its soundness.

1. Input the number of temperature readings (`n == 5`)
2. Input `aTemp` from user (`aTemp == -5`)
3. If `aTemp > highest` so far (`-5 > Whoops!`), store it as `highest`

There is no value for `highest` or `lowest`. Let us now assume the program will initialize `highest` and `lowest` to `0`:

```
lowest = 0;  highest = 0;
```

1. Input the number of temperature readings (`n == 5`)
2. Input `aTemp` from user (`aTemp == -5`)
3. If `aTemp` is greater than highest so far (`-5 > 0`), store it as `highest` (`highest` stays `0`)
4. If `aTemp` is less than lowest so far (`-5 < 0`), store it as `lowest` (`lowest` becomes `-5`)

Well, this seems to work. How about one more iteration?

2. Input `aTemp` from user (`aTemp == 8`)
3. If `aTemp` is greater than highest so far (`8 > 0`), store it as `highest` (`highest` becomes `8`)
4. If aTemp is less than lowest so far (`8 < 0`), store it as lowest (lowest stays `-5`)

Seems okay. Try three more inputs to verify that `highest` and `lowest` are correct. Finally, the last step in the algorithm (after the repetition) produces the range: range = highest - lowest.

SELF-CHECK

8-11 What is the range when `n` is `4` and the temperature readings are `1 2 3 4`?

If you did the previous self-check question correctly, you will notice that lowest stays 0. The initial value of lowest is less than all subsequent inputs. So what might have seemed to work does not. The first test set works only because a negative temperature was input. The same algorithm will not work on a warmer day when all temperatures are positive. So instead of initializing both highest and lowest to `0`, consider setting highest to something ridiculously low, say `-9999`, so low that any input will have to be higher. Set highest to something ridiculously high like `9999`, so high that any input will have to be lower. Better yet, set lowest to the largest integer that is defined in C++ as `INT_MAX`. Also set lowest to the minimum integer that is defined in C++ as `INT_MIN`. You may need to use `#include <climits>`.

```
#include <iostream>
#include <climits>  // for INT_MIN and INT_MAX

int main() {
  std::cout << INT_MIN << std::endl;
  std::cout << INT_MAX << std::endl;
  return 0;
}
```

Output (may vary with different compilers)

```
-2147483648
2147483647
```

8.3.3 IMPLEMENTATION

Since the problem stated that the user must first supply the number of inputs, the exact number of repetitions is determined. This is an instance of the Determinate Loop pattern.

```
for (int count = 1; count <= n; count++) {
  // Process one input
}
```

The following program implements a corrected algorithm (written now in C++ rather than pseudocode). Notice that the user need not input the same set of temperature readings twice—the checks are made for both the highest and the lowest within the same loop.

```
// Determine the range of temperatures in a set of known size

#include <iostream>
#include <climits> // For INT_MIN and INT_MAX
using namespace std;
```

```
int main() {
  int aTemp, n, range;
  int highest = INT_MIN; // All ints will be >= INT_MIN
  int lowest = INT_MAX;  // All ints will be <= INT_MAX

  cout << "Enter number of temperature readings: ";
  cin >> n;

  // Input first temperature to record it as highest and lowest
  cout << "Enter readings 1 per line" << endl;

  // Use a determinate loop to process n temperatures
  for (int count = 1; count <= n; count++) {
    // Get the next input
    cin >> aTemp;

    // Update the highest so far, if necessary
    if (aTemp > highest)
      highest = aTemp;

    // Update the lowest so far, if necessary
    if (aTemp < lowest)
      lowest = aTemp;
  }

  range = highest - lowest;
  cout << "Range: " << range << endl;
  return 0;
}
```

Dialogue

```
Enter number of temperature readings: 5
Enter readings 1 per line
-5
8
22
-7
15
Range: 29
```

8.3.4 TESTING

Programmers gain confidence that a program works by picking an arbitrary number of test cases. The first test case was letting `n` be `5` with readings of ***-5***, ***8***, ***22***, ***-7***, and ***15***. This set of inputs shows the difference between the highest and lowest is (22 – (–7)) or 29. Looking at the dialogue and seeing the range is 29 could lead us to believe that the algorithm and implementation are correct. However, the only thing that is sure is this: when those particular five temperatures were entered, the correct range was displayed. The data used in this previous test would indicate that everything is okay. Other test cases include letting `n` be `1` for a range of 0, two numbers that are the same,

a sequence of all negative integers, a sequence of all positive integers, a sequence in ascending order, and another sequence in descending order.

Testing only reveals the presence of errors, not the absence of errors. If the range were shown as an obviously incorrect answer (-11, for example), hopefully, you would detect the presence of the error. Now consider this slightly different implementation sometimes seen in introductory courses:

```
for (int count = 1; count <= n; count++) {
  cin >> aTemp;
  if (aTemp > highest)
    highest = aTemp;
  else if (aTemp < lowest)
    lowest = aTemp;
}
```

SELF-CHECK

8-12 Trace the code above using the same input (assume `n` is `5`):

```
-5  8  22  -7  15
```

and predict the value stored in `range`. Is it correct?

8-13 Trace through the same code with these inputs (assume `n` is `5`):

```
5  4  3  2  1
```

Predict the value stored in `range`. Is it correct?

8-14 Trace through the same code with these inputs (assume `n` is `3`):

```
1  2  3  4
```

Predict the value stored in `range`. Is it correct?

8-15 *Multiple Choice:* When is `range` incorrectly computed?

a. When the input is entered in descending order.

b. When the input is entered in ascending order.

c. When the input is entered in neither ascending or descending order.

8-16 What must be done to correct the error?

8.3.5 WHAT TO DO WHEN AN INTENT ERROR IS DETECTED

When you detect an intent error and a loop is involved, it is recommended that you display important values, such as `highest` and `lowest`, for each iteration of the loop. This simple debugging tool reveals what is happening and, in so doing, helps the debugging process. A few well-placed output statements can be very revealing. For example, a debugging output statement could be included in the loop that contained the intent error:

```
for (int count = 1; count <= n; count++) {
  cin >> aTemp;
  // Add an output statement in the loop to aid debugging
  cout << highest << "  " << lowest << endl;
  . . .
```

Now the dialogue, while testing the incorrect algorithm just before the preceding self-checks, would look like this:

```
Enter number of temperature readings: 3
Enter readings 1 per line
5
-2147483648  2147483647
7
5  2147483647
12
7  2147483647
Range: -2147483635
```

8.4 ALGORITHMIC PATTERN: THE INDETERMINATE LOOP

Although the Determinate Loop pattern occurs frequently in many algorithms, it has a serious limitation—someone, somehow, must determine the number of repetitions in advance. Quite often this is impossible, or at least very inconvenient and difficult. For example, an instructor may have a different number of tests to average as attendance varies between terms. A company may not have a constant number of employees as there are hires, fires, layoffs, transfers, and retirements. The schools where the software is distributed may have a different number of students each day.

It is often necessary to execute a set of statements an undetermined number of times, for example to process report cards for *every* student in a school—not precisely 310 every term. Programs cannot always depend on prior knowledge to determine the exact number of repetitions. It is often more convenient to think in terms of "process a report card for all students" rather than "process precisely 310 report cards." This leads to another recurring pattern in algorithm design that captures the essence of repeating a process an unknown number of times. It is a pattern to help design a process that iterates until some event occurs to indicate the looping is finished. Here are some events used in this textbook to terminate loops:

- The loop counter becomes greater than the desired number of iterations
- The mover on a Grid can no longer move forward
- The user enters a special value to indicate there is no more input
- The end of the file is reached (see Chapter 9: File Streams)

Whereas the number of repetitions for determinate loops is known in advance, the Indeterminate Loop pattern uses other techniques to stop. With indeterminate loops, the number of repetitions need not be known in advance.

The Indeterminate Loop Pattern

Pattern: Indeterminate Loop

Problem: Some process must repeat an unknown number of times so some event is needed to terminate the loop.

Algorithm:

```
while (the termination event has not occurred) {
   perform these actions
   do something to bring loop closer to termination
}
```

Code Example:

```
// Place things until the mover is blocked
while (aGrid.frontIsClear()) {
  aGrid.putDown();
  aGrid.move();
}
```

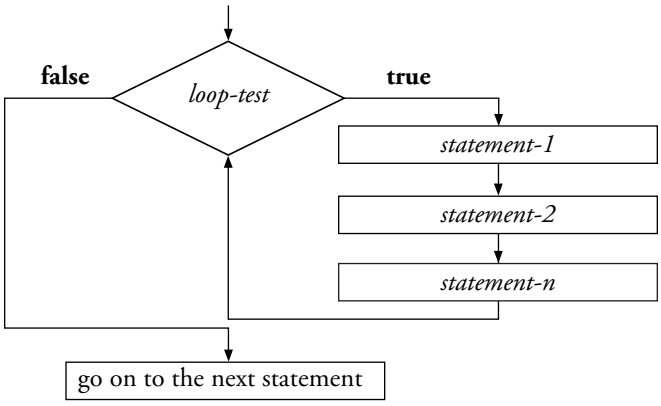
The C++ `while` statement is often used to implement the Indeterminate Loop pattern:

General Form 8.2 `while` *statement*

```
while (loop-test) {
    repeated-statements
}
```

The *loop-test* is a logical expression that evaluates to either true or false. The *repeated-statement(s)* may be any C++ statement, but it is usually a set of statements enclosed in `{` and `}`.

When a `while` loop is encountered, the loop test evaluates to either true or false. If true, the repeated part executes. This process continues while (as long as) the loop test is true.



8.4.1 THE USE OF `while` TO IMPLEMENT THE DETERMINATE LOOP PATTERN

The `while` loop could also implement the Determinate Loop pattern. It is simply a matter of moving the initialization before the `while` loop and the update step to the bottom of the repeated part.

```
// initialization
while ( loop-test ) {
  // Activities to be repeated
  update-step
}
```

The following code represents an alternate implementation of the determinate loop pattern:

```
// Sum the first n integers
int accumulator = 0;
int count = 1;                          // Initialization
int n = 5;                              // Initialization
while (count <= n) {                    // Loop test
  accumulator = accumulator + count ;   // Action
  count++;                              // Update step
}

cout << "Sum of the first " << n << " integers is " << accumulator;
```

Although the `while` loop can also be used for determinate loops, the `for` loop is more concise and convenient. It is recommended that you use the `for` loop when the number of iterations is known in advance. When this cannot be determined, as with indeterminate loop problems, use the `while` statement instead.

8.4.2 INDETERMINATE LOOP PATTERN WITH `Grid` OBJECTS

There are many events used to terminate the loop in an Indeterminate Loop pattern. Consider moving the mover up until the edge of a `Grid`, or perhaps a block, prevents the mover from continuing—a subproblem that will come in very handy for one of the `Grid`-related programming projects.

```
// The event loop terminates when the front is no longer clear
#include <iostream>   // For cout
using namespace std;  // allow cout instead of std::cout
#include "Grid.h"     // For the Grid class

void moveTillStopped(Grid & g) {
  // post: The mover is facing a block or edge in front
  while (g.frontIsClear()) {
    g.move();
  }
}

int main() {
  Grid tarpit(5, 10);
```

```
    cout << "When initialized with only the number of rows\n"
         << "and columns, a Grid object gets a random opening\n"
         << "with the mover at a random location and direction\n"
         << endl;

    moveTillStopped(tarpit);
    tarpit.display();

    return 0;
}
```

Dialogue

```
When initialized with only the number of rows
and columns, a Grid object gets a random opening
with the mover at a random location and direction

The Grid
# # # # # # # # # #
. . . . . . . . . #
# . . .         > #
# . . . . . . . . #
# # # # # # # # # #
```

Because of the randomness of the `Grid` object `tarpit`, `moveTillStopped` uses an indeterminate loop to advance the mover. The `g.move()` message may repeat the move message once, twice, or as many times as necessary to get the mover up against the "wall."

SELF-CHECK

8-17 Why must `moveTillStopped` use an Indeterminate Loop rather than a Determinate Loop pattern?

8.4.3 THE INDETERMINATE LOOP USING A SENTINEL

A *sentinel* is a specific input used to terminate an indeterminate loop. A sentinel value should be the same class of data as the other input. However, the sentinel is not meant to be processed as a valid part of the input. For example, the following set of inputs hints that the input of -1.0 is the event that terminates the loop and that -1.0 is not to be counted as a valid test score. Otherwise, the average would not be 80.0.

Dialogue

```
Enter tests scores [0.0 through 100.0] or -1.0 to quit
80.0
90.0
70.0
```

```
-1.0
Average of 3 tests = 80
```

This dialogue asks the user either to enter data in the range of 0.0 through 100.0 inclusive or to enter -1.0 to signal the end of data.

With sentinel indeterminate loops, a message is usually displayed to indicate how the user must end the input. It is important to inform the user that a sentinel is being used. The user must be told what that sentinel value is. It could have been -999 or any other negative number, for example.

8.4.4 USING `cin >>` AS A LOOP TEST

Up to this point, `cin >>` has often been used for input. What hasn't been revealed is this: a `cin` statement returns true when it is successful. If the input operation fails to get a number, `cin >>` is replaced with `false`. This means that a `cin >>` statement can be, and often is, used as the logical expression in an `if...else` or `while` statement:

```
if (cin >> intObject)     - or -      while (cin >> intObject)
```

Both of the above logical expressions return `true` when `cin` successfully extracts a valid integer from the input stream. However, the same logical expressions return `false` if an invalid integer is encountered in the input stream or, as shown later, the end of file is found.

With this new information, implementation of sentinel loops is simplified when the `cin` extraction is part of the loop test.

```
// The priming extraction is now part of the loop test
while ((cin >> testScore) && (testScore != sentinel)) {
  accumulator = accumulator + testScore;  // Update accumulator
  n++;                                    // Update total inputs
}
```

The actual return value of the input statement `cin >> testScore` isn't all that important. However, because `cin >> testScore` is guaranteed to execute first, `testScore` is guaranteed to have obtained a valid numeric value through keyboard input before it is compared to the sentinel. The second part `(testScore != sentinel)` evaluates to `true` *only* if the input was the sentinel (`-1.0` in this case). So for any valid data, this loop test is `true && true`, which evaluates to `true`. In this case, the loop executes the repeated part. For example, the loop test is evaluated like this when `95.0` is entered:

Loop Test Evaluation When Input Is 95.0

```
while ((cin >> testScore) &&  (testScore != sentinel))
      (     true          &&  (   95.0   !=   -1.0  ))
      (     true          &&           true         )
                         true
```

The loop test is `true` only if a valid number is input and that number is not `-1.0`. With `95.0`, the loop test is `true` (`true && true` is `true`). When the sentinel of `-1.0` is entered, the loop test is `false` (`true && false` is false)—the termination condition is reached.

Loop Test Evaluation When Input Is -1.0 (or -1)

```
while ((cin >> testScore) && (testScore != sentinel))
      (     true          && (   -1.0   !=    -1.0 ))
            true          &&           false
                         false
```

This loop test is now placed into the context of a program that computes the average of any number of inputs:

```
// Use a sentinel of -1 to terminate a loop
#include <iostream>
using namespace std;

int main() {
  const double sentinel = -1.0;  // User enters this to terminate
  double accumulator = 0.0;      // Maintain running sum of inputs
  int n = 0;                     // Maintain total number of inputs
  double testScore, average;

  // Prompt
  cout << "Enter test scores [0.0 through 100.0] or " << sentinel
       << " to quit" << endl;

  // Input and process at the same time
   while ((cin >> testScore) && (testScore != sentinel)) {
     accumulator += testScore;  // Update accumulator
     n++;                       // Update total inputs
   }

  if (n > 0) {
    average = accumulator / n;
    cout << "Average of " << n << " tests = " << average << endl;
  }
  else
    cout << "Can't average 0 numbers" << endl;
  return 0;
}
```

Dialogue

```
Enter test scores [0.0 through 100.0] or -1.0 to quit
80.0
90.0
70.0
-1.0
Average of 3 tests = 80
```

The following table traces the changing state of the important objects to simulate execution of the previous program. In addition to keeping the running sum of the test scores in `accumulator`, `n` must also be incremented by 1 for each valid `testScore`.

Iteration	`testScore`	`accumulator`	`n`	`testScore != sentinelNumber`
Before the loop	NA	`0.0`	`0`	NA
Loop 1	`70.0`	`70.0`	`1`	`true`
Loop 2	`90.0`	`160.0`	`2`	`true`
Loop 3	`80.0`	`240.0`	`3`	`true`
After the loop	NA	`240.0`	`3`	NA

SELF-CHECK

8-18 Determine the average for each of the following code fragments by simulating execution when the user inputs ***`70.0`***, ***`90.0`***, ***`80.0`***, ***`-1`***.

a.
```
cin >> testScore;
while (testScore != sentinel) {
  cin >> testScore;
  accumulator += testScore;  // Update accumulator
  n++;                       // Update total inputs
}
average = accumulator / n;   // Division by 0 possible
```

b.
```
cin >> testScore;
while (testScore != sentinel) {
  accumulator += testScore;  // Update accumulator
  n++;                       // Update total inputs
  cin >> testScore;
}
average = accumulator / n;   // Division by 0 possible
```

8-19 If you answered `80.0` for both a and b above, redo both until you get different answers.

8-20 Which code (a or b) is equivalent to the previous complete program where the loop test is `while ((cin >> testScore) && (testScore != sentinel))`?

8.4.5 INFINITE LOOPS

It is possible that a loop may never execute, not even once. It is also possible that a `while` loop will never terminate. Consider the following `while` loop that potentially continues to execute until external forces are applied (turning off the computer or a hardware failure, for example). This is potentially an *infinite loop*, something that is usually undesirable.

```
cin >> testScore;
while (testScore != sentinel) {
  accumulator += testScore;  // Update accumulator
  n++;                       // Update total inputs
}
```

The loop repeats virtually forever. The termination condition can never be reached. The loop test is always true because there is no statement in the repeated part that brings the loop closer to the termination condition of `testScore == sentinel`. When writing `while` loops, remember to ensure that the loop test will eventually become false.

When you do get a program that executes a loop over and over again—and you will—use the system-dependent method necessary to terminate the program that is executing the infinite loop (ask your instructor).

SELF-CHECK

8-21 How many iterations of the previous loop occur when the user enters the sentinel (-1.0) as the very first input?

8-22 What activity should be added to the previous `while` statement so each loop iteration brings the loop one step closer to termination?

8-23 The following code represents another example of an infinite loop. What must be done to make this loop terminate as intended?

```
while (g.frontIsClear());
{
  g.move();
}
```

8-24 Write the output from the following C++ program fragments:

a.
```
int n = 3;
int counter = 1;
while (counter <= n) {
  cout << counter << "  ";
  counter++;
}
```

b.
```
int last = 10;
int count = 2;
while (count <= last) {
  cout << count << "  ";
  count += 2;
}
```

8-25 Write the number of times `count` is output. Assume `count`, `sum`, and `n` have been declared as `int` objects. "Zero," "infinite," and "unknown" are valid answers.

a.
```
while (count <= n) {
  cout << count<< endl;
}
```

b.
```
n = 5;
count = 1;
while (count <= n)
  cout << count << endl;
  count++;
```

c.
```
count = 1;
n = 0;
while (count <= n)
  cout << " " << count;
```

d.
```
count = 1;
sum = 0;
while (count <= 5) {
  sum += count;
  sum++;
}
```

e.
```
count = 1;
n = 5;
while (count <= n) {
  count++;
}
```

f.
```
count = 10;
while (count >= 0);
{
  count = count - 2;
}
```

8-26 Write a code fragment that sums all integers until the user enters 999.

8.5 THE `do while` STATEMENT

The `do while` statement is similar to the `while` loop. It allows a collection of statements to be repeated while an expression is true. The primary difference is the time at which the loop test is evaluated. The `while` loop test is evaluated at the beginning of each iteration. The `do while` statement evaluates the loop test at the end of each iteration. This means that the `do while` loop always executes its repeated part at least once.

General Form 8.3 `do while` *loop*

```
do {
  repeated-statement(s)
} while ( loop-test ) ;
```

When a `do while` statement is encountered, all statements within the block (`{ }`) execute. The *loop-test* is evaluated at the *end* of the loop—not at the beginning. If true, the *repeated-statement(s)* executes again. If the test expression is false, the loop terminates. Although the block is not absolutely required with the `while` and `for` statements, braces must always exist between the `do` and the `while` in this statement. Here is an example of the `do while` loop that displays the increasing value of `counter` to simulate its execution.

```
int counter = 1;
int n = 4;
cout << endl << "Before loop..." << endl;
do {
  cout << "Loop #" << counter << endl;
  counter++;
} while (counter <= n);
cout << "...After loop" << endl;
```

Output

```
Before loop...
Loop #1
Loop #2
Loop #3
Loop #4
...After loop
```

The `do while` loop is a good choice for repetition whenever a set of statements must be executed at least once to initialize objects used later in the loop test. For example, the `do while` loop is the preferred statement when asking the user to enter one of several options. For example, the `do while` loop in the `char` type function `nextOption` repeatedly requests the user to enter one of three choices. The loop does not terminate until the user enters a valid option. `main` also uses a `do while` loop to process as many deposits and withdrawals as the user wants.

```
// Use a do while loop that repeatedly asks for a valid option
#include <cctype>   // For toupper
#include <iostream>  // For cout, cin, and endl
#include <string>
using namespace std;

char nextOption() {
  // post: Return an uppercase W, D, or Q
  string option;
  char firstChar;
  do {
    cout << "W)ithdraw, D)eposit, or Q)uit: ";
    cin >> option;
    firstChar = toupper(option.at(0));
  } while ((firstChar != 'W') && (firstChar != 'D') && (firstChar != 'Q'));
  return firstChar;
}

int main() {
  char choice = 'Q';

  do {
    choice = nextOption();
    // assert: choice is either 'Q', 'W', or 'D'

    if ('W' == choice)
      cout << "\nValid entry--process W\n" << endl;
```

```
    if ('D' == choice)
      cout << "\nValid entry--process D\n" << endl;

    if ('Q' == choice)
      cout << "\nHave a nice day :)" << endl;

  } while (choice != 'Q');

  return 0;
}
```

Dialogue (the user enters one valid entry, three invalid choices, and quits with Q)

```
W)ithdraw, D)eposit, or Q)uit: W

Valid entry--process W

W)ithdraw, D)eposit, or Q)uit: make
W)ithdraw, D)eposit, or Q)uit: 3
W)ithdraw, D)eposit, or Q)uit: invalid entries

W)ithdraw, D)eposit, or Q)uit: Q

Have a nice day :)
```

Because at least one character must be obtained from the keyboard before the test expression evaluates, the `do while` loop in `nextOption` is used instead of a `while` loop—the loop must iterate at least once. Also, a `do while` loop is used in `main` to get an option because it needs at least one user input to evaluate whether or not the user wants to quit. Although `do while` is not necessary, it is a bit easier to implement than using a `while` loop.

```
cout << "W)ithdraw, D)eposit, or Q)uit: ";
cin >> option;
firstChar = toupper(option.at(0));
while ((firstChar != 'W') && (firstChar != 'D') && (firstChar != 'Q')) {
  cout << "W)ithdraw, D)eposit, or Q)uit: ";
  cin >> option;
  firstChar = toupper(option.at(0));
}
```

SELF-CHECK

8-27 Write the output produced by the following code:

a.
```
int count = 1;
do {
  cout << count << endl;
  count++;
} while (count <= 3);
```

b.
```
double x = -1.0;
do {
  cout << x << endl;
  x = x + 0.5;
} while (x <= 1.0);
```

8-28 Write a `do while` loop that prompts for and reads numbers until the number is in the range of 1 through 10 inclusive.

8-29 Write a `do while` loop that prompts for and then reads characters until the user enters `w`, `W`, `d`, `D`, `q`, or `Q` at the prompt `Enter W)ithdraw D)eposit Q)uit:`.

8.6 LOOP SELECTION AND DESIGN

For some people, loops are easy to implement, even at first. For others, infinite loops and intent errors are more common. In either case, the following outline is offered to help you choose and design loops in a variety of situations:

1. Determine which type of loop to use
2. Determine the loop test
3. Write the statements to be repeated
4. Bring the loop one step closer to termination
5. Initialize objects if necessary

8.6.1 DETERMINE WHICH TYPE OF LOOP TO USE

If the number of repetitions is known in advance or read as input, use the Determinate Loop pattern, which has a statement specifically designed for this—the `for` loop. Although you can use the `while` loop to implement the Determinate Loop pattern, consider using the `for` loop instead. The `while` implementation allows you to omit one of the key counting parts, making any intent errors more difficult to detect and correct. If you omit one of the counting parts of a `for` loop, you'll get an easy-to-detect-and-correct compile time error.

If you need to wait until some event occurs during execution of the loop, the Indeterminate Loop pattern is more appropriate. If so, use the `while` loop. If the loop must always execute once, for example when input data must be checked for validity (an integer value that must be in the range of 0 through 100), use the `do while` loop. A `do while` loop is also a good choice for menu-driven programs that repeatedly request options until the menu choice for *quit* is entered.

8.6.2 DETERMINE THE LOOP TEST

If the loop test is not obvious, try writing the conditions that must be true for the loop to terminate. For example, if you want the user to enter `STOP` to stop entering input, the termination condition is:

```
inputName == "STOP";  // Termination condition
```

The logical negation `inputName != "STOP"` can be used directly as the loop test of a `while` or `do while` loop.

```
while (inputName != "STOP") {
  // . . .
}
```

```
do {
  // . . .
} while (inputName != "STOP")
```

8.6.3 WRITE THE STATEMENTS TO BE REPEATED

This is why the loop is being written in the first place. Some common tasks include keeping a running sum, keeping track of a high or low value, or counting the number of occurrences of some value. Other tasks that will be seen later include searching for a name in a list or repeatedly comparing all `string` elements of a list in order to alphabetize it.

8.6.4 BRING THE LOOP ONE STEP CLOSER TO TERMINATION

To avoid an infinite loop, at least one action in the loop body must bring it closer to termination. In a determinate loop, this might mean incrementing or decrementing a counter by some specific value. Inputting the next value is another way to bring loops closer to termination—for example, when the user inputs data until the sentinel is extracted from the input stream. In a `for` loop, the repeated statement should be designed to bring the loop closer to termination, usually by incrementing the counter. In general, the loop test should contain at least one object that is altered during each iteration of the loop.

8.6.5 INITIALIZE OBJECTS IF NECESSARY

Check to see if any objects used in either the body of the loop or the loop test need to be initialized. Doing this usually ensures that the objects of the loop and the objects used in the iterative part have been initialized. For example, consider this loop:

```
double sum, x, average;
int n;

cout << "Enter numbers or -1 to stop: ";
while (x != -1) {
  sum = sum + x;
  n++;
  cin >> x;
}
average = sum / n;
```

With this code, the values of `sum`, `average`, `x`, and `n` are garbage. What is the initial value of `sum`, perhaps -1,234.5 or 99,999.9? The first value of `x` is unknown, as is that of `n`. Consider each object in the loop test and the iterative part as potential candidates for initialization. This may require setting `n` to `0`, but it may also require that some object becomes initialized through the input statement. Here is the corrected code:

```
double sum = 0.0;
int n = 0;
double x, average;  // x and average don't require initialization
cout << "Enter numbers or -1 to stop: ";
cin >> x;
while (x != -1) {
  sum += x;
  n++;
  cin >> x;
}
average = sum / n;
```

SELF-CHECK

8-30 Which loop best accomplishes these tasks?

a. Sum the first five integers (1 + 2 + 3 + 4 + 5).

b. Find the average value for a set of numbers when the size of the set is known.

c. Find the average value for a set of numbers when the size of the set cannot be determined by the program or the user until the data has been completely entered.

d. Obtain a character from the user that must be an uppercase I, S, or Q.

8-31 For a loop to process inputs called `value` until `-1` is entered:

a. Write a termination condition.

b. Write the loop test for a `while` or `do while` loop.

8-32 For each loop, which objects are not initialized but should be?

a.
```
while (count <= n) {
  // . . . ;
}
```

b.
```
for (int count = 1; count <= n; count = count + inc) {
  // . . . ;
}
```

CHAPTER SUMMARY

- Repetition is an important method of control for all programming languages. Typically, the body of a loop has statements that may change the state of one or more objects during each loop iteration.
- The `for` loop is often used to implement the Determinate Loop pattern, which requires that the number of repetitions be determined *before* the loop is encountered.
- Determinate loops rely on this value (`n` perhaps) and a properly initialized and incremented loop counter (`count` perhaps) to track the number of repetitions. The counter is compared

to the known number of iterations at the start of each loop. The counter is automatically updated at the end of each `for` loop iteration.

- There are a number of ways to determine the number of loop iterations before the loop executes. The number of iterations may be input from the user, passed as an argument to a function, initialized in advance, or `n` may be part of the state of some object. For example, every `Grid` object knows its number of rows and number of columns. Every `string` object knows how many characters it has at any given moment.
- This Determinate Loop pattern is so common that a specific statement—the `for` loop—is built into almost all languages.
- Indeterminate loops rely on some external event for their termination. The terminating event may occur at any time.
- Indeterminate loops are used when the program is unable to determine, in advance, the number of times a loop must iterate. The terminating events include sentinels extracted from the input stream (-1 as a test or "Q" in a menu selection). These types of loops allow any number of bank customers to make any number of transactions or repeatedly prompt a user for input until valid input is entered.
- Although the `while` loop is the only repetitive statement needed to solve any computer problem, the `for` loop is more convenient under certain circumstances. The `for` loop requires the program to take care of the initialization, loop test, and repeated statement all at once. The compiler protests if one of these important steps is missing. The `for` loop provides a more compact and less error-prone determinate loop.
- Remember these steps if you are having trouble designing loops:
    - Determine which type of loop to use
    - Determine the loop test
    - Write the statements to be repeated
    - Bring the loop one step closer to termination
    - Initialize objects if necessary

EXERCISES

1. How many times will the following loops execute `cout << "Hello ";`? "Zero," "unknown," and "infinite" are perfectly legitimate answers.

    a.
    ```
    int n = 5;
    for (int count = 1; count <= n; count++) {
      cout << "Hello ";
    }
    ```

    b.
    ```
    int n = 0;
    for (int count = 5; count >= n; count --) {
      cout << "Hello ";
    }
    ```

c.
```
int n = 5;
for (int count = 1; count <= n; count --) {
  cout << "Hello ";
  count++;
}
```

d.
```
int n = 0;
for (int count = 1; count <= n; count++) {
  cout << "Hello ";
}
```

2. Write the output produced by these `for` loops:

```
for (int counter = 1; counter <= 5; counter++)
  cout << "  " << counter;
  cout << "Loop One";  // Incorrectly indented to confuse
for (int counter = 10; counter >= 1; counter--)
   cout << "  " << counter;
cout << "Blast Off";  // Correctly indented to avoid confusion
```

3. Write loops to produce the outputs shown:

a. `10  9  8  7  6  5  4  3  2  1  0`

b. `0  5  10  15  20  25  30  35  40  45  50`

c. `-1000 -900 -800 -700 -600 -500 -400 -300 -200 -100 0`

4. Write the output generated by the following code:

```
int count = 0;
while (count < 5) {
  cout << "  " << count ;
  count = count + 1;
}
```

5. Write a loop that sums all the integers between `start` and `stop` inclusive that are input from the keyboard. You may assume `start` is always less than or equal to `stop`. If the input were `5` for `start` and `10` for `stop`, the sum would be 5 + 6 + 7 + 8 + 9 + 10 (45).

6. How many times will `Hello` be displayed using the following program segments? "Zero," "undetermined," and "infinite" are perfectly legitimate answers.

a.
```
while (count <= 10)
  cout << "Hello";
```

b.
```
count = 1;
while (count <= 7) {
  cout << "Hello";
  count++;
}
```

c.
```
count = 7;
while (count <= 1) {
  cout << "Hello";
```

```
    }
```

d.
```
count = 1;
while (count <= 5)
  cout << "Hello";
  count++;
```

7. Write a `while` loop that produces this output:

```
-4  -3  -2  -1   0   1   2   3   4   5   6
```

8. Write a `while` loop that displays `100, 95, . . ., 5, 0` on separate lines.

9. Write a loop that counts how many perfect scores (the number 100) are entered from the keyboard.

10. Convert the following code to its `for` loop counterpart:

```
int counter = 1;
double sum = 0;
int n, number;

cout << "Enter number of ints to be summed: ";
cin >> n;
while (counter <= n) {
  cin >> number;
  sum = sum + number;
  counter++;
}
cout << sum;
```

11. Write a loop that counts the number of words input by a user until the user enters the `string ENDOFDATA` (must be uppercase letters, no spaces).

12. Write the complete output generated by the following program when the user enters `1`, `2`, `3`, `4`, and `-1` on separate lines.

```
#include <iostream>
using namespace std;

int main() {
  double test;
  double sum = 0.0;
  cout << "Enter tests or a negative number to stop: " << endl;
  while ((cin >> test) && (test >= 0.0)) {
    sum = sum + test;
  }
  cout << "Sum: " << sum << endl;
}
```

13. Write the output generated by the following code:

```
string choice("BDWBQDW");
int count = 0;
while (choice[count ] != 'Q') {
```

```
  cout << "Opt: " << choice[count ] << endl;
  count++;
}
```

14. How many times will the following loops execute `cout << "Hello ";`? "Zero," "unknown," and "infinite" are perfectly legitimate answers.

a.
```
count = 1;
n = 10;
do {
  cout << "Hello ";
} while (count > n);
```

b.
```
n = 10;
count = 1;
do {
  cout << "Hello ";
  count = count - 2;
} while (count <= n);
```

c.
```
count = -1;
do {
  cout << "Hello ";
  count++;
} while (count != -3);
```

d.
```
count = 1;
do {
  cout << "Hello ";
  count++;
} while (count <= 100);
```

15. Write a `do while` loop that generates this output:

```
10  9  8  7  6  5  4  3  2  1  0
```

16. Write the output generated by the following program:

```
#include <iostream>
using namespace std;

int main() {
  int count = -2;
  do {
    cout << "   " << count;
    count--;
  } while (count > -6);
}
```

17. Convert the following code to its `do while` counterpart:

```
char option;
cout << "Enter option A, B, or Q: ";
cin >> option;
option = toupper(option);
while ((option != 'A') && (option != 'B') && (option != 'Q')) {
  cout << "Enter option A, B, or Q: ";
  cin >> option;
  option = toupper(option);
}
```

18. Write a function named `option` that prompts for and returns an uppercase S, A, M, or Q only. The return type of the `option` function must be `char`. Return S, A, M, or Q through the function name, not as a reference. The following code must only assign one of four allowed letters to `choice`:

```
char choice = option();
cout << choice;  // Output must be either S, A, M, or Q only!
```

PROGRAMMING TIPS

1. Pick the type of loop you want to use. After recognizing the need for repetition, decide if the number of repetitions can be determined in advance. If so, this is a determinate loop that is best implemented as a `for` loop. If the number of iterations cannot be determined in advance, first determine the event that will terminate the loop. Use its logical negation as the loop test. For example, the loop will terminate when someone enters the word `STOP`. The termination condition is `(word == "STOP")`. The loop test is the logical negation `while (word != "STOP")`.

2. Beware of infinite loops. They are easy to create and sometimes very difficult to find. Can you spot why these are infinite loops?

   a.
   ```
   int count = 1;
   int sum = 0;
   while (count <= 100);
   { // Sum the first 100 integers
     sum += count ;
     count++;
   }
   ```

   b.
   ```
   for (int count = 0; count <=
   100; count++);
   { // Sum the first 100 integers
     sum += count ;
   }
   ```

   c.
   ```
   int count = 1;
   int sum = 0;
   while (count <= 100)
      // Sum the first 100 integers
      sum += count ;
      count++;
   ```

   d.
   ```
   for (int count = 0; count <= 100;
   count++) {
     // Sum the first 100 integers
     sum += count ;
     count --;
   }
   ```

3. Always write a compound statement for the iterative part of a `while` loop even if it is not necessary. This provides a better chance of including any increment statement as part of the loop rather than accidentally leaving it outside the loop.

4. Use debugging prints to find out what is going on in a loop. When in doubt, place a debugging `cout` statement inside the loop to display some important object that should be changing. This can be very revealing. Sometimes you'll spot an infinite loop. Other times you might spot that the loop test was never true.

   ```
   while ( . . . ) {
     // . . .
     mid = (lo + hi) / 2.0;
     cout << "In loop, mid == " << mid << endl;
   }
   ```

5. Loops may not always execute the iterative part. It is possible that a loop will execute zero times, or fewer than you might have thought.

6. Things become much simpler when the input statement is part of an indeterminate loop test. If you are used to a priming read for sentinel loops—especially you Pascal programmers—try to forget it. C++ allows input as part of the loop test, so it is easier to write sentinel loop tests like this:

```
while ((cin >> aNumber) && (aNumber != sentinel)) {
  // Process aNumber but not the sentinel
}
```

7. Sometimes a "quasi-infinite" loop with a break is the easiest way to implement a loop. If you are having trouble with loop tests, consider using a loop with a guarded break (this code is equivalent to the previous sentinel loop):

```
while ( true ) {
   cin >> aNumber;
   if (aNumber == sentinel) // The termination condition
      break;                // Exit this loop
   // Otherwise process aNumber
}
```

PROGRAMMING PROJECTS

8A WIND SPEED RECORDING

Write a program that determines the lowest, highest, average, and range of a set of wind speed readings which are all positive or zero. Terminate the loop with any negative input. Be sure you notify the user how to terminate data entry.

Dialogue

```
Enter wind speed readings or a number < 0 to quit:
5.0
6.0
2.0
8.0
-999
    n: 4
 High: 8
  Low: 2
Range: 6
  Ave: 5.25
```

8B BANK TELLER

Write a C++ program that allows the user to create exactly one `BankAccount` object and then make as many withdrawals and deposits as desired. The final line of output should be the balance.

Your code should not allow a withdrawal greater than the balance. Use the following dialogue as a guide to this problem's specification:

```
Enter customer name: Jackson
Enter initial balance: 0.00

W)ithdraw, D)eposit, or Q)uit: D
Enter deposit amount: 250.00

W)ithdraw, D)eposit, or Q)uit: W
Enter withdrawal amount: 300.00
**Amount requested exceeds account balance**

W)ithdraw, D)eposit, or Q)uit: w
Enter withdrawal amount: 200.00

W)ithdraw, D)eposit, or Q)uit: q
Ending balance: 50
```

8C FIND THE `Grid` EXIT

Write a C++ function named `findExit` that instructs the mover to find the lone exit in any `Grid`. Make sure you initialize the `Grid` object with only two arguments—number of rows and number of columns. This ensures that you will get a `Grid` that has only one exit. Also, the mover will be at a random location facing a random direction every time you run the program. This will help you test your solution. Use the following test driver:

```
#include "Grid.h"  // For the Grid class

void findExit(Grid & g) {
  // pre:  The Grid has exactly one exit, but not at a corner
  // post: The mover is located at the lone exit

  // You complete the function here

}

int main() {
   // Test drive findExit
   Grid tarpit(10, 16);
   // assert: The 10-by-16 Grid has the mover in a random location

   tarpit.display();
   findExit(tarpit);
   tarpit.display();

   return 0;
}
```

Output

```
The Grid:
# # # # # # # # # # # # # # # # #
#                               #
#   . . . . . . . . . . . .     #
#   . . . . . . . . . . . .     #
#   . . . . . . . . .           #
#   . . . . . . . . . . . . . . #
<   . . . . . . . . . . . . . . #
# . . . . . . . . . . . . . . . #
# . . . . . . . . . . . . . . . #
# # # # # # # # # # # # # # # # #
```

8D A HALF-DOZEN FUNCTIONS WITH LOOPS

Write one C++ program where your main method is a test driver of your own design that tests six new free functions implemented in the same file. You may write your own tests with `assert` functions.

```
/*
 * A test driver like this may be used to test the functions.
 *
 * File name: TestRepetitionFunctions (on the book's website)
 */
int main() {
  // Test firstNints
  assert(15 == firstNints(5));
  assert(21 == firstNints(6));
```

1. `int firstNints(int n)`

   Given an integer argument that represents the number of integers to sum, return the sum of the first `n` integers. Use a `for` loop. Do not use a formula. Assume the argument is always positive.

   ```
   firstNints(1) returns 1
   firstNints(2) returns 3, which is 1+2
   firstNints(5) returns 15, which is 1+2+3+4+5
   ```

2. `int factorial(int n)`

   Return `n` factorial, which is written as `n!`. `5! = 5*4*3*2*1` or in general, `n! = n*(n-1)*(n-2) …*2*1`. Use a `for` loop.

   ```
   factorial(1) returns 1
   factorial(2) returns 2, which is 2 * 1
   ```

```
factorial(4) returns 24, which is 4 * 3 * 2 * 1
```

3. `string reverseString(string arg)`

   Return a new string that has `arg`'s characters in reverse order.

```
reverseString("") returns ""
reverseString("1") returns "1"
reverseString("1234") returns "4321"
```

4. `int charPairs(string str)`

   Return the number of times two consecutive characters occur in the given string.

```
charPairs("") returns 0
charPairs("H") returns 0
charPairs("aabbcc") returns 3
charPairs("!!!") returns 2
charPairs("mmmm") returns 3
charPairs("mmOmm") returns 2
```

5. `int fibonacci(int n)`

   Return the correct Fibonacci number for the given argument. `precondition: n >= 0`. (*Hint:* Keep track of two consecutive Fibonacci numbers.)

n	fibonacci(n)	n	fibonacci(n)
0	0	5	5
1	1	6	8
2	1	7	13
3	2	8	21
4	3	9	34

6. `void replace(string & str, char oldC, char newC)`

   Modify the string argument associated with the parameter `str` so that all occurences of `oldC` are replaced with `newC`.

```
string arg = "bookkeeper";
replace(arg, 'e', 'X');
assert("bookkXXpXr" == arg);
```

8E MASTERMIND

In this project, you are going to implement a number guessing game known as Mastermind. This assignment will give you more experience with:

- Strings
- User input
- `if` statements
- `while` statements
- Testing
- Problem solving

To first give you an overall feeling for the finished game, we first present a dialog to show how the game will be played. Assuming your program has generated a "secret" number that has five unique digits, the game should prompt the player to guess the number. The input is error-checked only to ensure the user enters a string of length 5. Entering `"what?"` will not help at all, but it should be allowed and should count as a try at the secret number. If the user enters `"123456"` or `"1234"`, notify the user they must enter 5 digits but do not count this as an attempt at the secret number.

The game rules insist that you give the player some feedback on guesses. Based on that feedback, the player makes more guesses. Guessing continues until the secret number is guessed or until the maximum number of tries (32) is reached. Here is one sample dialog that plays one game where the user determines the secret number is ***12345***.

```
Enter your 5 digit guess: 11111
      Try number: 1
    Digits found: 1
Correct position: 1

Enter your 5 digit guess: 22222
      Try number: 2
    Digits found: 1
Correct position: 1

Enter your 5 digit guess: 99999
      Try number: 3
    Digits found: 0
Correct position: 0

Enter your 5 digit guess: 12333
      Try number: 4
    Digits found: 3
Correct position: 3

Enter your 5 digit guess: 12344
      Try number: 5
    Digits found: 4
Correct position: 4
```

```
Enter your 5 digit guess: what?
      Try number: 6
    Digits found: 0
Correct position: 0

Enter your 5 digit guess: 123456
'123456' must have a length of 5

Enter your 5 digit guess: 54321
      Try number: 7
    Digits found: 5
Correct position: 1

Enter your 5 digit guess: 12345
      Try number: 8
    Digits found: 5
Correct position: 5

You won in 8 tries!
```

Before implementing the `main` function, you are asked to first write four well-tested examples that will make writing the actual game itself much easier with far fewer bugs. These three methods listed next should be tested well and have the same exact function headings. Sample asserts are included below each function heading to help explain the method's use and behavior.

```
// Generates a 5-digit, valid secret "number" as a string.
// A secret number is valid if it contains no duplicates and
// all five characters are digits '0'..'9'
string generateSecretNumber()


// Return the number of digits that are contained in both the
// secret number and the guess. For example when secretNumber
// is 12345 and guess is 67821, the two numbers, actually strings,
// share two digits: 1 and 2.
int uniqueDigitsFound(string secretNumber, String guess)
// Sample assertions from MasterMindTest.java (not a complete test)
assert(5 == uniqueDigitsFound("12345", "21435"));
assert(0 == m.uniqueDigitsFound("12345", "67890"));


// Returns the number of matching digits between the guess
// and the secret number. For example when secretNumber is
// "12345" guess is "12675" returns 3 as the 1, 2, and 5 all
// have the same value at the same location.
int foundInPosition(String secretNumber, String guess)
// Sample assertions from MasterMindTest.java (not a complete test)
assert(1, m.foundInPosition("12345", "99399"));
assert(3, m.foundInPosition("12345", "19395"));
```

8F CLASS `Elevator`

Write the class definition and implement the member functions for class `elevator` with a constructor that places an elevator at a selected floor. Include a `void select(int goToFloor)` member function that allows floors to be selected. For every floor, the message `going up` or `going down` should be displayed before the current floor of the elevator. At that point, select should print `"open at"` the destination floor. The precondition is that the floor is selectable, or an `int` in the range of 1–100. Here is one sample output to give you an idea of what a simulated elevator will look like on your screen:

```
#include "Elevator.h" // For class Elevator
int main() {
  Elevator aLift(1); // Construct an Elevator object aLift
  aLift.select(5);
  aLift.select(3);
  return 0;
}
```

Output

```
start on floor 1
going up to 2
going up to 3
going up to 4
going up to 5
open at 5
going down to 4
going down to 3
open at 3
```

CHAPTER NINE

File Streams

SUMMING UP

The major control structures have now been presented—sequence, selection, and repetition. In the previous chapter, two major repetitive patterns emerged. The Determinate Loop pattern is used when the number of repetitions can be determined in advance. The Indeterminate Loop pattern occurs so frequently that the `while` loop is part of almost every programming language.

COMING UP

Chapter 9 presents two standard C++ classes—`ifstream` for obtaining input from an external file on a disk, and `ofstream` for saving program output onto a disk file. Processing input from a disk file is a classic instance of the Indeterminate Loop pattern. After studying this chapter, you will be able to

- use `ifstream` objects for disk file input
- use `ofstream` objects for disk file output

9.1 `ifstream` OBJECTS

Because keyboard input is fairly common, inclusion of `<iostream>` was designed to make `cin` immediately available. The `cin` object is automatically initialized and associated with the keyboard. However, input may also be obtained from many other sources, such as a mouse, a disk file, or a graphics tablet. An `ifstream` object is needed to read data from a disk file.

The `ifstream` (input file stream) class is declared in `fstream`. Therefore, this compiler directive must be added to programs intended to extract input from a disk file:

```
#include <fstream>  // For the ifstream class
```

The `ifstream` class is similar to the `istream` class. For example, the familiar extraction operator `>>` is also used to input data from a file stored on a disk. The same rules that apply to keyboard input for `int`s, `double`s, and `string`s also apply to input from a file.

An `ifstream` object is often constructed with the file name it will be associated with.

General Form 9.1 *Initializing* `ifstream` *objects for existing files*

```
ifstream object-name ("file-name");
```

The `file-name` is the name of an existing disk file. If the file is not found, the `ifstream` object initialization fails and an attempt to use the object name for input will fail. The state of the `ifstream` object can be tested immediately to determine if the file was found.

In the next example, `inFile` is the object name and `"input.data"` is the associated operating system file name.

```
ifstream inFile("input.data");  // Construct an ifstream object
```

Now this code will read input from the file input.data rather than from the keyboard.

```
inFile >> intObject;
```

The following program uses an `ifstream` object to read three integers from a disk file. Notice that there are a few differences between programs that extract keyboard input and the one below:

- Before, programs used `cin`—an `istream` object—for keyboard input. Now `inFile`—an `ifstream` object—is used for file input.
- Whereas `cin` is automatically constructed, your program must construct an `ifstream` object with an existing disk file name associated with it.
- Prompts aren't needed anymore. The same `>>` operator reads an integer and stores it into the `int` object, but there is no need to prompt the file for the next input.

```
// Include fstream for I/O streams dealing with disk files

#include <fstream>   // For the ifstream class
#include <iostream>  // For cout
using namespace std;

int main() {
  int n1, n2, n3;

  // Initialize an ifstream object so inFile is an input stream
  // associated with the operating system file named input.data
  ifstream inFile("input.data");

  // Extract three integers from the file input.data
  inFile >> n1 >> n2 >> n3;
  cout << "n1: " << n1 << endl;
  cout << "n2: " << n2 << endl;
  cout << "n3: " << n3 << endl;

  return 0;
}
```

Assuming the file `input.data` stores these three integers:

```
70    80    90
```

this output is generated:

Output

```
n1: 70
n2: 80
n3: 90
```

If the file `input.data` stores these three integers:

```
-45    77    23
```

this output is generated:

Output

```
n1: -45
n2: 77
n3: 23
```

File input works just like keyboard input—spaces and new lines separate the input data. This applies to all data seen so far: `string`, `int`, and `double`. If an integer is encountered in the file during an attempt to read a `double`, the `int` is promoted to a `double`. The one input difference is this: with an `ifstream` object, keyboard input is not necessary for stream extraction. Once the program begins to run, data can be read from the disk file without user input.

SELF-CHECK

9-1 Write a complete program that reads the first 30 `string`s from an input file named `student.data` and displays each string to the screen. Remember to `#include <fstream>`.

9.1.1 GETTING THE PATH RIGHT

If your input file is not stored in the current working directory, you may need to use an operating system path to locate it. For Windows, which uses `\` to separate directory names, you need the escape sequence `\\` (two backslashes) to specify full path names. So the file name may appear like this:

```
ifstream inFile( "c:\\mystuff\\input.data" );
```

"\\" represents only one backslash. Omitting one \ from \\ is virtually guaranteed to result in not finding the file:

```
ifstream inFile( "c:\mystuff\input.data" );  // Need \\, not \
```

This problem doesn't exist in Unix because the / character is used to separate directories, and so / can be used "as is":

```
ifstream inFile("myC++Stuff/input.data");
```

Also consider what happens if the file is not found. Input operations such as `inFile >>` will not execute. If you don't seem to be extracting input from the file or the values appear to be garbage, chances are the file does not exist as specified, it has a different name, it's in a different directory, you used \ rather than \\ in DOS or Windows, or your disk is bad, or. . . .

You can use the following alternate selection action to ensure that the user is notified that the file has not been found:

```
if( ! inFile ) {
  // If true, the input file was not found.
  cout << "Failed to find the file." << endl;
}
else {
  // Process file input data
  // . . .
}
```

9.2 THE INDETERMINATE LOOP PATTERN APPLIED TO DISK FILES

The previous chapter on repetition showed how sentinel loops process an undetermined number of keyboard inputs. The same type of logic works with the *end-of-file event*, which requires some knowledge of the operating system you are using. The end-of-file event is entered from the keyboard using the key sequence Ctrl-Z (^Z) with Windows or Ctrl-D (^D) in Unix.

When the end-of-file event is encountered on an input stream, the input statement (cin >>, for example) returns false (0, actually). So once again, the cin statement can be used as a loop test for processing an undetermined number of inputs.

```
while(cin >> x) {  // Input value at start of each iteration
  // Process value
}
```

Each time the `cin` statement returns true, the valid input is processed. When the user enters the end-of-file key sequence (Ctrl-C in DOS or Ctrl-D in Unix), the state of `cin` is altered to return false and the loop terminates.

The loop in the following program terminates when the user enters end of file. The loop test (`cin >> x`) returns false when end-of-file is detected.

Dialogue

```
Enter doubles, Ctrl-D, Ctrl-Z, or Command-Period to quit
1  3  4 ^D
Average: 2.66667
```

A word of warning: End-of-file sets the state of the input stream such that subsequent keyboard input is ignored unless some extra work is performed.

SELF-CHECK

9-2 What is the output of the preceding program if the user enters end-of-file first?

9.2.1 PROCESSING UNTIL END-OF-FILE

You can use the end-of-file event to process all data in a file without determining the amount of data in that file beforehand. This is shown in the next program where an indeterminate loop breaks the loop when there is no more data in `inFile`—the end of the input file was detected.

```
// Count how many numbers are in a disk file. The ifstream object
// named is used as the input stream, not cin.

#include <fstream>  // For the ifstream class
#include <iostream>
using namespace std;

int main() {
  ifstream inFile("numbers.data");
  double x = 0.0;  // Store file inputs here temporarily
  int n = 0;

  if( ! inFile ) {
    // If true, the input file was not found
    cout << "Failed to find the file numbers.data" << endl;
  }
  else {
    cout << "The file was successfully constructed" << endl;
    while( inFile >> x ) {
      n++;  // Track the number of loops
      cout << "iteration #" << n << ": " << x << endl;
    }
    cout << "End of file reached. " << n << " numbers found." << endl;
  }
  return 0;
}
```

To visualize this loop action, the repeated part simply displays each successfully extracted number. The output shown below appears when the file named `input.data` contains the following four numbers:

```
0.001   9
    8.0

1.5
```

Output

```
The file was successfully constructed
iteration #1: 0.001
iteration #2: 9
iteration #3: 8
iteration #4: 1.5
End of file reached. 4 numbers found.
```

SELF-CHECK

9-3 What is the output of the preceding program if:

a. the file `numbers.data` does not exist?

b. the file `numbers.data` contains one number?

c. the file `numbers.data` contains zero numbers (the file is empty)?

9-4 Write the output of the following program with the various data stored in the file `input.data`. (*Note:* `inFile >> intObject` will fail if an invalid number is encountered in the input file stream; input need not be on separate lines.)

a. `1 2 3`

b. `1 2 3 4 5`

c. `1 2 3 BAD`

d. `1.5 2.6 3.7`

```
#include <fstream>   // For the ifstream class
#include <iostream>  // For cout
using namespace std;
int main() {
  ifstream inFile("input.data");
  int sum = 0;
  int intObject;
  while(inFile >> intObject) {
    sum += intObject;
  }
  cout << sum << endl;
  return 0;
}
```

9.2.2 LETTING THE USER SELECT THE FILE NAME

It is sometimes appropriate to allow the user to enter the file name while the program is running. In this situation, it is appropriate to read the file name as a `string`. However, the `string` object itself cannot be used to initialize an `ifstream` object.

```
string fileName;
cout << "Enter file name: ";
cin >> fileName;
ifstream inFile(fileName);
// ERROR: ifstream::ifstream(string) not found
```

The `ifstream` constructor needs the character portion of a `string`, which is returned with `string::c_str`. This message returns the characters of the `string` object.

```
ifstream inFile( fileName.c_str() );
```

9.3 INDETERMINATE LOOP WITH MORE COMPLEX DISK FILE INPUT

The Indeterminate Loop pattern is often used to process data stored in a file—and that data can be quite complex. To accomplish this, the programmer must know the format of that data or must be able to specify their format. This is possible even if there is a collection of input data of different types and those data are spread out over two or more lines.

The example of this section uses an input file where all data concerning one employee is stored on one line in the file. The algorithm works like this: input one line of data and process it until there is no more data. The termination condition is end of file. So the loop test would be:

```
while (there is data in the input stream)
  process the newly read data
```

An indeterminate loop is capable of processing an unspecified number of inputs with data that need not be entered from the keyboard. With the end-of-file event as the termination condition, the number of iterations depends on the size of the file. The loop is easily written to effectively process all the employee data in a file whether there are zero, one, two, or many employees. For example, if the file `employee.data` contains the following data,

```
12.00  1 S Milan Archer
12.44  2 M Lennon Arrowsmith
11.11  3 M Oakley Baxter
10.00  0 S Charlie Bond
```

a properly constructed loop should process exactly four employees. The same code should also work with files of different sizes (different numbers of employees). This is an advantage over determinate loops that require the number of iterations to be determined before the loop begins to execute.

The next program implements a loop that uses the end-of-file event as the termination condition. During the loop test, all items needed to construct one `Employee` object (class `Employee`) are read from the `ifstream` object referenced by `inFile`.

```
while(inFile >> hourlyRate >> exemptions >> maritalStatus >> firstName >> lastName)
{
  // process the data
}
```

If there are enough data (of the proper format), the `while` loop executes the repeated part. Once inside this block, a new `Employee` object is constructed with the file input data just read in.

```
Employee anEmp(name, hourlyRate, maritalStatus, exemptions);
```

For each employee on file, the `getGrossPay()` message is sent to each `Employee` after setting the hours worked for the week.

```
// This program reads data from an input file to construct Employee objects,
// set the hours worked for the week, and show the gross pay for each.
#include <iostream>
#include <fstream>   // For the ifstream class
using namespace std;
#include "Employee.h"   // For the Employee class

int main() {
  string firstName, lastName;
  double hourlyRate, hoursThisWeek;
  int exemptions;
  string maritalStatus;

  // Initialize an input stream with a disk file as the source
  ifstream inFile("employee.data");
  if (!inFile) {
    // Show error if the file "payroll.data" is not found on the disk
    cout << "**Error opening file 'employee.data'" << endl;
  }
  else {
    // Process data until end of file
    while (inFile >> hourlyRate >> exemptions >> maritalStatus
                  >> firstName >> lastName) {
      string name (lastName + ", " + firstName);
      cout << "Hours worked for " << name << "? ";
      cin >> hoursThisWeek;
      Employee anEmp(name, hourlyRate, maritalStatus, exemptions);
      anEmp.setHoursWorked(hoursThisWeek);
      // Print the gross pay in a minimum of 3 spaces with 2 decimals places
      // with a preceding $ and a new line '\n' after the gross pay.
      printf("$%3.2f \n", anEmp.getGrossPay());
    }
  }
  return 0;
}
```

Output

```
Hours worked for Archer, Milan? 40
$480.00
Hours worked for Arrowsmith, Lennon? 30
373.20
```

```
Hours worked for Baxter, Oakley? 0
$0.00
Hours worked for Bond, Charlie? 42
$430.00
```

Notice that the output shows exactly four employees. Had the disk file contained a different number of employees, a different-sized report would have been generated without any change to the program or the need to determine the number of employees beforehand. This is a good time to use an indeterminate loop.

SELF-CHECK

9-5 Describe what would happen if the `S` were omitted from the last line in the file used for input in the preceding program:

```
12.00  1 S Milan Archer
12.44  2 M Lennon Arrowsmith
11.11  3 M Oakley Baxter
10.00  0   Charlie Bond
```

9-6 Describe what would happen if the `0` were omitted from the last line in the file used for input in the preceding program:

```
12.00  1 S Milan Archer
12.44  2 M Lennon Arrowsmith
11.11  3 M Oakley Baxter
10.00    S Charlie Bond
```

9.3.1 MIXING NUMBERS AND STRINGS

The preceding self-checks point to a problem that occurs when input contains numbers, characters, and strings. If one line of input is incorrect, the program will likely fail or produce incorrect output. Consider the following incorrect input:

```
12.00 S 1 Milan Archer
```

When that input is read and executes:

```
while(inFile >> hourlyRate >> exemptions >>
  maritalStatus >> firstName >> lastName)
```

The first time through the loop, the `S` is encountered while attempting to read an integer for exemptions. The input stream fails. The loop terminates. No objects are constructed inside the loop. This results from a file with just one out-of-place piece of data. If you are having problems reading data from a file, make sure the input statement has the proper objects and that the input file has the correct data.

9.3.2 THE `getline` FUNCTION

The previous example works because the program assumed there were two strings at the end of each line in the file. And just as importantly, the file had exactly two strings at the end of every line. But consider what would happen if the program could not assume there were going to be exactly two strings. For example, what if some employees had a middle initial, some had none, and others had two middle names for a total of four distinct strings in their names?

```
12.00  1 S Milan J. Archer
12.44  2 M Lennon Arrowsmith
11.11  3 M Oakley S. T. Baxter
10.00  0 S Charlie Bond
```

The previous program read a file in which each line ended with a first name followed by a last name. An alternative approach would now be required to read the string input at the end of each line in the file above. This can be accomplished with a function named `getline` from the string library.

Here is a simplified function heading for the `getline` function. Notice that two parameters have `&`, so they modify the arguments in the caller.

```
istream & getline(istream & is, string & str, char sentinel = '\n')
// post: Extracts string input from is (with blanks) until the end
//       of line has been encountered
```

This comes in handy for reading things like names and addresses. The nonmember `getline` function extracts all the characters from the input file stream until the end of file is encountered or the new-line character `'\n'` is found. This means that blank spaces normally used to separate strings become part of one larger string value.

The first argument to `getline` is any input file stream—`cin` or `inFile`, for example. The second argument is any string object that will be modified by `getline`. The `string` object will store all the characters from the current input stream until end of line. The third argument is optional. If omitted, the end-of-string marker is the new-line character `'\n'`.

This is the first example of a *default argument*. With the assignment of `'\n'` to sentinel in the parameter list, the `getline` function can be called with only two arguments. In this case, the third parameter is automatically assigned the value of the expression to the right of `=`. This is called a default argument. Therefore, the following two calls to `getline` are equivalent:

```
string fullName;
getline(inFile, fullName, '\n');
getline(inFile, fullName);
```

On the other hand, you can specify the third argument to be any sentinel character you wish. So to read an entire sentence from the keyboard, use this:

```
string sentence;
cout << "Enter a sentence ended with a period <'.'>: " << endl;
getline(cin, sentence, '.');
```

```
// assert: sentence has all characters up to, but not including
//         '.'. The '.' is pulled out of input stream (discarded).
```

The `getline` function also returns a reference to the input stream. The return value is true unless the end of file or the sentinel is found. This means `getline` can be used as a loop test. The following program demonstrates how `getline` can be used to read all the lines in any input file. The input is the program itself, so the number of lines should be 17.

```
#include <iostream>   // 1  File name: getline.cpp
#include <fstream>    // 2
#include <string>     // 3
using namespace std;  // 4
                      // 5
int main() {          // 6
  string aLine;       // 7
  ifstream inFile("getline.cpp");
  int lineCount = 0;  // 9
                      // 10
  while(getline(inFile, aLine)) {
    lineCount++;      // 12
  }                   // 13
                      // 14
  cout << "Lines in getline.cpp: " << lineCount << endl;
  return 0;           // 16
}                     // 17
```

Output

```
Lines in getline.cpp: 17
```

SELF-CHECK

9-7 What is the value of `street` when the user enters each line at the prompt?

a. `1313 Mockingbird Lane.`

b. `1214 Chestnut Drive.`

```
#include <iostream>  // For cout
#include <string>    // For getline and string
using namespace std;
int main() {
  string street;
  cout << "Enter street address, end with a period <.> " << endl;
  getline(cin, street, '.');
  cout << street;
  return 0;
}
```

Getting back to the problem of reading names that may have one, two, three, or any number of spaces, the `while` loop for the payroll problem could now be replaced by this to allow for any number of names.

```
string fullName;
// Process data until end of file
while (inFile >> hourlyRate >> exemptions >> maritalStatus
  && (getline(inFile, fullName))) {
  // Extract first blank character in fullName
  fullName = fullName.substr(1, fullName.length() - 1);
  cout << "Hours worked for " << fullName << "? ";
  cin >> hoursThisWeek;
  Employee anEmp(fullName, hourlyRate, maritalStatus, exemptions);
  anEmp.setHoursWorked(hoursThisWeek);

  // Print the gross pay in a minimum of 3 spaces with 2 decimals places
  // with a $ and a new line '\n' after the gross pay.
  printf("$%3.2f \n", anEmp.getGrossPay());
}
```

9.4 OFSTREAM OBJECTS

This section introduces class `ofstream` (output file stream) for storing program output to more permanent disk files. The `ofstream` class is a specialization of the `ostream` class, just as `ifstream` is a specialization of the `istream` class. Therefore, the operations and messages that could be sent to `cout` can also be sent to `ofstream` objects.

```
#include <iostream>  // For cout
#include <fstream>   // For the ofstream class
using namespace std;
int main() {
  ofstream outFile("out.data");
  outFile << "This string goes to a disk, not the screen" << endl;
  double x = 1.23;
  outFile << x << endl;
  outFile.width(30);
  outFile << x << endl;
  cout << "This string goes to the screen" << endl;
  return 0;
}
```

Output (to the file associated with the object named `outFile`)

```
This string goes to a disk file, not the screen
1.23
1.23
                          1.23
```

Output (to the screen)

```
This string goes to the screen
```

SELF-CHECK

9-8 What output goes to the disk file named `out.data`?

```
ofstream out("out.data");
for(int j = 1; j <= 5; j++)
  cout << j << " ";
```

CHAPTER SUMMARY

- An `ifstream` object may be associated with a disk file so large that amounts of data may be input quickly—with no human intervention.
- The `!` operator is overloaded to determine if a file has not been properly opened for input.
- Use the input operator `>>` in the loop test to read input until the end of any file of any size.
- You can use `ofstream` objects like `cout`. The only difference is that the output goes to a disk file rather than the computer screen.

EXERCISES

1. What does `ifstream` stand for?
2. Write the code that declares an input stream named `inFile` associated with the file called `numbers.data` located in the current working folder (directory).
3. Which `#include` is needed to construct `ifstream` objects?
4. Write a complete C++ program with the correct `#includes` with a loop that counts the number of words contained in a file. A word is any collection of characters separated by spaces, tabs, or new lines. For example, there are 14 words in the following sentence (recall that string constants are separated by blanks, tabs, and new lines):

```
Here's one
word, another,        and
 another.
        There are a total of 14 words here.
```

5. Write a sentinel event-controlled loop that counts the number of perfect test scores (the number 100) in a file named `tests.data`.

PROGRAMMING TIPS

1. Use `getline` to read strings with blank spaces. Sometimes several strings represent one string input. When asking for someone's name or address and you don't know how many values will be input, use the `getline` function.

```
string address;
cout << "Enter your address: ";
getline(cin, address);
cout << "Address: " << address << endl;
```

Dialogue

```
Enter your address: 1313 Mockingbird Lane, Washington D.C.
Address: 1313 Mockingbird Lane, Washington D.C.
```

2. Be careful when using `getline` and `>>` together. Be careful when mixing `getline` with the `>>` operator on the same input stream. The `>>` operator skips whitespace; `getline` does not. Worse yet, `cin >>` will stop at the new line. A subsequent `getline` will go up to the new line, effectively reading nothing. In this case, you will need an extra `getline` to get beyond the end of the line.
3. Use test drivers for reading complex data. Seemingly bizarre things can occur when you try to input complex data in an end-of-file loop. Consider first writing a test driver with code that inputs the first line from the file and then displays it.
4. Input is messy. Using `istream >>` and `getline` on the same input stream can cause difficult-to-detect errors. Additionally, when there is a mix of integer, floating-point, character, and string input, it is not always easy to get the input statements correct. The number of objects in an input statement must always be correct. The input file must always be correct.

PROGRAMMING PROJECTS

9A WIND SPEEDS ON FILE

Write a program that determines the lowest, highest, and average of a set of wind speed readings from a file. The number of readings is not known in advance. First create a file in your working (current) directory as `wind.data` and use the `ifstream` constructor to open the file for input as follows:

```
ifstream inFile("wind.data");
```

The program should work for all files containing only `int`s so any number of inputs should produce correct results. Run your program with the following file named `wind.dat`. Verify that the output is correct by producing results by hand and comparing your output.

```
 2  6  1  2  5
 5  4  3 12 16
10 11 12 13 14
```

9B WORDS IN A FILE

Write a C++ program that approximates the number of words in a file that has the file name input by the user. Remember to use `string::c_str` to initialize the `ifstream` object.

```
cin >> fileName;
ifstream inFile(fileName.c_str());
```

9C PAYROLL REPORT (PREREQUISITE 7D: CLASS EMPLOYEE)

In this project you are asked to use your `Employee` class as the basis for a payroll program that processes many employees. The input data to be processed are stored in an external file with the following format:

```
Sam Barker      40.0  15.00  2 S
Casey Baker     42.0  12.00  3 M
Joey Cook       30.5   9.99  1 S
Chris Glazer    40.0  11.57  1 M
```

Create a report in a new file named `payroll.report` that looks like the following (with `?` replaced by the correct answers, of course). Also show all totals for every category except the pay rate (*Note:* Income tax is based in the 2015 Employer Tax Guide; this changes yearly).

Output file named `payroll.report`

```
   Pay   Hours      Gross    Income   SocSec   Medi         Net  Employee
  Rate  Worked        Pay       Tax      Tax   care         Pay  Name
=====    ====    =======    ======   ====== ======    ========  =======
15.00    40.0     600.00     51.43    37.20   8.70      502.67  Barker, Sam
12.00    42.0          ?         ?        ?      ?           ?  Baker, Casey
 9.99    30.5          ?         ?        ?      ?           ?  Cook, Joey
11.57    40.0          ?         ?        ?      ?           ?  Glazer, Chris
       ------  ---------    ------   ------  -------  --------
Totals  152.5  ??????.??   ????.??  ????.??  ????.??   ????.??
```

CHAPTER TEN

Vectors

SUMMING UP

Almost all objects studied so far either store one element of a specific value such as `double` and `int` or are made up of two or more possibly dissimilar elements such as `Employee` and `BankAccount`.

COMING UP

To get interesting things done, we often use a collection of data. For example, we might need a list of students, a list of phone contacts, a list of text threads, a list of prices at different online stores, and so on. The ability to store many elements as one object is used to solve a wide variety of programming problems. In this chapter, we begin with one of the simplest, and arguably the most useful, way of storing data: the C++ `vector` type. After studying this chapter you will be able to

- construct and use `vector` objects that store collections of any type
- implement algorithms to process a collection of objects
- use the sequential search algorithm to locate a specific element in a `vector`
- pass `vector` objects to functions
- sort `vector` elements into ascending or descending order
- understand how to search with the classic binary search algorithm

10.1 THE STANDARD C++ vector CLASS

The `vector` class constructs objects that store *collections* of objects. All `vector` objects are considered *homogeneous* because the objects in the collection are of the same type—a collection of numbers or a collection of `string` objects, for example. The objects in the collection may be any one of the standard types such as `int`, `double`, or `string`. Additionally, any programmer-defined class that has a default constructor can be contained in a `vector`. You can have a collection of any objects that you can dream up. Here are two general forms for initializing `vector` objects:

General Form 10.1 `vector` *initialization*

```
    vector <type>  vector-name(capacity);
- or -
    vector <type>  vector-name(capacity, initial-value);
```

- *type* specifies the class of objects stored in the `vector`.
- *vector-name* is any valid C++ identifier.
- *capacity* is an integer expression representing the maximum number of elements that can be stored into the `vector`.
- The optional *initial-value* is the value that will be assigned to every element in the `vector`. If there is only one argument (*capacity*), then the default constructor for that class sets the initial values (recall that with `double` and `int`, the default values will be garbage).

Examples of `vector` Initializations

```
vector <int> garbage(1000000);    // A million integers of unknown value
vector <double> x(100, 99.9);     // Store 100 numbers, all equal to 99.9
vector <string> names(20, "TBA"); // Store 20 strings, all equal to "TBA"
```

To use `vector`, include `<vector>`, and when using `namespace std;` you can write `vector` instead of `std::vector`.

```
#include <vector>  // For the vector<type> class
using namespace std;
```

It should be noted that the `vector` syntax and algorithms that follow apply to primitive C++ arrays declared, such as `int garbage[100]` and `string names[20]`. The main benefits of using `vector`s include:

- `vector` objects check for invalid indexes such as accessing the element at `index -1`.
- `vector` has several useful member functions like `resize(200)`.
- `vector` objects can have all elements initialized when constructed, while primitive C++ arrays require an additional `for` loop to do the same thing.

10.1.1 ACCESSING INDIVIDUAL ELEMENTS IN A COLLECTION

Any `vector` object supports access to any element by using an index into the `vector`. An individual `vector` element can be referenced directly through subscripts that are written with square brackets `[` and `]`.

General Form 10.2 *Accessing one* `vector` *element*

```
    vector-name [integer-expression]
```

The subscript range of a C++ `vector` is an integer value in the range of `0` through its `capacity - 1`. Therefore, the individual objects of `x` declared as

```
vector <double> x(8, 0.0);
```

may be referenced using the integer subscripts `0`, `1`, `2`, `3`, . . . `7`, but not `8`. Values can be stored into the first two `vector` elements of `x` with these two assignment statements:

```
// Assign new values to the first two elements of vector named x
x[0] = 2.6;
x[1] = 5.7;
```

Because C++ has zero-based indexing, the first `vector` element is referenced with subscript `0` or as `x[0]`, and the fifth element with subscript `4` or `x[4]`. This subscript notation allows individual vector elements to be displayed, used in expressions, and modified with assignment and input operations. In fact, you can do anything to an individual `vector` element that can be done to an object of the same class.

The familiar assignment rules apply to `vector` elements. For example, a `string` constant cannot be assigned to a `double`, and a `string` constant cannot be stored in a `vector` element declared to store `int` values.

```
x[2] = "Wrong type of constant";  // ERROR: x stores numbers
```

Since any two `doubles` can be added with `+`, subscripted `vector` elements can also be used in arithmetic expressions like this:

```
x[2] = x[0] + x[1];  // Store 8.3
```

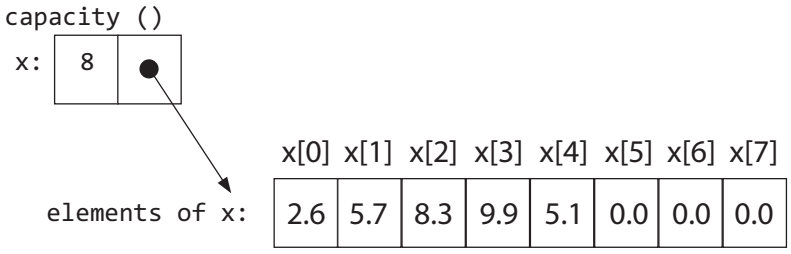
Keyboard input can also be used to set the state of `vector` elements like this:

```
cout << "Enter two numbers: ";
cin >> x[3] >> x[4];
```

Dialogue

```
Enter two numbers:  9.9  5.1
```

After this user input of ***9.9*** and ***5.1*** into the fourth and fifth `vector` elements and the previous assignments to the first three `vector` elements, the state of `x` now looks like the following.



10.1.2 vector PROCESSING WITH DETERMINATE for LOOPS

Programmers must frequently reference many consecutive `vector` elements. The simplest case might be to display all the meaningful elements of a `vector`. The C++ `for` loop provides a convenient way to do this. This program includes the same `vector` assignments as above, with a `for` loop added at the end to display the first `n = 5` elements. Notice that `x[5]`, `x[6]`, and `x[7]` still have the initial value of `0.0`.

```
#include <iostream>
#include <vector>  // For the vector<type> class
using namespace std;

int main() {
  vector<double> x(8, 0.0);

  // Assign new values to the first two elements of vector named x
  x[0] = 2.6;
  x[1] = 5.7;
  x[2] = x[0] + x[1];  // Store 8.3

  cout << "Enter two numbers: ";
  cin >> x[3] >> x[4];

  int n = 5;
  // assert: n represents the number of meaningful elements

  // Display the meaningful elements of x--the first n elements
  cout << "\nThe first " << n << " elements of x: " << endl;
  for (int index = 0; index < n; index++) {
    cout << "x[" << index << "]: ";
    cout << x[index] << endl;
  }

  return 0;
}
```

Dialogue

```
Enter two numbers: 9.9  5.1

The first 5 elements of x:
x[0]: 2.6
x[1]: 5.7
x[2]: 8.3
x[3]: 9.9
x[4]: 5.1
```

The first `n` elements of `x` are easily referenced by altering the `int` named `index`, which acts both as the counter in the `for` loop and as the subscript inside the `for` loop (`x[index]`). With `index` serving both roles—as shown in the code above—the specific `vector` element referenced as

x[index] will depend on the value of index. For example, when index is 0, x[index] is a reference to the first element in x; when index is 4, x[index] is a reference to the fifth element of x.

10.1.3 PROCESSING THE FIRST n ELEMENTS IN A vector

Here is another example of a for loop that compares the first n vector elements to find the largest floating-point value using the vector x in the preceding program.

```
// First set the largest as the first element . . .
double largest = x[0];

// . . . then compare all other vector elements x[1] through x[n-1]
for(int i = 1; i < n; i++) {
  if (x[i] > largest)
    largest = x[i];
}

// Display the largest
cout << "The largest element in vector x = " << largest;
```

Output

```
The largest element in vector x = 9.9
```

A vector often stores fewer meaningful elements than its capacity. Therefore, you usually need to have an object that stores the number of elements in the vector that are currently under consideration. In the previous code, n was used to limit the elements being referenced. Only the first five elements were searched to find the largest. Imagine trying to find the largest number in x without limiting the search to the first n elements. The largest could incorrectly be some garbage value at index 5, 6, or 7.

The Determinate Loop pattern with for loops conveniently performs vector processing, which is the inspection of, reference to, or modification of a selected number of vector elements. The number of elements (n here) is the predetermined number of vector elements that must be processed. Algorithms that include vector processing in this chapter include

- displaying some or all elements of a vector
- finding the sum, average, or largest of all vector elements
- searching for a particular object in the vector
- arranging elements in a certain order (ordering elements from largest to smallest or alphabetizing a vector of string objects from smallest to largest)

10.1.4 OUT-OF-RANGE SUBSCRIPT CHECKING

The standard vector class does not check subscripts to ensure that they are within the proper range of 0 through its capacity –1. Therefore, the programmer must be careful to avoid subscripts that are not in the range specified at initialization. If you are using the standard vector class

without subscript range checking, the following assignments may destroy some other portion of memory, such as another object's state:

```
x[-2] = 4.5;  // Careful! These out-of-range subscripts are not
x[8]  = 7.8;  // guarded against and could crash your computer.
```

The result could be seemingly unrelated errors, bugs, or even a system crash. All subscripts should be in the range of `0` through the `vector`'s capacity `-1`.

Without range checking, an out-of-range subscript destroys other areas of memory. This creates difficult-to-detect bugs. More dramatically, your computer may "hang" or crash. Even worse, with a workstation that runs all the time, you may get a latency error that affects computer memory now, but won't crash the system perhaps for weeks.

As an example of a problem an out-of-range subscript may create, consider what might happen with the following assignment:

```
result = x[n];
```

The value stored at `x[n]` is one beyond the `vector`'s capacity. It is some random garbage value. On one system, this statement produced the output shown in the comment:

```
// There is no warning or error with the statement
cout << "x[n]: " << x[n] << endl;
```

Output

```
x[n]: -33686019
```

The standard `vector` class provides the `at` member function to avoid out-of-range subscripts. The result may look different, but this message will gracefully terminate the program rather than store some random value into `result`:

```
result = x.at(n);  // Gracefully terminates the program. Good.
```

To ensure your program will not run with an out-of-range index, use the `at(int)` message. Your program will then terminate early with an error message indicating the reason. This is preferable to fixing errors that are difficult to locate. Here is what will happen with the `vector` class when using the `at` member function:

```
#include <vector>  // For the vector<type> class
#include <iostream>
using namespace std;

int main() {
  vector<double> x(8);

  // Attempt to assign 100 to all elements of vector named x
```

```
  for (int i = 1; i <= x.capacity(); i++) {
    x.at(i) = 100;
  }

  cout << "Program would terminated above with x[8]" << endl;

  return 0;
}
```

Output for a program that terminated early (this will vary among different systems)

```
libc++abi.dylib: terminating with uncaught exception
  of type std::out_of_range: vector
```

There may be a temptation to always use `vector::at` in subsequent examples. However, programmers have been using subscripts for a very long time. You will see a lot of code with the square brackets (`[ ]`), so this textbook will rely on subscripts. Feel free to use `at` messages when developing your own programs.

10.1.5 vector::capacity, vector::resize, =

Many messages can be sent to a standard C++ `vector` object. Each `vector` object is responsible for knowing how many objects it can store—its `capacity`. A `vector` also knows how to increase or decrease that `capacity`—a `vector` can `resize` itself.

After a `vector` has been initialized, the `vector::capacity` message returns the maximum number of elements that the `vector` can hold. The `vector::resize` message tells the `vector` to change to the new `capacity` supplied as the single argument. What is weird, however, is the `capacity` message returns a larger capacity when the argument is less than the `capacity`. In the example below, `v2`'s capacity still shows `100` even though `at(55)` terminates the program with the error message shown:

```
// Demonstrate capacity and resize
#include <vector>  // For the standard vector<type> class
#include <iostream>
using namespace std;

int main() {
  vector <int> v1;  // v1 cannot store any elements with 0 capacity
  vector <int> v2(100, -1);

  cout << "v1 can store " << v1.capacity() << endl;
  cout << "v2 can store " << v2.capacity() << endl;

  v1.resize(22);
  cout << "v1 can now store " << v1.capacity() << endl;
```

```
  // Odd behavior when the argument is less than the current capacity.
  // at(55) shows you can not access past the smaller capacity.
  v2.at(55) = 123;
  cout << "v2.at(55): " << v2.at(55) << endl;
  v2.resize(55);
  cout << "v2 can now store " << v2.capacity() << endl;
  cout << "v2 has this -1s: " << v2.size() << endl;
  cout << "v2.at(55): " << v2.at(55) << endl;

  return 0;
}
```

Output

```
v1 can store 0
v2 can store 100
v1 can now store 22
v2.at(55): 123
v2 can now store 100
v2 this many meaningless -1s: 55
v2.at(55): libc++abi.dylib: terminating with uncaught exception of type
std::out_of_range: vector
```

If you `resize` a `vector` to have more capacity, the original elements in the lower subscripts are still there. However, if you `resize` a `vector` to be smaller, the elements in the higher locations are lost. Truncation occurs.

One `vector` can be assigned to another. The `vector` to the left of the = operator becomes an exact copy of the `vector` to the right of =. The `vector` on the left, like any other object to the left of =, is destroyed.

```
// Demonstrate capacity and resize
#include <iostream>
#include <vector>  // For the vector<type> class
using namespace std;

int main() {
  vector <int> v1(3, -999);
  vector <int> v2;

  v2 = v1;
  // assert: v2 now stores 3 elements == -999
  for(int index = 0; index < v2.capacity(); index++) {
    cout.width(5);
    cout << v2[index];
  }

  return 0;
}
```

Output

```
-999 -999 -999
```

SELF-CHECK

Use this initialization to answer the questions that follow:

```
vector <int> x(100, 0);
```

10-1 How many integers can be stored in `x`?

10-2 Which integer subscript references the first element in `x`?

10-3 Which integer subscript references the last element in `x`?

10-4 What is the value of `x[23]`?

10-5 Write the code that stores `78` into the first element of `x`.

10-6 Write code that stores `1` into `x[99]`, `2` into `x[98]`, `3` into `x[97]`, . . ., `99` into `x[1]`, and `100` into `x[0]`. Use a `for` loop.

10-7 Write code that displays all elements of `x` on separate lines. Use a `for` loop.

10-8 What happens when this code executes: `x[-1] = 100;`

10-9 Name two `vector` member functions.

10-10 Write the output generated by the following program:

```
#include <vector>  // For the standard vector<type> class
#include <iostream>
using namespace std;

int main() {
  int n = 5;
  vector <int> x(n, 0);
  for(int i = 0; i < n; i++) {
    x[i] = i;
  }

  x.resize(2 * n);

  // Show the first five elements are still in x
  for(int i = 0; i < n; i++) {
    cout.width(5);
    cout << x[i];
  }
  cout << endl;

  for(int i = 0; i < x.capacity(); i++) {
    cout.width(5);
```

```
    cout << x[i];
  }
  cout << endl;

  return 0;
}
```

10.2 SEQUENTIAL SEARCH

One of the major reasons for using `vector` objects is to have individual elements retained in the computer's fast memory, where they will be frequently accessed. This often means searching for the existence of some element in the collection. So another common `vector`-processing operation involves searching. Searching examples include, but are certainly not limited to, searching for a student name in the registrar's database, looking up the price of an item in an inventory, or obtaining information about a bank account. One such algorithm used to look up a `vector` element is called *sequential search*.

The sequential search algorithm attempts to locate a given element by comparing the item being sought with every object in the `vector`. The algorithm searches in a one-after-the-other (sequential) fashion. Sequential search continues as long as the search value has not been found or until there are no more elements left in the `vector` to compare.

This sequential search algorithm is presented here within the context of a `vector` of `string` objects. Although the search element here will be a person's name, the `vector` being searched could contain other kinds of objects—numbers, students, or employees, for example—as long as the object of the class can be compared with the == operator.

```
// Initialize and show the first n elements of vector named name
#include <iostream>
#include <string>
#include <vector>  // For the standard vector<type> class
using namespace std;

// This free function uses the sequential search algorithm to return
// the index of searchName in the vector or -1 if searchName is not found.
int indexOf(string searchName, const vector<string> & names, int n) {
  // Just show the vector elements for now
  for (int i = 0; i < n; i++) {
    if (searchName == names[i])
      return i;
  }
  // searchName not found
  return -1;
}

int main() {
  vector<string> myFriends(10);

  int n = 5;  // Set the number of meaningful elements to be searched
```

```
  myFriends[0] = "Sage";
  myFriends[1] = "Harley";
  myFriends[2] = "Peyton";
  myFriends[3] = "Quinn";
  myFriends[4] = "Taylor";

  cout << "Sage is at index " << indexOf("Sage", myFriends, n) << endl;
  cout << "Peyton is at index " << indexOf("Peyton", myFriends, n) << endl;
  cout << "Taylor is at index " << indexOf("Taylor", myFriends, n) << endl;

  if(indexOf("Not Here", myFriends, n) == -1) {
    cout << "Not Here was not found" << endl;
  }

  return 0;
}
```

Output

```
Sage is at index 0
Peyton is at index 2
Taylor is at index 4
Not Here was not found
```

SELF-CHECK

10-11 What value is returned if `searchName` is not in the `vector` referenced by `names`?

10-12 How many comparisons (iterations of the search loop) are necessary when `searchName` matches my`Friends[0]`?

10-13 How many comparisons (iterations of the search loop) are necessary when `searchName` matches `myFriends[n-1]`?

10-14 How many comparisons are necessary when `searchName` matches `myFriends[3]`?

10-15 How many comparisons are necessary when `searchName` isn't in `myFriends`?

10-16 How many sequential search comparisons occur when the `vector` has no useful data in it—that is, when `n == 0`?

10.3 MESSAGES TO INDIVIDUAL OBJECTS IN A `vector`

Subscript notation is used to send messages to individual elements. The `vector` name must be accompanied by a *subscript* to specify the particular `vector` element to which the message is sent. The subscript distinguishes the specific object to which the operation is to be applied. For example, the length of `myFriends[0] "Sage"` is referenced with this expression:

```
myFriends [0].length(); // The length of the first name in the vector
```

The expression `myFriends.length()` would be an error because this would represent an attempt to find the length of the entire `vector`. The `length` function is defined for `string`, but not for the `vector` class (although `vector::resize` and `vector::capacity` are defined).

Now consider determining the total assets of all `BankAccount` objects in a `vector` of `BankAccounts`. The following program first sets up a tiny database of four `BankAccount` objects. Therefore, this statement

```
account[0] = BankAccount ("Baker", 0.00);
```

first constructs a `BankAccount` object with the name `"Baker"` and a balance of `0.00`. The `BankAccount` object is then assigned to the first `vector` element `account[0]`.

```
// Illustrates a vector of programmer-defined objects
#include <iostream>
#include <vector>    // For the vector<type> class
using namespace std;
#include "BankAccount.h"  // For the BankAccount class

int main() {
  vector<BankAccount> account(100);

  // Initialize the first n elements of account
  int n = 4;
  account[0] = BankAccount("Baker", 0.00);
  account[1] = BankAccount("Cook", 100.00);
  account[2] = BankAccount("Cartright", 200.00);
  account[3] = BankAccount("FensterMacher", 300.00);
  // assert: The first n elements of account are initialized

  double assets = 0.0;
  // Accumulate balance of n BankAccount objects stored in account
  for (int i = 0; i < n; i++) {
    assets += account[i].getBalance();
  }

  cout << "Assets: " << assets << endl;

  return 0;
}
```

Output

```
Assets: 600
```

SELF-CHECK

10-17 Write the output generated by the following program:

```
#include <iostream>
#include <vector>  // For the vector<type> class
```

```
#include <string>  // For the string class
using namespace std;

int main() {
  vector<string> s(10);
  // Initialize the first 4 elements of account
  s[0] = "First";
  s[1] = "Second";
  s[2] = "Third";
  s[3] = "Fourth";
  int n = 4;

  for (int i = 0; i < n; i++) {
    cout << s[i].substr(1, s[i].length() - 2) << "  ";
  }

  return 0;
}
```

10.3.1 INITIALIZING A VECTOR OF OBJECTS WITH FILE INPUT

In some of the preceding programs, the `vectors` of objects were initialized in several assignment statements. `vector` objects can also be initialized through disk file input. To demonstrate, imagine the following is part of the input data file named `bank.data` with a total of 12 accounts on 12 lines:

```
Cust0          0.00
AnyName      111.11
Alex         222.22
Andy         333.33
Ash          444.44
Cust5        555.55
```

. . . five lines are omitted . . .

```
Cust11      1111.11
```

If the `vector` is declared with a maximum capacity of 20 like this, then the first `BankAccount` object can be stored in `account[0]`:

```
vector <BankAccount> account(20);
// assert: account could store 20 default BankAccount objects
```

So an object named `numberOfAccounts` starts at `0`:

```
int numberOfAccounts = 0;
```

Then the `vector` of `BankAccount` objects can be initialized one account at a time with these steps:

1. Input two items per line—a `name` and a `balance`.
2. Construct a `BankAccount` and store it into the next available `vector` location.
3. Increase the number of accounts by 1.

The `vector::capacity` function will also be used to safeguard against using subscripts beyond the account's boundaries of `0` through `19`.

The following `while` loop test expression should be true before a `BankAccount` object can be added at the next available location in the `vector`. If there are no more data in the file, `(inFile >> name >> balance)` is false and the loop will terminate. Also, if there are more data in the file but no more room in the `vector`, `(numberOfAccounts < account.capacity())` is false and the loop terminates for a different reason—there is no room.

```
while ((inFile >> name >> balance) &&
       (numberOfAccounts < account.capacity())) {
  account[numberOfAccounts] = BankAccount(name, balance);
  numberOfAccounts++;
}
```

While there is room for another element and there are more data in the file, the repeated part executes. Inside the loop, the two objects (`name` and `balance`) are passed on to the `BankAccount` constructor to construct a `BankAccount`, which is then stored in the next consecutive `vector` element. This initialization and assignment must occur before `numberOfAccounts` is incremented from `0` to `1` during the first iteration of the loop.

Now `numberOfAccounts` accurately indicates the number of accounts processed so far, and the first `BankAccount` object is stored into `account[0]`. During each loop iteration, `numberOfAccounts` represents not only the total number of meaningful accounts stored in the `vector`, but also the next available `vector` subscript into which the next `BankAccount` object can be stored. When the end of the file is encountered, `numberOfAccounts` will have the correct value—one greater than the subscript storing the last account.

This processing is shown in the context of a complete program which sets up a small database of bank customers:

```
// Initialize a vector of BankAccount objects through file input
#include <vector>    // For the vector<type> class
#include <fstream>   // For the ifstream class
#include <iostream>  // For cout and endl
#include <string>    // For the string class
using namespace std;
#include "BankAccount.h"  // For the BankAccount class

int main() {
  string fileName = "bank.data";
  ifstream inFile(fileName.c_str());

  if (!inFile) {
    cout << "**Error** " << fileName << " was not found" << endl;
  }
  else {
    vector<BankAccount> account(20);
    string name;
    double balance = 0.0;
    int numberOfAccounts = 0;
```

```
    while ((inFile >> name >> balance)
        && (numberOfAccounts < account.capacity())) {
      account[numberOfAccounts] = BankAccount(name, balance);
      numberOfAccounts++;
    }

    cout << "Number of accounts on file: " << numberOfAccounts << endl;
    cout << endl;
    cout << "The accounts" << endl;
    cout << "==========================" << endl;
    for (int index = 0; index < numberOfAccounts; index++) {
      cout.width(2);
      cout << index << ". ";
      cout << account[index].getName();
      cout.width(20 -  account[index].getName().length());
      cout << account[index].getBalance() << endl;
    }
  } // end else

  return 0;
}
```

Input File: bank.data

```
Cust0         0.00
AnyName     111.11
Alex        222.22
Andy        333.33
Ash         444.44
Cust5       555.55
Cust6       666.66
Cust7       777.77
Cust8       888.88
Cust9       999.99
Cust10     1010.10
Cust11     1111.11
```

Output

```
Number of accounts on file: 12

The accounts
==========================
 0. Cust0               0
 1. AnyName        111.11
 2. Alex           222.22
 3. Andy           333.33
 4. Ash            444.44
 5. Cust5          555.55
 6. Cust6          666.66
 7. Cust7          777.77
 8. Cust8          888.88
 9. Cust9          999.99
10. Cust10         1010.1
11. Cust11        1111.11
```

SELF-CHECK

10-18 Write two assignment statements that initialize two additional `BankAccount` objects with assignment statements in the next two `vector` locations. Use any data you desire.

10-19 What would happen if the input file `bank.data` contained 21 lines, each line representing one account? Remember, `account.capacity()` is `20`.

10-20 Write code to initialize a `vector` of integers from a file named `int.dat`. Assume the file never has more than 1,000 integer values.

10-21 Which object in your code represents the number of initialized elements?

10-22 Write code that verifies proper initialization of the `vector` of the previous two self-check questions.

10.4 vector ARGUMENT/PARAMETER ASSOCIATIONS

Sometimes it may be necessary to pass a `vector` to either a member function or a nonmember function through argument/parameter association. This requires a different syntax in the parameter list. There are three ways to declare a `vector` parameter, but only these two should ever be used:

Pass by Reference (when the function must modify the associated `vector` argument)

```
return-type  function-name (vector <class> & vector-name)
```

Pass by `const` Reference (runtime efficient with `&` and safe with `const`)

```
return-type  function-name (const vector <class> & vector-name)
```

A `vector` object should not be passed by value. This parameter-passing mode is usually inefficient since `vector` objects can consume a large amount of memory.

```
void inefficient(vector <BankAccount> accounts, int n) {
  // VALUE parameter (should not be used with vectors). All elements
  // of acct are copied after allocating additional memory.
}
```

Recall that passing by value causes the function to allocate memory for a copy of the object passed by value. This could be thousands or even millions of bytes. The program could terminate because of lack of memory. Additionally, every byte of the `vector` needs to be copied, which could noticeably slow down the program. Passing by `const` reference has the same meaning, but is more efficient.

Use pass by reference (with `&`) when a function is supposed to modify the associated argument:

```
void initialize(vector <BankAccount> & accounts, int & n){
  // REFERENCE parameter (allows changes to argument)
  // Only a pointer to acct is copied
  // A change to acct here changes the argument in the caller
}
```

When a function requires a vector but should not modify the associated argument, pass the vector by const reference:

```
void display(const vector <BankAccount> & accounts, int & numberOfAccounts)
{
  // CONST REFERENCE parameter (for efficiency and safety)
  // Only a reference to the acct is copied (4 bytes)
  // A change to acct does NOT change the argument
}
```

The next program passes a vector by reference to the function initialize in order to communicate the initialized array back to main. The main function passes by reference a vector of doubles to a void function named initialize. Because the vector and int parameters x and numberOfAccounts are declared as a reference parameter with &, any change to x or numberOfAccounts inside of initialize also changes the arguments in the main function test and n.

```
#include <vector>  // For the vector<type> class
#include <iostream>
using namespace std;

void initialize(vector<int> & x, int & numberOfAccounts) { // Two reference
parameters
  // post: Initialize the first n elements of the argument
  numberOfAccounts = 5;
  x.resize(numberOfAccounts);
  x[0] = 75;
  x[1] = 88;
  x[2] = 67;
  x[3] = 92;
  x[4] = 51;
  // The arguments associated with x and n, test and n in main,
  // will also be modified.
}

void display(const vector<int> & x, int numberOfAccounts) { // Const refer-
ence
  // Display the vector with n meaningful values
  cout << "The vector: ";
  for (int i = 0; i < numberOfAccounts; i++) {
    cout.width(5);
    cout << x[i] << "  ";
  }
  cout << endl;
}

int main() {
  vector<int> vec(10, 0);
  int n;

  // Initialize test and n
  initialize(vec, n);
```

```
  display(vec, n);

  return 0;
}
```

Output

```
The vector:    75     88     67     92     51
```

10.4.1 const REFERENCE & PARAMETERS

The preceding program showed that the arguments—`test` and `n`—were passed to function `initialize` by reference. This was done to allow the function to modify both arguments and communicate the changes back to `main`. However, sometimes a `vector` is passed as input to a function, where no changes should be made. In this case, the `const` reference form should be used like in the `initialize` function above. Part of the reason is efficiency—the program executes more quickly. The other consideration is better memory utilization—less memory is required to store the `vector` in the called function. A `vector` object passed by value requires as much memory as the argument.

```
// A vector should not be passed by value like this
void display(vector <double> x, int n) { // Value parameter
  // This function must obtain the memory necessary to store x when x
  // could have a large capacity of large objects
}
```

So if the `vector` argument had a capacity of 100,000 elements, `void display` would need to consume an additional 100,000 elements. Additionally, every single element would need to be copied from the client code (the caller) to the called function. This can be time consuming, especially when the `vector`'s capacity is large and/or the size of each element is large. The computer has to do a lot of unnecessary work. The program would run noticeably slower and might exhaust available memory.

Here are two alternatives to make any program more efficient in terms of space (saves memory) and time (runs faster):

1. Pass the `vector` by reference—efficient but dangerous.
2. Pass the `vector` by `const` reference—efficient and safe.

The second option is highly recommended—the computer program has much less work to do.

Using `const` is also an antibugging technique that will let the compiler catch attempts to modify the constant objects. Any `const` member function may still be called—`vector::capacity`, for example. However, the compiler will flag any attempt to send a non-`const` message:

```
// precondition: x.capacity() > 0
void display(const vector <int> & x, const int n) {
  cout << "\nThe vector's capacity is " << x.capacity()  // <- Okay
  cout << x[0];  // <- OKAY to reference vector element
  x[0] = 123;    // <- ERROR caught during compilation
}
error: cannot assign to return value because function 'operator[]' returns a
const value
```

Pass `vector` objects or any large object by `const` reference.

SELF-CHECK

10-23 Why should `vector` and `Grid` objects be passed by `const` reference when you have always seen `int` and `double` variables passed by value?

10-24 If the average size of the `BankAccount` objects in a `vector` of capacity 100,000 is 57 bytes, how many bytes of additional memory would have to be reserved and then copied into each of the following functions? Remember, pass by reference typically requires four bytes of memory:

a. `void one(vector<BankAccount> v1)`

b. `void two(vector<BankAccount> & v1)`

c. `void one(const vector<BankAccount> & v1)`

10.5 SORTING

The elements of a `vector` are often arranged into either ascending or descending order through a process known as *sorting*. For example, a `vector` of test scores is sorted into ascending order by rearranging the numeric values in lowest-to-highest order. A `vector` of `string` objects sorted in ascending order establishes an alphabetized list (A's before B's, B's before C's). To sort a `vector`, the elements must be compared with the `<` operator. If one object can be less than another object of the same type, then the `vector` is *sortable*. For example, `85 < 79` and `"A" < "B"` are valid expressions.

The following code declares and gives meaningful values to a part of the `vector` named `data` to demonstrate sorting a `vector` of integers:

```
vector<int> data(10, 0);  // Store up to 10 integers
int n = 5;
data[0] = 76;
data[1] = 74;
data[2] = 100;
data[3] = 62;
data[4] = 89;
```

There are many sorting algorithms. Even though others are more efficient (run faster), the relatively simple selection sort algorithm is presented here. The goal here is to arrange a `vector` of integers into ascending order, the natural ordering of integers.

Object Name	Unsorted `vector`	Sorted `vector`
`data[0]`	`76.0`	`62.0`
`data[1]`	`91.0`	`76.0`
`data[2]`	`100.0`	`89.0`
`data[3]`	`62.0`	`91.0`
`data[4]`	`89.0`	`100.0`

With the selection sort algorithm, the largest integer must end up in `data[n - 1]` (where `n` is the number of meaningful `vector` elements). The smallest number should end up in `data[0]`. In general, a `vector x` of size `n` is sorted in ascending order if `x[i] <= x[i + 1]` for `i = 0` to `n-2`.

The selection sort begins by locating the smallest element in the `vector` by searching from the first element (`data[0]`) through the last (`data[4]`). The smallest element, `data[3]` in this `vector`, is then swapped with the top element, `data[0]`. Once this is done, the `vector` is sorted at least through the first element.

`top == 0`	Before	After	Sorted
`data[0]`	**`76.0`**	**`62.0`**	⇦ Placing the Smallest Value in the "Top" Position (`index 0`)
`data[1]`	`91.0`	`91.0`	
`data[2]`	`100.0`	`100.0`	
`data[3]`	**`62.0`**	**`76.0`**	
`data[4]`	`89.0`	`89.0`	

The task of finding the smallest element is accomplished by examining all `vector` elements and keeping track of the index with the smallest integer. After this, the smallest `vector` element is swapped with `data[top]` where top will range from `0` to `n-1`. Here is an algorithm that accomplishes these two tasks:

Algorithm: *Finding the smallest element in the vector and switching it with the topmost element*

```
(a) top = 0
// At first, assume that the first element is the smallest
(b) indexOfSmallest = top
// Check the rest of the vector (data[top + 1] through data[n - 1])
(c) for index ranging from top + 1 through n - 1
    (c1) if data[index] < data[indexOfSmallest]
             indexOfSmallest = index
// Place the smallest element into the first position and place the first vector
// element into the location where the smallest vector element was located.
(d) swap data[indexOfSmallest] with data[top]
```

The following algorithm walkthrough shows how the `vector` is sorted through the first element. The smallest integer in the `vector` will be stored at the "top" of the `vectordata[0]`. Notice that `indexOfSmallest` changes only when a `vector` element is found to be less than the one stored in `data[indexOfSmallest]`. This happens the first and third times step (c1) executes.

Step	top	indexOfSmallest	index	[0]	[1]	[2]	[3]	[4]	n
	?	?	?	76.0	91.0	100.0	62.0	89.0	5
(a)	0	"	"	"	"	"	"	"	"
(b)	"	0	"	"	"	"	"	"	"
(c)	"	"	1	"	"	"	"	"	"
(c1)	"	1	"	"	"	"	"	"	"
(c)	"	"	2	"	"	"	"	"	"
(c1)	"	"	"	"	"	"	"	"	"
(c)	"	"	3	"	"	"	"	"	"
(c1)	"	2	"	"	"	"	"	"	"
(c)	"	"	4	"	"	"	"	"	"
(c1)	"	"	"	"	"	"	"	"	"
(c)	"	"	5	"	"	"	"	"	"
(d)	"	"	"	62.0	"	"	76.0	"	"

This algorithm walkthrough shows `indexOfSmallest` changing twice to represent the index of the smallest integer in the `vector`. After traversing the entire `vector`, the smallest element is swapped with the top `vector` element. Specifically, the preceding algorithm swaps the values of the first and fourth `vector` elements, so `62.0` is stored in `data[0]` and `76.0` is stored in `data[3]`. The `vector` is now sorted through the first element!

The same algorithm can be used to place the second-smallest element into `data[1]`. The second traversal must begin at the new "top" of the `vector`—index `1` rather than `0`. This is accomplished by incrementing `top` from `0` to `1`. Now a second traversal of the `vector` begins at the second element rather than the first. The smallest element in the unsorted portion of the `vector` is swapped with the second element. A second traversal of the `vector` ensures that the first two elements are in order. In this example `vector`, `data[3]` is swapped with `data[1]` and the `vector` is sorted through the first two elements:

top == 1	Before	After	Sorted
data[0]	62.0	62.0	⇦
data[1]	**91.0**	**76.0**	⇦
data[2]	100.0	100.0	
data[3]	**76.0**	**91.0**	
data[4]	89.0	89.0	

This process repeats a total of `n-1` times:

top == 2	Before	After	Sorted
data[0]	62.0	62.0	⇦
data[1]	76.0	76.0	⇦
data[2]	**100.0**	**89.0**	⇦
data[3]	91.0	91.0	
data[4]	**89.0**	**100.0**	

An element may even be swapped with itself:

top == 3	Before	After	Sorted
data[0]	62.0	62.0	⇦
data[1]	76.0	76.0	⇦
data[2]	89.0	89.0	⇦
data[3]	**91.0**	**91.0**	⇦
data[4]	100.0	100.0	

When `top` goes to `data[4]`, the outer loop stops. The last element need not be compared to anything. It is unnecessary to find the smallest element in a `vector` of size 1. This element in `data[n - 1]` must be the largest (or equal to the largest), since all of the elements preceding the last element are already sorted in ascending order:

top == 3 and 4	Before	After	Sorted
data[0]	62.0	62.0	⇦
data[1]	76.0	**76.0**	⇦
data[2]	89.0	89.0	⇦
data[3]	91.0	91.0	⇦
data[4]	100.0	100.0	⇦

Therefore, the outer loop changes the index `top` from `0` through `n - 2`. The loop to find the smallest index in a portion of the `vector` is nested inside a loop that changes `top` from `0` through `n - 2` inclusive.

Algorithm: *Selection Sort*

```
for top ranging from 0 through n - 2  {
    indexOfSmallest = top
    for index ranging from top + 1 through n - 1  {
          if data[indexOfSmallest] < data[index] then
                                       indexOfSmallest = index
    }
swap  data[indexOfSmallest] with data[top]
}
```

Here is the C++ code that uses selection sort to sort the `vector` of numbers shown. The `vector` is printed before and after the numbers are sorted into ascending order.

```
#include <vector>
#include <iostream>
using namespace std;

void sort(vector<int> & data, int n) {
  int indexOfSmallest = 0;

  for (int top = 0; top < n - 1; top++) {
    // First assume that the smallest is the first element in the subvector
    indexOfSmallest = top;

    // Then compare all of the other elements, looking for the smallest
    for (int index = top + 1; index < data.capacity(); index++) {
      // Compare elements in the subvector
      if (data[index] < data[indexOfSmallest])
        indexOfSmallest = index;
    }

    // Then make sure the smallest from data[top] through data.size
    // is in data[top]. This message swaps two vector elements.
    double temp = data[top];  // Hold on to this value temporarily
    data[top] = data[indexOfSmallest];
    data[indexOfSmallest] = temp;
  }
}
```

```
vector<int> initialize() {
  vector<int> v(5);
  v[0] = 76;
  v[1] = 91;
  v[2] = 100;
  v[3] = 62;
  v[4] = 89;
  return v;
}

void display(vector<int> v) {
  for (int i = 0; i < v.capacity(); i++) {
    cout << v[i] << " ";
  }
  cout << endl;
}

int main() {
  vector<int> data = initialize();

  cout << "Before sorting: ";
  display(data);

  sort(data, data.capacity());
  cout << " After sorting: ";
  display(data);

  return 0;
}
```

Output

```
Before sorting: 76 91 100 62 89
After sorting: 62 76 89 91 100
```

Most sort routines arrange the elements from smallest to largest. However, with just a few simple changes, any type of elements that allow the < and > operators may be arranged into descending order using the > operator.

```
if (data[index] < data[indexOfSmallest])
     indexOfSmallest = index;
```

becomes

```
if (data[index] > data[indexOfLargest])
     indexOfLargest = index;
```

SELF-CHECK

10-25 Alphabetizing a `vector` of `string` objects requires a sort in which order—ascending or descending?

10-26 If the largest element in a `vector` already exists as the first, what happens when the `swap` function is called for the first time (when `top = 0`)?

10-27 Write code that searches for and stores the largest element of `vector x` into `largest`. Assume that all elements from `x[0]` through `x[n-1]` have been given meaningful values, so all `vector` elements should be considered.

10.6 BINARY SEARCH

This chapter has shown the sequential search algorithm used to locate a `string` in a `vector` of `string` objects. This section examines the more efficient binary search algorithm. Binary search accomplishes the same search task more quickly. It is faster than a sequential search, especially when the `vector` is large. However, one of its preconditions is that the `vector` must be sorted. By contrast, the slower sequential search does not require the `vector` to be sorted and the algorithm is simpler.

In general, binary search works like this. If a `vector` of objects is sorted, half of the `vector`'s elements are eliminated from the search each time a comparison is made. This is summarized in the following algorithm that searches for any element:

Algorithm: *Binary Search*

```
while the element is not found and it still may be in the vector {
  determine the position of the element in the middle of the vector
  if the element in the middle is not the one being searched for:
        eliminate the half of the vector that cannot contain the element
}
```

Each time the search element is compared to one `vector` element, the binary search effectively eliminates half the `vector` elements from the search field. In contrast, the sequential search only eliminates one element from the search field for each comparison. Assuming a `vector` of `string` objects is sorted in alphabetic order, sequentially searching for `"Ableson"` does not take long since `"Ableson"` is likely to be located as one of the first `vector` elements. However, sequentially searching for `"Zevon"` would take much more time because the sequential search algorithm first searches through all names beginning with A through Y before arriving at the Z's. Binary search gets to `"Zevon"` much more quickly.

The binary search algorithm has these preconditions:

1. The `vector` must be sorted (in ascending order for now).
2. The subscripts that reference the first and last elements must represent the entire range of meaningful elements.

The element in the middle of the `vector` is accessed by computing the `vector` subscript that is halfway between the first and last positions of the meaningful elements. This is the average

of the two subscripts that represent the first and last elements in the vector. These become subscripts in the search and will be referred to as first, mid, and last. Here is the vector to be searched:

```
vector <string> str(32);
int n = 7;

str[0]  = "ABE";  // first == 0
str[1]  = "CLAY";
str[2]  = "KIM";
str[3]  = "LAU";  // mid == 3
str[4]  = "LISA";
str[5]  = "PELE";
str[6]  = "ROE";  // last == 6
```

The binary search algorithm is preceded with several assignments to get things going:

searchString = the string being searched for
first = subscript of the first meaningful vector element
last = subscript of the last meaningful vector element
mid = (first + last) / 2

At this point, one of three things can happen:

1. The element in the middle of the vector matches the search name—the search is complete.
2. The search element precedes the middle element. The second half of the vector can be eliminated from the search field.
3. The search element follows the middle element. The first half of the vector can be eliminated from the search field.

This is written algorithmically as:

Algorithm: *Binary Search (more refined while assuming ascending sort)*

```
if searchString == str[mid] then
  searchString is found
else
  if searchString < str[mid]
    eliminate mid...last elements from the search
  else
    eliminate first...mid elements from the search
```

The binary search algorithm is implemented here as a free function assuming the vector named str has been constructed, initialized, and sorted:

```
#include <vector>
#include <iostream>
#include <string>
using namespace std;

vector<string> initialize() {
  vector<string> str(7);
  str[0] = "ABE";
  str[1] = "CLAY";
  str[2] = "KIM";
  str[3] = "LAU";
  str[4] = "LISA";
  str[5] = "PELE";
  str[6] = "ROE";
  return str;
}

// pre: The vector named str is sorted in ascending order.
//      str[0] through str[6] are defined vector elements.
//      string defines < and ==.
int indexOf(string searchString, vector<string> str, int n) {
  int first = 0;
  int last = n - 1;  // last = 6;

  while ((first <= last)) {
    int mid = (first + last) / 2;  // (0 + 6) / 2 = 3
    if (searchString == str[mid])  // Check the three possibilities
      return mid;  // 1) searchString is found
    else if (searchString < str[mid])  // 2) It's in first half so
      last = mid - 1;  //    eliminate second half
    else
      // 3) It's in second half so eliminate first half
      first = mid + 1;
  }
  return -1;  // searchString not found
}

void display(vector<string> v) {
  for (int i = 0; i < v.capacity(); i++)
    cout << v[i] << " ";
  cout << endl;
}

int main() {
  vector<string> data = initialize();
  cout << indexOf("LISA", data, data.capacity());
  return 0;
}
```

Objects Before Comparing `searchString` (`"LISA"`) to `str[mid]` (`"LAU"`)

```
str[0]  "ABE" ⇦ first == 0
str[1]  "CLAY"
str[2]  "KIM"
```

```
str[3]  "LAU" ⇦ mid == 3
str[4]  "LISA"
str[5]  "PELE"
str[6]  "ROE" ⇦ last == 6
```

After comparing `searchString` to `str[mid]`, `first` is increased and a new `mid` is computed:

```
str[0]  "ABE"   // Because "LISA" is greater than str[mid], the
str[1]  "CLAY"  // the objects str[0] through str[3] no longer need
str[2]  "KIM"   // to be searched and can now be eliminated from
str[3]  "LAU"   // subsequent search
str[4]  "LISA"   ⇦ first == 4
str[5]  "PELE"   ⇦ mid == 5
str[6]  "ROE"    ⇦ last == 6
```

Since `searchString < str[mid]` or `"LISA" < "PELE"` is true, `last` is decreased and a new `mid` is computed:

```
str[0]  "ABE"
str[1]  "CLAY"
str[2]  "KIM"
str[3]  "LAU"
str[4]  "LISA"   ⇦ first == 5    ⇦ last == 5     ⇦ mid == 5
str[5]  "PELE"  // Because "LISA" is less than str[mid], eliminate
str[6]  "ROE"   // str[5] through str[6] from the search field
```

Now `str[mid]` does equal `searchString`, so the algorithm will break out of the loop.

The binary search algorithm can be more efficient than the sequential search that only eliminates one element per comparison. Binary search eliminates half the elements for each comparison. For example, when `n == 1,024`, a binary search eliminates 512 elements from further search after the first comparison.

Now consider the possibility that the element being searched for is not in the `vector`. For example, to search for `"CARLA"`, the values of `first`, `mid`, and `last` progress as follows:

Comparison	`first`	`mid`	`last`	**Comment**
1	0	3	6	Compare `"CARLA"` to `"LAU"`
2	0	1	2	Compare `"CARLA"` to `"CLAY"`
3	0	0	0	Compare `"CARLA"` to `"ABE"`
4	1	0	0	`first <= last` is false and the function returns `-1`

The loop test `(first <= last)` evaluates to false when `searchString ("CARLA")` is not stored in the `vector`. Notice that `last` is less than `first`—the two subscripts have crossed each other.

```
str[0]  "ABE" ⇦ last == 0   ⇦ mid == 0
str[1]  "CLAY"⇦ first == 1
str[2]  "KIM"
str[3]  "LAU"
```

```
str[4]  "LISA"
str[5]  "PELE"
str[6]  "ROE"
```

After `searchString ("CARLA")` is compared to `str[1] ("ABE")`, no further comparisons are necessary. This is the second of two conditions that terminate the loop. Since `first` is no longer less than or equal to `last`, `searchString` cannot be in the `vector`.

SELF-CHECK

10-28 Write at least one precondition for a successful binary search.

10-29 What is the maximum number of comparisons (approximately) performed on a list of 1,024 elements during a binary search? (*Hint:* After one comparison, only 512 `vector` elements need be searched; after two searches, only 256 elements need be searched and so on.)

10-30 During a binary search, what condition signals that the search element does not exist in a `vector`?

10-31 What changes must be made to the binary search when the elements are sorted in descending order?

CHAPTER SUMMARY

- Whereas objects may store data of many different types at the same time (a `string`, an `int`, and even a `vector`, for example), a `vector` object stores collections of the same class (a `vector` of `char`, `int`, `string`, or `BankAccount` objects, for example).
- Individual `vector` elements are referenced with subscripts. With a C++ `vector`, the `int` expression of a subscript reference should be in the range of `0` through the `capacity - 1`. For example, the valid subscript range of `vector <double> x(100)` is `0` through `99` inclusive.
- Out-of-range subscripts may not be detected at compile time and may cause system crashes, destruction of other objects, or some other system-specific problems. It depends on the `vector` class you are using. Programmers must guard against these potential hazards. One of the easiest ways to do this is to use `vector::at`.
- An integer named `n` or `size` is usually an important piece of data that must be maintained in addition to the `vector` elements themselves. The number of meaningful elements is important in any `vector`-processing algorithm.
- Any `vector` object can be resized to have a different maximum capacity. If it is resized to be bigger, the meaningful elements remain. However, if a `vector` is resized to be smaller, truncation of meaningful elements may occur.

- The selection sort algorithm was used to arrange `vector` elements into ascending order. Any object that can be compared with `<` may be sorted.
- `vector` objects may also be sorted in ascending order, which is more appropriate sometimes, especially with `string` elements where ascending order means alphabetical order.
- The binary search algorithm is more efficient than sequential search. However, the `vector` must first be sorted for binary search to work properly.

EXERCISES

1. Show the output generated by the following program:

```
#include <iostream>
#include <vector>
using namespace std;

int main() {
  const int MAX = 10;
  vector<int> x(MAX);

  for (int i = 0; i < 3; i++)
    x[i] = i * 2;
  for (int i = 3; i < MAX; i++)
    x[i] = x[i - 1] + x[i - 2];
  for (int i = 0; i < MAX; i++)
    cout << i << ". " << x[i] << endl;
  return 0;
}
```

2. How many elements must be given meaningful values for a `vector` with 100 elements?
3. Declare a C++ `vector` called `vectorOfInts` that stores 10 integers with subscripts `0` through `9`.
4. Write code that determines the largest value of a `vector` named `list`. Assume all elements from index `0` through `list.size()-1` have been assigned meaningful values.
5. Write code to determine the average of integers in a `vector` named `list`. Assume all elements from index `0` through `list.size()-1` have been assigned meaningful values.
6. Write the output generated by the following program:

```
#include <iostream>
#include <vector>
#include <string>
using namespace std;

void init(vector<char> & data, int & n) {
  // postcondition: Initialize data as a vector of chars.
  // Initialize n as the number of meaningful elements.
```

```
  n = 5;
  data[0] = 'c';
  data[1] = 'b';
  data[2] = 'e';
  data[3] = 'd';
  data[4] = 'a';
}

void display(const vector<char> & data, int n) {
 // post: Show all meaningful elements of data
  cout << endl;
  cout << "Vector of chars:  ";
  for(int i = 0; i < n; i++)
    cout << data[i] << "  ";
  cout << endl;
}

void mystery(vector<char> & data, int n) {
  // post: Reverse the order of data
  int last;
  char temp;

  last = n - 1;
  for(int i = 0; i < n / 2 + 1; i++) {
    temp = data[i];
    data[i] = data[last];
    data[last] = temp;
    last--;
  }
}

int main() {
  vector<char> characters(10, ' ');
  int n;

  init(characters, n);
  display(characters, n);
  mystery(characters, n);
  display(characters, n);

  return 0;
}
```

7. Write code to declare and initialize a `vector` of 10 `string` objects with keyboard input. Your dialogue should look like this:

```
Enter 10 strings
#0 First
#1 Second
. . .
#9 Tenth
```

8. Write code that sets `found` to `true` if a given `string` is found in the following `vector`. If a `string` is not in the `vector`, let `found` be `false`. Assume only the first `n` `vector` elements are initialized and are to be considered.

```
vector<string> s(200);
int n = 127;
bool found = false;
```

9. How many comparisons does a sequential search make when the search element is stored in the first `vector` element and there are 1,000 meaningful elements in the `vector`?

10. How many comparisons does a sequential search make when the search element does not match any `vector` element and there are 1,000 elements in the `vector`?

11. Assuming a large number of searches are made on a `vector`, and it is just as likely that an element will be found in the first position as the last position, approximate the average number of comparisons after 1,000 searches when there are 1,000 elements in the `vector`.

12. Write the output generated by the following program (trick question):

```
#include <vector>  // For the vector<type> class
#include <iostream>
using namespace std;

void init(vector<int> x, int n) {
  // post: Supposedly modify n and the first n elements of test in main
  x[0] = 0;
  x[1] = 11;
  x[2] = 22;
  x[3] = 33;
  x[4] = 44;
  n = 5;
}

int main() {
  vector <int> test(100, 0);
  int n;

  // Initialize test and n
  init(test, n);
  // Display the vector with n meaningful values
  cout << "The vector: ";
  for(int i = 0; i < n; i++)
    cout << test[i] << "  ";

  return 0;
}
```

13. How would you change the code in exercise 12 so that the output is:

```
The vector: 0  11  22  33  44
```

14. Write the output generated by the following program:

```
#include <vector>  // For the vector<type> class
#include <iostream>
using namespace std;

void f(const vector<int> & x) {
  cout << x[0] << endl;
  cout << x.capacity() << endl;
}

int main() {
  vector <int> test(10000, -1);
  f(test);
  return 0;
}
```

15. Which lines contain compile time errors?

```
void f1(vector<int> x) {
  cout << x[0] << endl;          // Line 1
  cout << x.capacity() << endl;  // Line 2
  x[0] = 999;                    // Line 3
}
```

16. Which lines contain compile time errors?

```
void f2(const vector<int> & x) {
  cout << x[0] << endl;          // Line 1
  cout << x.capacity() << endl;  // Line 2
  x[0] = 999;                    // Line 3
}
```

17. Which of the previous two functions (exercises 15 and 16) is more efficient in terms of space and time—`f1` or `f2`?

18. Write the output generated by the program segment below using the initialized `vector` of `string` objects.

```
#include <iostream>
#include <string>
#include <vector>  // For the vector<type> class
using namespace std;

int main() {
  vector<string> x(10);
  int j;
  int top = 0;
  int n = 5;

  x[0] = "Alex";
  x[1] = "Andy";
```

```
  x[2] = "Ari";
  x[3] = "Ash";
  x[4] = "Aspen";
  for (top = 0; top < n - 1; top++) {
    int subscript = top;
    for (j = top + 1; j <= n - 1; j++) {
      if (x[j] < x[subscript])
        subscript = j;
    }
    string temp = x[subscript];
    x[subscript] = x[top];
    x[top] = temp;
  }
  for (int index = n - 1; index >= 0; index--) {
    cout << x[index] << endl;
  }
  return 0;
}
```

19. Write the output of the program segment below using this initialized `vector` of `string` objects.

```
vector <string> str(20);
str[0]  = "ABE";
str[1]  = "CLAY";
str[2]  = "KIM";
str[3]  = "LAU";
str[4]  = "LISA";
str[5]  = "PELE";
str[6]  = "ROE";
str[7]  = "SAM";
str[8]  = "TRUDY";

int first = 0;
int last = 8;
int mid;
string searchString("CLAY");

cout << "First Mid Last" << endl;
while (first <= last) {
   mid = (first + last) / 2;
   cout << first << "      " << mid << "    " << last << endl;
   if (searchString == str[mid])
     break;
   else
     if (searchString < str[mid])
       last = mid - 1;
     else
       first = mid + 1;
}
```

```
if (first <= last)
  cout << searchString << " found" << endl;
else
  cout << searchString << " was not" << endl;
```

20. Write the output generated by the program segment in exercise 19 when `searchString` is assigned each of the following values:

    a. `searchString = "LISA"`
    b. `searchString = "TRUDY"`
    c. `searchString = "ROE"`
    d. `searchString = "ABLE"`
    e. `searchString = "KIM"`
    f. `searchString = "ZEVON"`

21. List at least one condition that must be true before a successful binary search can be implemented.

22. Using a binary search, what is the maximum number of comparisons (approximately) that will be performed on a list of 256 sorted elements? (*Hint*: After one comparison, only 128 `vector` elements need be searched; after two searches, only 64 elements need be searched; and so on.)

PROGRAMMING TIPS

1. C++ begins to count at `0`. The first `vector` element is referenced with subscript `0`, not `1` as is done in some other programming languages.

2. A `vector` often has a capacity greater than its number of meaningful elements. Sometimes `vector` objects are initialized to store more elements than are actually needed. In this case, only the first `n` elements are meaningful.

3. Use a second variable named `n`, perhaps to maintain the number of meaningful `vector` elements. When `vector` objects are used as a data member, consider using another data member to store the number of meaningful elements. You may need to resize to allow additional capacity. However, when using `vector` objects outside of a class, make sure you have an integer that maintains the number of meaningful elements. Consider the following code that counts the number of elements from a file as individual `vector` elements are initialized. The number of meaningful elements is maintained in `n`, so it was necessary to initialize `n` to `0` and then increment `n` by `1` for each number on file.

```
vector <double> x(100, 0.0);
double aNumber;
int n = 0;
```

```
while ((inFile >> aNumber) && (n < x.capacity())) {
  x[n] = aNumber;
  n++;
}
```

4. Consider using `at(index)` instead of `[index]`. The `at` message is safer. You get a runtime error that is easier to track down than a change to some memory in an unknown place.

5. The last meaningful `vector` element is in `x[n-1]`, not `x[n]`. Don't reference `x[n]`. This can be done in the code of the third programming tip by accidentally writing the `for` loop like this:

```
int n = 10;
vector<int> x(n, 123);
for (int j = 0; j <= n; j++) { // Used <= instead of <
  cout.width(5);
  cout << x[j];  // Will eventually reference garbage
}
```

6. Prevent assignments to a `vector` with out-of-range subscripts. The code of the third programming tip has a loop test that terminates before assignment to `x[x.capacity()]`. When `n` equals the capacity, the loop terminates.

```
while ((inFile >> aNumber) && (n < x.capacity()) ) {
  // The loop test prevents assignment to x[x.capacity()]
  x[n] = aNumber;
  n++;
}
```

   It would also be useful to notify the user that something went wrong in this case. Terminating the program prematurely is an easy (but awkward) way of doing this:

```
if (n == x.capacity() && inFile) {
  cout << "**Error** Vector was too small. Terminating program" << endl;
  return 0;
}
```

7. Make your programs robust with `vector::resize` and `vector::capacity`. The code in programming tip 6 can be most irritating to users once they have purchased your software. A sounder way to handle the awkward situation of having too small a `vector` is to resize it when necessary. With the following code, the `vector`'s capacity will increase by 10 elements every time the `vector` fills up. This code also demonstrates the advantage of keeping track of the number of meaningful values in a separate integer variable because `size()` and `capacity()` are `20` when there were only 17 numbers in the input file.

```
int aNumber;
ifstream inFile("numbers");
vector<int> x(10);
int n = 0;
```

```
while (inFile >> aNumber) {
  if (n == x.capacity()) {
    x.resize(n + 10);
  }
  x[n] = aNumber;
  n++;
}

cout << "       n: " << n << endl;
cout << "    Size: " << x.size() << endl;
cout << "Capacity: " << x.capacity() << endl;
```

Output when the input file `numbers` has 17 integers:

```
       n: 17
    Size: 20
Capacity: 20
```

8. Do not pass `vector` objects by value. Passing any big object by value slows down program execution and requires unnecessary memory runtime allocation. If a function needs the values of a `vector` but is not supposed to modify the `vector`, pass the `vector` by `const` reference like this:

```
void constReferenceIsGood(const vector<double> & x, int n) {
    // This function can reference any element in x, but cannot change x
}
```

   As usual, if a function is meant to modify the argument (a `vector` in this case), pass it by reference like this:

```
void init(vector<double> & x, int & n) { // Reference parameter
  // This function can change any element in x
}
```

   Even `string` objects should be passed by `const` reference rather than by value because they are sometimes big.

9. The standard `vector` class does not check subscripts with `[]`, but it does with `vector::at(int)`. Consider using `x.at(subscript)` instead of `x[subscript]`. They are equivalent expressions with one notable exception—when the subscript is out of range, `vector::at` reports it as an error. You'll find out about the error right away during testing. This is preferable to using some random value accessed with an out-of-range subscript. Your code would look different than other C++ programs due to the historical use of `[]` and the newness of `at`.

```
#include <vector>  // For the vector<type> class
#include <iostream>
using namespace std;
```

```
int main() {
  int n;
  cout << "Enter vector capacity: ";
  cin >> n;
  vector <int> x(n);

  for(int index = 0; index < n; index++) {
    x.at(index) = index;
  }

  cout << "First: " << x.at(0) << endl;

  cout << "Last: " << x.at(x.capacity() - 1) << endl;

  return 0;
}
```

Dialogue

```
Enter vector capacity: 100
First: 0
Last: 99
```

The previous code once again demonstrates that the first element in the `vector` is referenced with a subscript of `0`, and the last element with index `capacity()-1`. So the following statement code would generate a runtime error and terminate the program:

```
cout << "Last: " << x.at(x.capacity()) << endl;  // Always an error
```

10. There are many sorting algorithms other than selection sort. Selection sort is only one of the many known sorting algorithms. Several others have approximately the same runtime efficiencies. Some are even better. For example, quicksort is usually much more efficient. This chapter was not written to cover sorting completely. It is only a very brief introduction to another category of `vector`-processing algorithms.
11. There are many searching algorithms. Sequential and binary search are only two of the known searching algorithms. For small amounts of data, sequential search works very nicely. For larger amounts of data stored in sorted `vector`s, binary search works well. Other ways to store very large amounts of data that can be searched rapidly include hash tables and binary trees, for example. These are topics usually covered in a second course.

PROGRAMMING PROJECTS

10A REVERSE

Write a complete C++ program that reads an undetermined number of integers (maximum of 100) and displays them in reverse order. The user may not supply the number of elements, so a sentinel loop must be used. Here is one sample dialogue:

```
Enter up to 100 ints using -1 to quit:
70
75
90
60
80
-1
Reversed:  80  60  90  75  70
```

10B SHOW THE ABOVE-AVERAGE ONES

Write a complete program that inputs an undetermined number of positive numeric values, determines the average, and displays every value that is greater than or equal to the average. The user may not supply the number of elements, so use a sentinel loop. Here is one sample dialogue:

```
Enter numbers or -1 to quit
70
75
90
60
80
-1
Average: 75
Inputs >= average:  75  90  80
```

10C SEQUENTIAL SEARCH FUNCTION

Write a function named `search` that returns the subscript of the first found search element in a `vector` of `string` objects. If the search element is not found, `search` should return `-1`.

10D A COLLECTION OF BANKACCOUNT OBJECTS

Write a complete C++ program that creates an undetermined number of `BankAccount` objects and stores them in a `vector`. The input should come from an external file that looks like the following, but may contain 1, 2, 3, or up to exactly 20 lines (each line represents all data necessary to create one `BankAccount` object):

```
Hall      100.00
Solly      53.45
Kirstein  999.99
  . . .
```

```
Pantone  8790.56
Brendle     0.00
Kentish  1234.45
```

After initializing the `vector` and determining the number of `BankAccount` objects, display every `BankAccount` that has a balance greater than or equal to $1,000.00. Then display every `BankAccount` that has a balance less than or equal to $100.00. Your output should look like this:

```
Balance >= 1000.00
Pantone:   8790.56
Kentish:   1234.56

Balance  < 100.00:
Solly:      53.45
Brendle:     0.00
```

10E PALINDROME 1

A *palindrome* is a collection of characters that read the same backward as forward. Write a program that extracts a `string` from the keyboard and determines whether or not the resulting `string` is a palindrome (recall that `string` objects reference individual characters with the subscript operator `[ ]`). Some examples of palindromes are YASISAY, racecar, 1234321, ABBA, level, and MADAMIMADAM. Here are two sample dialogues. (*Note:* Do not use any blank characters! If you prefer, complete programming project 10F instead.)

```
Enter string: MADAMIMADAM
    Reversed: MADAMIMADAM
  Palindrome: Yes

Enter string: RACINGCAR
Reversed: RACGNICAR
Palindrome: No
```

10F PALINDROME 2

A *palindrome* is a collection of characters that read the same backward as forward. Write a program that extracts a line of characters from the keyboard using

```
getline(istream& is, string& aString)
```

and then determines whether or not the resulting `string` is a palindrome. The blank characters should be ignored and it must be case-insensitive. (*Hint:* First convert the individual characters to uppercase with the `toupper` function from `<cctype>`, and then create a new `string` with no space characters.)

```
Enter a line: A man a plan a canal Panama
AMANAPLANACANALPANAMA is a palindrome
```

10G FIBONACCI NUMBERS

The Fibonacci numbers start as 1, 1, 2, 3, 5, 8, 13, 21. Notice that the first two are 1, and any successive Fibonacci number is the sum of the preceding two. Write an entire program that properly initializes a `vector` named `fib` to represent the first 20 Fibonacci numbers (`fib[1]` is the second Fibonacci number). Do not use 20 assignment statements to do this. Three should suffice.

10H SALARIES

Write a program that inputs an undetermined number of annual salaries from an input file. After this, display all salaries that are above average. Also show the percentage of salaries that are above average. If the input file contains this data:

```
30000.00
24000.00
35000.00
32000.00
25000.00
```

then your output should look like this:

```
Average salary = 29200.00
Above average salaries:
30000.00
35000.00
32000.00
60% of reported salaries were above average
```

10I BINARY SEARCH FUNCTION

Write a free function named `search` that returns the subscript location of the first found search element in a `vector`. Use the binary search algorithm. If the search element is not found, `search` should return `-1`. Test your function, of course.

10J FREQUENCY

Write a C++ program that reads integers from a file and reports the frequency of each integer. For example, if the input file contains the numbers as shown to the left below, your program should generate the output shown to the right below, with the highest numbers first. Create the input file so that all numbers are in the range of 0 through 100 inclusive. (*Hint*: Start with a `vector` of capacity 101 with all elements set to 0.)

The File `test.dat`

```
75   85   90  100
60   90   100  85
75   35   60   90
100  90   90   90
60   50   70   85
75   90   90   70
```

The Program Dialogue

```
Enter file name:  test.dat
100: 3
90: 8
85: 3
75: 3
70: 2
60: 3
50: 1
35: 1
```

10K EIGHT VECTOR PROCESSING FUNCTIONS

1. `int numberOfPairs(const vector<string> & strs)`

Complete `numberOfPairs` to return the number of times a pair occurs in `strs`. A pair is any two `string` elements that are equal (case sensitive) at consecutive `vector` indexes. The `vector` may be empty or have only one element. In both of these cases, return `0`. Here is some testing code that uses `push_back` messages to add elements at the end of the `vector` (you need `#include <cassert>` for the `assert` function).

```
vector<string> strs;
strs.push_back("a");
assert(0 == numberOfPairs(strs));
strs.push_back("a");
assert(1 == numberOfPairs(strs));
strs.push_back("a");
assert(2 == numberOfPairs(strs));
strs.push_back("b");
strs.push_back("b");
// a a a b b
assert(3 == numberOfPairs(strs));
```

2. `int numberOfVowels(const vector<char> & chars)`

Given a filled `vector` of `char` elements, complete `numberOfVowels` to return the number of vowels which could be the letters A, E, I, O, or U in either uppercase or lowercase. If the `vector` is empty, return `0`. Here is some testing code to help explain the expected behavior:

```
vector<char> chars;
chars.push_back('x');
assert(0 == numberOfVowels(chars));
chars.push_back('A');
chars.push_back('a');
assert(2 == numberOfVowels(chars));
chars.push_back('I');
chars.push_back('o');
```

```
chars.push_back('U');
chars.push_back('e');
assert(6 == numberOfVowels(chars));
```

3. `bool sumGreaterThan(const vector<double> & doubles, double sum)`

Given a filled `vector` of `double` elements, write function `sumGreaterThan` to return `true` if the sum of all `vector` elements is greater than `sum`. Return `false` if `sum` is less than or equal to the elements in `doubles`. Also return `false` if the `vector` is empty. Here is some testing code to help explain the expected behavior:

```
vector<double> doubles;
doubles.push_back(4.0);
assert(sumGreaterThan(doubles,  4.0)== false);
doubles.push_back(0.1);
assert(sumGreaterThan(doubles,  4.0)== true);
```

4. `int howMany(const vector<string> & vec, string valueToFind)`

Complete function `howMany` to return the number of elements in a `vector` of `strings` that equals `valueToFind`. The `vector` may be empty.

```
vector<string> strings;
strings.push_back("A");
strings.push_back("a");
strings.push_back("A");
assert(0 == howMany(strings, "x"));
assert(1 == howMany(strings, "a"));
assert(2 == howMany(strings, "A"));
```

5. `void sortOfSort(vector <int> & nums)`

Complete function `sortOfSort` that modifies the parameter `nums` to place the largest integer at index `n-1` and the smallest integer at `nums[0]`. The other elements must still be in the `vector`, but not in any particular order. You must modify the given `vector` argument by changing `nums` in method `sortOfSort`.

Original `vector`	**Modified `vector` (some elements may differ in order)**
`{4, 3, 2, 0, 1, 2}`	`{0, 3, 2, 1, 2, 4}`
`{4, 3, 2, 1}`	`{1, 3,  2, 4}`
`{4, 3, 1, 2}`	`{1, 3, 2, 4}`

```
vector<int> nums;
nums.push_back(4);
nums.push_back(3);
nums.push_back(1);
nums.push_back(2);
sortOfSort(nums);
assert(1 == nums[0]);
```

```
assert(4 == nums[3]);
assert(nums[1] == 2 || nums[1] == 3);  // depends on your algorithm
assert(nums[2] == 2 || nums[2] == 3);
```

(*Hint:* Get the smallest value at index `0` before you look for and swap the largest and the last index.)

6. `void evensLeft(vector<int> & nums)`

Modify the parameter `nums` so it still contains the exact same numbers as the given `vector`, but rearranged so that all the even numbers come before all the odd numbers. Other than that, the numbers can be in any order. You must modify the `vector` argument by changing `nums` in method `evensLeft`. The `vector` may be empty or have only one element. In both cases, no change should be made.

Original `vector`	**Modified `vector`**
`{1, 0, 1, 0, 0, 1, 1}`	`{0, 0, 0, 1, 1, 1, 1}`
`{3, 3, 2}`	`{2, 3, 3}`

```
vector<int> ints;
ints.push_back(3);
ints.push_back(3);
ints.push_back(2);
evensLeft(ints);
assert(2 == ints[0]);
assert(3 == ints[1]);
assert(3 == ints[2]);
```

7. `void shiftNTimes(vector<int> & nums, int numShifts)`

Complete `shiftNTimes` to modify `nums` so it is "left shifted" `n` times. So `shiftNTimes({6, 2, 5, 3}, 1)` changes the `vector` argument to `{2, 5, 3, 6}` and `shiftNTimes({6, 2, 5, 3}, 2)` changes the `vector` argument to `{5, 3, 6, 2}`. You must modify the `vector` argument by changing the parameter `nums` inside method `shiftNTimes`. Remember, a change to the parameter inside the method `shiftNTimes` changes the argument.

`shiftNTimes( {1, 2, 3, 4, 5, 6, 7},  3 )` modifies the vector to `{ 4, 5, 6, 7, 1, 2, 3 }`

`shiftNTimes( {1, 2, 3, 4, 5, 6, 7},  0 )` does not modify the vector

`shiftNTimes( {1, 2, 3},  5)` modifies the vector to `{ 3, 1, 2 }`

`shiftNTimes( {3},  5)` modifies the vector to `{ 3 }`

```
vector<int> nums2;
nums2.push_back(1);
nums2.push_back(2);
nums2.push_back(3);
```

```
nums2.push_back(4);
nums2.push_back(5);

shiftNTimes(nums2, 2);
assert(3 == nums2[0]);
assert(4 == nums2[1]);
assert(5 == nums2[2]);
assert(1 == nums2[3]);
assert(2 == nums2[4]);
```

8) `void replaced(char[] & vector, char oldChar, char newChar)`

Modify the `vector` arguments so all occurrences of `oldChar` are replaced by `newChar`. `replaced ({'A', 'B', 'C', 'D', 'B'}, 'B', '+')` must modify the vector argument to be `{'A', '+', 'C', 'D', '+'}`.

Original `vector`	**Modified** `vector`
`replaced({'A', 'B', 'C', 'D', 'B'}, 'C', 'L')`	`{ 'A', 'B', 'L', 'D', 'B' }`
`replaced({'n', 'n', 'D', 'N'}, 'n', 'T')`	`{ 'T', 'T', 'D', 'N' }`

```
vector<char> chars2;
chars2.push_back('n');
chars2.push_back('n');
chars2.push_back('D');
chars2.push_back('N');
replaced(chars2, 'n', 'T');
assert('T' == chars2[0]);
assert('T' == chars2[1]);
assert('D' == chars2[2]);
assert('N' == chars2[3]);
```

10L CLASS STATS

First create the header file `Stats.h` to store all member function declarations and any instance variables you would need. You will certainly need a `vector`. Then create a new file named `Stats.cpp` and implement all of the member functions of the class definition. The following test method must generate the output shown below when the input file `numbers` has these 10 integers:
`5 1 6 2 3 8 9 4 7 10`

```
/*
 * Stats.cpp
 *
 *  A test driver for class Stats
 */

#include <fstream>
#include <iostream>
#include "Stats.h"
```

```
using namespace std;

int main() {
  ifstream inFile("numbers");
  int x = 0;
  Stats tests;

  while (inFile >> x) {
    tests.add(x);
  }

  cout << "Elements before sort: ";
  tests.display();
  tests.sort();
  cout << endl << " Elements after sort: ";
  tests.display();

  cout << endl;
  cout << endl << "Statistics for the first 10 integers" << endl;
  cout << "   Size: " << tests.size() << endl;
  cout << "   Mean: " << tests.mean() << endl;
  cout << "   High: " << tests.max() << endl;
  cout << "    Low: " << tests.min() << endl;
  cout << " Median: " << tests.median() << endl;

  return 0;
}
```

Output

```
Elements before sort: 5 1 6 2 3 8 9 4 7 10
 Elements after sort: 1 2 3 4 5 6 7 8 9 10

Statistics for the first 10 integers
   Size: 10
   Mean: 5.5
   High: 10
    Low: 1
 Median: 6
```

CHAPTER ELEVEN

Generic Collections

SUMMING UP

You have now experienced generic `vector` objects as a way to store a collection of related elements of a specific type.

COMING UP

This chapter introduces another collection class named `Set` to provide a review of `vector` processing, class definitions, and member function implementations. This chapter also introduces the C++ template mechanism that allows a collection to store a specific type of object. After studying this chapter you will be able to

- build your own collection class to store any type of element
- better understand classes with data members, constructors, and member functions
- better understand how to develop functions that involve `vector` processing

11.1 COLLECTION CLASSES

As you continue your study of computing, you will spend a fair amount of time exploring ways to manage collections of data. The `vector` class presented in the previous chapter is only one of many classes designed for just this purpose. Collection classes have the following characteristics:

- Their main responsibility is to store a collection of objects.
- They usually add and remove objects from the collection.
- They allow access to individual elements in a variety of ways.

The `Set` collection class used in this chapter provides a review of class definitions and member function implementations. This time, however, member functions will employ `vector`-processing algorithms. You will also learn how collection classes can be made to store only a specific type. The type can be passed as an argument to the class when constructed.

The main purpose of the `Set` class is to store a collection of unique objects. A `Set` object has the following characteristics:

- A `Set` may store any type of object, as shown with class `vector`.
- `Set` elements are unique—duplicate elements are not allowed.
- `Set` elements need not be maintained in any particular order.

A `Set` object will understand the messages `isEmpty`, `insert`, `remove`, `size`, and `contains`. Data members include a `vector` named `elements`, which stores a collection, and an integer named `n` to store the current number of elements in the `Set` object. Before discussing this new type, consider the C++ template mechanism that permits one class to store any type of object.

11.1.1 PASSING TYPES AS ARGUMENTS

Expressions such as `x` or `1.5` can be passed as arguments to functions. Class names (types) such as `int`, `double`, `string`, and `BankAccount` can also be passed as arguments using the C++ template mechanism, `<int>` or `<string>` for example. Passing type names as arguments allows programmers to use the same collection class to hold any type of object. This means we need only one `Set` class instead of a different `Set` class for every type to be stored.

The C++ Standard Template Library (STL) uses the template mechanism to implement the standard collection types such as `vector`, `list`, `stack`, and `queue`. Rather than implementing a `vector`, `list`, `stack`, and `queue` for each new type of element that a programmer might think of, the compiler instead uses the single class template to create them automatically.

For each class name passed as an argument, a new class is automatically created to manage collections of that class. For example, we can have sets of any type:

```
Set<string> ids;            // Store string objects only
Set<double> nums;           // Store numbers only
Set<BankAccount> accounts;  // Store BankAccount objects only
```

Another advantage to templates is that we can restrict the type to insert only that one type. For example, these messages compile:

```
ids.insert("c1w4");
nums.insert(123);
accounts.insert(BankAccount("c1w4", 100.00));
```

These messages will not compile since the argument is not the proper type (which is a good thing, actually).

```
ids.insert(123);          // Argument must be a string
nums.insert("c1w4");      // Argument must be a num
accounts.insert(100.00);  // Argument must be a BankAccount
```

11.1.2 TEMPLATES

Type parameters allow programmers to pass a data type to a class to communicate the desired type of element to store.

General Form 11.1 *Class templates*

```
template<class template-parameter>
class class_name
```

Template declarations written before a class give the template parameter scope that extends throughout the entire class definition. For example, the `Set` template class in C++ could begin like this:

```
template<class Type>
class Set {
public:
  // Allow insertion of only one specific type
  void insert (Type element);
```

The `Set` type makes frequent use of the template parameter named `Type`. For example, when a `Set` is constructed like this:

```
Set <string> names;
```

the parameter `Type` is replaced by the `Type` name that was passed as the argument between angle brackets, which is `string` here. C++ then generates this code:

```
void insert(string element);
```

However, if a constructor were invoked to initialize a `Set` of `int`s as in

```
Set <int> x;
```

C++ generates this code where `Type` gets replaced with `int`:

```
void insert(int element);
```

Because `Set` is declared as a template class, the compiler can use it as a model to build any number of other classes to store different types of elements as a `Set`.

The class parameter named `Type` has scope that extends to the end of the class definition. This means that `Type` may be used anywhere in the class definition, such as in the public section or in the private data member section. For example, writing the type parameter (named `Type` here) before the class definition is critically important to the templated types:

```
template<class Type>
class Set {
public:
  Set();
  Type insert(Type element)
private:
  Type key;
};
```

The public method `insert` will accept parameters only of `Type` passed as the `Type` argument. The type of the private data member `key` is also the type passed as the `Type` argument. At declaration, the `Type` identifier is replaced with the argument specified at declaration. For example, these object initializations cause `s1` and `s2` to become templated to `string` and `double`, respectively:

```
Set <string> s1;                    Set <double> s2;

template<class Type>                template<class Type>
class Set {                         class Set {
public:                             public:
   Set();                              Set();
   void insert(string element){        void insert(double index){ }
}                                   private:
private:                               double key;
   string key;                      };
};
```

Here is a sample program to summarize the capabilities of the generic `Set` class:

```
#include <iostream>
#include <string>
using namespace std;
#include "Set.h"  // For a generic (with templates) Set class

int main() {
  Set<string> names;
  cout << "After contruction, size is " << names.size() << endl; // 0
  cout << "and the Set isEmpty: " << names.isEmpty() << endl;    // true

  // Add a few elements, duplicates not allowed
  names.insert("Chris");
  names.insert("Chris");
  names.insert("Dakota");
  names.insert("River");

  names.remove("River");     // Succeeds
  names.remove("Not here");  // No change to the Set

  cout << endl << "After 4 insert attempts and 2 remove attempts: " << endl;
  cout << "isEmpty: " << names.isEmpty() << endl; // false
  cout << "size: " << names.size() << endl;       // 2
  cout << "contains(\"Chris\")? " << names.contains("Chris") << endl;
  cout << "contains(\"Dakota\")? " << names.contains("Dakota") << endl;
  cout << "contains(\"River\")? " << names.contains("River") << endl;
  cout << "contains(\"No\")? " << names.contains("No") << endl;

  return 0;
}
```

Output (`1` means true, `0` means false)

```
After contruction, size is 0
and the Set isEmpty: 1

After 4 insert attempts and 2 remove attempts:
isEmpty: 0
size: 2
contains("Chris")? 1
contains("Dakota")? 1
contains("River")? 0
contains("No")? 0
```

One of the advantages of this `Set` class, and an issue that becomes important in many applications, is the number of elements that may be stored with one `Set` object. The maximum number of set elements cannot always be determined in advance. The number of objects that may be contained in one `Set` object depends on the size of the objects and the amount of available memory in the free store. The best answer is this: the class `Set` will store as many objects as memory allows; there is no fixed maximum size. The logic that handles this will be in the `insert` method.

To remove an object from a `Set`, the equality operator `==` must be defined for the type pass as a type parameter because it will be used in `contains` and `remove` messages. Here is code from `BankAccount.cpp` that overloads the `==` operator to return `true` if the `name` of the `BankAccount` to the left of `==` is equal to the `name` of the argument to the right of `==`.

```
// Overload the == operator to compare two BankAccount objects
  bool BankAccount::operator == (const BankAccount& right) const {
    return name == right.name;
  }
```

The binary operator `==` can now be applied to `BankAccount` objects:

```
BankAccount acct1("Ali", 123.44);
BankAccount acct2("Ali", 567.88);
BankAccount acct3("Billie", 567.88);

if(acct1 == acct2 && !(acct1 == acct3))  // true
  cout << "acct1 == acct, but not acct3: " << endl;
```

Output

```
acct1 == acct, but not acct3
```

Also, since `Set` is a collection using a `vector`, C++ requires the type of `Set` element to have a default constructor, a constructor with zero parameters like this one in `BankAccount.cpp`:

```
// A default constructor is require if you want a collection of these
BankAccount::BankAccount() {
  name = "???";
  balance = -9.99;
}
```

SELF-CHECK

Use this object declaration to answer the following questions:

```
Set<int> intSet;
```

11-1 How many integers can be stored in `intSet`?

11-2 Write code that prints the number of elements in `intSet`.

11-3 Write a message that attempts to add the integer 89 to the collection of integers in `intSet`.

11-4 Write a message that will remove 89 from `intSet`.

11.2 class Set<Type>

This section shows how a `vector` and templates are combined to implement a `Set` class. This `Set` object:

- is generic because any type of element is allowed with `<Type>`
- does not have a fixed maximum size—it allocates memory as long there is some memory available in the free store

For several reasons, this new `Set` type will have the class defined in one file, not the usual two files. The main reason for this is to prevent compile time errors. Some compilers require all code in one file to get templates to work. There will not be the usual separation of class definition in a header (`.h`) file from the implementation in a separate `.cpp` file.

A second reason for using just one `.h` file is it prevents writing the same line before every method heading. The code looks cleaner with a dozen fewer of these repeated lines: `template <class Type>`. Also there are about a dozen fewer occurrences of `Set::` before each method definition. So the generic (`template`) `Set` class will be built in the same file: `Set.h`. All methods are in the same file:

```
/**
  * Set.h
  *
  * This is a collection class to represent sets of any type.
  * Duplicate elements are not allowed.
  */
```

```
#ifndef SET_H_
#define SET_H_

#include <vector>

template<class Type>
class Set {
```

A `vector` will be used to store the elements in any `Set<Type>`. This `Set` will also maintain an `int` variable `n` to store the number of unique elements:

```
private:
  std::vector<Type> elements;
  int n;
```

The member data `n` will be initialized to 0 in the constructor, must be increased by 1 for each successful insert, and must be decreased by 1 for each successful remove.

11.2.1 THE CONSTRUCTOR `Set()`

The `Set` constructor guarantees that a `Set` starts empty with a capacity of 20, which could be larger or smaller.

```
// The public constructor
public:
  //--constructor
  Set() {
    elements.resize(20);
    n = 0;  // This Set object has zero elements when constructed
  }
```

The programmer may construct `Set` objects like this:

```
Set <double> tests;
Set <string> names;
Set <BankAccount> names;
```

11.2.2 `bool contains(Type const& value) const`

When working with `Set` objects, it is often important to know if a set contains a specific element. The `contains` member function uses a loop to sequentially search the `vector`. Once found, `contains` immediately returns true.

```
// Return true if value is in this set
bool contains(Type const& value) const {
  for (int i = 0; i < n; i++) {
    if (value == elements[i])
      return true;
  }
  return false;
}
```

If all n elements are searched for and none were == to element, the loop terminates and contains returns false to indicate element is not in this set.

11.2.3 void insert(Type const& element)

Since this collection class is a Set, insert must first ensure the collection does not contain the element. If so, a check is made to ensure the vector can store more elements. If not, the vector capacity is increased before the new element is stored.

```
// If element is not == to any element, add element to this Set
// The vector will be resized to hold more elements if needed.
void insert(Type const& element) {
  if (contains(element))
    return;
  // Otherwise add the new element at the end of the vector
  // First make sure there is enough capacity
  if (n == elements.size()) {
    // Add memory for 10 more elements whenever needed
    elements.resize(n + 10);
  }
  // Insert after the last meaningful element in this set.
  elements.at(n) = element;
  n++;
}
```

11.2.4 bool remove(Type const& removalCandidate)

The remove method will remove a found element by overwriting it with the last element in the collection. If removalCandidate is not found, the method simply returns false.

```
// pre: The removalCandidate type must overload the == operator
// post: If found, removalCandidate is removed from this Set.
//
// Remove removalCandidate if found and return true.
// If removalCandidate is not in this Set, return false.
bool remove(Type const& removalCandidate) {
  // Find the index of the element to remove
  int index = 0;
  while (index < n && !(removalCandidate == elements[index])) {
    index++;
  }

  // When subscript == size() removalCandidate was not found
  if (index == n) {
    return false;
  } else {  // Found it when elements[subscript] == removalCandidate.
    // Overwrite removalCandidate with the element at the largest index
    elements[index] = elements[n - 1];
    // decrease size by 1, and
    n--;
    // report success to the client code where the message was sent
    return true;
  }
}
```

SELF-CHECK

11-5 How many different classes are built when this code is compiled?

```
Set<string> ids;
Set<int> studentNumber;
Set<double> points;
Set<double> tests;
```

11-6 What is the value of a `Set`'s `size()` after each of these situations? Assume the `Set` is constructed before each situation.

a) 10 successful inserts, then 5 successful removals

b) 40 successful inserts

c) 40 successful inserts, then 40 successful removals

11.3 THE ITERATOR PATTERN

Because each `Set` object always knows how many elements it stores (`n`), a collection object can be given functions designed to sequentially iterate over the entire collection of items. This can be made a part of any collection class.

This textbook's `Set` class uses iterator methods to visit the contained objects. The following program shows how the client code could iterate over the entire collection without having to worry about going out of bounds. It is a preview of the four methods that will be added to class `Set<Type>` to allow access to all elements.

```
#include <iostream>
using namespace std;
#include "Set.h"  // For a generic (with templates) Set class
#include "BankAccount.h"

int main() {
  Set<BankAccount> set;  // Store set of 3 BankAccount objects
  BankAccount anAcct("Devon", 100.00);
  set.insert(anAcct);
  set.insert(BankAccount("Chris", 300.00));
  set.insert(BankAccount("Kim", 200.00));

  set.first(); // Initialize an iteration over all elements
  double total = 0.00;
  while(set.hasMore()) {
    cout << set.current().getName() << " has ";
    cout << set.current().getBalance() << endl;
    total += set.current().getBalance();
    set.next();
  }
```

```
  cout << "Total balance: " << total << endl;

  return 0;
}
```

Output

```
Devon has 100
Chris has 300
Kim has 200
Total balance: 600
```

The initial statement in the loop—`first()`—sets the `Set` object's internal index to refer to the first item in the collection. The loop test with `hasMore()` is true as long as there is at least one more element to visit. At the end of each loop iteration, the repeated statement `set.next()` updates the internal index either to refer to the next item in the collection or to make sure `hasMore()` will return false. Inside the loop, `current()` returns a reference to the element in the collection that is the element that can be accessed.

SELF-CHECK

11-7 Write code that determines the maximum `BankAccount` balance no matter how many elements are in the `Set<BankAccount>`.

11.3.1 THE ITERATOR MEMBER FUNCTIONS

The `Set` iterator member functions exist for the sole purpose of allowing client code to access any and all of the `Set` elements in a sequential fashion, from the first element to the last. The `first()` function must be called to begin the iteration to set the private data member `current` to refer to the first element in the `Set` object:

```
void first() {
  currentIndex = 0;
}
```

The `hasMore()` member function returns true if there is at least one more element to access. You will see this message used as the loop test:

```
while(set.hasMore())
```

The `hasMore()` member function compares the private data member `currentIndex` to return true when there is at least one more element to visit:

```
bool hasMore() const {
  return currentIndex < n;
}
```

The `next()` member function simply increments the internal index:

```
void next() {
  currentIndex++;
}
```

And finally, `current()` returns the element referred to by the internal cursor `current`. Notice that the return type is whatever the client code specified in constructing the `Set<Type>`.

```
Type current() const {
  return elements[currentIndex];
}
```

CHAPTER SUMMARY

- Classes with type parameters allow the user to pass a type name as an argument to a class. This allows collection classes such as `vector`, `list`, and `Set` to manage any type of object.
- A class template permits the compiler to create many different classes. The compiler does the work. The programmer need not implement separate `StringVector`, `IntVector`, and `BankAccountVector` classes, for example.
- Member functions may be implemented in one file with no separate header, while some compilers require it. This also reduces a large amount of repeated syntax. `Set` was built that way as will be the projects. Here is an outline of the `Set` class in one file with comments and the code between curly braces removed. Use this as a model for implementing the `Stack` and `PriorityList` programming projects.

```
/*
 * File name: Set.h
 * /
#ifndef SET_H_
#define SET_H_

#include <vector>

template<class Type>
class Set {

private:
  std::vector<Type> elements;
  int n;
  int currentIndex;

public:

  Set() { }

  void insert(Type const& element) { }

  bool remove(Type const& removalCandidate) { }
```

```
    int size() const { }

    bool contains(Type const& value) const { }

    bool isEmpty() const { }

    void first() { }

    bool hasMore() const { }

    void next() { }

    Type current() const { }
};

#endif /* SET_H_ */
```

- The `Set` class illustrates how a `vector` can be utilized as a storage mechanism in a class that provides higher-level messages such as `insert` and `remove`—no subscripts required.
- Collection classes such as `Set` and `vector` store collections of objects while providing suitable access to the elements.
- The `Set` class introduced the notion of iterator member functions that allow client code to traverse the entire collection without revealing the underlying structure. Sets are not ordered or indexed, so iterators are needed to visit the nodes. Other types such as `vector` are indexed and have the `[]` and `at` operations.

EXERCISES

1. Use this code to answer each of the questions below:

```
#include "Set.h"
int main()  {
   Set<double> db;
   // . . .
```

   a) How many `doubles` can `db` store?

   b) Write code that adds at least four unique elements to `db`.

   c) Write code that displays all elements in `db` on separate lines using the iterator methods.

   d) Write code that determines the range of values in `db`. Range is defined as the largest values minus the smallest.

2. Code a templated class named `plus` that shows what happens to two values when + is applied. You may place the class definition and method implementation in one file named `Plus.h`. The following code should generate the output shown in the comments:

```
// You only need one template class
Plus<int> a(2, 3);
Plus<double> b(2.2, 3.3);
Plus<string> c("Abe", "Lincoln");
a.show();  // 5
b.show();  // 5.5
c.show();  // AbeLincoln
```

3. Write code that finds the range of integers in `Set<int> intSet;`. Range is defined as the largest integer minus the smallest integer.

PROGRAMMING TIPS

1. There are many standard C++ collection classes (`vector`, `list`, `stack`, `queue`) that are more versatile and robust than our `Set` class. You do not need to use the `Set` class for any real work. The `Set` class was presented here as a review of class definitions and `vector` processing. C++ even has a generic class set. The `Set` class in this chapter introduced how to build generic collections using templates in one file.
2. When implementing generic collections, put all code in one file. This reduces the amount of repeated code before each member function. Some compilers require one file only for template classes.
3. Iteration is prevalent; sets are not. The iterator functions were shown to make you aware that this pattern is frequently used, while showing one way to access all elements of a collection. The syntax and method names are different in the C++ Standard Template Library. Sets are not used as often as other collections such as lists, stacks, and maps.
4. Templates provide genericity. The value of templates can be appreciated if you realize that one only needs one template class to create a new class for any C++ type or any new type you create. As you continue your study of C++, you will see other template classes.
5. Templates provide a lot of extra syntax. Consider the following simple and incomplete collection class that stores elements like a wait line: first in, first out. The column on the left shows two files and oft-repeated syntax, about 80 words. The single `.h` file on the right column is shorter—fewer lines, fewer words, and fewer symbols such as `<`, `>`, and `::`.

```
// File Queue.h
#include <vector>

template<class Type>
class Queue {

private:
  std::vector<Type> elements;
  int first;
  int last;

public:
  Queue();
  void add(Type const& element);
  Type remove();

};
```

```
// File Queue.cpp
#include "Queue.h"

template<class Type>
Queue<Type>::Queue() {
  elements.resize(1000);
  first = -1;
  last = -1;
}

template<class Type>
void Queue<Type>::add(Type const& element) {
  last = (last+1) % elements.capacity();
  elements[last] = element;
}

template<class Type>
Type Queue<Type>::remove() {
  first = (first+1) % elements.capacity();
  return elements[first];
}
```

```
// File Queue.h
#include <vector>

template<class Type>
class Queue {

private:
  std::vector<Type> elements;
  int first;
  int last;

public:
  Queue() {
    elements.resize(1000);
    first = -1;
    last = -1;
  }

  void add(Type const& element) {
    last = (last+1) % elements.capacity();
    elements[last] = element;
  }

  Type remove() {
    first = (first+1) % elements.capacity();
    return elements[first];
  }
};
```

PROGRAMMING PROJECTS

11A `class Stack<Type>`

Implement a generic (with templates) `Stack`. A `Stack` allows elements to be added and removed in a last-in, first-out (LIFO) manner. `Stacks` have an operation called `push` to place elements at the "top" of the stack, and another operation called `pop` to remove and return the element at the top of the stack. The only element on the stack that may be referenced is the one on the top. This means that if two elements are pushed onto the stack, the topmost element must be "popped"

(removed) from the stack before the first-pushed element can be referenced. Here is a `Stack` for storing up to 20 integers. Your program must compile and generate the output.

```
#include <iostream>
#include "Stack.h"
using namespace std;

int main() {
  Stack<int> intStack(20);  // stack of 20 ints

  // Use intStack
  intStack.push(1);
  intStack.push(2);
  intStack.push(3);
  intStack.push(4);
  cout << "4? " << intStack.peek() << endl;
  cout << "4? " << intStack.pop() << endl;
  cout << "3? " << intStack.peek() << endl;

  cout << "isEmpty 0? " << intStack.isEmpty() << endl;
  cout << "3 2 1? ";
  while(! intStack.isEmpty()) {
    cout << intStack.pop() << " ";
  }
  cout << endl;
  cout << "isEmpty 1? " << intStack.isEmpty() << endl;

  return 0;
}
```

Output

```
4? 4
4? 4
3? 3
isEmpty 0? 0
3 2 1? 3 2 1
isEmpty 1? 1
```

Note: See the beginning of a `Queue` class in the Programming Tips section of this chapter for a complete class in one `.h` file.

11B PriorityList<Type>

This project asks you to implement a collection class `PriorityList<Type>` using a `vector` data member. This new type will store a collection of elements as a zero-based indexed list where the element at index `0` is considered to have higher priority than the element at index `1`. The element at index `size()-1` has the lowest priority. An instance of this collection class will be able to store just one type of element such as `<string>`. Remember that the element at index `0` is the top priority; the element at index `size()-1` is the lowest priority.

```
PriorityList<string> todos;
todos.insertElementAt(0, "Study for the CS exam");
todos.insertElementAt(0, "Get groceries");
todos.insertElementAt(0, "Sleep");

for(int priority = 0; priority < todos.size(); priority++)
  cout << todos.getElementAt(priority) << endl;
```

Output

```
Sleep
Get groceries
Study for the CS exam
```

Complete these methods in `PriorityList<Type>` so it uses a `vector` to store the elements.

```
// Construct an empty PriorityList with capacity to store 20 elements
PriorityList();

// Return the number of elements currently in this PriorityList
int size();

// Return true if size() == 0 or false if size() > 0
bool isEmpty();

// Insert the element at the given index. If the vector
// is too small, resize it.
// precondition: index is on the range of 0 through size()
void insertElementAt(int index, Type el);

// Return a reference to the element at the given index.
// precondition: index is on the range of 0 through size()-1
Type getElementAt(int index);

// Remove the element at the given index.
// precondition: index is on the range of 0 through size()-1
void removeElementAt(int index);

// Swap the element located at index with the element at index+1.
// Lower the priority of the element at index size()-1 has no effect.
// precondition: index is on the range of 0 through size()
void lowerPriorityOf(int index);

// Swap the element located at index with the element at index-1.
// An attempt to raise the priority at index 0 has no effect.
// precondition: index is on the range of 0 through size()
void raisePriorityOf(int index);

// Move the element at the given index to the end of this list.
// An attempt to move the last element to the last has no effect.
```

```
// precondition: index is on the range of 0 through size()-1
void moveToLast(int index);

// Move the element at the given index to the front of this list.
// An attempt to move the top element to the top has no effect.
// precondition: index is on the range of 0 through size()-1
void moveToTop(int index);
```

To help you understand how these methods work, consider the program below which shows the changing list as each of the messages is sent to the list. *Recommended:* implement one method at a time, and write tests to ensure that it works.

```
#include <iostream>
#include <string>  // Needed by Visual Studio
#include "PriorityList.h"
using namespace std;

int main() {
  PriorityList<string> list;
  list.insertElementAt(0, "a");
  list.insertElementAt(1, "b");
  list.insertElementAt(2, "c");
  list.insertElementAt(3, "d");
  for (int i = 0; i < list.size(); i++) // a b c d
    cout << list.getElementAt(i) << " ";
  cout << endl;

  list.insertElementAt(1, "f");
  for (int i = 0; i < list.size(); i++) // a f b c d
    cout << list.getElementAt(i) << " ";
  cout << endl;

  list.removeElementAt(0);
  for (int i = 0; i < list.size(); i++) // f b c d
    cout << list.getElementAt(i) << " ";
  cout << endl;

  list.lowerPriorityOf(3); // no effect
  list.lowerPriorityOf(0); // move f right
  list.lowerPriorityOf(1); // move f right
  list.lowerPriorityOf(2); // move f right
  for (int i = 0; i < list.size(); i++)  // b c d f
    cout << list.getElementAt(i) << " ";
  cout << endl;

  list.raisePriorityOf(0); // no effect
  list.raisePriorityOf(2); // move d left
  list.raisePriorityOf(1); // move d left
  for (int i = 0; i < list.size(); i++)  // d b c f
    cout << list.getElementAt(i) << " ";
  cout << endl;

  list.moveToLast(list.size() - 1); // no effect
  list.moveToLast(0); // move d from top priority to last priority
```

```
  for (int i = 0; i < list.size(); i++)  // b c f d
    cout << list.getElementAt(i) << " ";
  cout << endl;

  list.moveToTop(0); // no effect
  list.moveToTop(2); // move f to top priority again
  for (int i = 0; i < list.size(); i++)  // f b c d
    cout << list.getElementAt(i) << " ";

  return 0;
}
```

11C PriorityList<Type> THROWS EXCEPTIONS

Optional: Change your code so it throws an exception when the index is out of range. To do this, first add this `#include` to `PriorityList<Type>`:

```
#include <stdexcept>
```

Then add an `if` statement to every method that takes `index` as a parameter. An exception will be thrown if the programmer supplies an incorrect index like `-1` or an `index > size()`, which is a good thing:

```
// Insert the element at the given index.
// precondition: index is on the range of 0 through size()
void insertElementAt(int index, Type element) {
   if (index < 0 || index > size()) {
      throw std::invalid_argument(
              "\ninsertElementAt: index must be 0..size()");
    }
    // . . .
```

CHAPTER TWELVE

Pointers and Memory Management

SUMMING UP

Up until now, the memory needed to store all objects has been allocated behind the scenes. We access that memory with variables names or sending messages.

COMING UP

This chapter introduces the notion of *indirection*. Indirection occurs when there is a substitute for something. Consider a library catalog card that holds the Dewey decimal number of a book. The card itself is not the book. Rather, the card is a reference to the book. Because the card names the location of the book, in a sense, the card contains an "address." C++ has its own method for implementing indirection through *pointers*—variables that store addresses of, or pointers to, other variables. This chapter also introduces the primitive C array and memory management. After studying this chapter, you will be able to

- understand that pointer objects store addresses of other objects
- use primitive C++ arrays with no range checking
- use several methods for initializing pointers
- use the `new` and `delete` operators for memory management

12.1 MEMORY CONSIDERATIONS

Every object has a name, state, and set of available operations. Objects also have *scope*—where they are known—and *lifetime*—the length of time from when they are constructed to when they go out of existence. From initializations such as

```
int able = 123;
int baker = 987;
```

most of these characteristics of the objects can be ascertained. However, the location of the object in memory—its address—is not so obvious. Until now, we have relied on the system to manage addresses. C++ allows programmers to manipulate those addresses directly.

Each object resides in a specific memory location, which is one or more bytes of computer memory. Each object is located by using the address of the first byte in the object memory loca-

tion. For example, here is a machine-level view of values showing `able` stored at address `6300` and `baker` at address `6304`. These addresses are arbitrary and could be stored at any other address. Also with C++, `int`s are usually, but are not required to be, stored in four bytes of memory.

Address	Type	Name	State
6300	int	able	123
6304	int	baker	987

The object named `able` is shown to reside in the bytes `6300`, `6301`, `6302`, and `6303`. The address of `able` is the first of those four bytes of memory, or `6300`. Although we do not always need to know the exact addresses of objects, the concept of objects that store addresses eventually becomes important in the study of computing fundamentals with C++.

The memory allocated for many objects is determined at compile time. A `char` object might require one byte of memory, an `int` usually requires either two or four depending on the computer system, and a `double` object requires a specific and predictable (at least by machine) number of bytes. These types are said to be *static* because the memory is allocated at compile time. The amount of memory allocated for a static variable is fixed and will not change while the program is running.

Pointer objects allow programmers to write code that allows for runtime allocation of memory. The space is made available while the program is running. These runtime-allocated objects are *dynamic* because they consume chunks of memory at runtime. The major benefit is this: memory is allocated on an as-needed basis. The memory can also be deallocated, or returned, to the system when no longer needed so it can be used later.

Dynamic objects manage collections that may shrink and grow in size, where the size is limited only by available memory. Programmers can more effectively control computer resources. For example, `string` objects employ behind-the-scenes dynamic memory allocation that permits a runtime sizing of `string` objects. This implementation of the `string` class was chosen because there is no way to predict how many characters will be entered by the user at runtime:

```
string name;  // Memory allocated during input
cout << "Enter your name: ";
cin >> name;
```

The `string` class also allows programmers to assign varying-length `string`s:

```
string a, b; // Appropriate memory is allocated on assignment

a = "The string a should have its own space";  // 38 chars
b = "The string b should also";                // 24 chars
```

An alternative would be to allocate a `vector` of `char`s of arbitrary size for every `string` object during the call to the constructor. But what size should we use? We could pick a size large enough to accommodate most `string`s, but this would waste large amounts of memory. Imagine a `vector`

of 1,000 `strings` in which each `string` is allocated 128 or 200 bytes of memory, even if the average length of the `strings` ends up to be only 9 characters. Without pointers, the programmer might be forced into this alternative of wasted computer memory. To understand memory management, pointers must be understood.

12.1.1 POINTERS

Pointers store the addresses of other objects—they point *to* other objects. A pointer object is declared with an asterisk (*) after the class name.

General Form 12.1 *Declaring pointer variables*

```
class-name* identifier;
```

The asterisk indicates that *`identifier`* can store the address of an object of type *`class-name`*. For example, in the declaration

```
int* intPtr;
```

the pointer object named `intPtr` may store the address of one `int` object. The object named `intPtr` does not represent an `int`—it represents the address of an `int`.

A pointer object may have one of these states:

1. It may be undefined (garbage, as `intPtr` currently is).
2. It may contain the special pointer value `nullptr`, signifying the pointer points to nothing.
3. It may point to an instance of the class it was declared to point to.

Currently any attempt to use the undefined value of `intPtr` will result in undefined system behavior. One way to set the state of `intPtr` is to assign it the special pointer constant `nullptr` that means the pointer does not point to anything.

```
intPtr = nullptr;  // intPtr points to nothing
```

Because pointer objects store addresses, their values become more meaningful when visibly written in a box with an arrow pointing to the object. So these statements

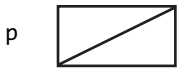
```
int anInt = 123;  // Allocate memory for an int and initialize it
int* p;  // Allocate memory to store the address of an int object
```

can be graphically represented as follows:

The `?` signifies a pointer object that has not yet been assigned a value. The `?` is a garbage value. To indicate the pointer is pointing to nothing, we use the C++ keyword `nullptr`:

```
p = nullptr;
```

When `nullptr` is assigned to the pointer `p`, the state of `p` could be pictured with a symbol such as the diagonal line show here:



Pointer objects may be assigned values through the *address of* operator `&`. The `&` operator returns the address of the object that follows it.

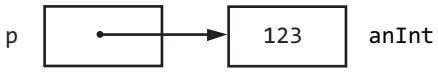
General Form 12.2 *Obtaining the address of an object*

```
&object-name;
```

For example, the expression `&anInt` evaluates to the address of `anInt`. The following statement stores the address of `anInt` in the pointer object `p` (the expression `&anInt` is read as "address of `anInt`"):

```
p = &anInt;  // &anInt returns memory location (address) of anInt
```

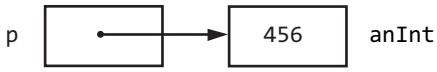
This assignment is best presented pictorially by moving the arrow from `?` to the memory that holds the address of `anInt`:



The arrow from `p` to `anInt` indicates that `p` is now pointing to the object `anInt`; however, the actual value stored in `p` is an address—the memory location of `anInt`.

The state of the object pointed to by a pointer object can be altered indirectly. For example, the state of `anInt` can be changed without even using the object name. This *indirect addressing* with the dereference, or indirection, operator `*` allows the program to inspect or change the memory pointed to by the pointer object. Here is an example of how the memory for the `anInt` pointed to by `p` may be altered:

```
= 456;  // Indirect addressing stores 456 in anInt
```



General Form 12.3 *Indirect addressing*

```
*pointer-object;
```

The assignment to *p does not change p. Instead, it changes the state of the object pointed to by p.

Note that the * has two different meanings for a pointer. First, when you declare a pointer, the asterisk means you are declaring a pointer, for example:

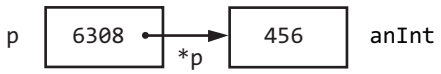
```
int* pInteger;
double* pDouble;
```

Second, when you use the asterisk with an existing pointer, it means you are dereferencing the pointer:

```
*pInteger = 456;
*pDoube = 123.45;
```

In math, * signifies multiplication. As you can see, the asterisk is truly an overloaded operator. Pay close attention to how it is used in your code to determine the meaning of the asterisk.

The asterisk that precedes a pointer object tells the pointer to go to the address that the pointer is storing and change the value at that address. So for example, if anInt were stored at address 6308, 6308 is stored in p:



To illustrate the differences between p, *p, and &anInt, consider the indirect addressing method used in the following program that interchanges the value of two pointers. By the end of the program, the two pointer objects p1 and p2 point to each other's original int object.

Note that since the pointers are pointing to double values, the pointers must be declared as double pointers. This tells the compiler to go to the address stored in the double pointer and read enough bytes for a double object (usually 8 bytes).

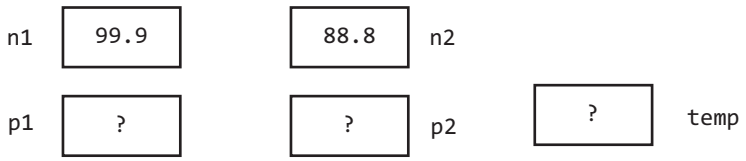
```
// Interchange two pointer values. The pointers are switched
// to point to the other's original int object.
#include <iostream>
using namespace std;

int main() {
  double* p1;
  double* p2;
  double* temp;
  double n1 = 99.9;
  double n2 = 88.8;

  // Let p1 point to n1 and p2 point to n2
  p1 = &n1;
  p2 = &n2;

  cout << "*p1 and *p2 before switch" << endl;
  // Get the integers indirectly with the * operator
```

```
  cout << (*p1) << "    " << (*p2) << endl;

  // Swap the pointers by letting p1 point to where p2 is pointing.
  // Also let p2 point to where p1 is pointing.
  temp = p1;
  p1 = p2;
  p2 = temp;

  // Now the values of the pointers are switched to point to each
  // other's int object. The ints themselves do not move.
  cout << "*p1 and *p2 after switch" << endl;
  cout << (*p1) << "    " << (*p2) << endl << endl;

  cout << "Actual memory locations in hexadecimal:" << endl;
  cout << p1 << "  " << p2  << endl;

  return 0;
}
```

Output

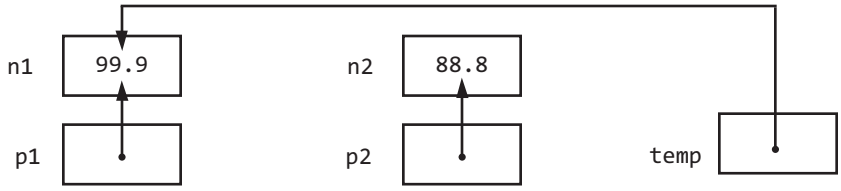
```
*p1 and *p2 before switch
99.9    88.8
*p1 and *p2 after switch
88.8    99.9

Actual memory locations in hexadecimal:
0x7fff5d00cbf0  0x7fff5d00cbf8
```

The values `99.9` and `88.8` were not moved in memory. Instead, the pointers to these `double` objects were interchanged. The following graphic representation traces this program execution. First, all five objects are initialized as follows. *Note:* All boxes represent memory storing the state of an object.



The next two statements (`p1 = &n1;` and `p2 = &n2;`) store the addresses of the `double`s in the pointers. The statement `temp = p1;` means that the pointer object `temp` is set to point to the same memory location as `p1`.

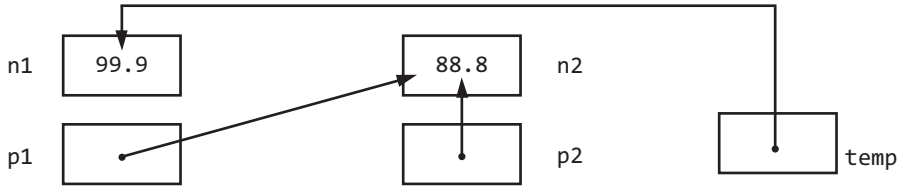
```
p1  = &n1;
p2  = &n2;
temp = p1;  // Both temp and p1 are pointers to an integer
```



The address (shown as arrows) of `p1` was stored in `temp`. At this point the expression `temp == p1` would be true. This change is indicated by the fact that arrows from both `p1` and `temp` point to the same location—the object named `n1`.

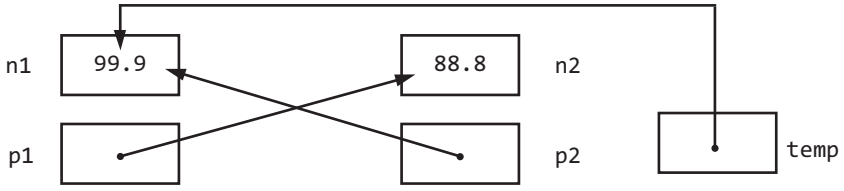
Next, the assignment `p1 = p2;` causes `p1` to point to the same place as `p2`. So `p1` and `p2` now store the same address. The two pointer values are equal.

```
p1 = p2;
```



And finally, `p2 = temp;` causes `p2` to point to the same `double` to which `p1` was originally pointing.

```
p2 = temp
```



Now that `p2` points to `n1` and `p1` points to `n2`, `cout << (*p1)` displays `88.8` rather than the original `99.9`.

At first, working with pointers is not easy. It takes a shift from understanding objects that store values to understanding objects that store addresses of other objects that store values. Algorithm design and debugging are different when using pointers. One low-cost tool that helps during debugging is the use of arrows to represent pointer values. Algorithms are traced by moving the arrow rather than writing the address.

Also when writing debugging code, the value being pointed to is usually more telling than the address of where that object is located. So debug with * as in `cout << (*aPointer);` rather than `cout << aPointer;`. With this, you see the more useful values of the objects, not their addresses.

12.1.2 POINTERS TO OBJECTS

Pointers to `int`s and `double`s refer to one single value stored in those locations. There are no associated member functions. Now consider what happens with a pointer to an object during a message. Because the dereference operator has a lower priority than a function call, this code will not work:

```
BankAccount anAcct("Functions > Dereference", 123.45);
BankAccount* bp;
bp = &anAcct;
*bp.deposit(123.45);  // ERROR
```

One way to fix this is to override the priority scheme by wrapping the pointer dereference in parentheses. Now `*bp` returns the `BankAccount` object *before* the `deposit` function gets called:

```
(*bp).deposit(123.45);  // OKAY
```

Or you could use the C++ arrow operator `->` as a shortcut to denote that the pointer is pointing to an instance of a true class:

```
bp->deposit(123.45);  // SHORTCUT
```

Both techniques are used in the following program:

```
#include <iostream>
using namespace std;
#include "BankAccount.h"

int main() {
  BankAccount anAcct("both (*bp) and bp-> work ", 100.00);
  BankAccount* bp;
  bp = &anAcct;

  // Wrap the dereference in parentheses because the dereference
  // operator * has lower precedence than function calls
  (*bp).deposit(123.45);
  cout << (*bp).getName() << (*bp).getBalance() << endl;

  // Use -> for pointers to objects other than int or double
  bp->withdraw(111.11);
  cout <<  bp->getName()  <<  bp->getBalance() << endl;

  return 0;
}
```

Output

```
both (*bp) and bp-> work 223.45
both (*bp) and bp-> work 112.34
```

SELF-CHECK

12-1 What do pointer objects store?

12-2 Use these statements to answer the questions below:

```
double* doublePtr;
double aDouble = 1.23;
doublePtr = &aDouble;
```

a. What is the name of the pointer object?

b. What is the value of `doublePtr`?

c. What is the value of `*doublePtr`?

d. Write code to *indirectly* change the value of `aDouble` from `1.23` to `2.23`.

12-3 What is the value of *ptr after this code runs:

```
int anInt = 123;
int* ptr = &anInt;
*ptr += *ptr;
```

12-4 What is the value of s3 after this code runs:

```
string s1 = string("one");
string* p1 = &s1;
string s3 = p1->c_str();
s3 += p1->c_str();
cout << s3;
```

12-5 Write an expression that evaluates to the sum of the two BankAccount balances indirectly.

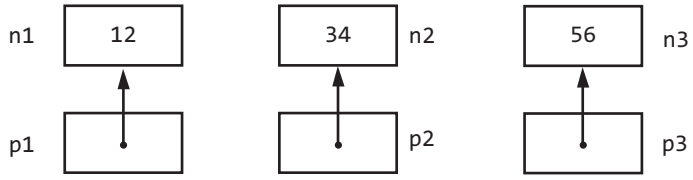
```
BankAccount ba1("one", 100.00);
BankAccount ba2("two", 200.00);
BankAccount* a = &ba1;
BankAccount* b = &ba2;
```

12-6 Write the output generated by the following program:

```
#include <iostream>
using namespace std;
int main() {
  int* p;
  int j = 12;
  p = &j;
  cout << ((*p) + (*p)) << "   " << ((*p) * (*p)) << endl;
  return 0;
}
```

12-7 Write statements that store the address of `ch`, a `char` object, into a `char` pointer object named `charPtr`.

12-8 Write the minimum code that declares and initializes all the objects as shown in the diagram below:



12-9 Using the code from your answer to the previous question, write a statement that indirectly displays the sum of all the integers using * (the dereference operator).

12-10 Write the output generated by the following code:

```
int p = 111;
int* q = &p;
p += 222;
cout << "p? " <<  p << endl;
cout << "q? " <<  *q << endl;
```

12-11 Write the output generated by the following code:

```
int n1 = 4;
int n2 = 8;
int* ptr1;
int* ptr2;
ptr1 = &n1;
ptr2 = &n2;
cout << (*ptr1) << "  " << (*ptr2) << endl;
```

12-12 Write the output generated by the following code:

```
double* p = new double;
double* q = new double;
*p = 1.23;
*q = 4.56;
p = q;
cout << (*p) << "  " << (*q);
```

12-13 In the preceding code of 12-12, is it possible to retrieve the value `1.23` by modifying the last line?

12.2 THE PRIMITIVE C ARRAY

The `vector` class is a relatively new addition to C++. In the past, the built-in, primitive C array was frequently used to store collections of objects. Because an array actually stores the address of the first element, it is a useful example for illustrating pointer usage. The C array is used so frequently for implementing programs that you are likely to see it in existing code. But more importantly, the primitive C array illustrates the benefits of dynamic memory management. It

provides a peek under the hood of `vector::resize` and `string` assignments. Both use pointers and dynamic allocation to better manage memory.

The primitive C array is a fixed-size collection of elements that are of the same class. Arrays are homogeneous because they store collections of like objects. The objects in the collection may be one of the built-in classes `char`, `int`, `long`, or `double`. The objects may also be declared as a programmer-defined class such as `BankAccount` as long as the class has a default constructor.

Here is the general form for declaring a primitive C array:

General Form 12.4 *Array declaration*

```
type array-name[capacity];
```

The *`type`* specifies the type of objects stored under *`array-name`*. The *`capacity`* specifies the maximum number of elements that can be stored under the array name. The capacity must be an integer constant (such as 100) or a named integer constant. An array cannot be sized or resized at runtime as a `vector` object can, at least not as a standard operation.

The array shown next stores a maximum of one hundred:

```
double x[100];
```

Individual array elements are referenced through subscripts in the same manner seen with `vector` objects:

General Form 12.5 *Referencing individual array elements*

```
array-name[int-expression];
```

The subscript range of a primitive array is the same as a `vector` going from `0` through `capacity - 1`.

12.2.1 DIFFERENCES BETWEEN PRIMITIVE ARRAYS AND `vectors`

There are many similarities between arrays and `vectors`—especially in the referencing of individual elements. In fact, the same `vector`-processing algorithms of chapter 10, "Vectors," could also be applied to primitive C arrays. The most noticeable difference is that primitive C arrays cannot be made to automatically check for out-of-bounds subscripts. This is one of the drawbacks of the C array. It is safer to have the subscript range-checking feature available, especially when first learning about arrays and `vectors`.

Some very strange errors occur when the code lets the computer "walk off" the end of an array. The important state of other objects may be accidentally destroyed. With the subscript range checking of `vector` objects, the program can notify the programmer whenever there is an attempt to reference out-of-bounds memory. This can be a preferable situation.

Here are the differences between the `vector` class and primitive C arrays:

Difference	`vector` Example	C Array Example
`vector`s can initialize all `vector` elements at construction; arrays cannot.	`vector <int> x(100, 0);` `// All elements are 0`	`int x[100];` `// Elements are garbage`

`vector`s can be easily resized at runtime; arrays take a lot more work.	`int n;`
	`cin >> n;`
	`x.resize(n);`
		`// See growing an array`
		`// in a later chapter`

`vector`s can be made to prevent out-of-range subscripts.	`// You are told`
	`// something is wrong`
	`cin >> x.at(100);`
		`// Destroys other variables`
		`cin >> x[100];`

`vector`s require an `#include`; primitive, built-in arrays do not.	`#include <vector>`	`// No #include required`

12.2.2 THE ARRAY / POINTER CONNECTION

It turns out that all primitive C array variables actually store the pointer to—or the address of—the first array element. Whenever the subscript operator is applied to an array object, an address is computed. For example, if `x` is an array of integers, each array element is four bytes long, and `x` has the value of address `6000`, the following formula computes `x[3]` as `6000 + (3 * 4)`.

Formula for Computing the Address of Individual Array Elements

address of first array element + (*subscript* * *size of one element*)

Therefore, `x[3]` is stored at address `6012`.

Reference	Address	Value
`x[0]`	`6000`	`?`
`x[1]`	`6004`	`?`
`x[2]`	`6008`	`?`
`x[3]`	`6012`	`?`
`x[4]`	`6016`	`?`

12.2.3 PASSING PRIMITIVE ARRAY ARGUMENTS

When an array is passed to a function, the address of the first array element gets sent. Arrays are automatically passed by reference. An array parameter is declared with the class and the parameter name followed by `[ ]`. This is illustrated in the next program where `main()` passes an array to the

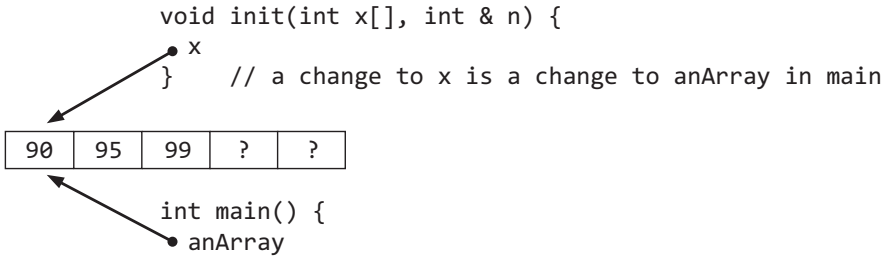
function `init`. Notice that when the function `init` alters the array parameter `x`, the associated array argument `anArray` is also altered. Both `x` and `anArray` have the first three array elements assigned a value (`90`, `95`, `99`). This occurs even though `&` is not used for the parameter `anArray`. `anArray` is passed by value.

```
// Pass the address of the array to a function.
// The & is not required. An array stores an address.
#include <iostream>
using namespace std;

void init(int x[], int & n) {
  // x and n are reference parameters; however, x does not need &
  x[0] = 90;
  x[1] = 95;
  x[2] = 99;
  n = 3;
}

int main() {
  int n = 5;
  int anArray[5];

  init(anArray, n);  // init will change x and anArray
  for (int index = 0; index < n; index++) {
    cout << anArray[index] << "  ";
  }
  cout << endl;

  return 0;
}
```

Output

```
90  95  99
```

Since the value stored in the array name is an address—a reference to the first array element, passing the array name to a function actually passes an address. Therefore, arrays are automatically passed by reference, which is the address of the first array element. Subscripting parameter `x` results in the equivalent of subscripting argument `anArray`. The following figure depicts that `anArray` was passed by reference, even though `&` was not used:



12.3 ALLOCATING MEMORY WITH new

Pointer objects are frequently assigned values through the `new` operator. When the `new` operator precedes a class name, the resulting expression allocates a contiguous block of memory large enough to store one instance of that class. Additionally, the same expression returns the address, or a pointer to, this memory.

General Form 12.6 *Dynamic memory allocation (for one object only)*

```
new class-name;
```

The memory is allocated at runtime from the *free store*—a portion of computer memory reserved for this purpose (the free store is sometimes called the *heap*). For example, the following expression allocates enough memory to store one `int` value. The expression returns a pointer to that memory.

```
new int; // Allocate memory, return a pointer value (an address)
```

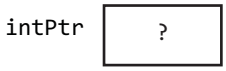
Instead of ignoring the returned pointer value (the address where an integer could be stored), such pointer expressions are usually combined with pointer objects in initializations.

```
int* intPtr = new int; // Allocate memory, store address in intPtr
```

The above is an abbreviated form of the following equivalent code:

```
int* intPtr;
intPtr = new int;  // Allocate memory, store address in intPtr
```

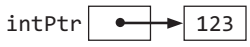
Now we have a situation where `intPtr` holds the address of an `int` object—where an `int` could be stored. This is shown in the next figure where the undefined `int` value is signified as `?` and the pointer value is represented as an arrow indicating a value that points to that undefined `int`:



This statement initializes that new allocation of memory:

```
*intPtr = 123;
```

This resulting representation shows the state of the pointer and the `int`:



The following program shows dynamic allocation of one `int` object:

```
// Illustrate one pointer object and one int object
#include <iostream>
```

```
using namespace std;

int main() {
  // Declare an intPtr as a pointer to an int
  int* intPtr;

  // Allocate memory for an int and store address in intPtr
  intPtr = new int;

  // Store 123 into memory referenced by intPtr
  *intPtr = 123;

  cout << "\n The address stored in the pointer object: " << intPtr;
  cout << "\nThe value of the int pointed to by intPtr: " << *intPtr;

  return 0;
}
```

Output (address shown in hexadecimal (`a` is `10`, `f` is `15`)

```
The address stored in the pointer object: 0x7fbd3bc04a20
The value of the int pointed to by intPtr: 123
```

Notice that the pointer object, with value `25,360` (`0x7fbd3bc04a20` hexadecimal), is referenced as `intPtr`. The actual `int` with value `123` is dereferenced as `*intPtr`.

12.3.1 ALLOCATING MEMORY FOR ARRAYS AT RUNTIME

At times it is convenient to allocate arrays at runtime, when a maximum capacity is better known. The C++ `new` operator accomplishes this by allocating memory for many objects with `[`*`capacity`*`]`, where *`capacity`* represents the number of objects to allocate.

General Form 12.7 *Dynamic memory allocation (capacity objects)*

```
new type[capacity];
```

Example: allocate memory for 10 integers

```
new int[10]; // Allocate memory for 10 integers and return
             // a pointer to this newly allocated memory
```

Because `new` returns a pointer to the first byte of the array, it can be used for pointer object initialization with this shortcut:

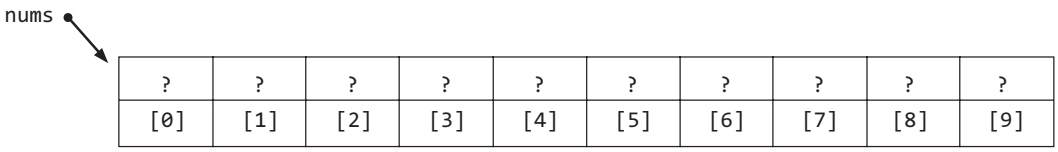
General Form 12.8 *Initializing pointer objects*

```
type* identifier = new class-name[number of elements];
```

Example:

```
int* nums = new int[10];
```

Now the pointer object `nums` points to the first of `4 * 10` bytes of uninitialized (garbage) memory where each `4` bytes stores one integer:



One time you might find this dynamic allocation of memory useful is when you have an array of objects set to an initial capacity, and then at runtime, you need to store more than the maximum capacity. This can be done with the following algorithm:

- Make a temporary array that is bigger than the instance variable.
- Copy the original contents (`num[0]` through `nums[n - 1]`) into this temporary array.
- Assign the reference to the temporary array to refer to the original array.

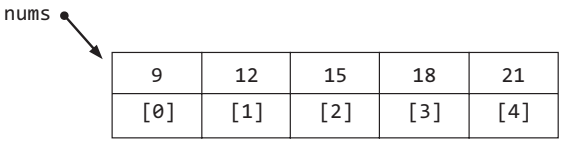
```
// This code dynamically (at runtime) "grows" an array
#include <iostream>
using namespace std;

int main() {
  int n = 10;
  int* nums = new int[n];  // Some C++ compilers can not handle int[n]
  int anInt = 1;
  // Initialize n array elements with a for loop
  for (int i = 0; i < n; i++) {
    nums[i] = anInt;
    anInt += 3;
  }

  // Show the filled array
  for (int i = 0; i < n; i++) {
    cout << nums[i] << " ";
  }

  // Need more room? Grow the array at runtime
  int* temp = new int[n+5];  // Some C++ compilers can not handle int[n+5]
  // 2) copy the elements to the temporary array
  for (int i = 0; i < n; i++) {
    temp[i] = nums[i];
  }

  // Make the original array pointer refer to the "bigger" array
  nums = temp;
```

```
  // Add 3 more elements to the bigger array
  nums[n++] = 997;
  nums[n++] = 998;
  nums[n++] = 999;

  // Print the larger array with the added elements
  cout << endl << "Larger array" << endl;
  for (int i = 0; i < n; i++) {
    cout << nums[i] << " ";
  }
  return 0;
}
```

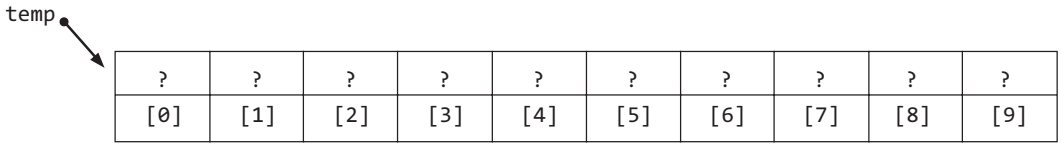
Output

```
1 4 7 10 13 16 19 22 25 28
Larger array
1 4 7 10 13 16 19 22 25 28 997 998 999
```

Here are the arrays through pictures—first the original array filled to capacity:



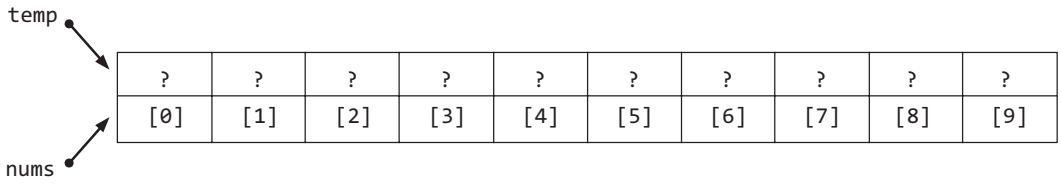
This is the new array with twice the capacity of the original:



Finally, `nums` is made to point to the new array, the same one referenced by `temp` with this one assignment statement:

```
nums = temp;
```

After three integers are added to the larger-capacity array, we have this situation:



SELF-CHECK

12-14 Write the output of the following code:

```
int* x = new int[10];
x[0] = 4;
x[1] = 8;
cout << x[0] + x[1] << endl;
```

12-15 Write one initialization using `new` to allocate an array that can store 1000 `doubles`.

12-16 Write the code that initializes all 1000 `doubles` of the previous question to `-1`.

12-17 Write the output generated by the following code:

```
const int MAX = 6;
int* x = new int[MAX];

for(int i = 0; i < MAX; i++) {
  x[i] = 2 * i;
}
for(int i = 0; i < MAX; i++) {
  cout << x[i] << "  ";
}
```

12-18 Primitive arrays can be declared and initialized at the same time with array initializers such as the following:

```
int x[] = {3, -4, -3, 6, 1};
int n = 5;
```

Write the code that finds the range of the array elements in `x`. Range is defined as the largest minus the smallest integer. Your code must work for arrays that have array initializers with different values and capacities.

12-19 Declare an array of `strings` with an array initializer that has the following `strings` in this order: `"a"`, `"b"`, `"c"`, and `"d"`.

12.4 THE `delete` OPERATOR

So far, the `new` operator examples allocated only small amounts of memory. However, consider what happens when dynamic data grows to a large size. Using `new` without returning memory to the free store results in a *memory leak*. This limits the amount of memory available to a program.

At some point, a program no longer needs dynamically allocated memory. When this occurs, the unneeded memory should be allocated back to the free store. This makes it available for other

objects that have yet to be dynamically allocated. This return of memory, or *deallocation*, is accomplished with the C++ built-in *delete* operator. The `delete` operator has two general forms:

General Form 12.9 *Deallocating memory—a form of recycling*

```
delete pointer-object;
delete[] pointer-to-array;
```

The first form returns the memory allocated for one dynamic object back to the free store. The second form returns memory allocated for a group of objects with `new` and `[ ]`. In the following program, the `delete` operator allocates enough memory for one `double` pointed to by `p`, ten `char`s pointed to by `charArray`, and 100 integers pointed to by `x`.

```
// Allocate and deallocate memory at runtime
#include <iostream>
using namespace std;

int main() {
  int* p = new int;
  *p = 123;

  int* x = new int[10000]; // claim 40,000 bytes from the free store
  x[0] = 76;
  x[1] = 89;
  // ...
  x[9999] = *p;

  // When no longer needed, free the memory to avoid memory leaks
  delete p;
  delete[] x;
  // All the bytes of memory pointed to by p and x can be allocated later

  return 0;
}
```

After the two `delete` statements return the allocated memory back to the free store, the pointers should not be used. Using them at this point results in unpredictable behavior.

Our programs with arrays should use `delete` to return the memory no longer needed. There are no notifications or errors shown. Instead, we get memory leaks, which means memory no longer needed cannot be recycled later.

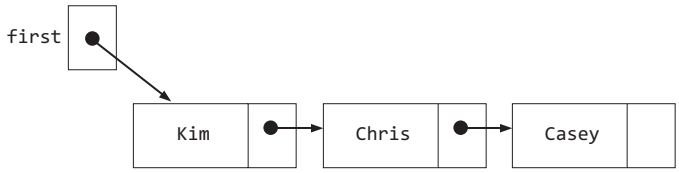
```
double* temp = new double[n+5];
for (int i = 0; i < 10; i++) {
  temp[i] = nums[i];
}

delete[] nums; // Avoid a memory leak by freeing up memory
```

12.5 THE SINGLY LINKED STRUCTURE WITH C `structs`

A singly linked data structure is an alternative way to store a collection of elements in a sequential fashion. There is high probability that your standard C++ `list` class has been implemented using a linked structure with some of the concepts presented in this section.

Instead of having elements stored in contiguous memory, this singly linked structure will have a collection of linked node objects where each node stores an element and a link to the next node in the sequential collection. We also need a pointer to the first node, which is named `first` here.

To accomplish this, a pointer data member is added to a class or a `struct`. A `struct` is the same thing as a class except that by default, members of a class are private and members of a `struct` are public. However, if you use public and private explicitly, there is no difference other than the name. The `struct` is presented here for historical reasons and because `structs` typically have constructors and data members only. Because `struct` data members are public by default, adding `public:` is not necessary.



An example struct with two public data members and a start to `LinkedList`:

```
#ifndef LINKEDLIST_H_
#define LINKEDLIST_H_

/**
 * This file contains two types:
 *
 *   1) struct node to hold an element and a link to another node
 *   2) class LinkedList to hold an indexed sequential collection using
 *      the singly linked data structure
 *
 * A LinkedList can only store string elements. Templates are not
 * used here to allow focus on pointers and memory management.
 */
struct node {

  // Two public data members
  std::string data;
  node* next;

  // Two public constructors
  node() {
```

```
    next = nullptr;
  }

  node(std::string element) {
    data = element;
    next = nullptr;
  }

};

// class LinkedList will go here . . .

#endif /* LINKEDLIST_H_ */
```

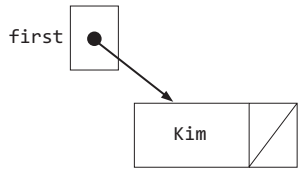
The following code constructs a new `node` object pointed to by `first` and displays the value using the `->` operator, which is necessary for dereferencing the public data members of `node`.

```
#include <iostream>
#include <string>
#include "LinkedList.h"
using namespace std;

int main() {
  // Let nodePointer reference a dynamically allocated node object
  node* first = new node("Kim");
  // assert: nodePointer->next == nullptr

  // Display the state of the public data member my_data
  cout << "  The value: " << first->data << endl;
  cout << "#characters: " << first->data.length() << endl;
}
```

Output:

```
The value: Kim
#characters: 3
```

Here is a representation of what this looks like in memory:

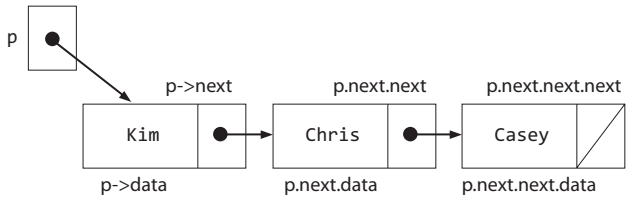


A linked structure has the characteristic that one element can be referenced from another element. With a data member to store a pointer to another object of the same class, objects can be linked together in such a way that the pointer in the first node object can be used to find the

second node. The following code constructs three node objects that are linked together. Notice that a reference to the data of the second node is made using the pointer `p ->next`.

```
// Build the first node
node* p = new node("One");

// Construct a second node pointed to by the first node's next
p->next = new node("Two");

// Build a third node pointed to by p->next->next
p->next->next = new node("Three");
```

Here is a representation of what three linked nodes look like in memory:



These three nodes can be traversed by allowing a pointer, named `ptr` here, to refer to all three nodes. It begins by having `ptr` point to the first node. If `ptr` is not `nullptr`, the node's data is displayed (inside the loop).

```
// Traverse the nodes until a next field is nullptr
node* ptr = p;  // Don't change p, which is a pointer to the first node
while(ptr != nullptr) {
  cout << ptr->data << endl;
  ptr = ptr->next;
}
```

`ptr` is updated to point to the next node or it is set to `nullptr` at the end of each loop iteration with the statement `ptr = ptr >next`.

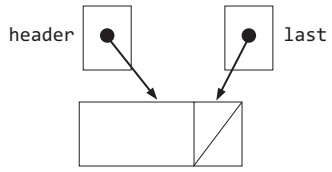
12.5.1 A LIST CLASS USING THE SINGLY-LINKED DATA STRUCTURE

This section describes `LinkedList` member functions that use these `node` objects. The constructor establishes an empty list using a dummy header node. This makes the coding easier during add and remove.

```
class LinkedList {

private:
  node* header;
  node* last;
  int n;
```

```
public:
//--constructor
  LinkedList() {
    // Create a dummy header node to make things easier
    header = new node; // call node's default constructor
    last = first;
    n = 0;
  }
```

Here is a representation of what an empty list with a dummy first node looks like in memory:



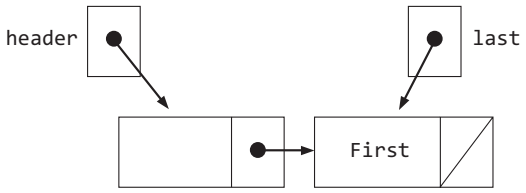
12.5.2 add(std::string)

Adding an element to a linked list has different meanings for ordered and unordered lists. An ordered list stores objects in an ascending order based on the meaning of <. The linked list developed here is not ordered so the elements will not be in alphabetic order. Since this linked list here is unordered, all new elements can be added at the very end of the list. This is easy when a dummy headed node is employed to avoid the special case of adding to an empty list or removing an element. Elements are added by creating a new object pointed to by `last->next`. The member data `last` must then be updated to point to the last node. The current count must also be incremented.

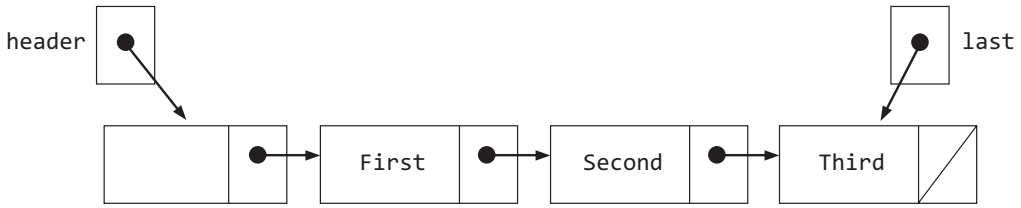
```
void add(const std::string newElement) {
  // Allocate and initialize a new node
  last->next = new node(newElement);

  // Update the last pointer
  last = last->next;

  // Maintain current size
  n++;
}
```

This one adds message results in the pictures of memory shown below:

```
LinkedList stringList;    // n == 0
stringList.add("First");  // n == 1
```




```
stringList.add("Second");  // n == 2
stringList.add("Third");   // n == 3
```



12.5.3 get(int index)

The `get` operation uses a `for` loop to advance an external pointer `ptr` to the correct node. Notice that if `index` is `0`, the `for` loop does not advance `ptr`, leaving it to point to the first real node—the one pointed to by `header->next`, which would be the value `"first"`.

```
std::string get(int index) {
  node* ptr = first->next;
  for (int i = 0; i < index; i++) {
    ptr = ptr->next;
  }
  return ptr->data;
}
```

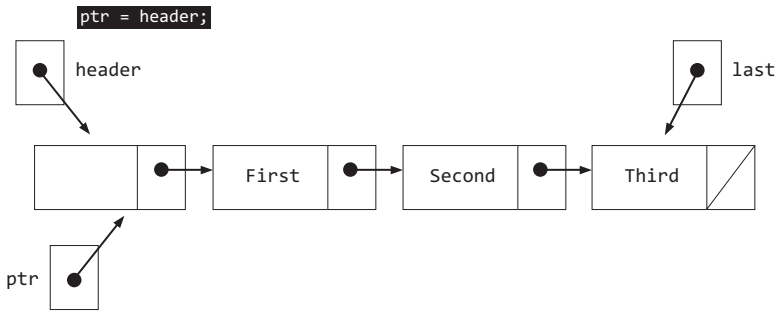
12.5.4 remove(string removalCandidate)

These two possibilities must be considered when removing an element from a linked list:

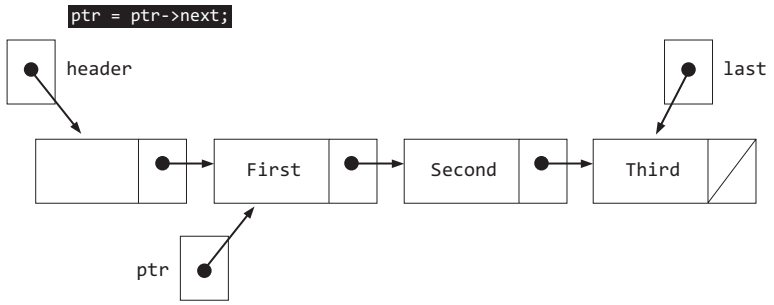
1. the == operation does not match an element in the list
2. the == operation does match an element in the list

The search for a particular element in a linked list is similar to a sequential search through a `vector` or array. The difference is that now, instead of a subscript, a pointer will be used to access the data members.

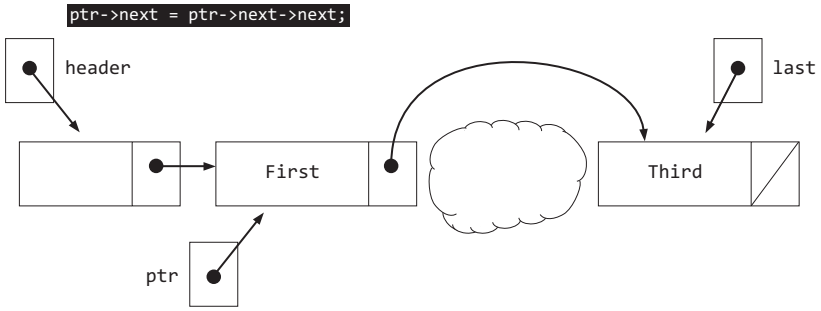
The search for `"Second"` begins by pointing a variable named `ptr` to the first element in the list. With the node `header`, we can peek one node ahead in the search while maintaining a pointer to the node that precedes the node to be removed.



A sequential search continues until `ptr->next->data` equals the `removalCandidate` or there are no more elements to search. Since `ptr->data == removalElement ("First" == "Second")` is false, the loop advances `ptr` to the next node in the list.



Now the node pointed to by `ptr` points to the node before the node to be removed: `ptr->next->data == "Second"` is true now. With the help of the dummy header node, this algorithm is able to peek at the data one node ahead. This comes in handy as we need to send a pointer around the node to be deleted with `ptr->next = ptr->next->next`.



Now the node pointed to `ptr->next` can safely be returned to the free store with `delete`.

```
bool remove(const std::string removalElement) {
  // Create an external pointer to point to the node before the first node
  node* ptr = header;

  // Search the remaining list elements until
  // found or the end of the list is found
  while (ptr->next != nullptr && ptr->next->data != removalElement) {
    ptr = ptr->next;
  }

  // Don't delete a nonexistent node
  if (ptr->next == nullptr) { // removalElement was not found
    return false;
  } else {
    // Check if the last node is being removed so last gets corrected
    if(ptr->next == last) {
      last = ptr;
    }
    // Send the link around the node to be removed
    ptr->next = ptr->next->next;
    if (ptr != header)
      delete ptr->next;  // Deallocate memory
    n--;                 // Maintain current size
    return true;         // Report successful removal
  }
 }
```

If the last node is to be removed, `last` must be adjusted to the preceding node. If `ptr` points to the last node, the element was not found so `remove` returns `false`.

SELF-CHECK

12-20 Draw a picture of a linked list with two nodes before and after removing the first node.

12-21 Draw a picture of a linked list with one node before and after removing the first node.

12-22 What happens if `removalCandidate` is not found in the list?

12-23 True or False

a. The size of a dynamically linked list must be determined before the program begins to execute.

b. Elements in a linked list are referenced through subscripts.

c. Elements may be inserted into or deleted from a linked list at the beginning, end, or even the middle of a linked list.

d. When an element is to be inserted into or deleted from a linked list, the list should be checked to see if it is empty.

e. When an element has been removed from a dynamically linked list, the memory it used should be returned to the free store.

12-24 Write method `bool removeLast()` to remove the last element in a `LinkedList`. Return `false` if the list is empty. The program should generate the output shown in comments.

```
#include <iostream>
#include <string>
#include "LinkedList.h"
using namespace std;

int main() {
  LinkedList list;
  cout << list.removeLast() << endl; // 0
  list.add("A");
  cout << list.removeLast() << endl; // 1
  list.add("B");
  list.add("C");
  list.add("D");
  cout << list.removeLast() << endl; // 1
  list.add("E");
  cout << list.get(0) << " ";
  cout << list.get(1) << " ";
  cout << list.get(2) <<  endl;     // B C E
  cout << list.size() << endl;      // 3
  return 0;
}
```

CHAPTER SUMMARY

- Pointers store addresses of other objects. A pointer object points to some object. For example, `ptr` is a pointer and `*ptr` is a reference to the `double` object `x` that starts as `99.9`.

```
double * ptr;
double x = 99.9;
ptr = &x;
*ptr = 1.234;
```

In the last statement, the pointer changes the value stored in `x` to `1.234`. The `*` (asterisk) dereferences the pointer. This means the pointer goes to the address stored in the pointer, which in this case is the address of `x` and changes the value stored at that address. Therefore, the pointer changes the value stored in `x` indirectly.

- The address of a variable is the first address at the location where the state is stored. If it takes 4 bytes to store an `int`, the address of the `int` is the address of the first byte of the `int` value, which is the address stored in the pointer. The pointer knows when to stop reading addresses because the pointer was declared as an `int` pointer. Therefore, it reads 4 bytes (this may vary depending on your computer system).
- The address operator `&` gives us the address of a variable.
- The primitive C array—similar to the C++ `vector` class—is available on all compilers and will often be seen in existing C and C++ code.
- The `new` operator allocates memory from the free store. The `delete` operator deallocates memory. If more than one object is allocated as in `char* name = new char[10];` it must be deallocated with `[ ]` like this: `delete [] name;`
- You can allocate memory at runtime with `new` and return it to the free store with `delete`.

PROGRAMMING TIPS

1. Draw linked structures when debugging programs with pointers. The value of a pointer object represents a location in the memory of the computer. These values are difficult to use in a program trace. A diagram with arrows and boxes makes execution simulation and pointer debugging much clearer.
2. Pointers allow dynamic allocation of arrays. One problem when using arrays involves how big to make them at compile time. It may be big enough one time, but not another. Sometimes memory gets wasted when declared too big.
3. Use `vectors` instead of arrays. The standard `vector` type can be dynamically grown, or shrunk even, at runtime with `resize` messages. Let this well-tested class do the work for you.
4. Avoid memory leaks. Use the `delete` operator to return the memory back to the free store for single variables. Use the `delete[]` operator to free an array of values.

EXERCISES

1. Write the values of the attributes supplied by this initialization:

```
double x = 987.65;
```

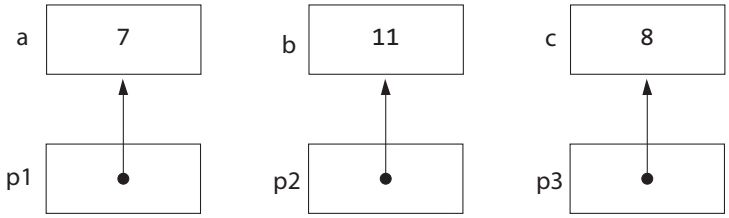
a. class
b. name
c. state
d. address

2. Declare a pointer to an `int` and initialize the pointer somehow.
3. Use these statements to answer the questions that follow:

```
int* intPtr;
int anInt = 123;
intPtr = &anInt;
```

   a. What is the name of the pointer object?
   b. What is the value of `*intPtr`?
   c. Without using `anInt`, write a statement that adds 100 to the memory storing `123`.

4. Write the minimum declarations and statements that declare and initialize all the objects as they are shown in the diagram below.



5. Using your code from the previous question, write the statements that will have a pointer object named `largestPtr` pointing to the largest integer no matter where it is stored among `a`, `b`, and `c`.
6. Using the declarations shown, which of the following are valid assignments that do not generate an error?

```
int j = 456;
int* p;
```

   a. `p = j`
   b. `p = &j`
   c. `p = 0`
   d. `j = p`
   e. `j = 123`
   f. `*p = j`
   g. `p = &p`
   h. `p = 123`
   i. `*p = "abc"`
   j. `*j = 123`
   k. `j = &p`
   l. `*p = *p`

7. Write the output generated by this code:

```
int * intPtr;
int anInt = 987;
intPtr = &anInt;
*intPtr = *intPtr + 111;
cout << *intPtr << " " << anInt;
```

8. Trace the following program segment by drawing pictures of the modified objects:

```
n1 = 123;
p1 = &n1;
*p1 = *p1 + 111;
```

9. Trace the following program segment by drawing pictures of the modified objects:

```
n2 = 999;
p3 = &n2;
p2 = p3;
```

10. Trace the following program segment by drawing pictures of the modified objects:

```
int * intPtr;
intPtr = p3;
```

PROGRAMMING PROJECTS

12A ENHANCE `LinkedList`

Add two methods to the `LinkedList` class:

1. `void toString()` to return a `string` containing all elements with 10 elements separated by a new line "`\n`".
2. `void insertInOrder(std::string element)` to insert `string` elements into the singly linked structure while maintaining alphabetical ordering.

12B CLASS `LinkedStack` WITH A SINGLY LINKED STRUCTURE

Implement class `LinkedStack` which allows elements to be added and removed in a last-in, first-out (LIFO) manner. This class must use a singly-linked structure to store the elements.

Stacks have an operation called `push` to place elements at the "top" of the stack and another operation called `pop` to remove and return the element at the top of the stack. The only element on the stack that may be referenced is the one on the top. This means that if two elements are

pushed onto the stack, the topmost element must be popped (removed) from the stack before the first-pushed element can be referenced. Here is a stack program for storing strings:

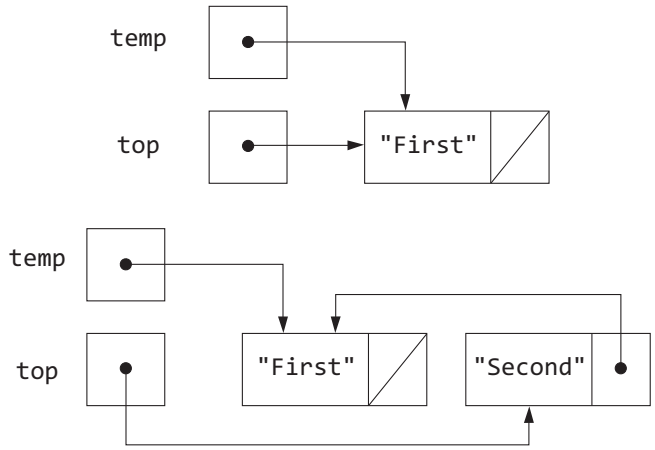
```
#include <iostream>
#include <string> // Needed by Visual Studio
#include "LinkedStack.h"
using namespace std;

int main() {
  LinkedStack stack;  // stack of 20 strings

  // Use intStack
  stack.push("a");
  stack.push("b");
  stack.push("c");
  stack.push("d");
  cout << "d? " << stack.peek() << endl;
  cout << "d? " << stack.pop() << endl;
  cout << "c? " << stack.peek() << endl;

  cout << "isEmpty 0? " << stack.isEmpty() << endl;
  cout << "c b a? ";
  while(! stack.isEmpty()) {
    cout << stack.pop() << " ";
  }
  cout << endl;
  cout << "isEmpty 1? " << stack.isEmpty() << endl;

  return 0;
}
```

Using the class `LinkedStack` that you generate, this program must compile and generate the following output:

Output

```
d? d
d? d
c? c
isEmpty 0? 0
c b a? c b a
isEmpty 1? 1
```

`LinkedStack` must use a singly linked structure. It is recommended you keep a pointer to the top of the stack and push new elements onto the front. If `top == nullptr`, you can have `top` refer to a new node with the element. When the stack is not empty, you can add to the first so `top` references the most recently added. In this case, if you have pushed `"First"` then `stack.push("Second")` you could use code shown here in pictures of memory.



12C LinkedPriorityList

This project asks you to implement a collection class `LinkedPriorityList` using a singly linked structure to store a sequence of `string` objects (no templates). This new type will store a collection of elements as a zero-based indexed list where the element at index `0` is considered to have higher priority than the element at index `1`. The element at index `size()-1` has the lowest priority. An instance of this collection class will be able to store just one type of element such as `<string>`.

Output

```
Sleep
Get groceries
Study for the CS exam
```

Complete these methods in `LinkedPriorityList` so it uses a singly linked structure to store elements. Don't forget to add `struct node` in the same file as this class.

```
// Construct an empty LinkedPriorityList
LinkedPriorityList();

// Return the number of elements currently in this LinkedPriorityList
int size();

// Return true if size() == 0 or false if size() > 0
bool isEmpty();

// Insert the element at the given index.
// precondition: index is on the range of 0 through size()
void insertElementAt(int index, std::string el);

// Return a reference to the element at the given index.
```

```
// precondition: index is on the range of 0 through size()-1
std::string getElementAt(int index);

// Remove the element at the given index.
// precondition: index is on the range of 0 through size()-1
void removeElementAt(int index);

// Swap the element located at index with the element at index+1.
// Lower the priority of the element at index size()-1 has no effect.
// precondition: index is on the range of 0 through size()
void lowerPriorityOf(int index);

// Swap the element located at index with the element at index-1.
// An attempt to raise the priority at index 0 has no effect.
// precondition: index is on the range of 0 through size()
void raisePriorityOf(int index);

// Move the element at the given index to the end of this list.
// An attempt to move the last element to the last has no effect.
// precondition: index is on the range of 0 through size()-1
void moveToLast(int index);

// Move the element at the given index to the front of this list.
// An attempt to move the top element to the top has no effect.
// precondition: index is on the range of 0 through size()-1
void moveToTop(int index);
```

To help you understand how these methods work, consider the program below that shows the changing list as each of the messages is sent to list. Recommended: implement one member function at a time, and write tests to ensure that it works.

```
#include <iostream>
#include "LinkedPriorityList.h"
using namespace std;

int main() {
  LinkedPriorityList list;
  list.insertElementAt(0, "a");
  list.insertElementAt(1, "b");
  list.insertElementAt(2, "c");
  list.insertElementAt(3, "d");
  for (int i = 0; i < list.size(); i++) // a b c d
    cout << list.getElementAt(i) << " ";
  cout << endl;

  list.insertElementAt(1, "f");
  for (int i = 0; i < list.size(); i++) // a f b c d
    cout << list.getElementAt(i) << " ";
  cout << endl;

  list.removeElementAt(0);
  for (int i = 0; i < list.size(); i++) // f b c d
    cout << list.getElementAt(i) << " ";
  cout << endl;
```

```
  list.lowerPriorityOf(3); // no effect
  list.lowerPriorityOf(0); // move f right
  list.lowerPriorityOf(1); // move f right
  list.lowerPriorityOf(2); // move f right
  for (int i = 0; i < list.size(); i++)  // b c d f
    cout << list.getElementAt(i) << " ";
  cout << endl;

  list.raisePriorityOf(0); // no effect
  list.raisePriorityOf(2); // move d left
  list.raisePriorityOf(1); // move d left
  for (int i = 0; i < list.size(); i++)  // d b c f
    cout << list.getElementAt(i) << " ";
  cout << endl;

  list.moveToLast(list.size() - 1); // no effect
  list.moveToLast(0); // move d from top priority to last priority
  for (int i = 0; i < list.size(); i++)  // b c f d
    cout << list.getElementAt(i) << " ";
  cout << endl;

  list.moveToTop(0); // no effect
  list.moveToTop(2); // move f to top priority again
  for (int i = 0; i < list.size(); i++)  // f b c d
    cout << list.getElementAt(i) << " ";

  return 0;
}
```

12D LinkedPriorityList<Type> THROWS EXCEPTIONS

Change your code so it throws an exception when the index is out of range. To do this, first add this `#include` to `PriorityList<Type>`:

```
#include <stdexcept>
```

Then add an `if` statement to every method that takes `index` as a parameter. An exception will be thrown if the programmer supplies an incorrect index like `-1` or an `index > size()`, which is a good thing:

```
// Insert the element at the given index.
// precondition: index is on the range of 0 through size()
void insertElementAt(int index, Type element) {
   if (index < 0 || index > size()) {
      throw std::invalid_argument(
              "\ninsertElementAt: index must be 0..size()");
    }
    // . . .
```

CHAPTER THIRTEEN

Vector of Vectors (2D Arrays)

SUMMING UP

You have now experienced the control structures necessary to implement any algorithm. You have also experienced ways to build programs with free functions and have written standalone classes that will help you understand the code in this chapter. The `vector` processing explained in the previous two chapters will also help.

COMING UP

This chapter discusses a class that uses two subscripts to manage data logically stored in a table-like format using rows and columns. This proves useful for storing and managing data in applications such as electronic spreadsheets, games, topographical maps, grade books, and many other data best viewed as collections of rows and columns. This chapter also reviews the C++ class construct, as the code examples use a class with the topic under study as a data member. After studying this chapter, you will be able to

- process data stored as a `vector` of `vector`s (rows and columns)
- use nested `for` loops

13.1 vector of vectors

Data that conveniently presents itself in a tabular format is represented well with a `vector` of `vector` object.

General Form 13.1 *Constructing a* `vector` *of* `vector`*s*

```
vector <vector<type> > identifier(rows,
  vector<type> (cols, initialValueoptional));
```

The following are example constructions:

```
vector <vector<double> > table(4, vector<double> (8, 0.0));    // 32 zeros
vector <vector<string> > name(5, vector<string> (100, "TBA")); // 500 TBAs
```

Reference to individual elements in a `vector` of `vectors` requires two subscripts, one for the row and another for the column. Because of this, another name for this data structure is the *two-dimensional (2D) array*.

General Form 13.2 *Accessing individual elements*

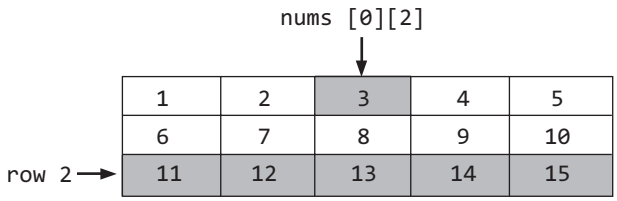
```
vectorName [row][column]
```

Each subscript must be bracketed individually. It is the programmer's responsibility to keep the subscripts in range. The first subscript of a doubly subscripted object specifies the row, and the second subscript specifies the column.

Nested looping is commonly used to process the data of 2D arrays. This code begins with a `vector` of `vectors` that has 15 random garbage values. The nested loops then initialize all elements to the integers 1 . . . 15:

Make sure you have one space here with older versions of C++.

```
vector <vector<int> > nums(3, vector<int> (5));

int count = 1;
for(int row = 0; row < nums.size(); row++) {
  // Initialize one row
  for(int col = 0; col < nums[row].size(); col++) {
     nums[row][col] = count;
     count++;
  }
}
```



SELF-CHECK

13-1 Which type more appropriately manages lists of data—a `vector` or a `vector` of `vectors`?

13-2 Which type more appropriately manages data viewed in a row-by-column format—a `vector` or `vector` of `vectors`?

13-3 Construct a `vector` of `vectors` object named `sales` where 120 numbers can be stored in 10 rows.

13-4 Construct a `vector` of `vectors` object named `sales2` where 120 numbers are stored in 10 columns.

13.2 class Matrix

In mathematics, a *matrix* (plural *matrices*) is a rectangular vector—of numbers, symbols, or expressions, arranged in rows and columns—that is treated in certain prescribed ways. One such way is to state the *order* of the matrix. For example, the order of this matrix is a 2 x 2 matrix because there are two rows and two columns:

$$\begin{bmatrix} 12 & 4 \\ -1 & 9 \end{bmatrix}$$

The individual items in a matrix are called its *elements* or *entries*.

Applications of matrices are found in most scientific fields including every branch of physics. These include classical mechanics, optics, electromagnetics, quantum mechanics, quantum electrodynamics, and the study of physical phenomena such as the motion of rigid bodies. In computer graphics, matrices are used to project a three-dimensional image onto a two-dimensional screen. In probability theory and statistics, stochastic matrices are used to describe sets of probabilities; for instance, they are used within the PageRank algorithm that ranks the pages in a Google search.

Matrices can be modeled as a C++ class that maintains the number of rows, number of columns, and a `vector` of `vector`s to store the elements. Here is a header file containing the declaration of this particular `Matrix` type (different designs are certainly possible):

```
// File name: Matrix.h

#ifndef MATRIX_H_
#define MATRIX_H_
#include <vector>

class Matrix {

private:

  int rows, columns;
  // Make sure there is a space between > and >
  //                                ||
  std::vector<std::vector<int> > table;

public:

  // Construct a new Matrix and read data from an input file
  Matrix(std::string fileName);

  // Construct a new Matrix given a vector of vectors
  Matrix(const std::vector<std::vector<int> > & vecOfVecs);

  // Return a string representation of this object.
  std::string toString();
```

```
  // Multiply each element by val
  void scalarMultiply(int val);

  // Return the sum of this Matrix + other
  Matrix add(Matrix other);

};

#endif // MATRIX_H_
```

In programs with little data required, interactive input suffices. Initialization of `vector` objects quite often involves large amounts of data. Therefore, the data will come from an external file. This will also provide another example of file input. The first line in the file of integers named `matrix.data` specifies the number of rows and columns of the input file:

```
3 4
6 7 8 9
4 5 6 7
8 7 7 8
```

Each remaining line represents the quiz scores of one student. We'll be using this intentionally small input file while showing examples of processing a `vector` of `vector`s in class `Matrix`.

The `ifstream` object `inFile` will be associated with this external file in the constructor, and the number of rows and columns will be extracted from the first line in the file (`3` and `4`) with this statement. Then the `vector` gets resized to `row` (number of rows) and `columns` (number of columns). This is necessary because memory for the `vector` of `vector`s is being allocated at runtime, dynamically and in the way C++ has built these classes: with a `Matrix` precisely large enough to store three rows of data where each row has four integers and the `vector` of `vector`s gets initialized with the file data using a nested `for` loop (a loop inside another loop). These steps are encapsulated in the `Matrix` constructor in the file `Matrix.cpp`:

```
/*
 * Matrix.cpp
 */
#include <string>
#include <fstream>
#include "Matrix.h"
using namespace std;

// Constructs a new object and reads data from
// the input file specified as the fileName argument.
Matrix::Matrix(string fileName) {
  rows = columns = 0;  // Avoid a warning from one compiler
  // Make sure the file named filename is stored in the same directory
  ifstream inFile(fileName);
  inFile >> rows >> columns;

  // Resize the vector of vectors to any capacity at runtime (dynamically).
  table.resize(rows, vector<int>(columns));
```

```
  // Initialize the vector of vectors from file input
  for (int row = 0; row < rows; row++) {
    for (int col = 0; col < columns; col++) {
      inFile >> table[row][col];
    }
  }
}
```

As with `vector` objects, the antibugging technique of displaying all initialized elements of a `Matrix` can help prevent errors. This echo of the input data is accomplished again with the help of nested loops in `Matrix::toString`.

```
string Matrix::toString() {
  string result("");
  // Concatenate all elements into one string
  for (int i = 0; i < rows; i++) {
    for (int j = 0; j < columns; j++) {
      result = result + std::to_string((int) table[i][j]) + " ";
    }
    result = result + "\n";  // new line"
  }
  return result;
}
```

The following program initializes and displays the data stored in a `Matrix` after using file input to initialize the individual `Matrix` elements:

```
#include "Matrix.h"
#include <iostream>
using namespace std;

int main() {
  Matrix m("matrix.data");
  cout << m.toString();

  return 0;
}
```

Output

```
6 7 8 9
4 5 6 7
8 7 7 8
```

This `Matrix` object is now correctly initialized and stores 12 integers.

13.2.1 SCALAR MULTIPLICATION

Scalar multiplication is the multiplication of a `vector` by a `scalar` where the product is a `vector`. This operation is implemented below as a modifier that changes the state of the `matrix` object:

```
void Matrix::scalarMultiply(int val) {
  for (int i = 0; i < rows; i++) {
    for (int j = 0; j < columns; j++) {
      table[i][j] *= val;
    }
  }
}
```

Each element is multiplied by the argument, so this code produces the output shown:

```
m.scalarMultiply(3);
cout << m.toString() << endl;
```

Output

```
18 21 24 27
12 15 18 21
24 21 21 24
```

13.2.2 MATRIX ADDITION

Matrix addition occurs when the corresponding entries of two matrices are added together:

$$\begin{bmatrix} 12 & 4 \\ -1 & 9 \end{bmatrix} + \begin{bmatrix} 7 & -2 \\ 5 & -4 \end{bmatrix} = \begin{bmatrix} 19 & 2 \\ 4 & 5 \end{bmatrix}$$

To allow code like this to return a new `Matrix`,

```
Matrix a("a.data");
Matrix b("b.data");  // Uses another input file to initialize
Matrix c = a.add(b);
```

we need a second constructor that can construct a `Matrix` object given a `vector` of `vectors` as the argument. Here is that second constructor that accepts a `vector` of `vectors` as a `const` reference parameter:

```
// Construct a new Matrix object given a vector of vectors
Matrix::Matrix(const std::vector<std::vector<int> > & vecOfVecs) {
  rows = vecOfVecs.size();
  columns = vecOfVecs[0].size();
  table = vecOfVecs;
}
```

This will be called to construct a new `Matrix` object returned by `add`:

```
Matrix Matrix::add(Matrix other) {
  vector<vector<int> > temp(rows, vector<int>(columns));
  for (int i = 0; i < rows; i++) {
    for (int j = 0; j < columns; j++) {
      temp[i][j] += table[i][j] + other.table[i][j];
    }
```

```
    }
    Matrix result(temp); // Use the second constructor
    return result;
}
```

Using input files representing the three matrices above, this code will generate the output shown:

```
cout << "Matrix a: " << endl << a.toString() << endl;
cout << "Matrix b: " << endl << b.toString() << endl;
cout << "Matrix c: " << endl << c.toString() << endl;
```

Output

```
Matrix a:
12 4
-1 9

Matrix b:
7 -2
5 -4

Matrix c:
19 2
4 5
```

SELF-CHECK

13-5 In row-by-row processing, which subscript increments more slowly—row or column?

13-6 In column-by-column processing, which subscript increments more slowly—row or column?

In the next problems, use this 2 × 2 `Matrix`:

```
12 4
-1 9
```

13-7 Complete method `get` as a member of `Matrix` to return the element at the given row and column. `Matrix.get(1, 0)` would return `-1`.

```
// Assume get is in class Matrix
int Matrix::get(int row, int column) {
```

13-8 Complete method `sum` as a member of `Matrix` to return the sum of all elements. The sum of the 2 x 2 `Matrix` is 24.

```
// Assume sum is in class Matrix
int Matrix::sum() {
```

13.3 PRIMITIVE 2D ARRAYS

The concepts of row-by-row and column-by-column processing also apply to primitive C arrays declared with two subscripts. A primitive C array declared with two subscripts use `int` expressions that specify the number of rows and columns. For example, `x` is declared here to store 10 rows and five columns of data for a total of 50 numbers:

```
double x[10][5];  // Row subscripts 0...9, column subscripts 0...4
```

The other important difference is that the primitive C array has no range checking of the subscripts. The following table compares the `Matrix` class to the primitive C array declared with two subscripts:

	`vector` of `vector`s	**Primitive C Array**
General Form	`vector <vector<`*`type`*`> >` `  `*`identifier`*` (`*`rows`*`, vector<`*`type`*`>(`*`columns`*`));`	*`type identifier`* `  [`*`rows`*`][`*`columns`*`];`
Example	`vector <vector<int> >` `  unitsSold(4, vector<int>(6));`	`int unitsSold` `  [4][6];`
Range Check	Yes	No
Resizable	Yes	No
`#include`	`#include<vector>`	Not needed

The `vector` of `vector`s, `unitsSold`, manages four rows and six columns of integers (24 elements all together). The primitive C array of the same name (declared in the right column above) manages the same number of integers with the same subscript range. Differences include the fact that primitive arrays do not range check subscripts. Individual array elements are referenced in the same manner whether you are using a primitive C array or a `vector` of `vector`s. Subscripts always start at `0` in both data structures. This means that the following code may be used with either a `vector` of `vector`s or a primitive doubly subscripted C array:

```
int unitsSold[4][6];
//  vector<vector<int> > unitsSold(4, vector<int>(6));

for (int r = 0; r < 4; r++) {
  for (int c = 0; c < 6; c++)
    unitsSold[r][c] = r + c;
}

for (int r = 0; r < 4; r++) {
  for (int c = 0; c < 6; c++) {
    cout << unitsSold[r][c] << " ";
  }
  cout << endl;
}
```

Output with either a `vector` of `vector`s or primitive C array

```
0 1 2 3 4 5
1 2 3 4 5 6
2 3 4 5 6 7
3 4 5 6 7 8
```

SELF-CHECK

Use this declaration to answer the questions that follow:

```
int a[3][4];
```

13-9 What is the value of `a[0][0]`?

13-10 Does `a` get its subscripts checked?

13-11 How many `int` elements are properly managed by `a`?

13-12 What is the row (first) subscript range for `a`?

13-13 What is the column (second) subscript range for `a`?

13-14 Write code to initialize all elements of `a` to `999`.

13-15 Write code to display all elements in each row of `a` on separate lines with eight spaces for each element.

13.4 ARRAYS WITH MORE THAN TWO SUBSCRIPTS

Singly and doubly subscripted `vector`s occur more frequently than `vector`s with more than two subscripts. However, `vector`s with three or even more subscripts are sometimes useful. Triply subscripted arrays are possible because C++ does not limit the number of subscripts. For example, the declaration

```
double q[3][11][6]
```

could represent the quiz grades for three courses, since 198 (3 × 11 × 6) grades can be stored under the same name (`q`). This triply subscripted object

```
q[1][9][3]
```

is a reference to quiz index `3` of student index `9` in course index `1`. In the following program, an array with three subscripts is initialized (with meaningless data). The first subscript—representing a course—changes the most slowly. So the `vector` object `q` is initialized and then displayed in a course-by-course manner:

```
// Declare, initialize, and display a triply subscripted vector
// object. The primitive C subscripted object is used here, but we
```

```
// could also use a vector of Matrix objects to do the same thing.
#include <iostream>
using namespace std;

int main() {
  const int courses = 3;
  const int students = 11;
  const int quizzes = 6;
  int q[courses][students][quizzes];

  for (int c = 0; c < courses; c++) {
    for (int row = 0; row < students; row++) {
      for (int col = 0; col < quizzes; col++) {
        // Give each quiz a value using a meaningless formula
        q[c][col][row] = (col + 1) * (row + 2) + c + 25;
      }
    }
  }

  for (int course = 0; course < courses; course++) {
    cout << endl;
    cout << "Course #" << course << endl;
    for (int row = 0; row < students; row++) {
      cout.width(3);
      cout << row << ": ";
      for (int col = 0; col < quizzes; col++) {
        cout.width(4);
        cout << q[course][col][row];
      }
      cout << endl;
    }
  }
  return 0;
}
```

Output with updated student line

```
Course #0
  0:   27  33  41  49  57  65
  1:   28  34  43  52  61  70
  2:   29  35  45  55  65  75
  3:   30  36  47  58  69  80
  4:   31  37  49  61  73  85
  5:   32  39  46  53  60  67
  6:   33  41  49  57  65  73
  7:   34  43  52  61  70  79
  8:   35  45  55  65  75  85
  9:   36  47  58  69  80  91
 10:   37  49  61  73  85  97
```

```
Course #1
  0:   28  34  42  50  58  66
  1:   29  35  44  53  62  71
  2:   30  36  46  56  66  76
  3:   31  37  48  59  70  81
  4:   32  38  50  62  74  86
  5:   33  40  47  54  61  68
  6:   34  42  50  58  66  74
  7:   35  44  53  62  71  80
  8:   36  46  56  66  76  86
  9:   37  48  59  70  81  92
 10:   38  50  62  74  86  98

Course #2
  0:   29  35  43  51  59  67
  1:   30  36  45  54  63  72
  2:   31  37  47  57  67  77
  3:   32  38  49  60  71  82
  4:   33  39  51  63  75  87
  5:   34  41  48  55  62  69
  6:   35  43  51  59  67  75
  7:   36  45  54  63  72  81
  8:   37  47  57  67  77  87
  9:   38  49  60  71  82  93
 10:   39  51  63  75  87  99
```

CHAPTER SUMMARY

- A doubly subscripted `vector` of `vector`s and a primitive C++ 2D array both manage data that is logically organized in a tabular format—in rows and columns.
- The first subscript specifies the rows of data in a table; the second represents the columns.
- The elements stored in these data structures can be processed row by row or column by column.
- Nested `for` loops are commonly used to process these data structures.
- Primitive 2D arrays do not check the subscript, which can lead to difficult errors. `vector` can check with `at` messages, as in `nums.at(5).at(20);` to reference the 21st element in the 6th row.

EXERCISES

1. For each doubly subscripted object declaration below, determine:

   a. The total number of elements

b. The value of all elements

```
vector<vector<string> > teacher(5, vector<string>(7, "to hire"));
vector<vector<double> > quiz(10, vector<double>(32, 0.0));
vector<vector<int> > nums(10, vector<int>(10, -999));
double budget[6][100];
```

2. Detect the error(s) in the following attempts to declare a doubly subscripted `vector`:

   a. `int x(5,6);`

   b. `double x[5,6];`

   c. `vector<vector<int> > x(5, 6);`

3. Declare a doubly subscripted object identified with three rows and four columns of floating-point numbers.

4. Write C++ code to accomplish the following tasks:

   a. Declare a doubly subscripted object called `aTable` that stores 10 rows and 14 columns of floating-point numbers.

   b. Set every element in `aTable` to `0.0`.

   c. Write a `for` loop that sets all elements in row 4 to `-1.0`.

5. Show the output from the following program when the dialogue is:

a.
```
# rows? 2
# cols? 3
```

b.
```
# rows? 3
# cols? 2
```

c.
```
# rows? 4
# cols? 4
```

d.
```
# rows? 1
# cols? 1
```

e.
```
# rows? 1
# cols? 2
```

f.
```
# rows? 2
# cols? 1
```

```
#include <iostream>
#include <vector>
using namespace std;

int main() {
  int maxRow, maxCol;
  cout << "# rows? ";
  cin >> maxRow;
  cout << "# cols? ";
  cin >> maxCol;
  vector<vector<int> > aTable(maxRow, vector<int>(maxCol, -999));

  // Initialize Matrix elements
```

```
  for (int row = 0; row < maxRow; row++) {
    for (int col = 0; col < maxCol; col++) {
      aTable[row][col] = row * col;
    }
  }

  // Display table elements
  for (int row = 0; row < maxRow; row++) {
    for (int col = 0; col < maxCol; col++) {
      cout.width(5);
      cout << aTable[row][col];
    }
    cout << endl;
  }
  return 0;
}
```

Use this class to answer questions 6 through 9:

```
class huh {
public:
  huh(int initLastRow, int initLastColumn);
  void add(int increment);
  void show() const;
  int rowSum(int currentRow) const;
private:
  int lastRow, lastCol;
  std::vector <std:vector<int> > m;
};

huh::huh(int initLastRow, int initLastColumn) {
  lastRow = initLastRow;
  lastCol = initLastColumn;
  // The vector of vectors must be initialized in the constructor.
  // Use a resize message with two arguments to avoid a loop for each row.
  m.resize(lastRow, vector<int>(lastCol));

  for(int row = 0; row < lastRow; row++) {
    for(int col = 0; col < lastCol; col++) {
     // Give each item a meaningless formula
      m[row][col] = (row + 1) + (col + 1);
    }
  }
}

void huh::show() const {
  int row, col;
  for(row = 0; row < lastRow; row++) {
     for(col = 0; col < lastCol; col++) {
       cout.width(4);
       cout << m[row][col];
    }
    cout << endl;
  }
}
```

6. Write the output generated by the following program:

```
int main() {
  huh h(1, 2);
  h.show();
  return 0;
}
```

7. Write the output generated by the following program:

```
int main() {
  huh h(3, 7);
  h.show();
  return 0;
}
```

8. Complete the member function `huh::rowSum` that returns the sum of all the elements in a given row. The program below must generate the output of 22.

```
int main() {
  huh h(4, 4);
  cout << h.rowSum(2);
  return 0;
}
```

9. Complete the member function `huh::showDiagonal` that prints all elements on the diagonal. Assume rows and columns are the same. The program to the left must generate the output on the right. *Hint:* You may use `cout.width` to get the required indentation.

```
int main() {
    huh h(4, 4);
    h.showDiagonal();
    return 0;
}
```

Output

```
2
  4
    6
      8
```

10. To class `Matrix`, add member function `transpose` that changes the `Matrix` to its transpose. The transpose of a `Matrix` has the rows replace the columns and the columns replace the rows. You will need to declare a temporary `vector` of `vector`s.

    Here is what the matrix should look like before:

```
1 4
2 5
3 6
```

    Here is what the matrix should look like after:

```
1 2 3
4 5 6
```

PROGRAMMING TIPS

1. When constructing vectors of vectors, be careful not to write >> in your constructions with some compilers.

```
vector<vector<int>> error(10, vector<int> (10, -1));
// Error: Need space between > and >
```

2. When using vectors of vectors, consider using the range-checking member function vector::at, especially when first using two subscripts. The standard vector class does not automatically check the subscripts, but it can be made to do so with the vector::at member function.

```
vector<vector<int> > aTable(3, vector<int> (3, -1));
aTable.at(2).at(3) = 23;    // Column 3 out of bounds
aTable.at(3).at(2) = 32;    // Row 3 out of bounds
cout << aTable.at(0).at(0);  // Output: -1
```

   It is common to get a subscript variable that is out of bounds. The sooner you know about it, the better. With range checking on, you'll know immediately.

3. Many of the programming tips for vectors with one subscript can be applied to doubly and triply subscripted objects:

   - The elements of any vector must be of the same class. For example, a Matrix cannot store both string and integer values.
   - Any object that uses a large amount of memory may be passed as a const reference parameter. As with singly subscripted vectors, memory is saved and only one value (the address of the Matrix) needs to be copied. However, when a Matrix is passed as a value parameter, every single element gets copied, making the program less efficient.

     ```
     void function(const Matrix<double> & m)  // Pass by const reference
     ```

     is more efficient than

     ```
     void function(Matrix<double> m)
     ```

   - Range checking should be employed while you are learning to manipulate doubly subscripted objects.

PROGRAMMING PROJECTS

13A MAGIC SQUARE

A magic square is an *n*-by-*n* vector of vectors where the integers 1 to n^2 appear exactly once where *n* must be a positive integer like 1, 3, or 5. Additionally, the sum of the integers in every

row, every column, and on both diagonals is the same. Implement class `MagicSquare` with two member functions: a constructor and `display`. The following code should generate the output shown:

```
MagicSquare magic(1);
magic.display();

1 by 1 magic square

  1
```

```
MagicSquare magic(3);
magic.display();

3 by 3 magic square

  8   1   6
  3   5   7
  4   9   2
```

```
MagicSquare magic(5);
magic.display();

5 by 5 magic square

 17  24   1   8  15
 23   5   7  14  16
  4   6  13  20  22
 10  12  19  21   3
 11  18  25   2   9
```

You should be able to construct an *n*-by-*n* magic square for any odd value *n* from 1 to 15. When *j* is 1, place the value of *j* in the middle of the first row. Then, for a counter value ranging from 1 to n^2, move up one row and to the right one column, and store the counter value—unless one of the following events occurs:

1. When the next row becomes 0, make the next row equal to $n - 1$.
2. When the next column becomes *n*, make the next column equal to 0.
3. If a position is already filled or the upper-right corner element has just obtained a value, place the next counter value in the position that is one row below the position where the last counter value has been placed.

You will need to resize the `vector` of `vectors` instance variable which can be done like this:

```
// An instance variable
vector<vector<int> > magic;

// Resize the vector to be a size by size vector
magic = vector<vector<int> >(size, vector<int>(size));
```

13B GAME OF LIFE

The Game of Life was invented by John Conway to simulate the birth and death of cells in a society. The following rules govern the birth and/or death of cells between two consecutive time periods. At time *T*:

- A cell is born if there was none at time $T - 1$ and exactly three of its neighbors were alive.
- An existing cell remains alive if at time $T - 1$ there were either two or three neighbors.

- A cell dies from isolation if at time $T-1$ there were fewer than two neighbors.
- A cell dies from overcrowding if at time $T-1$ there were more than three neighbors.

A neighborhood consists of the eight elements around any element (`N` represents one neighbor):

```
NNN
N N
NNN
```

The neighborhood can extend to the other side of the society. For example, a location in the first row has a neighborhood that includes three locations in the last row. The following patterns would occur when `T` ranges from 1 to 5, with the initial society shown at `T=1`. `O` represents a live cell; a blank indicates that no cell exists at that particular location in the society.

```
T=0       T=1      T=2      T=3      T=4
.......   .......  .......  .......  .......
..O.O..   ..O.O..  .......  .......  .......
..OOO..   ..O.O..  ..O.O..  ...O...  .......
.......   ...O...  ...O...  ...O...  .......
.......   .......  .......  .......  .......
```

Other societies may stabilize like this:

```
T=0       T=1      T=2       T=3      T=4
.......   .......  .......  .......   .......
.......   ...O...  .......  .. O...   .......
..OOO..   ...O...  ..OOO..  ...O...   ..OOO..
.......   ...O...  .......  ...O...   .......
.......   .......  .......  .......   .......
```

Use a test driver like this to see the first five versions of a society. Design your own file to be read by the `GameOfLife` constructor.

```
#include "GameOfLife.h"  // For the GameOfLife class

int main() {
  GameOfLife society("5by7");
  for (int updates = 1; updates <= 5; updates++) {
    society.toString();
    society.update();
  }
  return 0;
}
```

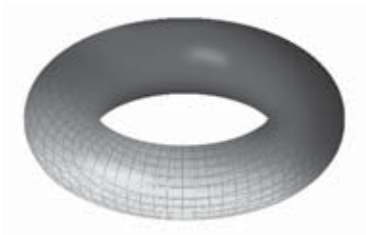
Implement the following member functions defined in this header file:

```
/*
 * File name: GameOfLife.h
 *
 * A model for John Conway's Game of Life to simulate the birth and death
 * of cells.  This is an example of cellular automata.
 */
```

```
#ifndef GAMEOFLIFE_H_
#define GAMEOFLIFE_H_

#include <vector>
#include <string>

class GameOfLife {

private:
  std::vector<std::vector<bool> > theSociety;
  int nRows;
  int nCols;

public:
  /*
   * Write the constructor to initialize a vector of vectors so
   * all elements are false. Also set nRows and nCols
   *
   */
  GameOfLife(int rows, int cols);

  /*
   * Return the number of rows, which is indexed from 0..numberOfRows()-1.
   */
  int numberOfRows();

  /*
   * The number of columns, which is indexed from 0..numberOfColumns()-1.
   */
  int numberOfColumns();

  /*
   * Place a new cell in the society.
   * Precondition: row and col are in range.
   *
   * row The row to grow the cell.
   * col The column to grow the cell.
   */
  void growCellAt(int row, int col);

  /*
   * Return true if there is a cell at the given row and column.
   * Return false if there is none at the specified location.
   *
   * row The row to check.
   * col The column to check.
   */
  bool cellAt(int row, int col);

  /*
   * Return one big string of cells to represent the current state of the
   * society of cells (see output below where '.' represents an empty space
```

```
     * and 'O' is a live cell. There is no need to test toString. Simply use
     * it to visually inspect. Here is one sample output from toString:
     *
     *  GameOfLife society(4, 14);
     *  society.growCellAt(1, 2);
     *  society.growCellAt(2, 3);
     * society.growCellAt(3, 4);
     *  cout << society.toString();
     *
     * Output
     * ..............
     * ..O...........
     * ...O..........
     * ....O.........
     * */
    std::string toString();

    /*
     * Count the neighbors around the given location. Use wraparound. A cell
     * in row 0 has neighbors in the last row if a cell is in the same column
     * or the column to the left or right. In this example, cell 0,5 has two
     * neighbors in the last row, cell 2,8 has four neighbors, cell 2,0 has
     * four neighbors, cell 1,0 has three neighbors. Cell 3,8 has 3 neighbors.
     * The potential location for a cell at 4,8 would have 3 neighbors.
     *
     * .....O..O
     * O........
     * O.......O
     * O.......O
     * ....O.O..
     *
     * The return values should always be in the range of 0 through 8.
     */
    int neighborCount(int row, int col);

    /*
     * Update the state to represent the next society.
     * Typically, some cells will die off while others are born.
     */
    void update();

};

#endif /* GAMEOFLIFE_H_ */
```

This `GameOfLife` has wraparound. It is recommended that you use nested `for` loops to visit all eight neighbors. Use an additional two `int` variables to be the actual row and column that are set, while checking to see if a loop index is negative or too large. Try to imagine the cells covering a torus:



The `O` below has eight neighbors labeled `a` through `h`. Wraparound is needed for neighbors labeled `d` through `h`. The labels are repeated to show where they need to be checked.

f	g	h				
e	O	a				e
d	c	b				d
	g	h				

Another hint: During update, initialize all elements of a temporary `vector` of `vector`s to false. Look at the `vector` instance variable. Only grow cells in the temporary `vector`. When done, assign this to the instance variable like this:

```
theSociety = temporary;
```

Here are two examples of updates in two different cell societies. After 21 updates, the society on the right will return to its original form shifted five spaces to the right. If you do 63 updates, you will see the form that begins on the right shifted to be on the left due to wraparound.

```
#include <iostream>
using namespace std;
#include "GameOfLife.h"

int main() {
  GameOfLife game(3, 8);

  game.growCellAt(1, 2);
  game.growCellAt(1, 3);
  game.growCellAt(1, 4);
  cout << game.toString();

  for (int t = 1; t <= 5; t++) {
    game.update();
    cout << game.toString();
  }
  return 0;
}
```

```
#include <iostream>
using namespace std;
#include "GameOfLife.h"

int main() {
  GameOfLife society(5, 30);

  society.growCellAt(1, 6);
  society.growCellAt(2, 7);
  society.growCellAt(2, 8);
  society.growCellAt(3, 7);
  society.growCellAt(3, 6);

  society.growCellAt(1, 16);
  society.growCellAt(2, 17);
  society.growCellAt(2, 18);
  society.growCellAt(3, 17);
  society.growCellAt(3, 16);
```

Output:

```
........
..OOO...
........

...O....
...O....
...O....

..OOO...
..OOO...
..OOO...

.O...O..
.O...O..
.O...O..

OOO.OOO.
OOO.OOO.
OOO.OOO.

........
........
........
```

```
  for (int t = 1; t <= 6; t++) {
    society.update();
    cout << society.toString();
  }
  return 0;
}
```

Output:

```
............................
.......O.........O...........
........O.........O..........
......OOO.......OOO..........
............................

............................
............................
......O.O.......O.O..........
.......OO........OO..........
.......O.........O...........

............................
............................
........O.........O..........
......O.O.......O.O..........
.......OO........OO..........

............................
............................
.......O.........O...........
........OO.......OO..........
.......OO........OO..........

............................
............................
........O.........O..........
.........O.........O.........
.......OOO.......OOO.........

........O.........O..........
............................
............................
.......O.O.......O.O..........
........OO.......OO..........
```

Note: The sixth update shows wraparound.

APPENDIX

Answers to Self-Check Questions

CHAPTER 1: PROBLEM SOLVING WITH C++

1-1 input: `pounds` or perhaps `todaysConversionRate`

output: `USDollars`

1-2 `cdCollection`, `selectedCD`

1-3

Problem	Object Names	Input or Output	Sample Problem

Compute the future value of an investment	`presentValue`
	`periods`
	`rate`
	`futureValue`
		Input
		"
		"
		Output
			1000.00
			360
			0.0075
			14730.58

1-4 Turn the oven off (you might have recognized some other activity has been omitted).

1-5 No (at least the author thinks it's okay).

1-6 No (at least the author thinks it's okay).

1-7 No. The `courseGrade` would be computed using undefined values for `test1`, `test2`, and `finalExam`.

1-8 No. The details of the process step are not present. Need a formula to compute a weighted average.

1-9 The program is wrong.

1-10 The prediction is wrong.

1-11 The program is wrong.

1-12 Numbers with a fractional part—floating-point numbers such as –1.2 or 1.023.

1-13 `+ - *` (also = output with `cout<<` and input with `cin>>`)

1-14 Integers—numbers without a decimal point. The actual range of integers is system dependent (unfortunately). Most C++ systems implement int to store integers in the range of –2,147,483,648 to 2,147,483,647.

1-15 `+ - *` (also = output with `cout<<` and input with `cin>>`)

1-16 A collection of characters.

1-17 `float`, `double`, `int`, `bool`, `char`, `short`, `unsigned int`, `unsigned long`

CHAPTER 2: C++ FUNDAMENTALS

2-1 22 plus or minus two. Actually it is easy to miscount, so let the compiler worry about it.

2-2
a. VALID
b. `1` can't start identifier
c. VALID
d. `#` not allowed
e. space not allowed
f. `#` not allowed
g. `!` not allowed
h. VALID
i. `( )` are not allowed
j. VALID (`double` is not)
k. VALID
l. periods`'.'` not allowed
m. `double` is a reserved word
n. can't start identifiers with `5`
o. space not allowed
p. VALID
q. VALID
r. `å)` not allowed
s. VALID (but weird)
t. `/` not allowed
u. VALID

2-3 `+ -` other possible answers `, : ; ! ( ) = { }`

2-4 `<< >>` other possible answers `!= == <= >=`

2-5 `cin` and `cout` (also `string` `vector` `width` `sqrt`)

2-6 `thisIsOne` and this `Is_YET_Another_1$`

2-7
a. string literals: `"'"` and `"H"`
b. integer constants: `234` and `-123`
c. floating-point constants: `1.0` and `1.0e+03`
d. boolean literals: `false` `true`
e. char literals: `'\n' 'h'`

2-8 a and d only

2-9
```
double aNumber = -1.5;

double anotherNumber = -1.5;
```

2-10
```
string address;
```

2-11
```
#include <iostream>
using namespace std;
int main() {
  cout << "Kim" << endl;
  cout << "Miller" << endl;
  return 0;
}
-or-

#include <iostream>
int main() {
  std::cout << "Kim" << std::endl;
  std::cout << "Miller" << std::endl;
  return 0;
}
```

2-12
a. error, can't assign `int` to `boolean`
b. `123` (truncation occurs)
c. `123.0;`
d. error, can't assign `double` to `long`
e. `'B'` or `66`
f. error, `ui` is not a known symbol

2-13
a. `10.5`
b. `1.75`
c. `3.5`
d. `-0.75`
e. `-0.5`
f. `1.0`

2-14
```
97 % 25 % 10 / 5
   22   % 10 / 5
        2    /  5
             0
```

2-15
a. `0`
b. `1`
c. `0`
d. `1`
e. `0`
f. `0`

2-16
a. `0`
b. `0.5555556`
c. `0.5555556`
d. `10`
e. `12`
f. `2`

2-17 Dialogue #1: Dialogue #2: Dialogue #3:

a. **3.2** (16.0/5.0) b. **1.9** (9.5/5.0) c. **2.8** (14.0/5.0)

2-18 That depends on the garbage value of `x`. Compilers usually warn about `x` being undefined.

2-19 The predicted answer `25` does not match `0.04`.

2-20 change `cin >> n` to `cin >> sum` and `cin >> sum` to `cin >> n`.

2-21 a. intent

b. compile time

c. compile time

CHAPTER 3: USING FREE FUNCTIONS

3-1 `pow(4.0, 3.0) is 4*4*4 or 64`

3-2 `pow(3.0, 4.0) is 3.0*3.0*3.0*3.0 or 81`

3-3 `floor(1.6+0.5) is 2.0`

3-4 `ceil(1.6-0.5) is 2.0`

3-5 `1.0`

3-6 `4.0`

3-7 Trace 9.99 rounded to 1 decimal place.

	x	n
Input n	9.99	1
Let x become x * 10^n	99.9	1
Add 0.5 to x	100.4	"
Let x become floor(x)	100.0	"
Let x become x divided by 10^n	10.0	"

3-8 Three Sample Problems (other answers certainly possible)

x	n	changed x
0.567	1	0.6
1234.56789	2	1234.57
-1.5	1	-1.0

3-9 `3.2`

3-10
```
x = x * pow(10, n)
x = x - 0.5     // subtract 0.5
x = ceil(x)     // take the ceiling of x
x = x / pow(10,n)
```

3-11 a. `16.0` or `16`
b. `4.0` or `4`
c. `-1.0` or `-1`
d. `1.0`
e. `23.4`
f. `16.0`

3-12 a. valid
b. wrong function name
c. too many arguments
d. incorrect type of argument
e. missing `(` and `)`
f. valid (the `int` is promoted to a `double`)

3-13 a. missing parameter type (need `int`, `double`, `string`, `or`, . . .)
b. missing two commas
c. no return type
d. okay only if `myClass` exists
e. extra `,` before `)`
f. attempt at parameter is a `string` literal

3-14 1. `floor(1.9999)`
2. `floor(0.99999)`
3. `floor (-1.9)`
4. `floor(-1)` (other answers possible)

3-15 1. `1.0` (or `1` will do)
2. `0.0`
3. `-2.0`
4. `-1.0`

3-16 `"1st"`

3-17 `3.4`

3-18 a. `double`
b. `pow`
c. `2`
d. `double`
e. `double`
f. there is no third argument

3-19 `pow(-81.0, 2)` (other answers possible)

3-20 No, the preconditions are not met. The return value is undefined. Return could be NaN (not a number).

3-21 Yes, `100.0`.

3-22 Yes, `32.0`.

3-23 Yes, `2.0` (you might have needed a scientific calculator. $x^{0.5}$ is the square root of `x`).

3-24 No, missing 2nd argument. Return value cannot be determined.

3-25
```
double remainder(double dividend, double divisor).
// pre:  divisor is not zero
// post: return the floating point remainder of dividend/divisor
```

CHAPTER 4: IMPLEMENTING FREE FUNCTIONS

4-1 a. `-1.0` d. `ERROR`, one too many arguments

b. `7.0` d. One two few arguments

c. `17.0` e. `66.28`

4-2 `0.375`

4-3 No. The argument is supposed to be positive. The result depends on the system you are using. You could get Infinity, NaN for not a number, or a square root of a negative number error.

4-4 a. Remove `;` after `)` d. return missing, you cannot assign a number to a function name.

b. `j` is unkown in `f2` e. must return a number, not the `double` class name.

c. `j` is unkown in `f3` f. must return an `int`, `f6` tries to return a `string` instead.

4-5
```
double times3(double x) {
  return 3 * x;
}
```

4-6

`cout`	`f1`, `f2`, and `main`	`a`	`f1` only
`b`	`f1` only	`d`	`f2` only
`cin`	`f1`, `f2`, and `main`	`f2`	`f2` and `main`
`MAX`	`f1`, `f2`, and `main`	`main`	from nowhere inside this file
`c`	`f2` only	`e`	`main` only
`f1`	`f1`, `f2`, and `main`		

4-7 Parameters and variables declared within the function's block.

4-8 Anywhere to the end of the file unless it is redeclared within a block, then the global is hidden from that particular function.

4-9 a. `// arg1 5 arg2 5`

b. `// arg1 11 arg2 123`

CHAPTER 5: USING MEMBER FUNCTIONS

5-1 a. Missing second argument.

b. Missing first argument.

c. `bankAccount` is an undefined symbol. Change `b` to `B`.

d. Missing a numeric argument between `(` and `)`.

e. Missing `(`, the argument, and `)`.

f. Wrong class of argument. Pass a number, not a `string`.

g. `B1` is undefined.

h. `Deposit` is not a member of `BankAccount`. Change `D` to `d`.

i. Need an object and a dot before withdraw.

j. `b4` is not a `BankAccount` object, it was never declared to be anything.

k. missing `()` after `name`.

l. `name` takes zero arguments, not one.

5-2
```
Chris: 202.22
Kim: 545.55
```

5-3
```
14
S
k
7
```
`18446744073709551615` or `string::npos`. Answer may vary on different systems
```
Net
N
Network
o
```

5-4 a. `UnSocial` c. `Socl`

b. `Societal` d. `NoTiaX`

5-5
```
string aString = "abcd";
int midChar = aString.length() / 2;
char mid = aString.at(midChar);
```

5-6 a. error, `length` is not a function

b. error , missing `()`

c. error, `length` is unknown

d. `3`

e. `y Str`

f. error

5-7
```
123456789012345
1  2.3   who
```

5-8
```
9.88
1
1.2
```

5-9 a.
```
Enter an integer: 123
  Good? 1
```

b.
```
Enter an integer: XYZ
  Good? 0
```

5-10 a. `istream`

b. `Grid`

c. `ostream`

c. `string`

d. `BankAccount`

e. `istream`

5-11
```
. . . . . .
. . <     .
. . . .   .
. . . .   .
. .       .
. . . . . .
row: 1
row: 2
```

5-12 1. Moving off the edge of the `Grid` (another answer is possible).

2. Moving through a block.

3. Attempting to pick up something that isn't there.

5-13 `1`

5-14 `35`

5-15
```
#include "Grid.h"
#include <iostream>
using namespace std;
int main() {
  Grid g(5, 5, 2, 3, east);
  g.move(1);
  g.face(north);
  g.move(1);
  g.face(west);
  g.move(1);
  g.face(south);
  g.move();
  g.display();
  return 0;
}
```

5-16 There is less code to write (another answer is possible).

Abstraction allows us to think of what the function does, not the details of the implementation.

The same code is often needed in more than one location. Writing that code as a function avoids duplicated code, which is a very bad thing.

5-17 Use your cell phone without worrying about how the network works.

Can do a lot without worrying about how to walk and breathe.

CHAPTER 6: IMPLEMENTING MEMBER FUNCTIONS

6-1 `LibraryBook`

6-2 `borrowBook returnBook`

6-3 `isAvailable getBorrower getBookInfo`

6-4 `author title borrower available`

6-5 `string`

6-6 `bool`

6-7 `LibraryBook aBook("Computing Fundamentals with Java, "River Tanner");`

6-8 `abook.borrowBook("Madison");`

6-9 `abook.getBorrower();`

6-10 Add the class name and `::` before the function name (after the return type). Also match the rest of the function heading in the class definition. The parameter names may differ.

6-11 Yes

6-12 No

6-13
```
'Tinker Tailor Soldier Spy' by John le Carre
CAN BORROW
1
Charlie Archer
0
1
CAN BORROW
```

6-14 The function is not supposed to change the state. This is enforced when passing the argument by `const` reference: `const&`.

6-15 The constructor(s).

6-16 Allow access to the state of any object so humans or other objects can either inspect or use that state. An accessor may return a data member, or some sort of processing may occur to return some information about the state of the object.

6-17 Modify the state of the object. At least one data member gets changed for each modifying message—otherwise it is an accessor.

6-18 Allow programmers to initialize objects with either the default state or their own initial values.

6-19 To store the state of any object. Each instance of the class has its own copy of the data members.

6-20 Lines 2 and 3 are attempts to send a modifying message to a `const` object (the parameter `b`).

CHAPTER 7: SELECTION

7-1 a. `true`
b. `false`
c. `false`
d. `true`
e. `true`
f. `true`
h. `true` (`165` is non-zero)
g. `false` (= is assignment, not equality,`j = 0` is evaluates to `false`)

7-2 a. `addRecord`
b. `deleteRecord`
c. `None option is lower case`
d. `dubious`
`failing`
e. `dubious`
f.
```
g: 45
at cutoff
g: 70
you get one
g: 1
```

7-3
```
Tune-up due in 0 miles
```

7-4 a. `38.0` c. `43.0`

b. `40.0` d. `45.25`

7-5 a. `true` c. `x is low`

`after if...else` d. `neg`

b. `zero or pos`

7-6
```
if (option == 1)
  cout << "My name" << endl;
else
  cout << "My school" << endl;
```

7-7 a. `true` e. `true`

b. `false` f. `false`

c. `true` g. `true`

d. `false` h. `true`

7-8 `(score >= 1) && (score <= 10)`

7-9 `(test > 100) || (score < 0)`

7-10 `President's list` (always `true` because `=` was used instead of `==`).

7-11

Row	Column	Output
3	4	`not`
4	3	`not`
2	2	`not`
0	2	`On edge`
2	0	`On edge`

7-12 a. `true` c. `false`

b. `false` d. `false`

7-13 All four evaluate. The fourth expression (`|| g.column()==g.nColumns()-1`) had to be evaluated because the first three are false (as is the fourth).

7-14 The last three `cout`s were not evaluated. This is weird code meant to vividly demonstrate short circuit Boolean Evaluation.

a. okay c. okay

b. failed d. failed

7-15 `70`

7-16 This unfortunate student gets a `D` instead of the deserved `C`.

7-17 I wouldn't be happy, and I doubt you would either.

7-18
```
-40: extremely frigid    20: warm               -1: below freezing
42: toast                15: freezing to mild   31: very hot
```

7-19 `20` through `29` inclusive.

7-20 `0` through `19` inclusive.

7-21
```
int main() {
  assert("extremely frigid" == weather(-41));
  assert("extremely frigid" == weather(-40));
  assert("below freezing" == weather(-39));
  assert("below freezing" == weather(-1));
  assert("freezing to mild" == weather(0));
  assert("freezing to mild" == weather(19));
  assert("warm" == weather(20));
  assert("warm" == weather(29));
  assert("very hot" == weather(30));
  assert("very hot" == weather(39));
  assert("toast" == weather(40));
  assert("toast" == weather(41));
  return 0;
}
```

7-22 `AAA`

7-23 `BBB`

7-24 `Invalid`

7-25 `Invalid`

7-26
```
switch(choice) {
  case 1:
    cout << "Favorite music is Jazz" << endl;
    break;
  case 2:
    cout << "Favorite food is Tacos" << endl;
    break;
  case 3:
    cout << "Favorite teacher is you" << endl;
    break;
  default;
    cout << "Error" << endl;
}
```

CHAPTER 8: REPETITION

8-1 No, the init-statement happens first (and only once).

8-2 No, you can use increments of any amount, including negative increments (or decrements).

8-3 No, consider the example `for (int i = 1; i < n; i++)` when `n==0`.

8-4 Consider if the update step does not increment `j`, or `j` is decremented as much as it is incremented inside the loop: `for (j = 1; j < n; j){ }` *or* `for (j = 1; j < n; j++){j--;}`

8-5 a. `1 2 3 4`

b. `1 2 3 4 5`

c. `-3 -1 1 3`

d. `0 1 2 3 4`

e. `5 4 3 2 1`

f.
```
before
  after
```

8-6
```
for (int i = 1; i <= 100; i++) {
  cout << i << endl;
}
```

8-7
```
for (int i = 10; i >= 1; i--) {
  cout << i << " ";
}
```

8-8 An attempt is made to block an intersection at a non-existent row; the program terminates.

8-9 It's no big deal. The right corners would be blocked twice.

8-10 The function would alter a copy of the `Grid`, not the `Grid` in `main`. The border would be set locally in `setBorder`, but it would not modify the arguments `aGrid` or `anotherGrid` in `main`.

8-11 `Range = 3`

8-12 `Range = 29 (this is correct).`

highest	-2147483648	-5	8	22	22	22
lowest	2147483647	-5	-5	-5	-7	-7

8-13 `Range = 4` (this is correct).

highest	-2147483648	5	5	5	5	5
lowest	2147483647	2147483647	4	3	2	1

8-14 `Range = Range: -2147483642` (this is obviously incorrect)

highest	-2147483648	1	2	3
lowest	2147483647	2147483647	2147483647	2147483647

8-15 b. When the input is entered in ascending order.

8-16 Get rid of the `else`.

8-17 The client code will never know in advance how many moves must be made. It cannot be determined in advance

8-18 a. `56.33333` the first test (`70.0`) is destroyed before its added to the accumulator. Additionally, the `sentinel-1` is incorrectly added to the accumulator.

b. `80.0`

8-19 a. Observe the location of the second `cin>>testScore`. Redo till you arrive at the preceding answers of `56.3333` for a. and `80.0` for b.

8-20 b. The input statement comes immediately before it is compared to –1.

8-21 zero

8-22 Input another `cin >> testscore` at the bottom of the loop.

8-23 A tricky question: remove the `;` after `)`. This loop does nothing infinitely because `;` represents the null statement. It is legal code, but it was not likely intended.

8-24 a. `1 2 3` b. `2 4 6 8 10`

8-25 a. unknown

b. forever

c. 0

d. forever

e. 5

f. forever notice the `;` after `count >= 0);`

8-26
```
int sum = 0;
int x = 0;
while ( (cin >> x) && (x != 999) ) {
  sum += x;
}
```

8-27 a.
```
1
2
3
```
b.
```
-1
-0.5
0
0.5
1
```

8-28
```
int x;
do {
  cout << "Enter a number in the range of 1 through 10: ";
  cin >> x;
} while ( x < 1 || x > 10);
```

8-29
```
do {
  cout << "Enter A)dd W)ithdraw Q)uit: ";
  cin >> option;
  option = toupper(option);
} while ( option != 'A' && option != 'W' && option != 'Q');
```

8-30 a. determinate `for` loop

b. determinate `for` loop

c. indeterminate `while` loop

d. indeterminate `do-while` loop

8-31 a. `value == -1`

b. `while (value != -1)`

8-32 For each loop, which objects are not initialized but should be?

a. count and n

b. `n` and `inc`

CHAPTER 9: FILE STREAMS

9-1
```
// file name: THISPROG.CPP
#include <fstream>  // for class ifstream
#include <iostream> // for cout
#include <string>
using namespace std;

int main() {
  string aString;
  ifstream inFile("THISPROG.CPP");
  for(int j = 1; j <= 4; j++)   {
    inFile >> aString;
    cout << aString << " ";
  }
  cout << endl;
  return 0;
}
```

9-2 `Can't average 0 numbers.`

9-3 a. `Failed to find the file numbers.dat`

b.
```
iteration # 1: 0.001
  End of file reached. 1 numbers found.
```

c. `End of file reached. 0 numbers found.`

9-4 a. `6` c. `6`

b. `15` d. `1` the period '`.`' sets `inFile` to a bad state and the loop terminates.

9-5 The loop would terminate since there would be no last name for `Kline`. The status would be `Kline`, the last name `Sue`. The employee `Kline` would never be constructed.

9-6 The loop would terminate when `S` was encountered for exempts. The employee Kline would never be constructed.

9-7 a. `1313 Mocking Bird Lane`

b. `1214 West Walnut Tree Drive`

CHAPTER 10: VECTORS

10-1 100

10-2 `0`

10-3 `99`

10-4 `0`

10-5 `x[0] = 78;`

10-6
```
int n = 100;
for(int j = 0; j < n; j++) {
  x[j] = n-j;
}
```

10-7
```
for(j = 0; j < n; j++) {
  cout << x[j] << endl;
}
```

10-8 It depends. The computer may "crash." You may destroy the state of another object. Or, with subscript range checking, you may get a runtime error before the program terminates.

10-9 `vector::resize` and `vector::capacity`

10-10
```
0    1    2    3    4
0    1    2    3    4    0    0    0    0    0
```

10-11 `-1`

10-12 1

10-13 5

10-14 4

10-15 `n`

10-16 0 (because of short circuit Boolean evaluation).

10-17 `irst econ hir ourt`

10-18
```
account[12] = BankAccount("A12thCustomer", 1212.12);
account[13] = BankAccount("Cust13", 1313.13);
```

10-19 The 21st account on the 21st line of the file would not become part of the account database. The `vector` size would not be big enough and the loop would terminate because `numberOfAccounts < account.capacity()` would be `false`.

10-20
```
#include <iostream>
#include <fstream>
using namespace std;
int main() {
  vector <int> vectorOfInts(1000);
  // File name will do if it is in the working directory
  ifstream inFile("int.dat");
  int n = 0;
  int el;

  while( (inFile >> el) && (n < vectorOfInts.capacity()) )  {
    vectorOfInts[n] = el;
    n++;
  }
  return 0;
}
```

10-21 `n`

10-22
```
cout << "Number of meaningful ints in vectorOfInts is " << n << endl;
cout << "Here they are" << endl;
for(int j = 0; j < n; j++) {
  cout << j << ". " << vectorOfInts[j] << endl;
}
```

10-23 `Grid` and `vector` objects are much bigger than `int` and `double`. That is, it takes more memory to store a grid than an `int` (appoximately 800 bytes versus 4 bytes). A `vector` of 1,000 `double`s is 1,000 times larger than one `double`.

10-24 a. 100,000 × 57 or 5.7 million bytes.

b. 4

c. 4

10-25 ascending

10-26 The first element in the `vector` is swapped with itself. That means three extra assignments, but it is not worth worrying about this special case.

10-27
```
double largest = x[0];
for(int j = 1; j < n; j++) {
  if( x[j] > largest )
    largest = x[j];
}
```

10-28 The `vector` is sorted and the binary search knows whether it is either ascending or descending order.

10-29 1: 1024 2: 512 3: 256 4: 128 5: 64 6: 32 7: 16 8: 8 9: 4 10: 2 11:

Therefore, the largest number of comparisons is 11.

10-30 When `first` exceeds `last`, that is the beginning and end of the `vector` no longer make any sense. For example when `first == 1028` and `last == 1026`.

10-31 Swap the location of the two statements.

```
last = mid - 1;
```

and

```
first = mid + 1;
```

or change the expression

```
if (searchString < str[mid]
```

to

```
if (str[mid] < searchString)
```

but NOT both changes.

CHAPTER 11: GENERIC COLLECTIONS

11-1 Any number can be used as long as the computer has more memory to grow the `vector`.

11-2 `cout << intSet.size() << endl;`

11-3 `intSet.insert(89);`

11-4 `intSet.remove(89);`

11-5 three

11-6 a. `5`

b. `40`

c. `0`

11-7
```
#include <iostream>
using namespace std;
#include "Set.h" // For a generic Set class
#include "BankAccount.h"
int main() {
  Set<BankAccount> set; // Store a set of 4 BankAccounts
  set.insert(BankAccount("Chris", 300.00));
  set.insert(BankAccount("Devon", 100.00));
  set.insert(BankAccount("Kim", 444.44));
  set.insert(BankAccount("Dakota", 99.99));

  double largest = 0.0;
  set.first(); // Initialize an iteration over all elements
```

```
  while (set.hasMore()) {
    double currentBalance = set.current().getBalance();
    if (currentBalance > largest)
      largest = currentBalance;
    set.next();
  }
  cout << "Max balance is " << largest << endl;
  return 0;
}
```

CHAPTER 12: POINTERS AND MEMORY MANAGEMENT

12-1 The addresses of other objects

12-2 a. `doublePtr`

b. Can't know. One run with `cout << & doublePtr;` was `0x7fff5b44cc78`.

c. `1.23`

d. `*doublePtr += 1.0;`

12-3 246

12-4 1

12-5 `a->getBalance() + b->getBalance();`

-or-

(*a).getBalance() + (*b).getBalance();

12-6 `24 144`

12-7
```
char ch = 'C';
char* charPtr = &ch;
```

12-8
```
int n1 = 12;
int n2 = 34;
int n3 = 56;
int *p1 = &n1;
int *p2 = &n2;
int *p3 = &n3;
```

12-9 `cout << *p1 + *p2 + *p3 <<endl`

12-10
```
p? 333
q? 333
```

12-11 `4 8`

12-12 `4.56 4.56`

12-13 There is no way to get the value memory that was found at *p.

12-14
```
12
```

12-15
```
int array[1000];
```

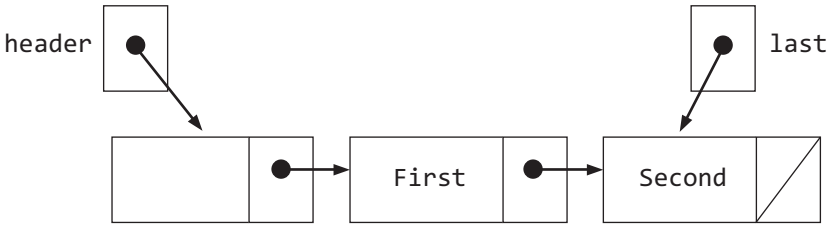
12-16
```
for(int i = 0; i < 1000; i++) {
  array[i] = -1;
}
```

12-17
```
0 2 4 6 8 10
```

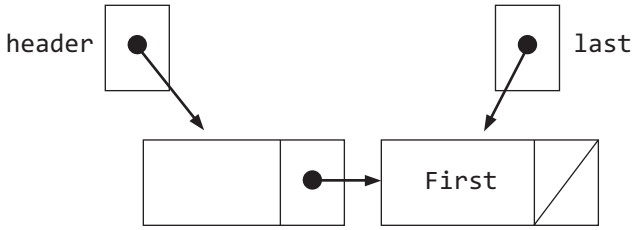
12-18
```
int min = x[0];
  int max = x[0];
  for (int i = 1; i < n; i++) {
    if (x[i] > max)
      max = x[i];
    if (x[i] < min)
      min = x[i];
 }
```

12-19
```
string strs[] = {"one", "two", "three", "four"};
```

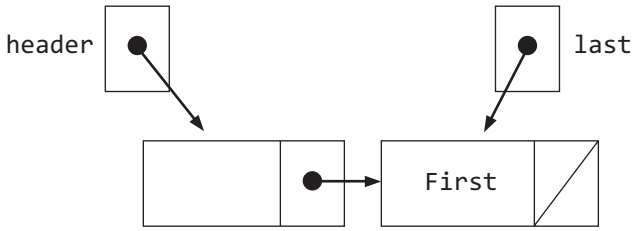
12-20 Before:



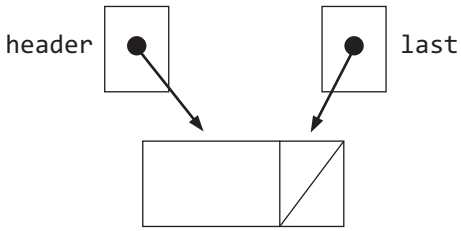
After:



12-21 Before:



After:



12-22 Remove returns false. No changes are made to the state of the list.

12-23 a. False, it can grow at runtime.

b. False, not in this list anyway. Use `get(int)`. The `[]` could be overridden.

c. True

d. False, this is not necessary with the unused header node.

e. True, to avoid a memory leak. In small program it doesn't matter, but in large programs a lot of time is spent chasing down and removing memory leaks unfortunately.

12-24
```
bool removeLast() {
 if (n == 0)
   return false;

 // Get ptr to point to the last node
 node* ptr = header;
 while (ptr->next != last) {
   ptr = ptr->next;
 }

 // Adjust last to the node before it, clean up memory, decrease size
 last = ptr;
 delete ptr->next;
 n--;

 return true;
}
```

CHAPTER 13: VECTOR OF VECTORS

13-1 `vector`

13-2 matrix (or a `vector` of `vector`s)

13-3 `matrix<double> sales(10, 12);`

13-4 `matrix<double> sales2(12, 10);`

13-5 row

13-6 column

13-7
```
int Matrix::get(int row, int column) {
  return table[row][column];
}
```

13-8
```
int Matrix::sum() {
  int result = 0;
  for (int i = 0; i < rows; i++) {
    for (int j = 0; j < columns; j++) {
      result += table[i][j];
    }
  }
  return result;
}
```

13-9 Undefined, could be anything (just had `a[0][0]` return `1550093504`).

13-10 No, this is a primitive array.

13-11 `12`

13-12 `0` through `2`

13-13 `0` through `3`

13-14
```
for (int row = 0; row < 3; row++) {
  for(int col = 0; col < 4; col++)  {
    a[row][col] = 999;
   }
}
```

13-15
```
for (int row = 0; row < 3; row++) {
  for (int col = 0; col <  4; col++) {
    cout.width(8);
    cout << a[row][col];
  }
  cout << endl;
}
```

INDEX