Java™ How to Program

NINTH EDITION

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26

Multithreading

The most general definition of beauty…Multeity in Unity.
—Samuel Taylor Coleridge

Do not block the way of inquiry.
—Charles Sanders Peirce

A person with one watch knows what time it is; a person with two watches is never sure.
—Proverb

Learn to labor and to wait.
—Henry Wadsworth Longfellow

The world is moving so fast these days that the man who says it can't be done is generally interrupted by someone doing it.
—Elbert Hubbard

Objectives

In this chapter you'll learn:

- What threads are and why they're useful.
- How threads enable you to manage concurrent activities.
- The life cycle of a thread.
- To create and execute `Runnable`s.
- Thread synchronization.
- What producer/consumer relationships are and how they're implemented with multithreading.
- To enable multiple threads to update Swing GUI components in a thread-safe manner.

Outline

26.1 Introduction

It would be nice if we could focus our attention on performing only one action at a time and performing it well, but that's usually difficult to do. The human body performs a great variety of operations *in parallel*—or, as we'll say throughout this chapter, **concurrently**. Respiration, blood circulation, digestion, thinking and walking, for example, can occur concurrently, as can all the senses—sight, touch, smell, taste and hearing.

Computers, too, can perform operations concurrently. It's common for personal computers to compile a program, send a file to a printer and receive electronic mail messages over a network concurrently. Only computers that have multiple processors can truly execute multiple instructions concurrently. Operating systems on single-processor computers create the illusion of concurrent execution by rapidly switching between activities, but on such computers only a single instruction can execute at once. Today's multicore computers have multiple processors that enable computers to perform tasks truly concurrently. Multicore smartphones are starting to appear.

Historically, concurrency has been implemented with operating system primitives available only to experienced systems programmers. The Ada programming language—developed by the United States Department of Defense—made concurrency primitives widely available to defense contractors building military command-and-control systems. However, Ada has not been widely used in academia and industry.

Java Concurrency

Java makes concurrency available to you through the language and APIs. Java programs can have multiple **threads of execution**, where each thread has its own method-call stack and program counter, allowing it to execute concurrently with other threads while sharing with them application-wide resources such as memory. This capability is called **multithreading**.

Performance Tip 26.1

A problem with single-threaded applications that can lead to poor responsiveness is that lengthy activities must complete before *others can begin. In a multithreaded application, threads can be distributed across multiple processors (if available) so that multiple tasks execute* truly *concurrently and the application can operate more efficiently. Multithreading can also increase performance on single-processor systems that* simulate *concurrency—when one thread cannot proceed (because, for example, it's waiting for the result of an I/O operation), another can use the processor.*

Concurrent Programming Uses

We'll discuss many applications of **concurrent programming**. For example, when downloading a large file (e.g., an image, an audio clip or a video clip) over the Internet, the user may not want to wait until the entire clip downloads before starting the playback. To solve this problem, multiple threads can be used—one to download the clip, and another to play it. These activities proceed concurrently. To avoid choppy playback, the threads are **synchronized** (that is, their actions are coordinated) so that the player thread doesn't begin until there's a sufficient amount of the clip in memory to keep the player thread busy. The Java Virtual Machine (JVM) creates threads to run programs and threads to perform housekeeping tasks such as garbage collection.

Concurrent Programming Is Difficult

Writing multithreaded programs can be tricky. Although the human mind can perform functions concurrently, people find it difficult to jump between parallel trains of thought. To see why multithreaded programs can be difficult to write and understand, try the following experiment: Open three books to page 1, and try reading the books concurrently. Read a few words from the first book, then a few from the second, then a few from the third, then loop back and read the next few words from the first book, and so on. After this experiment, you'll appreciate many of the challenges of multithreading—switching between the books, reading briefly, remembering your place in each book, moving the book you're reading closer so that you can see it and pushing the books you're not reading aside—and, amid all this chaos, trying to comprehend the content of the books!

Use the Prebuilt Classes of the Concurrency APIs Whenever Possible

Programming concurrent applications is difficult and error prone. If you must use synchronization in a program, you should follow some simple guidelines. *Use existing classes from the Concurrency APIs (such as the* `ArrayBlockingQueue` *class we discuss in Section 26.6) that manage synchronization for you.* These classes are written by experts, have been thoroughly tested and debugged, operate efficiently and help you avoid common traps and pitfalls.

If you need even more complex capabilities, use interfaces `Lock` and `Condition` that we introduce in Section 26.9. These interfaces should be used only by advanced programmers who are familiar with concurrent programming's common traps and pitfalls. We explain these topics in this chapter for several reasons:

- They provide a solid basis for understanding how concurrent applications synchronize access to shared memory.
- The concepts are important to understand, even if an application does not use these tools explicitly.

- By showing you the complexity involved in using these low-level features, we hope to impress upon you the importance of *using prebuilt concurrency capabilities whenever possible*.

Section 26.10 provides an overview of Java's pre-built concurrent collections.

26.2 Thread States: Life Cycle of a Thread

At any time, a thread is said to be in one of several **thread states**—illustrated in the UML state diagram in Fig. 26.1. Several of the terms in the diagram are defined in later sections. We include this discussion to help you understand what's going on "under the hood" in a Java multithreaded environment. Java hides most of this detail from you, greatly simplifying the task of developing multithreaded applications.

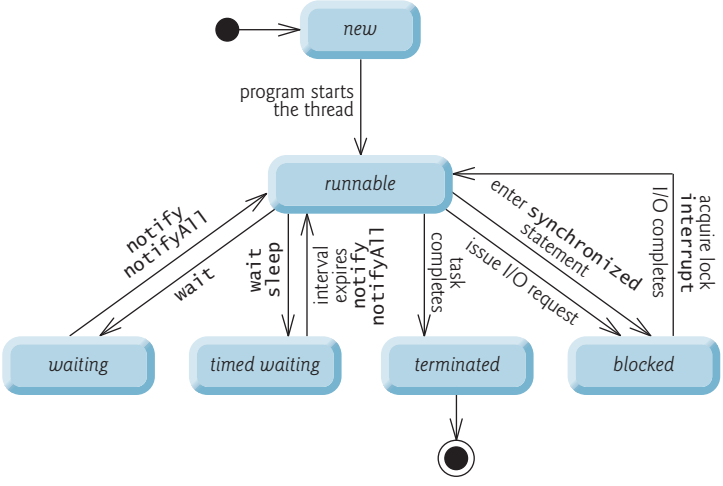

Fig. 26.1 | Thread life-cycle UML state diagram.

New *and* Runnable *States*

A new thread begins its life cycle in the ***new*** state. It remains in this state until the program starts the thread, which places it in the ***runnable*** state. A thread in the *runnable* state is considered to be executing its task.

Waiting *State*

Sometimes a *runnable* thread transitions to the ***waiting*** state while it waits for another thread to perform a task. A *waiting* thread transitions back to the *runnable* state only when another thread notifies it to continue executing.

Timed Waiting *State*

A *runnable* thread can enter the ***timed waiting*** state for a specified interval of time. It transitions back to the *runnable* state when that time interval expires or when the event it's waiting for occurs. *Timed waiting* and *waiting* threads cannot use a processor, even if one

is available. A *runnable* thread can transition to the *timed waiting* state if it provides an optional wait interval when it's waiting for another thread to perform a task. Such a thread returns to the *runnable* state when it's notified by another thread or when the timed interval expires—whichever comes first. Another way to place a thread in the *timed waiting* state is to put a *runnable* thread to sleep. A **sleeping thread** remains in the *timed waiting* state for a designated period of time (called a **sleep interval**), after which it returns to the *runnable* state. Threads sleep when they momentarily do not have work to perform. For example, a word processor may contain a thread that periodically backs up (i.e., writes a copy of) the current document to disk for recovery purposes. If the thread did not sleep between successive backups, it would require a loop in which it continually tested whether it should write a copy of the document to disk. This loop would consume processor time without performing productive work, thus reducing system performance. In this case, it's more efficient for the thread to specify a sleep interval (equal to the period between successive backups) and enter the *timed waiting* state. This thread is returned to the *runnable* state when its sleep interval expires, at which point it writes a copy of the document to disk and reenters the *timed waiting* state.

Blocked *State*

A *runnable* thread transitions to the ***blocked*** state when it attempts to perform a task that cannot be completed immediately and it must temporarily wait until that task completes. For example, when a thread issues an input/output request, the operating system blocks the thread from executing until that I/O request completes—at that point, the *blocked* thread transitions to the *runnable* state, so it can resume execution. A *blocked* thread cannot use a processor, even if one is available.

Terminated *State*

A *runnable* thread enters the ***terminated*** state (sometimes called the ***dead*** state) when it successfully completes its task or otherwise terminates (perhaps due to an error). In the UML state diagram of Fig. 26.1, the *terminated* state is followed by the UML final state (the bull's-eye symbol) to indicate the end of the state transitions.

Operating-System View of the Runnable *State*

At the operating system level, Java's *runnable* state typically encompasses *two separate* states (Fig. 26.2). The operating system hides these states from the Java Virtual Machine (JVM), which sees only the *runnable* state. When a thread first transitions to the *runnable* state from the *new* state, it's in the ***ready*** state. A *ready* thread enters the ***running*** state (i.e., begins executing) when the operating system assigns it to a processor—also known as **dispatching the thread**. In most operating systems, each thread is given a small amount of processor time—called a **quantum** or **timeslice**—with which to perform its task. Deciding how large the quantum should be is a key topic in operating systems courses. When its quantum expires, the thread returns to the *ready* state, and the operating system assigns another thread to the processor. Transitions between the *ready* and *running* states are handled solely by the operating system. The JVM does not "see" the transitions—it simply views the thread as being *runnable* and leaves it up to the operating system to transition the thread between *ready* and *running*. The process that an operating system uses to determine which thread to dispatch is called **thread scheduling** and is dependent on thread priorities.

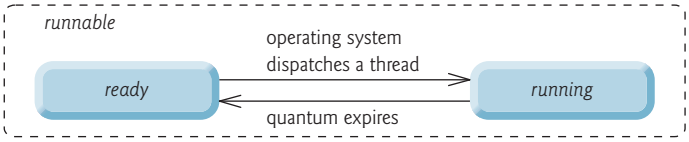

Fig. 26.2 | Operating system's internal view of Java's *runnable* state.

Thread Priorities and Thread Scheduling

Every Java thread has a **thread priority** that helps determine the order in which threads are scheduled. Each new thread inherits the priority of the thread that created it. Informally, higher-priority threads are more important to a program and should be allocated processor time before lower-priority threads. *Nevertheless, thread priorities cannot guarantee the order in which threads execute.*

It's recommended that you do not explicitly create and use `Thread` *objects to implement concurrency, but rather use the* `Executor` *interface (which is described in Section 26.3).* The Thread class does contain some useful static methods, which you *will* use later in the chapter.

Most operating systems support timeslicing, which enables threads of equal priority to share a processor. Without timeslicing, each thread in a set of equal-priority threads runs to completion (unless it leaves the *runnable* state and enters the *waiting* or *timed waiting* state, or gets interrupted by a higher-priority thread) before other threads of equal priority get a chance to execute. With timeslicing, even if a thread has *not* finished executing when its quantum expires, the processor is taken away from the thread and given to the next thread of equal priority, if one is available.

An *operating system's* **thread scheduler** determines which thread runs next. One simple thread-scheduler implementation keeps the highest-priority thread *running* at all times and, if there's more than one highest-priority thread, ensures that all such threads execute for a quantum each in **round-robin** fashion. This process continues until all threads run to completion.

When a higher-priority thread enters the *ready* state, the operating system generally preempts the currently *running* thread (an operation known as **preemptive scheduling**). Depending on the operating system, higher-priority threads could postpone—possibly indefinitely—the execution of lower-priority threads. Such **indefinite postponement** is sometimes referred to more colorfully as **starvation**. Operating systems employ a technique called *aging* to prevent starvation—as a thread waits in the *ready* state, the operating system gradually increases the thread's priority, thus ensuring that the thread will eventually run.

Java provides higher-level concurrency utilities to hide much of this complexity and make multithreaded programming less error prone. Thread priorities are used behind the scenes to interact with the operating system, but most programmers who use Java multithreading will not be concerned with setting and adjusting thread priorities.

Portability Tip 26.1

Thread scheduling is platform dependent—the behavior of a multithreaded program could vary across different Java implementations.

26.3 Creating and Executing Threads with Executor Framework

This section demonstrates how to perform concurrent tasks in an application by using `Executors` and `Runnable` objectss.

Creating Concurrent Tasks with the `Runnable` Interface

You implement the **`Runnable`** interface (of package `java.lang`) to specify a task that can execute concurrently with other tasks. The `Runnable` interface declares the single method **`run`**, which contains the code that defines the task that a `Runnable` object should perform.

Executing `Runnable` Objects with an `Executor`

To allow a `Runnable` to perform its task, you must execute it. An **`Executor`** object executes `Runnable`s. An `Executor` does this by creating and managing a group of threads called a **thread pool**. When an `Executor` begins executing a `Runnable`, the `Executor` calls the `Runnable` object's `run` method, which executes in the new thread.

The `Executor` interface declares a single method named **`execute`** which accepts a `Runnable` as an argument. The `Executor` assigns every `Runnable` passed to its `execute` method to one of the available threads in the thread pool. If there are no available threads, the `Executor` creates a new thread or waits for a thread to become available and assigns that thread the `Runnable` that was passed to method `execute`.

Using an `Executor` has many advantages over creating threads yourself. `Executors` can *reuse existing threads* to eliminate the overhead of creating a new thread for each task and can improve performance by *optimizing the number of threads* to ensure that the processor stays busy, without creating so many threads that the application runs out of resources.

Software Engineering Observation 26.1

Though it's possible to create threads explicitly, it's recommended that you use the `Executor` interface to manage the execution of `Runnable` objects.

Using Class `Executors` to Obtain an `ExecutorService`

The **`ExecutorService` interface** (of package `java.util.concurrent`) *extends* `Executor` and declares various methods for managing the life cycle of an `Executor`. An object that implements the `ExecutorService` interface can be created using `static` methods declared in class **`Executors`** (of package `java.util.concurrent`). We use interface `ExecutorService` and a method of class `Executors` in our example, which executes three tasks.

Implementing the `Runnable` Interface

Class `PrintTask` (Fig. 26.3) implements `Runnable` (line 5), *so that multiple `PrintTask`s can execute concurrently*. Variable `sleepTime` (line 7) stores a random integer value from 0 to 5 seconds created in the `PrintTask` constructor (line 17). Each thread running a `PrintTask` sleeps for the amount of time specified by `sleepTime`, then outputs its task's name and a message indicating that it's done sleeping.

A `PrintTask` executes when a thread calls the `PrintTask`'s `run` method. Lines 25–26 display a message indicating the name of the currently executing task and that the task is going to sleep for `sleepTime` milliseconds. Line 27 invokes `static` method **`sleep`** of class `Thread` to place the thread in the *timed waiting* state for the specified amount of time. At this point, the thread loses the processor, and the system allows another thread to execute.

```
1  // Fig. 26.3: PrintTask.java
2  // PrintTask class sleeps for a random time from 0 to 5 seconds
3  import java.util.Random;
4
5  public class PrintTask implements Runnable
6  {
7     private final int sleepTime; // random sleep time for thread
8     private final String taskName; // name of task
9     private final static Random generator = new Random();
10
11    // constructor
12    public PrintTask( String name )
13    {
14       taskName = name; // set task name
15
16       // pick random sleep time between 0 and 5 seconds
17       sleepTime = generator.nextInt( 5000 ); // milliseconds
18    } // end PrintTask constructor
19
20    // method run contains the code that a thread will execute
21    public void run()
22    {
23       try // put thread to sleep for sleepTime amount of time
24       {
25          System.out.printf( "%s going to sleep for %d milliseconds.\n",
26             taskName, sleepTime );
27          Thread.sleep( sleepTime ); // put thread to sleep
28       } // end try
29       catch ( InterruptedException exception )
30       {
31          System.out.printf( "%s %s\n", taskName,
32             "terminated prematurely due to interruption" );
33       } // end catch
34
35       // print task name
36       System.out.printf( "%s done sleeping\n", taskName );
37    } // end method run
38 } // end class PrintTask
```

Fig. 26.3 | `PrintTask` class sleeps for a random time from 0 to 5 seconds.

When the thread awakens, it reenters the *runnable* state. When the `PrintTask` is assigned to a processor again, line 36 outputs a message indicating that the task is done sleeping, then method `run` terminates. The `catch` at lines 29–33 is required because method `sleep` might throw a *checked* exception of type **`InterruptedException`** if a sleeping thread's **`interrupt`** method is called.

Using the `ExecutorService` *to Manage Threads that Execute* `PrintTask`s

Figure 26.4 uses an `ExecutorService` object to manage threads that execute `PrintTasks` (as defined in Fig. 26.3). Lines 11–13 create and name three `PrintTasks` to execute. Line 18 uses `Executors` method **`newCachedThreadPool`** to obtain an `ExecutorService` that's capable of creating new threads as they're needed by the application. These threads are used by `ExecutorService` (`threadExecutor`) to execute the `Runnables`.

```
1  // Fig. 26.4: TaskExecutor.java
2  // Using an ExecutorService to execute Runnables.
3  import java.util.concurrent.Executors;
4  import java.util.concurrent.ExecutorService;
5
6  public class TaskExecutor
7  {
8     public static void main( String[] args )
9     {
10       // create and name each runnable
11       PrintTask task1 = new PrintTask( "task1" );
12       PrintTask task2 = new PrintTask( "task2" );
13       PrintTask task3 = new PrintTask( "task3" );
14
15       System.out.println( "Starting Executor" );
16
17       // create ExecutorService to manage threads
18       ExecutorService threadExecutor = Executors.newCachedThreadPool();
19
20       // start threads and place in runnable state
21       threadExecutor.execute( task1 ); // start task1
22       threadExecutor.execute( task2 ); // start task2
23       threadExecutor.execute( task3 ); // start task3
24
25       // shut down worker threads when their tasks complete
26       threadExecutor.shutdown();
27
28       System.out.println( "Tasks started, main ends.\n" );
29    } // end main
30 } // end class TaskExecutor
```

```
Starting Executor
Tasks started, main ends

task1 going to sleep for 4806 milliseconds
task2 going to sleep for 2513 milliseconds
task3 going to sleep for 1132 milliseconds
task3 done sleeping
task2 done sleeping
task1 done sleeping
```

```
Starting Executor
task1 going to sleep for 3161 milliseconds.
task3 going to sleep for 532 milliseconds.
task2 going to sleep for 3440 milliseconds.
Tasks started, main ends.

task3 done sleeping
task1 done sleeping
task2 done sleeping
```

Fig. 26.4 | Using an `ExecutorService` to execute `Runnable`s.

Lines 21–23 each invoke the `ExecutorService`'s `execute` method, which executes the `Runnable` passed to it as an argument (in this case a `PrintTask`) some time in the future. The specified task may execute in one of the threads in the `ExecutorService`'s thread pool, in a new thread created to execute it, or in the thread that called the `execute` method—the `ExecutorService` manages these details. Method `execute` returns immediately from each invocation—the program does *not* wait for each `PrintTask` to finish. Line 26 calls `ExecutorService` method **`shutdown`**, which notifies the `ExecutorService` to *stop accepting new tasks, but continues executing tasks that have already been submitted*. Once all of the previously submitted `Runnables` have completed, the `threadExecutor` terminates. Line 28 outputs a message indicating that the tasks were started and the `main` thread is finishing its execution.

The code in `main` executes in the **main thread**, a thread created by the JVM. The code in the `run` method of `PrintTask` (lines 21–37 of Fig. 26.3) executes whenever the `Executor` starts each `PrintTask`—again, this is sometime after they're passed to the `ExecutorService`'s `execute` method (Fig. 26.4, lines 21–23). When `main` terminates, the program itself continues running because there are still tasks that must finish executing. The program will not terminate until these tasks complete.

The sample outputs show each task's name and sleep time as the thread goes to sleep. The thread with the shortest sleep time *normally* awakens first, indicates that it's done sleeping and terminates. In Section 26.8, we discuss multithreading issues that could prevent the thread with the shortest sleep time from awakening first. In the first output, the `main` thread terminates *before* any of the `PrintTasks` output their names and sleep times. This shows that the `main` thread runs to completion before any of the `PrintTasks` gets a chance to run. In the second output, all of the `PrintTasks` output their names and sleep times *before* the `main` thread terminates. This shows that the `PrintTasks` started executing before the main thread terminated. Also, notice in the second example output, `task3` goes to sleep before `task2` last, even though we passed `task2` to the `ExecutorService`'s `execute` method before `task3`. This illustrates the fact that *we cannot predict the order in which the tasks will start executing, even if we know the order in which they were created and started.*

26.4 Thread Synchronization

When multiple threads share an object and it's modified by one or more of them, indeterminate results may occur (as we'll see in the examples) unless access to the shared object is managed properly. If one thread is in the process of updating a shared object and another thread also tries to update it, it's unclear which thread's update takes effect. When this happens, the program's behavior cannot be trusted—sometimes the program will produce the correct results, and sometimes it won't. In either case, there'll be no indication that the shared object was manipulated incorrectly.

The problem can be solved by giving only one thread at a time *exclusive access* to code that manipulates the shared object. During that time, other threads desiring to manipulate the object are kept waiting. When the thread with exclusive access to the object finishes manipulating it, one of the threads that was waiting is allowed to proceed. This process, called **thread synchronization**, coordinates access to shared data by multiple concurrent threads. By synchronizing threads in this manner, you can ensure that each thread accessing a shared object excludes all other threads from doing so simultaneously—this is called **mutual exclusion**.

Monitors

A common way to perform synchronization is to use Java's built-in **monitors**. Every object has a monitor and a **monitor lock** (or **intrinsic lock**). The monitor ensures that its object's monitor lock is held by a maximum of only one thread at any time. Monitors and monitor locks can thus be used to enforce mutual exclusion. If an operation requires the executing thread to hold a lock while the operation is performed, a thread must acquire the lock before proceeding with the operation. Other threads attempting to perform an operation that requires the same lock will be *blocked* until the first thread releases the lock, at which point the *blocked* threads may attempt to acquire the lock and proceed with the operation.

To specify that a thread must hold a monitor lock to execute a block of code, the code should be placed in a **`synchronized` statement**. Such code is said to be **guarded** by the monitor lock; a thread must **acquire the lock** to execute the guarded statements. The monitor allows only one thread at a time to execute statements within `synchronized` statements that lock on the same object, as only one thread at a time can hold the monitor lock. The `synchronized` statements are declared using the **`synchronized` keyword**:

```
synchronized ( object )
{
   statements
} // end synchronized statement
```

where *object* is the object whose monitor lock will be acquired; *object* is normally `this` if it's the object in which the `synchronized` statement appears. If several `synchronized` statements are trying to execute on an object at the same time, only one of them may be active on the object—all the other threads attempting to enter a `synchronized` statement on the same object are placed in the *blocked* state.

When a `synchronized` statement finishes executing, the object's monitor lock is released and one of the *blocked* threads attempting to enter a `synchronized` statement can be allowed to acquire the lock to proceed. Java also allows **`synchronized` methods**. Before executing, a non-`static` `synchronized` method must acquire the lock on the object that's used to call the method. Similary, a `static` `synchronized` method must acquire the lock on the class that's used to call the method.

26.4.1 Unsynchronized Data Sharing

First, we illustrate the dangers of sharing an object across threads without proper synchronization. In this example, two `Runnables` maintain references to a single integer array. Each `Runnable` writes three values to the array, then terminates. This may seem harmless, but we'll see that it can result in errors if the array is manipulated without synchronization.

Class `SimpleArray`

A `SimpleArray` object (Fig. 26.5) will be *shared* across multiple threads. `SimpleArray` will enable those threads to place `int` values into `array` (declared at line 8). Line 9 initializes variable `writeIndex`, which will be used to determine the array element that should be written to next. The constructor (lines 13–16) creates an integer array of the desired size.

Method `add` (lines 19–40) allows new values to be inserted at the end of the array. Line 21 stores the current `writeIndex` value. Line 26 puts the thread that invokes `add` to sleep for a random interval from 0 to 499 milliseconds. This is done to make the problems associated with *unsynchronized access to shared data* more obvious. After the thread is done

```
1  // Fig. 26.5: SimpleArray.java
2  // Class that manages an integer array to be shared by multiple threads.
3  import java.util.Arrays;
4  import java.util.Random;
5
6  public class SimpleArray // CAUTION: NOT THREAD SAFE!
7  {
8     private final int[] array; // the shared integer array
9     private int writeIndex = 0; // index of next element to be written
10    private final static Random generator = new Random();
11
12    // construct a SimpleArray of a given size
13    public SimpleArray( int size )
14    {
15       array = new int[ size ];
16    } // end constructor
17
18    // add a value to the shared array
19    public void add( int value )
20    {
21       int position = writeIndex; // store the write index
22
23       try
24       {
25          // put thread to sleep for 0-499 milliseconds
26          Thread.sleep( generator.nextInt( 500 ) );
27       } // end try
28       catch ( InterruptedException ex )
29       {
30          ex.printStackTrace();
31       } // end catch
32
33       // put value in the appropriate element
34       array[ position ] = value;
35       System.out.printf( "%s wrote %2d to element %d.\n",
36          Thread.currentThread().getName(), value, position );
37
38       ++writeIndex; // increment index of element to be written next
39       System.out.printf( "Next write index: %d\n", writeIndex );
40    } // end method add
41
42    // used for outputting the contents of the shared integer array
43    public String toString()
44    {
45       return "\nContents of SimpleArray:\n" + Arrays.toString( array );
46    } // end method toString
47 } // end class SimpleArray
```

Fig. 26.5 | Class that manages an integer array to be shared by multiple threads.

sleeping, line 34 inserts the value passed to `add` into the array at the element specified by `position`. Lines 35–36 output a message indicating the executing thread's name, the value that was inserted in the array and where it was inserted. The expression `Thread.currentThread.getName()` (line 36) first obtains a reference to the currently executing `Thread`,

then uses that Thread's getName method to obtain its name. Line 38 increments writeIndex so that the next call to add will insert a value in the array's next element. Lines 43–46 override method toString to create a String representation of the array's contents.

Class ArrayWriter

Class ArrayWriter (Fig. 26.6) implements the interface Runnable to define a task for inserting values in a SimpleArray object. The constructor (lines 10–14) takes two arguments—an integer value, which is the first value this task will insert in the SimpleArray object, and a reference to the SimpleArray object. Line 20 invokes method add on the SimpleArray object. The task completes after three consecutive integers beginning with startValue are added to the SimpleArray object.

```
1  // Fig. 26.6: ArrayWriter.java
2  // Adds integers to an array shared with other Runnables
3  import java.lang.Runnable;
4
5  public class ArrayWriter implements Runnable
6  {
7     private final SimpleArray sharedSimpleArray;
8     private final int startValue;
9
10    public ArrayWriter( int value, SimpleArray array )
11    {
12       startValue = value;
13       sharedSimpleArray = array;
14    } // end constructor
15
16    public void run()
17    {
18       for ( int i = startValue; i < startValue + 3; i++ )
19       {
20          sharedSimpleArray.add( i ); // add an element to the shared array
21       } // end for
22    } // end method run
23 } // end class ArrayWriter
```

Fig. 26.6 | Adds integers to an array shared with other Runnables.

Class SharedArrayTest

Class SharedArrayTest (Fig. 26.7) executes two ArrayWriter tasks that add values to a single SimpleArray object. Line 12 constructs a six-element SimpleArray object. Lines 15–16 create two new ArrayWriter tasks, one that places the values 1–3 in the SimpleArray object, and one that places the values 11–13. Lines 19–21 create an ExecutorService and execute the two ArrayWriters. Line 23 invokes the ExecutorService's shutDown method to *prevent additional tasks from starting* and to enable the application to terminate when the currently executing tasks complete execution.

Recall that ExecutorService method shutdown returns immediately. Thus any code that appears *after* the call to ExecutorService method shutdown in line 23 *will continue executing as long as the* main *thread is still assigned to a processor*. We'd like to output the SimpleArray object to show you the results *after* the threads complete their tasks. So, we

need the program to wait for the threads to complete before `main` outputs the `SimpleArray` object's contents. Interface `ExecutorService` provides the **`awaitTermination`** method for this purpose. This method returns control to its caller either when all tasks executing in the `ExecutorService` complete or when the specified timeout elapses. If all tasks are completed before `awaitTermination` times out, this method returns `true`; otherwise it returns `false`. The two arguments to `awaitTermination` represent a timeout value and a unit of measure specified with a constant from class `TimeUnit` (in this case, `TimeUnit.MINUTES`).

```
1  // Fig 26.7: SharedArrayTest.java
2  // Executes two Runnables to add elements to a shared SimpleArray.
3  import java.util.concurrent.Executors;
4  import java.util.concurrent.ExecutorService;
5  import java.util.concurrent.TimeUnit;
6
7  public class SharedArrayTest
8  {
9     public static void main( String[] arg )
10    {
11       // construct the shared object
12       SimpleArray sharedSimpleArray = new SimpleArray( 6 );
13
14       // create two tasks to write to the shared SimpleArray
15       ArrayWriter writer1 = new ArrayWriter( 1, sharedSimpleArray );
16       ArrayWriter writer2 = new ArrayWriter( 11, sharedSimpleArray );
17
18       // execute the tasks with an ExecutorService
19       ExecutorService executor = Executors.newCachedThreadPool();
20       executor.execute( writer1 );
21       executor.execute( writer2 );
22
23       executor.shutdown();
24
25       try
26       {
27          // wait 1 minute for both writers to finish executing
28          boolean tasksEnded = executor.awaitTermination(
29             1, TimeUnit.MINUTES );
30
31          if ( tasksEnded )
32             System.out.println( sharedSimpleArray ); // print contents
33          else
34             System.out.println(
35                "Timed out while waiting for tasks to finish." );
36       } // end try
37       catch ( InterruptedException ex )
38       {
39          System.out.println(
40             "Interrupted while waiting for tasks to finish." );
41       } // end catch
42    } // end main
43 } // end class SharedArrayTest
```

Fig. 26.7 | Executes two `Runnable`s to insert values in a shared array. (Part 1 of 2.)

```
pool-1-thread-1 wrote  1 to element 0.
Next write index: 1
pool-1-thread-1 wrote  2 to element 1.
Next write index: 2
pool-1-thread-1 wrote  3 to element 2.
Next write index: 3
pool-1-thread-2 wrote 11 to element 0.
Next write index: 4
pool-1-thread-2 wrote 12 to element 4.
Next write index: 5
pool-1-thread-2 wrote 13 to element 5.
Next write index: 6

Contents of SimpleArray:
[11, 2, 3, 0, 12, 13]
```

First `pool-1-thread-1` wrote the value `1` to element `0`. Later `pool-1-thread-2` wrote the value `11` to element `0`, thus *overwriting* the previously stored value.

Fig. 26.7 | Executes two `Runnable`s to insert values in a shared array. (Part 2 of 2.)

In this example, if *both* tasks complete before `awaitTermination` times out, line 32 displays the `SimpleArray` object's contents. Otherwise, lines 34–35 print a message indicating that the tasks did not finish executing before `awaitTermination` timed out.

The output in Fig. 26.7 demonstrates the problems (highlighted in the output) that can be *caused by failure to synchronize access to shared data*. The value `1` was written to element `0`, then *overwritten* later by the value `11`. Also, when `writeIndex` was incremented to 3, *nothing was written to that element*, as indicated by the 0 in that element of the printed array.

Recall that we added calls to `Thread` method `sleep` between operations on the shared data to emphasize the *unpredictability of thread scheduling* and increase the likelihood of producing erroneous output. Even if these operations were allowed to proceed at their normal pace, you could still see errors in the program's output. However, modern processors can handle the simple operations of the `SimpleArray` method `add` so quickly that you might not see the errors caused by the two threads executing this method concurrently, even if you tested the program dozens of times. *One of the challenges of multithreaded programming is spotting the errors—they may occur so infrequently that a broken program does not produce incorrect results during testing, creating the illusion that the program is correct.*

26.4.2 Synchronized Data Sharing—Making Operations Atomic

The output errors of Fig. 26.7 can be attributed to the fact that the shared object, `SimpleArray`, is not **thread safe**—`SimpleArray` is susceptible to errors if it's *accessed concurrently by multiple threads*. The problem lies in method `add`, which stores the value of `writeIndex`, places a new value in that element, then increments `writeIndex`. Such a method would present no problem in a single-threaded program. However, if one thread obtains the value of `writeIndex`, there's no guarantee that another thread cannot come along and increment `writeIndex` *before* the first thread has had a chance to place a value in the array. If this happens, the first thread will be writing to the array based on a **stale value** of `writeIndex`—a value that's no longer valid. Another possibility is that one thread might obtain the value of `writeIndex` *after* another thread adds an element to the array but *before* `writeIndex` is incremented. In this case, too, the first thread would write to the array based on an invalid value for `writeIndex`.

`SimpleArray` is *not thread safe because it allows any number of threads to read and modify shared data concurrently*, which can cause errors. To make `SimpleArray` thread safe, we must ensure that no two threads can access it at the same time. We also must ensure that while one thread is in the process of storing `writeIndex`, adding a value to the array, and incrementing `writeIndex`, no other thread may read or change the value of `writeIndex` or modify the contents of the array at any point during these three operations. In other words, we want these three operations—storing `writeIndex`, writing to the array, incrementing `writeIndex`—to be an **atomic operation**, which cannot be divided into smaller suboperations. We can simulate atomicity by ensuring that only one thread carries out the three operations at a time. Any other threads that need to perform the operation must *wait* until the first thread has finished the `add` operation in its entirety.

Atomicity can be achieved using the `synchronized` keyword. By placing our three suboperations in a `synchronized` statement or `synchronized` method, we allow only one thread at a time to acquire the lock and perform the operations. When that thread has completed all of the operations in the `synchronized` block and releases the lock, another thread may acquire the lock and begin executing the operations. This ensures that a thread executing the operations will see the actual values of the shared data and that *these values will not change unexpectedly in the middle of the operations as a result of another thread's modifying them.*

Software Engineering Observation 26.2

Place all accesses to mutable data that may be shared by multiple threads inside `synchronized` statements or `synchronized` methods that synchronize on the same lock. When performing multiple operations on shared data, hold the lock for the entirety of the operation to ensure that the operation is effectively atomic.

Class `SimpleArray` with Synchronization

Figure 26.8 displays class `SimpleArray` with the proper synchronization. Notice that it's identical to the `SimpleArray` class of Fig. 26.5, except that `add` is now a `synchronized` method (line 20). So, only one thread at a time can execute this method. We reuse classes `ArrayWriter` (Fig. 26.6) and `SharedArrayTest` (Fig. 26.7) from the previous example.

```
1  // Fig. 26.8: SimpleArray.java
2  // Class that manages an integer array to be shared by multiple
3  // threads with synchronization.
4  import java.util.Arrays;
5  import java.util.Random;
6
7  public class SimpleArray
8  {
9     private final int[] array; // the shared integer array
10    private int writeIndex = 0; // index of next element to be written
11    private final static Random generator = new Random();
12
```

Fig. 26.8 | Class that manages an integer array to be shared by multiple threads with synchronization. (Part 1 of 2.)

```
13      // construct a SimpleArray of a given size
14      public SimpleArray( int size )
15      {
16         array = new int[ size ];
17      } // end constructor
18
19      // add a value to the shared array
20      public synchronized void add( int value )
21      {
22         int position = writeIndex; // store the write index
23
24         try
25         {
26            // put thread to sleep for 0-499 milliseconds
27            Thread.sleep( generator.nextInt( 500 ) );
28         } // end try
29         catch ( InterruptedException ex )
30         {
31            ex.printStackTrace();
32         } // end catch
33
34         // put value in the appropriate element
35         array[ position ] = value;
36         System.out.printf( "%s wrote %2d to element %d.\n",
37            Thread.currentThread().getName(), value, position );
38
39         ++writeIndex; // increment index of element to be written next
40         System.out.printf( "Next write index: %d\n", writeIndex );
41      } // end method add
42
43      // used for outputting the contents of the shared integer array
44      public String toString()
45      {
46         return "\nContents of SimpleArray:\n" + Arrays.toString( array );
47      } // end method toString
48   } // end class SimpleArray
```

```
pool-1-thread-1 wrote  1 to element 0.
Next write index: 1
pool-1-thread-2 wrote 11 to element 1.
Next write index: 2
pool-1-thread-2 wrote 12 to element 2.
Next write index: 3
pool-1-thread-2 wrote 13 to element 3.
Next write index: 4
pool-1-thread-1 wrote  2 to element 4.
Next write index: 5
pool-1-thread-1 wrote  3 to element 5.
Next write index: 6

Contents of SimpleArray:
1 11 12 13 2 3
```

Fig. 26.8 | Class that manages an integer array to be shared by multiple threads with synchronization. (Part 2 of 2.)

Line 20 declares method as `synchronized`, making all of the operations in this method behave as a single, atomic operation. Line 22 performs the first suboperation—storing the value of `writeIndex`. Line 35 defines the second suboperation, writing an element to the element at the index `position`. Line 39 increments `writeIndex`. When the method finishes executing at line 41, the executing thread implicitly releases the `SimpleArray` lock, making it possible for another thread to begin executing the `add` method.

In the `synchronized add` method, we print messages to the console indicating the progress of threads as they execute this method, in addition to performing the actual operations required to insert a value in the array. We do this so that the messages will be printed in the correct order, allowing us to see whether the method is properly synchronized by comparing these outputs with those of the previous, unsynchronized example. We continue to output messages from `synchronized` blocks in later examples for demonstration purposes only; typically, however, I/O *should not* be performed in `synchronized` blocks, because it's important to minimize the amount of time that an object is "locked." Also, line 27 in this example calls `Thread` method `sleep` to emphasize the *unpredictability of thread scheduling. You should never call* `sleep` *while holding a lock in a real application.*

Performance Tip 26.2

Keep the duration of `synchronized` *statements as short as possible while maintaining the needed synchronization. This minimizes the wait time for blocked threads. Avoid performing I/O, lengthy calculations and operations that do not require synchronization while holding a lock.*

Another note on thread safety: We've said that it's necessary to synchronize access to all data that may be shared across multiple threads. Actually, this synchronization is necessary only for **mutable data**, or data that may *change* in its lifetime. If the shared data will not change in a multithreaded program, then it's not possible for a thread to see old or incorrect values as a result of another thread's manipulating that data.

When you share immutable data across threads, declare the corresponding data fields `final` to indicate that the values of the variables will *not* change after they're initialized. This prevents accidental modification of the shared data later in a program, which could compromise thread safety. *Labeling object references as* `final` *indicates that the reference will not change, but it does not guarantee that the object itself is immutable—this depends entirely on the object's properties.* However, it's still good practice to mark references that will not change as `final`, as doing so forces the object's constructor to be atomic—the object will be fully constructed with all its fields initialized before the program accesses it.

Good Programming Practice 26.1

Always declare data fields that you do not expect to change as `final`*. Primitive variables that are declared as* `final` *can safely be shared across threads. An object reference that's declared as* `final` *ensures that the object it refers to will be fully constructed and initialized before it's used by the program, and prevents the reference from pointing to another object.*

26.5 Producer/Consumer Relationship without Synchronization

In a **producer/consumer relationship**, the **producer** portion of an application generates data and *stores it in a shared object*, and the **consumer** portion of the application *reads data*

from the shared object. The producer/consumer relationship separates the task of identifying work to be done from the tasks involved in actually carrying out the work. One example of a common producer/consumer relationship is **print spooling**. Although a printer might not be available when you want to print from an application (i.e., the producer), you can still "complete" the print task, as the data is temporarily placed on disk until the printer becomes available. Similarly, when the printer (i.e., a consumer) is available, it doesn't have to wait until a current user wants to print. The spooled print jobs can be printed as soon as the printer becomes available. Another example of the producer/consumer relationship is an application that copies data onto DVDs by placing data in a fixed-size buffer, which is emptied as the DVD drive "burns" the data onto the DVD.

In a multithreaded producer/consumer relationship, a **producer thread** generates data and places it in a shared object called a **buffer**. A **consumer thread** reads data from the buffer. This relationship requires *synchronization* to ensure that values are produced and consumed properly. All operations on mutable data that's shared by multiple threads (e.g., the data in the buffer) must be guarded with a lock to prevent corruption, as discussed in Section 26.4. Operations on the buffer data shared by a producer and consumer thread are also **state dependent**—the operations should proceed only if the buffer is in the correct state. If the buffer is in a *not-full state*, the producer may produce; if the buffer is in a *not-empty state*, the consumer may consume. All operations that access the buffer must use synchronization to ensure that data is written to the buffer or read from the buffer only if the buffer is in the proper state. If the producer attempting to put the next data into the buffer determines that it's full, the producer thread must *wait* until there's space to write a new value. If a consumer thread finds the buffer empty or finds that the previous data has already been read, the consumer must also *wait* for new data to become available.

Consider how logic errors can arise if we do not synchronize access among multiple threads manipulating shared data. Our next example (Fig. 26.9–Fig. 26.13) implements a producer/consumer relationship without the proper synchronization. A producer thread writes the numbers 1 through 10 into a shared buffer—a single memory location shared between two threads (a single `int` variable called `buffer` in line 6 of Fig. 26.12 in this example). The consumer thread reads this data from the shared buffer and displays the data. The program's output shows the values that the producer writes (produces) into the shared buffer and the values that the consumer reads (consumes) from the shared buffer.

Each value the producer thread writes to the shared buffer must be consumed *exactly once* by the consumer thread. However, the threads in this example are not synchronized. Therefore, *data can be lost or garbled if the producer places new data into the shared buffer before the consumer reads the previous data*. Also, data can be incorrectly *duplicated* if the consumer consumes data again before the producer produces the next value. To show these possibilities, the consumer thread in the following example keeps a total of all the values it reads. The producer thread produces values from 1 through 10. If the consumer reads each value produced once and only once, the total will be 55. However, if you execute this program several times, you'll see that the total is not always 55 (as shown in the outputs in Fig. 26.13). To emphasize the point, the producer and consumer threads in the example each sleep for random intervals of up to three seconds between performing their tasks. Thus, we do not know when the producer thread will attempt to write a new value, or when the consumer thread will attempt to read a value.

Implementing the Producer/Consumer Relationship

The program consists of interface `Buffer` (Fig. 26.9) and classes `Producer` (Fig. 26.10), `Consumer` (Fig. 26.11), `UnsynchronizedBuffer` (Fig. 26.12) and `SharedBufferTest` (Fig. 26.13). Interface `Buffer` (Fig. 26.9) declares methods `set` (line 6) and `get` (line 9) that a `Buffer` (such as `UnsynchronizedBuffer`) must implement to enable the `Producer` thread to place a value in the `Buffer` and the `Consumer` thread to retrieve a value from the `Buffer`, respectively. In subsequent examples, methods `set` and `get` will call methods that throw `InterruptedExceptions`. We declare each method with a `throws` clause here so that we don't have to modify this interface for the later examples.

```
1  // Fig. 26.9: Buffer.java
2  // Buffer interface specifies methods called by Producer and Consumer.
3  public interface Buffer
4  {
5     // place int value into Buffer
6     public void set( int value ) throws InterruptedException;
7
8     // return int value from Buffer
9     public int get() throws InterruptedException;
10 } // end interface Buffer
```

Fig. 26.9 | Buffer interface specifies methods called by `Producer` and `Consumer`.

Class `Producer` (Fig. 26.10) implements the `Runnable` interface, allowing it to be executed as a task in a separate thread. The constructor (lines 11–14) initializes the `Buffer` reference `sharedLocation` with an object created in `main` (line 14 of Fig. 26.13) and passed to the constructor. As we'll see, this is an `UnsynchronizedBuffer` object that implements interface `Buffer` *without synchronizing access to the shared object*. The `Producer` thread in this program executes the tasks specified in the method `run` (lines 17–39). Each iteration of the loop (lines 21–35) invokes `Thread` method `sleep` (line 25) to place the `Producer` thread into the *timed waiting* state for a random time interval between 0 and 3 seconds. When the thread awakens, line 26 passes the value of control variable `count` to the `Buffer` object's `set` method to set the shared buffer's value. Lines 27–28 keep a total of all the values produced so far and output that value. When the loop completes, lines 37–38 display a message indicating that the `Producer` has finished producing data and is terminating. Next, method `run` terminates, which indicates that the `Producer` completed its task. Any method called from a `Runnable`'s `run` method (e.g., `Buffer` method `set`) executes as part of that task's thread of execution. This fact becomes important in Sections 26.6–26.8 when we add synchronization to the producer/consumer relationship.

```
1  // Fig. 26.10: Producer.java
2  // Producer with a run method that inserts the values 1 to 10 in buffer.
3  import java.util.Random;
4
5  public class Producer implements Runnable
6  {
```

Fig. 26.10 | `Producer` with a `run` method that inserts the values 1 to 10 in buffer. (Part 1 of 2.)

```
7     private final static Random generator = new Random();
8     private final Buffer sharedLocation; // reference to shared object
9
10    // constructor
11    public Producer( Buffer shared )
12    {
13        sharedLocation = shared;
14    } // end Producer constructor
15
16    // store values from 1 to 10 in sharedLocation
17    public void run()
18    {
19       int sum = 0;
20
21       for ( int count = 1; count <= 10; count++ )
22       {
23          try // sleep 0 to 3 seconds, then place value in Buffer
24          {
25             Thread.sleep( generator.nextInt( 3000 ) ); // random sleep
26             sharedLocation.set( count ); // set value in buffer
27             sum += count; // increment sum of values
28             System.out.printf( "\t%2d\n", sum );
29          } // end try
30          // if lines 25 or 26 get interrupted, print stack trace
31          catch ( InterruptedException exception )
32          {
33             exception.printStackTrace();
34          } // end catch
35       } // end for
36
37       System.out.println(
38          "Producer done producing\nTerminating Producer" );
39    } // end method run
40 } // end class Producer
```

Fig. 26.10 | `Producer` with a `run` method that inserts the values 1 to 10 in buffer. (Part 2 of 2.)

Class `Consumer` (Fig. 26.11) also implements interface `Runnable`, allowing the `Consumer` to execute concurrently with the `Producer`. Lines 11–14 initialize `Buffer` reference `sharedLocation` with an object that implements the `Buffer` interface (created in `main`, Fig. 26.13) and passed to the constructor as the parameter `shared`. As we'll see, this is the same `UnsynchronizedBuffer` object that's used to initialize the `Producer` object—thus, the two threads share the same object. The `Consumer` thread in this program performs the tasks specified in method `run` (lines 17–39). Lines 21–35 iterate 10 times. Each iteration invokes `Thread` method `sleep` (line 26) to put the `Consumer` thread into the *timed waiting* state for up to 3 seconds. Next, line 27 uses the `Buffer`'s `get` method to retrieve the value in the shared buffer, then adds the value to variable `sum`. Line 28 displays the total of all the values consumed so far. When the loop completes, lines 37–38 display a line indicating the sum of the consumed values. Then method `run` terminates, which indicates that the `Consumer` completed its task. Once both threads enter the *terminated* state, the program ends.

```
1  // Fig. 26.11: Consumer.java
2  // Consumer with a run method that loops, reading 10 values from buffer.
3  import java.util.Random;
4
5  public class Consumer implements Runnable
6  {
7     private final static Random generator = new Random();
8     private final Buffer sharedLocation; // reference to shared object
9
10    // constructor
11    public Consumer( Buffer shared )
12    {
13       sharedLocation = shared;
14    } // end Consumer constructor
15
16    // read sharedLocation's value 10 times and sum the values
17    public void run()
18    {
19       int sum = 0;
20
21       for ( int count = 1; count <= 10; count++ )
22       {
23          // sleep 0 to 3 seconds, read value from buffer and add to sum
24          try
25          {
26             Thread.sleep( generator.nextInt( 3000 ) );
27             sum += sharedLocation.get();
28             System.out.printf( "\t\t\t%2d\n", sum );
29          } // end try
30          // if lines 26 or 27 get interrupted, print stack trace
31          catch ( InterruptedException exception )
32          {
33             exception.printStackTrace();
34          } // end catch
35       } // end for
36
37       System.out.printf( "\n%s %d\n%s\n",
38          "Consumer read values totaling", sum, "Terminating Consumer" );
39    } // end method run
40 } // end class Consumer
```

Fig. 26.11 | `Consumer` with a `run` method that loops, reading 10 values from buffer.

[*Note:* We call method `sleep` in method `run` of the `Producer` and `Consumer` classes to emphasize the fact that, *in multithreaded applications, it's unpredictable when each thread will perform its task and for how long it will perform the task when it has a processor*. Normally, these thread scheduling issues are beyond the control of the Java developer. In this program, our thread's tasks are quite simple—the `Producer` writes the values 1 to 10 to the buffer, and the `Consumer` reads 10 values from the buffer and adds each value to variable `sum`. Without the `sleep` method call, and if the `Producer` executes first, given today's phenomenally fast processors, the `Producer` would likely complete its task before the `Consumer` got a chance to execute. If the `Consumer` executed first, it would likely consume garbage data ten times, then terminate before the `Producer` could produce the first real value.]

Class `UnsynchronizedBuffer` (Fig. 26.12) implements interface `Buffer` (line 4). An object of this class is shared between the `Producer` and the `Consumer`. Line 6 declares instance variable `buffer` and initializes it with the value `-1`. This value is used to demonstrate the case in which the `Consumer` attempts to consume a value *before* the `Producer` ever places a value in `buffer`. Methods `set` (lines 9–13) and `get` (lines 16–20) do *not* synchronize access to the field `buffer`. Method `set` simply assigns its argument to `buffer` (line 12), and method `get` simply returns the value of `buffer` (line 19).

```
1  // Fig. 26.12: UnsynchronizedBuffer.java
2  // UnsynchronizedBuffer maintains the shared integer that is accessed by
3  // a producer thread and a consumer thread via methods set and get.
4  public class UnsynchronizedBuffer implements Buffer
5  {
6     private int buffer = -1; // shared by producer and consumer threads
7
8     // place value into buffer
9     public void set( int value ) throws InterruptedException
10    {
11       System.out.printf( "Producer writes\t%2d", value );
12       buffer = value;
13    } // end method set
14
15    // return value from buffer
16    public int get() throws InterruptedException
17    {
18       System.out.printf( "Consumer reads\t%2d", buffer );
19       return buffer;
20    } // end method get
21 } // end class UnsynchronizedBuffer
```

Fig. 26.12 | `UnsynchronizedBuffer` maintains the shared integer that is accessed by a producer thread and a consumer thread via methods `set` and `get`.

In class `SharedBufferTest` (Fig. 26.13), line 11 creates an `ExecutorService` to execute the `Producer` and `Consumer` `Runnable`s. Line 14 creates an `UnsynchronizedBuffer` object and assigns it to `Buffer` variable `sharedLocation`. This object stores the data that the `Producer` and `Consumer` threads will share. Lines 23–24 create and execute the `Producer` and `Consumer`. The `Producer` and `Consumer` constructors are each passed the same `Buffer` object (`sharedLocation`), so each object is initialized with a reference to the same `Buffer`. These lines also implicitly launch the threads and call each `Runnable`'s `run` method. Finally, line 26 calls method `shutdown` so that the application can terminate when the threads executing the `Producer` and `Consumer` complete their tasks. When `main` terminates (line 27), the main thread of execution enters the *terminated* state.

```
1  // Fig. 26.13: SharedBufferTest.java
2  // Application with two threads manipulating an unsynchronized buffer.
3  import java.util.concurrent.ExecutorService;
4  import java.util.concurrent.Executors;
```

Fig. 26.13 | Application with two threads manipulating an unsynchronized buffer. (Part 1 of 3.)

```
5
6  public class SharedBufferTest
7  {
8     public static void main( String[] args )
9     {
10       // create new thread pool with two threads
11       ExecutorService application = Executors.newCachedThreadPool();
12
13       // create UnsynchronizedBuffer to store ints
14       Buffer sharedLocation = new UnsynchronizedBuffer();
15
16       System.out.println(
17          "Action\t\tValue\tSum of Produced\tSum of Consumed" );
18       System.out.println(
19          "------\t\t-----\t---------------\t---------------\n" );
20
21       // execute the Producer and Consumer, giving each of them access
22       // to sharedLocation
23       application.execute( new Producer( sharedLocation ) );
24       application.execute( new Consumer( sharedLocation ) );
25
26       application.shutdown(); // terminate application when tasks complete
27    } // end main
28 } // end class SharedBufferTest
```

```
Action          Value   Sum of Produced Sum of Consumed
------          -----   --------------- ---------------

Producer writes  1        1
Producer writes  2        3                 —— 1 is lost
Producer writes  3        6                 —— 2 is lost
Consumer reads   3                        3
Producer writes  4       10
Consumer reads   4                        7
Producer writes  5       15
Producer writes  6       21                 —— 5 is lost
Producer writes  7       28                 —— 6 is lost
Consumer reads   7                       14
Consumer reads   7                       21 —— 7 read again
Producer writes  8       36
Consumer reads   8                       29
Consumer reads   8                       37 —— 8 read again
Producer writes  9       45
Producer writes 10       55                 —— 9 is lost

Producer done producing
Terminating Producer
Consumer reads  10                       47
Consumer reads  10                       57 —— 10 read again
Consumer reads  10                       67 —— 10 read again
Consumer reads  10                       77 —— 10 read again

Consumer read values totaling 77
Terminating Consumer
```

Fig. 26.13 | Application with two threads manipulating an unsynchronized buffer. (Part 2 of 3.)

```
Action          Value   Sum of Produced Sum of Consumed
------          -----   --------------- ---------------

Consumer reads  -1                      -1 ---- reads -1 bad data
Producer writes  1       1
Consumer reads   1                      0
Consumer reads   1                      1 ---- 1 read again
Consumer reads   1                      2 ---- 1 read again
Consumer reads   1                      3 ---- 1 read again
Consumer reads   1                      4 ---- 1 read again
Producer writes  2       3
Consumer reads   2                      6
Producer writes  3       6
Consumer reads   3                      9
Producer writes  4      10
Consumer reads   4                     13
Producer writes  5      15
Producer writes  6      21                ---- 5 is lost
Consumer reads   6                     19

Consumer read values totaling 19
Terminating Consumer
Producer writes  7      28                ---- 7 never read
Producer writes  8      36                ---- 8 never read
Producer writes  9      45                ---- 9 never read
Producer writes 10      55                ---- 10 never read

Producer done producing
Terminating Producer
```

Fig. 26.13 | Application with two threads manipulating an unsynchronized buffer. (Part 3 of 3.)

Recall from the overview of this example that we would like the `Producer` to execute first and every value produced by the `Producer` to be consumed exactly once by the `Consumer`. However, when we study the first output of Fig. 26.13, we see that the `Producer` writes the values `1`, `2` and `3` before the `Consumer` reads its first value (`3`). Therefore, the values `1` and `2` are lost. Later, the values `5`, `6` and `9` are lost, while `7` and `8` are read twice and `10` is read four times. So the first output produces an incorrect total of 77, instead of the correct total of 55. In the second output, the `Consumer` reads the value `-1` before the `Producer` ever writes a value. The `Consumer` reads the value `1` five times before the `Producer` writes the value `2`. Meanwhile, the values `5`, `7`, `8`, `9` and `10` are all lost—the last four because the `Consumer` terminates before the `Producer`. An incorrect consumer total of 19 is displayed. (Lines in the output where the `Producer` or `Consumer` has acted out of order are highlighted.)

Error-Prevention Tip 26.1

Access to a shared object by concurrent threads must be controlled carefully or a program may produce incorrect results.

To solve the problems of lost and duplicated data, Section 26.6 presents an example in which we use an `ArrayBlockingQueue` (from package `java.util.concurrent`) to synchronize access to the shared object, guaranteeing that each and every value will be processed once and only once.

26.6 Producer/Consumer Relationship: ArrayBlockingQueue

One way to synchronize producer and consumer threads is to use classes from Java's concurrency package that *encapsulate the synchronization for you*. Java includes the class **ArrayBlockingQueue** (from package `java.util.concurrent`)—a fully implemented, *thread-safe buffer class* that implements interface **BlockingQueue**. This interface extends the `Queue` interface discussed in Chapter 20 and declares methods **put** and **take**, the blocking equivalents of `Queue` methods `offer` and `poll`, respectively. Method `put` places an element at the end of the `BlockingQueue`, waiting if the queue is full. Method `take` removes an element from the head of the `BlockingQueue`, waiting if the queue is empty. These methods make class `ArrayBlockingQueue` a good choice for implementing a shared buffer. Because method `put` blocks until there's room in the buffer to write data, and method `take` blocks until there's new data to read, the producer must produce a value first, the consumer correctly consumes only after the producer writes a value and the producer correctly produces the next value (after the first) only after the consumer reads the previous (or first) value. `ArrayBlockingQueue` stores the shared data in an array. The array's size is specified as an argument to the `ArrayBlockingQueue` constructor. Once created, an `ArrayBlockingQueue` is fixed in size and will not expand to accommodate extra elements.

Figures 26.14–26.15 demonstrate a `Producer` and a `Consumer` accessing an `ArrayBlockingQueue`. Class `BlockingBuffer` (Fig. 26.14) uses an `ArrayBlockingQueue` object that stores an `Integer` (line 7). Line 11 creates the `ArrayBlockingQueue` and passes `1` to the constructor so that the object holds a single value, as we did with the `UnsynchronizedBuffer` of Fig. 26.12. Lines 7 and 11 use generics, which we discussed in Chapters 20–21. We discuss multiple-element buffers in Section 26.8. Because our `BlockingBuffer` class uses the thread-safe `ArrayBlockingQueue` class to manage access to the shared buffer, `BlockingBuffer` is itself *thread safe*, even though we have not implemented the synchronization ourselves.

```
1  // Fig. 26.14: BlockingBuffer.java
2  // Creating a synchronized buffer using an ArrayBlockingQueue.
3  import java.util.concurrent.ArrayBlockingQueue;
4
5  public class BlockingBuffer implements Buffer
6  {
7     private final ArrayBlockingQueue<Integer> buffer; // shared buffer
8
9     public BlockingBuffer()
10    {
11       buffer = new ArrayBlockingQueue<Integer>( 1 );
12    } // end BlockingBuffer constructor
13
14    // place value into buffer
15    public void set( int value ) throws InterruptedException
16    {
17       buffer.put( value ); // place value in buffer
```

Fig. 26.14 | Creating a synchronized buffer using an `ArrayBlockingQueue`. (Part 1 of 2.)

```
18          System.out.printf( "%s%2d\t%s%d\n", "Producer writes ", value,
19             "Buffer cells occupied: ", buffer.size() );
20       } // end method set
21
22       // return value from buffer
23       public int get() throws InterruptedException
24       {
25          int readValue = buffer.take(); // remove value from buffer
26          System.out.printf( "%s %2d\t%s%d\n", "Consumer reads ",
27             readValue, "Buffer cells occupied: ", buffer.size() );
28
29          return readValue;
30       } // end method get
31    } // end class BlockingBuffer
```

Fig. 26.14 | Creating a synchronized buffer using an `ArrayBlockingQueue`. (Part 2 of 2.)

`BlockingBuffer` implements interface `Buffer` (Fig. 26.9) and uses classes `Producer` (Fig. 26.10 modified to remove line 28) and `Consumer` (Fig. 26.11 modified to remove line 28) from the example in Section 26.5. This approach demonstrates that *the threads accessing the shared object are unaware that their buffer accesses are now synchronized*. The synchronization is handled entirely in the `set` and `get` methods of `BlockingBuffer` by calling the synchronized `ArrayBlockingQueue` methods `put` and `take`, respectively. Thus, the `Producer` and `Consumer` `Runnable`s are properly synchronized simply by calling the shared object's `set` and `get` methods.

Line 17 in method `set` (Fig. 26.14, lines 15–20) calls the `ArrayBlockingQueue` object's `put` method. This method call blocks if necessary until there's room in the `buffer` to place the `value`. Method `get` (lines 23–30) calls the `ArrayBlockingQueue` object's `take` method (line 25). This method call blocks if necessary until there's an element in the `buffer` to remove. Lines 18–19 and 26–27 use the `ArrayBlockingQueue` object's **`size`** method to display the total number of elements currently in the `ArrayBlockingQueue`.

Class `BlockingBufferTest` (Fig. 26.15) contains the `main` method that launches the application. Line 12 creates an `ExecutorService`, and line 15 creates a `BlockingBuffer` object and assigns its reference to the `Buffer` variable `sharedLocation`. Lines 17–18 execute the `Producer` and `Consumer` `Runnable`s. Line 19 calls method `shutdown` to end the application when the threads finish executing the `Producer` and `Consumer` tasks.

```
1  // Fig. 26.15: BlockingBufferTest.java
2  // Two threads manipulating a blocking buffer that properly
3  // implements the producer/consumer relationship.
4  import java.util.concurrent.ExecutorService;
5  import java.util.concurrent.Executors;
6
7  public class BlockingBufferTest
8  {
9     public static void main( String[] args )
10    {
```

Fig. 26.15 | Two threads manipulating a blocking buffer that properly implements the producer/consumer relationship. (Part 1 of 2.)

```
11         // create new thread pool with two threads
12         ExecutorService application = Executors.newCachedThreadPool();
13
14         // create BlockingBuffer to store ints
15         Buffer sharedLocation = new BlockingBuffer();
16
17         application.execute( new Producer( sharedLocation ) );
18         application.execute( new Consumer( sharedLocation ) );
19
20         application.shutdown();
21      } // end main
22   } // end class BlockingBufferTest
```

```
Producer writes  1      Buffer cells occupied: 1
Consumer reads   1      Buffer cells occupied: 0
Producer writes  2      Buffer cells occupied: 1
Consumer reads   2      Buffer cells occupied: 0
Producer writes  3      Buffer cells occupied: 1
Consumer reads   3      Buffer cells occupied: 0
Producer writes  4      Buffer cells occupied: 1
Consumer reads   4      Buffer cells occupied: 0
Producer writes  5      Buffer cells occupied: 1
Consumer reads   5      Buffer cells occupied: 0
Producer writes  6      Buffer cells occupied: 1
Consumer reads   6      Buffer cells occupied: 0
Producer writes  7      Buffer cells occupied: 1
Consumer reads   7      Buffer cells occupied: 0
Producer writes  8      Buffer cells occupied: 1
Consumer reads   8      Buffer cells occupied: 0
Producer writes  9      Buffer cells occupied: 1
Consumer reads   9      Buffer cells occupied: 0
Producer writes 10      Buffer cells occupied: 1

Producer done producing
Terminating Producer
Consumer reads  10      Buffer cells occupied: 0

Consumer read values totaling 55
Terminating Consumer
```

Fig. 26.15 | Two threads manipulating a blocking buffer that properly implements the producer/consumer relationship. (Part 2 of 2.)

While methods `put` and `take` of `ArrayBlockingQueue` are properly synchronized, `BlockingBuffer` methods `set` and `get` (Fig. 26.14) are not declared to be synchronized. Thus, the statements performed in method `set`—the `put` operation (line 17) and the output (lines 18–19)—are *not atomic*; nor are the statements in method `get`—the `take` operation (line 25) and the output (lines 26–27). So there's no guarantee that each output will occur immediately after the corresponding `put` or `take` operation, and the outputs may appear out of order. Even if they do, the `ArrayBlockingQueue` object is properly synchronizing access to the data, as evidenced by the fact that the sum of values read by the consumer is always correct.

26.7 Producer/Consumer Relationship with Synchronization

The previous example showed how multiple threads can share a single-element buffer in a thread-safe manner by using the `ArrayBlockingQueue` class that encapsulates the synchronization necessary to protect the shared data. For educational purposes, we now explain how you can implement a shared buffer yourself using the `synchronized` keyword and methods of class `Object`. Using an `ArrayBlockingQueue` will result in more-maintainable and better-performing code.

The first step in synchronizing access to the buffer is to implement methods `get` and `set` as `synchronized` methods. This requires that a thread obtain the *monitor lock* on the `Buffer` object before attempting to access the buffer data, but it does not automatically ensure that threads proceed with an operation only if the buffer is in the proper state. We need a way to allow our threads to wait, depending on whether certain conditions are true. In the case of placing a new item in the buffer, the condition that allows the operation to proceed is that the *buffer is not full*. In the case of fetching an item from the buffer, the condition that allows the operation to proceed is that the *buffer is not empty*. If the condition in question is true, the operation may proceed; if it's false, the thread must wait until it becomes true. When a thread is waiting on a condition, it's removed from contention for the processor and placed into the *waiting* state and the lock it holds is released.

Methods `wait`, `notify` *and* `notifyAll`

`Object` methods `wait`, `notify` and `notifyAll`, which are inherited by all other classes, can be used with conditions to make threads *wait* when they cannot perform their tasks. If a thread obtains the *monitor lock* on an object, then determines that it cannot continue with its task on that object until some condition is satisfied, the thread can call `Object` method **`wait`** on the `synchronized` object; this releases the monitor lock on the object, and the thread waits in the *waiting* state while the other threads try to enter the object's `synchronized` statement(s) or method(s). When a thread executing a `synchronized` statement (or method) completes or satisfies the condition on which another thread may be waiting, it can call `Object` method **`notify`** on the `synchronized` object to allow a waiting thread to transition to the *runnable* state again. At this point, the thread that was transitioned from the *waiting* state to the *runnable* state can attempt to reacquire the monitor lock on the object. Even if the thread is able to reacquire the monitor lock, it still might not be able to perform its task at this time—in which case the thread will reenter the *waiting* state and implicitly release the monitor lock. If a thread calls **`notifyAll`** on the `synchronized` object, then *all* the threads waiting for the monitor lock become eligible to reacquire the lock (that is, they all transition to the *runnable* state).

Remember that only one thread at a time can obtain the monitor lock on the object—other threads that attempt to acquire the same monitor lock will be *blocked* until the monitor lock becomes available again (i.e., until no other thread is executing in a `synchronized` statement on that object).

Common Programming Error 26.1

It's an error if a thread issues a `wait`*,* `notify` *or a* `notifyAll` *on an object without having acquired a lock for it. This causes an* **`IllegalMonitorStateException`**.

Error-Prevention Tip 26.2

It's a good practice to use `notifyAll` *to notify* waiting *threads to become* runnable. *Doing so avoids the possibility that your program would forget about waiting threads, which would otherwise starve.*

The application in Fig. 26.16 and Fig. 26.17 demonstrates a `Producer` and a `Consumer` accessing a shared buffer with synchronization. In this case, the `Producer` always produces a value *first*, the `Consumer` correctly consumes only *after* the `Producer` produces a value and the `Producer` correctly produces the next value only after the `Consumer` consumes the previous (or first) value. We reuse interface `Buffer` and classes `Producer` and `Consumer` from the example in Section 26.5, except that line 28 is removed from class `Producer` and class `Consumer`. The synchronization is handled in the `set` and `get` methods of class `SynchronizedBuffer` (Fig. 26.16), which implements interface `Buffer` (line 4). Thus, the `Producer`'s and `Consumer`'s `run` methods simply call the shared object's `synchronized` `set` and `get` methods.

```
1  // Fig. 26.16: SynchronizedBuffer.java
2  // Synchronizing access to shared data using Object
3  // methods wait and notifyAll.
4  public class SynchronizedBuffer implements Buffer
5  {
6     private int buffer = -1; // shared by producer and consumer threads
7     private boolean occupied = false; // whether the buffer is occupied
8
9     // place value into buffer
10    public synchronized void set( int value ) throws InterruptedException
11    {
12       // while there are no empty locations, place thread in waiting state
13       while ( occupied )
14       {
15          // output thread information and buffer information, then wait
16          System.out.println( "Producer tries to write." );
17          displayState( "Buffer full. Producer waits." );
18          wait();
19       } // end while
20
21       buffer = value; // set new buffer value
22
23       // indicate producer cannot store another value
24       // until consumer retrieves current buffer value
25       occupied = true;
26
27       displayState( "Producer writes " + buffer );
28
29       notifyAll(); // tell waiting thread(s) to enter runnable state
30    } // end method set; releases lock on SynchronizedBuffer
31
```

Fig. 26.16 | Synchronizing access to shared data using `Object` methods `wait` and `notifyAll`. (Part 1 of 2.)

```
32      // return value from buffer
33      public synchronized int get() throws InterruptedException
34      {
35         // while no data to read, place thread in waiting state
36         while ( !occupied )
37         {
38            // output thread information and buffer information, then wait
39            System.out.println( "Consumer tries to read." );
40            displayState( "Buffer empty. Consumer waits." );
41            wait();
42         } // end while
43
44         // indicate that producer can store another value
45         // because consumer just retrieved buffer value
46         occupied = false;
47
48         displayState( "Consumer reads " + buffer );
49
50         notifyAll(); // tell waiting thread(s) to enter runnable state
51
52         return buffer;
53      } // end method get; releases lock on SynchronizedBuffer
54
55      // display current operation and buffer state
56      public void displayState( String operation )
57      {
58         System.out.printf( "%-40s%d\t\t%b\n\n", operation, buffer,
59            occupied );
60      } // end method displayState
61   } // end class SynchronizedBuffer
```

Fig. 26.16 | Synchronizing access to shared data using `Object` methods `wait` and `notifyAll`. (Part 2 of 2.)

Fields and Methods of Class `SynchronizedBuffer`

Class `SynchronizedBuffer` contains fields `buffer` (line 6) and `occupied` (line 7). Methods `set` (lines 10–30) and `get` (lines 33–53) are declared as `synchronized`—only one thread can call either of these methods at a time on a particular `SynchronizedBuffer` object. Field `occupied` is used to determine whether it's the `Producer`'s or the `Consumer`'s turn to perform a task. This field is used in conditional expressions in both the `set` and `get` methods. If `occupied` is `false`, then `buffer` is empty, so the `Consumer` cannot read the value of `buffer`, but the `Producer` can place a value into `buffer`. If `occupied` is `true`, the `Consumer` can read a value from `buffer`, but the `Producer` cannot place a value into `buffer`.

Method `set` *and the* `Producer` *Thread*

When the `Producer` thread's `run` method invokes `synchronized` method `set`, the thread implicitly attempts to acquire the `SynchronizedBuffer` object's monitor lock. If the monitor lock is available, the `Producer` thread implicitly acquires the lock. Then the loop at lines 13–19 first determines whether `occupied` is `true`. If so, `buffer` is full, so line 16 outputs a message indicating that the `Producer` thread is trying to write a value, and line 17 invokes method `displayState` (lines 56–60) to output another message indicating that `buffer` is

full and that the Producer thread is waiting until there's space. Line 18 invokes method wait (inherited from Object by SynchronizedBuffer) to place the thread that called method set (i.e., the Producer thread) in the *waiting* state for the SynchronizedBuffer object. The call to wait causes the calling thread to *implicitly* release the lock on the SynchronizedBuffer object. This is important because the thread cannot currently perform its task and because other threads (in this case, the Consumer) should be allowed to access the object to allow the condition (occupied) to change. Now another thread can attempt to acquire the SynchronizedBuffer object's lock and invoke the object's set or get method.

The Producer thread remains in the *waiting* state until another thread notifies the Producer that it may proceed—at which point the Producer returns to the *runnable* state and attempts to implicitly reacquire the lock on the SynchronizedBuffer object. If the lock is available, the Producer thread reacquires it, and method set continues executing with the next statement after the wait call. Because wait is called in a loop, the loop-continuation condition is tested again to determine whether the thread can proceed. If not, then wait is invoked again—otherwise, method set continues with the next statement after the loop.

Line 21 in method set assigns the value to the buffer. Line 25 sets occupied to true to indicate that the buffer now contains a value (i.e., a consumer can read the value, but a Producer cannot yet put another value there). Line 27 invokes method displayState to output a message indicating that the Producer is writing a new value into the buffer. Line 29 invokes method notifyAll (inherited from Object). If any threads are waiting on the SynchronizedBuffer object's monitor lock, those threads enter the *runnable* state and can now attempt to reacquire the lock. Method notifyAll returns immediately, and method set then returns to the caller (i.e., the Producer's run method). When method set returns, it implicitly releases the monitor lock on the SynchronizedBuffer object.

Method `get` *and the* `Consumer` *Thread*

Methods get and set are implemented similarly. When the Consumer thread's run method invokes synchronized method get, the thread attempts to acquire the *monitor lock* on the SynchronizedBuffer object. If the lock is available, the Consumer thread acquires it. Then the while loop at lines 36–42 determines whether occupied is false. If so, the buffer is empty, so line 39 outputs a message indicating that the Consumer thread is trying to read a value, and line 40 invokes method displayState to output a message indicating that the buffer is empty and that the Consumer thread is waiting. Line 41 invokes method wait to place the thread that called method get (i.e., the Consumer) in the *waiting* state for the SynchronizedBuffer object. Again, the call to wait causes the calling thread to implicitly release the lock on the SynchronizedBuffer object, so another thread can attempt to acquire the SynchronizedBuffer object's lock and invoke the object's set or get method. If the lock on the SynchronizedBuffer is not available (e.g., if the Producer has not yet returned from method set), the Consumer is blocked until the lock becomes available.

The Consumer thread remains in the *waiting* state until it's notified by another thread that it may proceed—at which point the Consumer thread returns to the *runnable* state and attempts to implicitly reacquire the lock on the SynchronizedBuffer object. If the lock is available, the Consumer reacquires it, and method get continues executing with the next statement after wait. Because wait is called in a loop, the loop-continuation condition is tested again to determine whether the thread can proceed with its execution. If not, wait is invoked again—otherwise, method get continues with the next statement after the loop.

Line 46 sets `occupied` to `false` to indicate that `buffer` is now empty (i.e., a `Consumer` cannot read the value, but a `Producer` can place another value in `buffer`), line 48 calls method `displayState` to indicate that the consumer is reading and line 50 invokes method `notifyAll`. If any threads are in the *waiting* state for the lock on this `SynchronizedBuffer` object, they enter the *runnable* state and can now attempt to reacquire the lock. Method `notifyAll` returns immediately, then method `get` returns the value of `buffer` to its caller. When method `get` returns, the lock on the `SynchronizedBuffer` object is implicitly released.

Error-Prevention Tip 26.3

Always invoke method `wait` *in a loop that tests the condition the task is waiting on. It's possible that a thread will reenter the* runnable *state (via a timed wait or another thread calling* `notifyAll`*) before the condition is satisfied. Testing the condition again ensures that the thread will not erroneously execute if it was notified early.*

Testing Class `SynchronizedBuffer`

Class `SharedBufferTest2` (Fig. 26.17) is similar to class `SharedBufferTest` (Fig. 26.13). `SharedBufferTest2` contains method `main` (lines 8–24), which launches the application. Line 11 creates an `ExecutorService` to run the `Producer` and `Consumer` tasks. Line 14 creates a `SynchronizedBuffer` object and assigns its reference to `Buffer` variable `sharedLocation`. This object stores the data that will be shared between the `Producer` and `Consumer`. Lines 16–17 display the column heads for the output. Lines 20–21 execute a `Producer` and a `Consumer`. Finally, line 23 calls method `shutdown` to end the application when the `Producer` and `Consumer` complete their tasks. When method `main` ends (line 24), the main thread of execution terminates.

```
1  // Fig. 26.17: SharedBufferTest2.java
2  // Two threads correctly manipulating a synchronized buffer.
3  import java.util.concurrent.ExecutorService;
4  import java.util.concurrent.Executors;
5
6  public class SharedBufferTest2
7  {
8     public static void main( String[] args )
9     {
10       // create a newCachedThreadPool
11       ExecutorService application = Executors.newCachedThreadPool();
12
13       // create SynchronizedBuffer to store ints
14       Buffer sharedLocation = new SynchronizedBuffer();
15
16       System.out.printf( "%-40s%s\t\t%s\n%-40s%s\n\n", "Operation",
17          "Buffer", "Occupied", "---------", "------\t\t--------" );
18
19       // execute the Producer and Consumer tasks
20       application.execute( new Producer( sharedLocation ) );
21       application.execute( new Consumer( sharedLocation ) );
22
```

Fig. 26.17 | Two threads correctly manipulating a synchronized buffer. (Part 1 of 3.)

```
23          application.shutdown();
24       } // end main
25    } // end class SharedBufferTest2
```

```
Operation                               Buffer          Occupied
---------                               ------          --------

Consumer tries to read.
Buffer empty. Consumer waits.           -1              false

Producer writes 1                       1               true

Consumer reads 1                        1               false

Consumer tries to read.
Buffer empty. Consumer waits.           1               false

Producer writes 2                       2               true

Consumer reads 2                        2               false

Producer writes 3                       3               true

Consumer reads 3                        3               false

Producer writes 4                       4               true

Producer tries to write.
Buffer full. Producer waits.            4               true

Consumer reads 4                        4               false

Producer writes 5                       5               true

Consumer reads 5                        5               false

Producer writes 6                       6               true

Producer tries to write.
Buffer full. Producer waits.            6               true

Consumer reads 6                        6               false

Producer writes 7                       7               true

Producer tries to write.
Buffer full. Producer waits.            7               true

Consumer reads 7                        7               false

Producer writes 8                       8               true

Consumer reads 8                        8               false

Consumer tries to read.
Buffer empty. Consumer waits.           8               false
```

Fig. 26.17 | Two threads correctly manipulating a synchronized buffer. (Part 2 of 3.)

```
Producer writes 9                       9               true

Consumer reads 9                        9               false

Consumer tries to read.
Buffer empty. Consumer waits.           9               false

Producer writes 10                      10              true

Consumer reads 10                       10              false


Producer done producing
Terminating Producer

Consumer read values totaling 55
Terminating Consumer
```

Fig. 26.17 | Two threads correctly manipulating a synchronized buffer. (Part 3 of 3.)

Study the outputs in Fig. 26.17. Observe that *every integer produced is consumed exactly once—no values are lost, and no values are consumed more than once*. The synchronization ensures that the `Producer` produces a value only when the buffer is empty and the `Consumer` consumes only when the buffer is full. The `Producer` always goes first, the `Consumer` waits if the `Producer` has not produced since the `Consumer` last consumed, and the `Producer` waits if the `Consumer` has not yet consumed the value that the `Producer` most recently produced. Execute this program several times to confirm that every integer produced is consumed exactly once. In the sample output, note the highlighted lines indicating when the `Producer` and `Consumer` must wait to perform their respective tasks.

26.8 Producer/Consumer Relationship: Bounded Buffers

The program in Section 26.7 uses thread synchronization to guarantee that two threads manipulate data in a shared buffer correctly. However, the application may not perform optimally. If the two threads operate at different speeds, one them will spend more (or most) of its time waiting. For example, in the program in Section 26.7 we shared a single integer variable between the two threads. If the `Producer` thread produces values faster than the `Consumer` can consume them, then the `Producer` thread *waits* for the `Consumer`, because there are no other locations in the buffer in which to place the next value. Similarly, if the `Consumer` consumes values faster than the `Producer` produces them, the `Consumer` *waits* until the `Producer` places the next value in the shared buffer. Even when we have threads that operate at the same relative speeds, those threads may occasionally become "out of sync" over a period of time, causing one of them to wait for the other. *We cannot make assumptions about the relative speeds of concurrent threads*—interactions that occur with the operating system, the network, the user and other components can cause the threads to operate at different and ever-changing speeds. When this happens, threads wait. When threads wait excessively, programs become less efficient, interactive programs become less responsive and applications suffer longer delays.

Bounded Buffers

To minimize the amount of waiting time for threads that share resources and operate at the same average speeds, we can implement a **bounded buffer** that provides a fixed number of buffer cells into which the `Producer` can place values, and from which the `Consumer` can retrieve those values. (In fact, we've already done this with the `ArrayBlockingQueue` class in Section 26.6.) If the `Producer` temporarily produces values faster than the `Consumer` can consume them, the `Producer` can write additional values into the extra buffer cells, if any are available. This capability enables the `Producer` to perform its task even though the `Consumer` is not ready to retrieve the current value being produced. Similarly, if the `Consumer` consumes faster than the `Producer` produces new values, the `Consumer` can read additional values (if there are any) from the buffer. This enables the `Consumer` to keep busy even though the `Producer` is not ready to produce additional values.

Even a *bounded buffer* is inappropriate if the `Producer` and the `Consumer` operate consistently at different speeds. If the `Consumer` always executes faster than the `Producer`, then a buffer containing one location is enough. Additional locations would simply waste memory. If the `Producer` always executes faster, only a buffer with an "infinite" number of locations would be able to absorb the extra production. However, if the `Producer` and `Consumer` execute at about the same average speed, a bounded buffer helps to smooth the effects of any occasional speeding up or slowing down in either thread's execution.

The key to using a *bounded buffer* with a `Producer` and `Consumer` that operate at about the same speed is to provide the buffer with enough locations to handle the anticipated "extra" production. If, over a period of time, we determine that the `Producer` often produces as many as three more values than the `Consumer` can consume, we can provide a buffer of at least three cells to handle the extra production. Making the buffer too small would cause threads to wait longer; making the buffer too large would waste memory.

Performance Tip 26.3

Even when using a bounded buffer*, it's possible that a producer thread could fill the buffer, which would force the producer to wait until a consumer consumed a value to free an element in the buffer. Similarly, if the buffer is empty at any given time, a consumer thread must wait until the producer produces another value. The key to using a bounded buffer is to optimize the buffer size to minimize the amount of thread wait time, while not wasting space.*

Bounded Buffers Using `ArrayBlockingQueue`

The simplest way to implement a bounded buffer is to use an `ArrayBlockingQueue` for the buffer so that *all of the synchronization details are handled for you*. This can be done by modifying the example from Section 26.6 to pass the desired size for the bounded buffer into the `ArrayBlockingQueue` constructor. Rather than repeat our previous `ArrayBlockingQueue` example with a different size, we instead present an example that illustrates how you can build a bounded buffer yourself. Again, using an `ArrayBlockingQueue` will result in more-maintainable and better-performing code. In Exercise 26.11, we ask you to reimplement this section's example, using the Java Concurrency API techniques presented in Section 26.9.

Implementing Your Own Bounded Buffer as a Circular Buffer

The program in Fig. 26.18 and Fig. 26.19 demonstrates a `Producer` and a `Consumer` accessing a *bounded buffer with synchronization*. Again, we reuse interface `Buffer` and classes

`Producer` and `Consumer` from the example in Section 26.5, except that line 28 is removed from class `Producer` and class `Consumer`. We implement the bounded buffer in class `CircularBuffer` (Fig. 26.18) as a **circular buffer** that uses a shared array of three elements. A circular buffer writes into and reads from the array elements in order, beginning at the first cell and moving toward the last. When a `Producer` or `Consumer` reaches the last element, it returns to the first and begins writing or reading, respectively, from there. In this version of the producer/consumer relationship, the `Consumer` consumes a value only when the array is not empty and the `Producer` produces a value only when the array is not full. The statements that created and started the thread objects in the `main` method of class `SharedBufferTest2` (Fig. 26.17) now appear in class `CircularBufferTest` (Fig. 26.19).

```
1  // Fig. 26.18: CircularBuffer.java
2  // Synchronizing access to a shared three-element bounded buffer.
3  public class CircularBuffer implements Buffer
4  {
5     private final int[] buffer = { -1, -1, -1 }; // shared buffer
6
7     private int occupiedCells = 0; // count number of buffers used
8     private int writeIndex = 0; // index of next element to write to
9     private int readIndex = 0; // index of next element to read
10
11    // place value into buffer
12    public synchronized void set( int value ) throws InterruptedException
13    {
14       // wait until buffer has space available, then write value;
15       // while no empty locations, place thread in blocked state
16       while ( occupiedCells == buffer.length )
17       {
18          System.out.printf( "Buffer is full. Producer waits.\n" );
19          wait(); // wait until a buffer cell is free
20       } // end while
21
22       buffer[ writeIndex ] = value; // set new buffer value
23
24       // update circular write index
25       writeIndex = ( writeIndex + 1 ) % buffer.length;
26
27       ++occupiedCells; // one more buffer cell is full
28       displayState( "Producer writes " + value );
29       notifyAll(); // notify threads waiting to read from buffer
30    } // end method set
31
32    // return value from buffer
33    public synchronized int get() throws InterruptedException
34    {
35       // wait until buffer has data, then read value;
36       // while no data to read, place thread in waiting state
37       while ( occupiedCells == 0 )
38       {
39          System.out.printf( "Buffer is empty. Consumer waits.\n" );
```

Fig. 26.18 | Synchronizing access to a shared three-element bounded buffer. (Part 1 of 2.)

```
40            wait(); // wait until a buffer cell is filled
41         } // end while
42
43         int readValue = buffer[ readIndex ]; // read value from buffer
44
45         // update circular read index
46         readIndex = ( readIndex + 1 ) % buffer.length;
47
48         --occupiedCells; // one fewer buffer cells are occupied
49         displayState( "Consumer reads " + readValue );
50         notifyAll(); // notify threads waiting to write to buffer
51
52         return readValue;
53      } // end method get
54
55      // display current operation and buffer state
56      public void displayState( String operation )
57      {
58         // output operation and number of occupied buffer cells
59         System.out.printf( "%s%s%d)\n%s", operation,
60            " (buffer cells occupied: ", occupiedCells, "buffer cells:  " );
61
62         for ( int value : buffer )
63            System.out.printf( " %2d  ", value ); // output values in buffer
64
65         System.out.print( "\n               " );
66
67         for ( int i = 0; i < buffer.length; i++ )
68            System.out.print( "---- " );
69
70         System.out.print( "\n               " );
71
72         for ( int i = 0; i < buffer.length; i++ )
73         {
74            if ( i == writeIndex && i == readIndex )
75               System.out.print( " WR" ); // both write and read index
76            else if ( i == writeIndex )
77               System.out.print( " W   " ); // just write index
78            else if ( i == readIndex )
79               System.out.print( "  R  " ); // just read index
80            else
81               System.out.print( "     " ); // neither index
82         } // end for
83
84         System.out.println( "\n" );
85      } // end method displayState
86   } // end class CircularBuffer
```

Fig. 26.18 | Synchronizing access to a shared three-element bounded buffer. (Part 2 of 2.)

Line 5 initializes array `buffer` as a three-element `int` array that represents the circular buffer. Variable `occupiedCells` (line 7) counts the number of elements in `buffer` that contain data to be read. When `occupiedBuffers` is 0, there's no data in the circular buffer and the `Consumer` must wait—when `occupiedCells` is 3 (the size of the circular buffer),

the circular buffer is full and the `Producer` must wait. Variable `writeIndex` (line 8) indicates the next location in which a value can be placed by a `Producer`. Variable `readIndex` (line 9) indicates the position from which the next value can be read by a `Consumer`.

`CircularBuffer` Method `set`

`CircularBuffer` method `set` (lines 12–30) performs the same tasks as in Fig. 26.16, with a few modifications. The loop at lines 16–20 determines whether the `Producer` must wait (i.e., all buffer cells are full). If so, line 18 indicates that the `Producer` is waiting to perform its task. Then line 19 invokes method `wait`, causing the `Producer` thread to release the `CircularBuffer`'s lock and wait until there's space for a new value to be written into the buffer. When execution continues at line 22 after the `while` loop, the value written by the `Producer` is placed in the circular buffer at location `writeIndex`. Then line 25 updates `writeIndex` for the next call to `CircularBuffer` method `set`. This line is the key to the buffer's *circularity*. When `writeIndex` is incremented past the end of the buffer, the line sets it to `0`. Line 27 increments `occupiedCells`, because there's now one more value in the buffer that the `Consumer` can read. Next, line 28 invokes method `displayState` (lines 56–85) to update the output with the value produced, the number of occupied buffer cells, the contents of the buffer cells and the current `writeIndex` and `readIndex`. Line 29 invokes method `notifyAll` to transition *waiting* threads to the *runnable* state, so that a waiting `Consumer` thread (if there is one) can now try again to read a value from the buffer.

`CircularBuffer` Method `get`

`CircularBuffer` method `get` (lines 33–53) also performs the same tasks as it did in Fig. 26.16, with a few minor modifications. The loop at lines 37–41 determines whether the `Consumer` must wait (i.e., all buffer cells are empty). If the `Consumer` must wait, line 39 updates the output to indicate that the `Consumer` is waiting to perform its task. Then line 40 invokes method `wait`, causing the current thread to release the lock on the `CircularBuffer` and wait until data is available to read. When execution eventually continues at line 43 after a `notifyAll` call from the `Producer`, `readValue` is assigned the value at location `readIndex` in the circular buffer. Then line 46 updates `readIndex` for the next call to `CircularBuffer` method `get`. This line and line 25 implement the *circularity* of the buffer. Line 48 decrements `occupiedCells`, because there's now one more position in the buffer in which the `Producer` thread can place a value. Line 49 invokes method `displayState` to update the output with the consumed value, the number of occupied buffer cells, the contents of the buffer cells and the current `writeIndex` and `readIndex`. Line 50 invokes method `notifyAll` to allow any `Producer` threads waiting to write into the `CircularBuffer` object to attempt to write again. Then line 52 returns the consumed value to the caller.

`CircularBuffer` Method `displayState`

Method `displayState` (lines 56–85) outputs the application's state. Lines 62–63 output the values of the buffer cells. Line 63 uses method `printf` with a `"%2d"` format specifier to print the contents of each buffer with a leading space if it's a single digit. Lines 70–82 output the current `writeIndex` and `readIndex` with the letters `W` and `R`, respectively.

Testing Class `CircularBuffer`

Class `CircularBufferTest` (Fig. 26.19) contains the `main` method that launches the application. Line 11 creates the `ExecutorService`, and line 14 creates a `CircularBuffer` ob-

ject and assigns its reference to `CircularBuffer` variable `sharedLocation`. Line 17 invokes the `CircularBuffer`'s `displayState` method to show the initial state of the buffer. Lines 20–21 execute the `Producer` and `Consumer` tasks. Line 23 calls method `shutdown` to end the application when the threads complete the `Producer` and `Consumer` tasks.

Each time the `Producer` writes a value or the `Consumer` reads a value, the program outputs a message indicating the action performed (a read or a write), the contents of `buffer`, and the location of `writeIndex` and `readIndex`. In the output of Fig. 26.19, the `Producer` first writes the value 1. The buffer then contains the value 1 in the first cell and the value –1 (the default value that we use for output purposes) in the other two cells. The write index is updated to the second cell, while the read index stays at the first cell. Next, the `Consumer` reads 1. The buffer contains the same values, but the read index has been updated to the second cell. The `Consumer` then tries to read again, but the buffer is empty and the `Consumer` is forced to wait. Only once in this execution of the program was it necessary for either thread to wait.

```
1  // Fig. 26.19: CircularBufferTest.java
2  // Producer and Consumer threads manipulating a circular buffer.
3  import java.util.concurrent.ExecutorService;
4  import java.util.concurrent.Executors;
5
6  public class CircularBufferTest
7  {
8     public static void main( String[] args )
9     {
10       // create new thread pool with two threads
11       ExecutorService application = Executors.newCachedThreadPool();
12
13       // create CircularBuffer to store ints
14       CircularBuffer sharedLocation = new CircularBuffer();
15
16       // display the initial state of the CircularBuffer
17       sharedLocation.displayState( "Initial State" );
18
19       // execute the Producer and Consumer tasks
20       application.execute( new Producer( sharedLocation ) );
21       application.execute( new Consumer( sharedLocation ) );
22
23       application.shutdown();
24    } // end main
25 } // end class CircularBufferTest
```

```
Initial State (buffer cells occupied: 0)
buffer cells:   -1   -1   -1
               ---- ---- ----
                WR

Producer writes 1 (buffer cells occupied: 1)
buffer cells:    1   -1   -1
               ---- ---- ----
                 R   W
```

Fig. 26.19 | `Producer` and `Consumer` threads manipulating a circular buffer. (Part 1 of 3.)

```
Consumer reads 1 (buffer cells occupied: 0)
buffer cells:    1   -1   -1
               ---- ---- ----
                     WR

Buffer is empty. Consumer waits.
Producer writes 2 (buffer cells occupied: 1)
buffer cells:    1    2   -1
               ---- ---- ----
                      R   W

Consumer reads 2 (buffer cells occupied: 0)
buffer cells:    1    2   -1
               ---- ---- ----
                          WR

Producer writes 3 (buffer cells occupied: 1)
buffer cells:    1    2    3
               ---- ---- ----
                W          R

Consumer reads 3 (buffer cells occupied: 0)
buffer cells:    1    2    3
               ---- ---- ----
                WR

Producer writes 4 (buffer cells occupied: 1)
buffer cells:    4    2    3
               ---- ---- ----
                 R   W

Producer writes 5 (buffer cells occupied: 2)
buffer cells:    4    5    3
               ---- ---- ----
                 R        W

Consumer reads 4 (buffer cells occupied: 1)
buffer cells:    4    5    3
               ---- ---- ----
                      R   W

Producer writes 6 (buffer cells occupied: 2)
buffer cells:    4    5    6
               ---- ---- ----
                W     R

Producer writes 7 (buffer cells occupied: 3)
buffer cells:    7    5    6
               ---- ---- ----
                     WR

Consumer reads 5 (buffer cells occupied: 2)
buffer cells:    7    5    6
                ---- ---- ----
                     W     R

Producer writes 8 (buffer cells occupied: 3)
buffer cells:    7    8    6
               ---- ---- ----
                          WR
```

Fig. 26.19 | `Producer` and `Consumer` threads manipulating a circular buffer. (Part 2 of 3.)

```
Consumer reads 6 (buffer cells occupied: 2)
buffer cells:    7    8    6
               ---- ---- ----
                 R        W

Consumer reads 7 (buffer cells occupied: 1)
buffer cells:    7    8    6
               ---- ---- ----
                      R   W

Producer writes 9 (buffer cells occupied: 2)
buffer cells:    7    8    9
               ---- ---- ----
                W     R

Consumer reads 8 (buffer cells occupied: 1)
buffer cells:    7    8    9
               ---- ---- ----
                W          R

Consumer reads 9 (buffer cells occupied: 0)
buffer cells:    7    8    9
               ---- ---- ----
                WR

Producer writes 10 (buffer cells occupied: 1)
buffer cells:   10    8    9
               ---- ---- ----
                 R   W


Producer done producing
Terminating Producer
Consumer reads 10 (buffer cells occupied: 0)
buffer cells:   10    8    9
               ---- ---- ----
                     WR


Consumer read values totaling: 55
Terminating Consumer
```

Fig. 26.19 | `Producer` and `Consumer` threads manipulating a circular buffer. (Part 3 of 3.)

26.9 Producer/Consumer Relationship: The Lock and Condition Interfaces

Though the `synchronized` keyword provides for most basic thread-synchronization needs, Java provides other tools to assist in developing concurrent programs. In this section, we discuss the `Lock` and `Condition` interfaces. These interfaces give you more precise control over thread synchronization, but are more complicated to use.

Interface `Lock` *and Class* `ReentrantLock`

Any object can contain a reference to an object that implements the **`Lock`** interface (of package `java.util.concurrent.locks`). A thread calls the `Lock`'s **`lock`** method (analogous to entering a `synchronized` block) to acquire the lock. Once a `Lock` has been obtained by one thread, the `Lock` object will not allow another thread to obtain the `Lock` until the first thread releases the `Lock` (by calling the `Lock`'s **`unlock`** method—analogous to ex-

iting a synchronized block). If several threads are trying to call method lock on the same Lock object at the same time, only one of these threads can obtain the lock—all the others are placed in the *waiting* state for that lock. When a thread calls method unlock, the lock on the object is released and a waiting thread attempting to lock the object proceeds.

Class **ReentrantLock** (of package java.util.concurrent.locks) is a basic implementation of the Lock interface. The constructor for a ReentrantLock takes a boolean argument that specifies whether the lock has a **fairness policy**. If the argument is true, the ReentrantLock's fairness policy is "the longest-waiting thread will acquire the lock when it's available." Such a fairness policy guarantees that *indefinite postponement* (also called *starvation*) cannot occur. If the fairness policy argument is set to false, there's no guarantee as to which waiting thread will acquire the lock when it's available.

Software Engineering Observation 26.3

Using a ReentrantLock with a fairness policy avoids indefinite postponement.

Performance Tip 26.4

Using a ReentrantLock with a fairness policy can decrease program performance.

Condition Objects and Interface `Condition`

If a thread that owns a Lock determines that it cannot continue with its task until some condition is satisfied, the thread can wait on a **condition object**. Using Lock objects allows you to explicitly declare the condition objects on which a thread may need to wait. For example, in the producer/consumer relationship, producers can wait on *one* object and consumers can wait on *another*. This is not possible when using the synchronized keywords and an object's built-in monitor lock. Condition objects are associated with a specific Lock and are created by calling a Lock's **newCondition** method, which returns an object that implements the **Condition** interface (of package java.util.concurrent.locks). To wait on a condition object, the thread can call the Condition's **await** method (analogous to Object method wait). This immediately releases the associated Lock and places the thread in the *waiting* state for that Condition. Other threads can then try to obtain the Lock. When a *runnable* thread completes a task and determines that the *waiting* thread can now continue, the *runnable* thread can call Condition method **signal** (analogous to Object method notify) to allow a thread in that Condition's *waiting* state to return to the *runnable* state. At this point, the thread that transitioned from the *waiting* state to the *runnable* state can attempt to reacquire the Lock. Even if it's able to reacquire the Lock, the thread still might not be able to perform its task at this time—in which case the thread can call the Condition's await method to release the Lock and reenter the *waiting* state. If multiple threads are in a Condition's *waiting* state when signal is called, the default implementation of Condition signals the longest-waiting thread to transition to the *runnable* state. If a thread calls Condition method **signalAll** (analogous to Object method notifyAll), then all the threads waiting for that condition transition to the *runnable* state and become eligible to reacquire the Lock. Only one of those threads can obtain the Lock on the object—the others will wait until the Lock becomes available again. If the Lock has a *fairness policy*, the longest-waiting thread acquires the Lock. When a thread is finished with a shared object, it must call method unlock to release the Lock.

Common Programming Error 26.2

Deadlock occurs when a waiting thread (let's call this thread1) cannot proceed because it's waiting (either directly or indirectly) for another thread (let's call this thread2) to proceed, while simultaneously thread2 cannot proceed because it's waiting (either directly or indirectly) for thread1 to proceed. The two threads are waiting for each other, so the actions that would enable each thread to continue execution can never occur.

Error-Prevention Tip 26.4

When multiple threads manipulate a shared object using locks, ensure that if one thread calls method `await` *to enter the* waiting *state for a condition object, a separate thread eventually will call* `Condition` *method* `signal` *to transition the thread waiting on the condition object back to the* runnable *state. If multiple threads may be waiting on the condition object, a separate thread can call* `Condition` *method* `signalAll` *as a safeguard to ensure that all the waiting threads have another opportunity to perform their tasks. If this is not done, starvation might occur.*

Common Programming Error 26.3

An `IllegalMonitorStateException` *occurs if a thread issues an* `await`*, a* `signal`*, or a* `signalAll` *on a* `Condition` *object that was created from a* `ReentrantLock` *without having acquired the lock for that* `Condition` *object.*

`Lock` and `Condition` vs. the `synchronized` Keyword

In some applications, using `Lock` and `Condition` objects may be preferable to using the `synchronized` keyword. `Lock`s allow you to *interrupt* waiting threads or to specify a *timeout* for waiting to acquire a lock, which is not possible using the `synchronized` keyword. Also, a `Lock` is *not* constrained to be acquired and released in the *same* block of code, which is the case with the `synchronized` keyword. `Condition` objects allow you to specify multiple conditions on which threads may wait. Thus, it's possible to indicate to waiting threads that a specific condition object is now true by calling `signal` or `signallAll` on that `Condition` object. With `synchronized`, there's no way to explicitly state the condition on which threads are waiting, and thus there's no way to notify threads waiting on one condition that they may proceed without also signaling threads waiting on any other conditions. There are other possible advantages to using `Lock` and `Condition` objects, but generally it's best to use the `synchronized` keyword unless your application requires advanced synchronization capabilities.

Error-Prevention Tip 26.5

Using interfaces `Lock` *and* `Condition` *is error prone—*`unlock` *is not guaranteed to be called, whereas the monitor in a* `synchronized` *statement will always be released when the statement completes execution.*

Using `Lock`s and `Condition`s to Implement Synchronization

To illustrate how to use the `Lock` and `Condition` interfaces, we now implement the producer/consumer relationship using `Lock` and `Condition` objects to coordinate access to a shared single-element buffer (Fig. 26.20 and Fig. 26.21). In this case, each produced value is correctly consumed exactly once. Again, we reuse interface `Buffer` and classes `Producer` and `Consumer` from the example in Section 26.5, except that line 28 is removed from class `Producer` and class `Consumer`.

Class SynchronizedBuffer (Fig. 26.20) contains five fields. Line 11 creates a new object of type ReentrantLock and assigns its reference to Lock variable accessLock. The ReentrantLock is created without the *fairness policy* because at any time only a single Producer or Consumer will be waiting to acquire the Lock in this example. Lines 14–15 create two Conditions using Lock method newCondition. Condition canWrite contains a queue for a Producer thread waiting while the buffer is full (i.e., there's data in the buffer that the Consumer has not read yet). If the buffer is full, the Producer calls method await on this Condition. When the Consumer reads data from a full buffer, it calls method signal on this Condition. Condition canRead contains a queue for a Consumer thread waiting while the buffer is empty (i.e., there's no data in the buffer for the Consumer to read). If the buffer is empty, the Consumer calls method await on this Condition. When the Producer writes to the empty buffer, it calls method signal on this Condition. The int variable buffer (line 17) holds the shared data. The boolean variable occupied (line 18) keeps track of whether the buffer currently holds data (that the Consumer should read).

```
1  // Fig. 26.20: SynchronizedBuffer.java
2  // Synchronizing access to a shared integer using the Lock and Condition
3  // interfaces
4  import java.util.concurrent.locks.Lock;
5  import java.util.concurrent.locks.ReentrantLock;
6  import java.util.concurrent.locks.Condition;
7
8  public class SynchronizedBuffer implements Buffer
9  {
10    // Lock to control synchronization with this buffer
11    private final Lock accessLock = new ReentrantLock();
12
13    // conditions to control reading and writing
14    private final Condition canWrite = accessLock.newCondition();
15    private final Condition canRead = accessLock.newCondition();
16
17    private int buffer = -1; // shared by producer and consumer threads
18    private boolean occupied = false; // whether buffer is occupied
19
20    // place int value into buffer
21    public void set( int value ) throws InterruptedException
22    {
23       accessLock.lock(); // lock this object
24
25       // output thread information and buffer information, then wait
26       try
27       {
28          // while buffer is not empty, place thread in waiting state
29          while ( occupied )
30          {
31             System.out.println( "Producer tries to write." );
32             displayState( "Buffer full. Producer waits." );
33             canWrite.await(); // wait until buffer is empty
34          } // end while
```

Fig. 26.20 | Synchronizing access to a shared integer using the Lock and Condition interfaces. (Part 1 of 3.)

```
35
36          buffer = value; // set new buffer value
37
38          // indicate producer cannot store another value
39          // until consumer retrieves current buffer value
40          occupied = true;
41
42          displayState( "Producer writes " + buffer );
43
44          // signal any threads waiting to read from buffer
45          canRead.signalAll();
46       } // end try
47       finally
48       {
49          accessLock.unlock(); // unlock this object
50       } // end finally
51    } // end method set
52
53    // return value from buffer
54    public int get() throws InterruptedException
55    {
56       int readValue = 0; // initialize value read from buffer
57       accessLock.lock(); // lock this object
58
59       // output thread information and buffer information, then wait
60       try
61       {
62          // if there is no data to read, place thread in waiting state
63          while ( !occupied )
64          {
65             System.out.println( "Consumer tries to read." );
66             displayState( "Buffer empty. Consumer waits." );
67             canRead.await(); // wait until buffer is full
68          } // end while
69
70          // indicate that producer can store another value
71          // because consumer just retrieved buffer value
72          occupied = false;
73
74          readValue = buffer; // retrieve value from buffer
75          displayState( "Consumer reads " + readValue );
76
77          // signal any threads waiting for buffer to be empty
78          canWrite.signalAll();
79       } // end try
80       finally
81       {
82          accessLock.unlock(); // unlock this object
83       } // end finally
84
85       return readValue;
86    } // end method get
```

Fig. 26.20 | Synchronizing access to a shared integer using the `Lock` and `Condition` interfaces. (Part 2 of 3.)

```
87
88     // display current operation and buffer state
89     public void displayState( String operation )
90     {
91        System.out.printf( "%-40s%d\t\t%b\n\n", operation, buffer,
92           occupied );
93     } // end method displayState
94  } // end class SynchronizedBuffer
```

Fig. 26.20 | Synchronizing access to a shared integer using the `Lock` and `Condition` interfaces. (Part 3 of 3.)

Line 23 in method `set` calls method `lock` on the `SynchronizedBuffer`'s `accessLock`. If the lock is available (i.e., no other thread has acquired it), this thread now owns the lock and the thread continues. If the lock is unavailable (i.e., it's held by another thread), method `lock` waits until the lock is released. After the lock is acquired, lines 26–46 execute. Line 29 tests `occupied` to determine whether `buffer` is full. If it is, lines 31–32 display a message indicating that the thread will wait. Line 33 calls `Condition` method `await` on the `canWrite` condition object, which temporarily releases the `SynchronizedBuffer`'s `Lock` and waits for a signal from the `Consumer` that `buffer` is available for writing. When `buffer` is available, the method proceeds, writing to `buffer` (line 36), setting `occupied` to `true` (line 40) and displaying a message indicating that the producer wrote a value (line 42). Line 45 calls `Condition` method `signal` on condition object `canRead` to notify the waiting `Consumer` (if there is one) that the buffer has new data to be read. Line 49 calls method `unlock` from a `finally` block to release the lock and allow the `Consumer` to proceed.

Error-Prevention Tip 26.6

Place calls to `Lock` method `unlock` in a `finally` block. If an exception is thrown, `unlock` must still be called or deadlock could occur.

Line 57 of method `get` (lines 54–86) calls method `lock` to acquire the `Lock`. This method waits until the `Lock` is available. Once the `Lock` is acquired, line 63 tests whether `occupied` is `false`, indicating that the buffer is empty. If so, line 67 calls method `await` on condition object `canRead`. Recall that method `signal` is called on variable `canRead` in the `set` method (line 45). When the `Condition` object is signaled, the `get` method continues. Line 72–74 set `occupied` to `false`, store the value of `buffer` in `readValue` and output the `readValue`. Then line 78 signals the condition object `canWrite`. This awakens the `Producer` if it's indeed waiting for the buffer to be emptied. Line 82 calls method `unlock` from a `finally` block to release the lock, and line 85 returns `readValue` to the caller.

Common Programming Error 26.4

Forgetting to `signal` a waiting thread is a logic error. The thread will remain in the waiting *state, which will prevent it from proceeding. Such waiting can lead to indefinite postponement or deadlock.*

Class `SharedBufferTest2` (Fig. 26.21) is identical to that of Fig. 26.17. Study the outputs in Fig. 26.21. *Observe that every integer produced is consumed exactly once—no values are lost, and no values are consumed more than once.* The `Lock` and `Condition` objects ensure that the `Producer` and `Consumer` cannot perform their tasks unless it's their turn.

The `Producer` must go first, the `Consumer` must wait if the `Producer` has not produced since the `Consumer` last consumed and the `Producer` must wait if the `Consumer` has not yet consumed the value that the `Producer` most recently produced. Execute this program several times to confirm that every integer produced is consumed exactly once. In the sample output, note the highlighted lines indicating when the `Producer` and `Consumer` must wait to perform their respective tasks.

```
1  // Fig. 26.21: SharedBufferTest2.java
2  // Two threads manipulating a synchronized buffer.
3  import java.util.concurrent.ExecutorService;
4  import java.util.concurrent.Executors;
5
6  public class SharedBufferTest2
7  {
8     public static void main( String[] args )
9     {
10       // create new thread pool with two threads
11       ExecutorService application = Executors.newCachedThreadPool();
12
13       // create SynchronizedBuffer to store ints
14       Buffer sharedLocation = new SynchronizedBuffer();
15
16       System.out.printf( "%-40s%s\t\t%s\n%-40s%s\n\n", "Operation",
17          "Buffer", "Occupied", "---------", "------\t\t--------" );
18
19       // execute the Producer and Consumer tasks
20       application.execute( new Producer( sharedLocation ) );
21       application.execute( new Consumer( sharedLocation ) );
22
23       application.shutdown();
24    } // end main
25 } // end class SharedBufferTest2
```

```
Operation                               Buffer          Occupied
---------                               ------          --------

Producer writes 1                       1               true

Producer tries to write.
Buffer full. Producer waits.            1               true

Consumer reads 1                        1               false

Producer writes 2                       2               true

Producer tries to write.
Buffer full. Producer waits.            2               true

Consumer reads 2                        2               false

Producer writes 3                       3               true

Consumer reads 3                        3               false
```

Fig. 26.21 | Two threads manipulating a synchronized buffer. (Part 1 of 2.)

```
Producer writes 4                       4               true

Consumer reads 4                        4               false

Consumer tries to read.
Buffer empty. Consumer waits.           4               false

Producer writes 5                       5               true

Consumer reads 5                        5               false

Consumer tries to read.
Buffer empty. Consumer waits.           5               false

Producer writes 6                       6               true

Consumer reads 6                        6               false

Producer writes 7                       7               true

Consumer reads 7                        7               false

Producer writes 8                       8               true

Consumer reads 8                        8               false

Producer writes 9                       9               true

Consumer reads 9                        9               false

Producer writes 10                      10              true


Producer done producing
Terminating Producer
Consumer reads 10                       10              false


Consumer read values totaling 55
Terminating Consumer
```

Fig. 26.21 | Two threads manipulating a synchronized buffer. (Part 2 of 2.)

26.10 Concurrent Collections Overview

In Chapter 20, we introduced various collections from the Java Collections API. We also mentioned that you can obtain synchronized versions of those collections to allow only one thread at a time to access a collection that might be shared among several threads. The collections from the `java.util.concurrent` package are specifically designed and optimized for use in programs that share collections among multiple threads.

Figure 26.22 lists the many concurrent collections in package `java.util.concurrent`. For more information on these collections, visit

```
download.oracle.com/javase/6/docs/api/java/util/concurrent/
   package-summary.html
```

For information on the additional concurrent collections that are new in Java SE 7, visit

```
download.java.net/jdk7/docs/api/java/util/concurrent/
   package-summary.html
```

Collection	Description
`ArrayBlockingQueue`	A fixed-size queue that supports the producer/consumer relationship—possibly with many producers and consumers.
`ConcurrentHashMap`	A hash-based map that allows an arbitrary number of reader threads and a limited number of writer threads.
`ConcurrentLinkedQueue`	A concurrent linked-list implementation of a queue that can grow dynamically.
`ConcurrentSkipListMap`	A concurrent map that is sorted by its keys.
`ConcurrentSkipListSet`	A sorted concurrent set.
`CopyOnWriteArrayList`	A thread-safe `ArrayList`. Each operation that modifies the collection first creates a new copy of the contents. Used when the collection is traversed much more frequently than the collection's contents are modified.
`CopyOnWriteArraySet`	A set that's implemented using `CopyOnWriteArrayList`.
`DelayQueue`	A variable-size queue containing `Delayed` objects. An object can be removed only after its delay has expired.
`LinkedBlockingDeque`	A double-ended blocking queue implemented as a linked list that can optionally be fixed in size.
`LinkedBlockingQueue`	A blocking queue implemented as a linked list that can optionally be fixed in size.
`PriorityBlockingQueue`	A variable-length priority-based blocking queue (like a `PriorityQueue`).
`SynchronousQueue`	A blocking queue implementation that does not have an internal capacity. Each insert operation by one thread must wait for a remove operation from another thread and vice versa.
Concurrent Collections Added in Java SE 7	
`ConcurrentLinkedDeque`	A concurrent linked-list implementation of a double-ended queue.
`LinkedTransferQueue`	A linked-list implementation of interface `TransferQueue`. Each producer has the option of waiting for a consumer to take an element being inserted (via method `transfer`) or simply placing the element into the queue (via method put). Also provides overloaded method `tryTransfer` to immediately transfer an element to a waiting consumer or to do so within a specified timeout period. If the transfer cannot be completed, the element is not placed in the queue. Typically used in applications that pass messages between threads.

Fig. 26.22 | Concurrent collections summary (package `java.util.concurrent`).

26.11 Multithreading with GUI

Swing applications present a unique set of challenges for multithreaded programming. All Swing applications have a single thread, called the **event dispatch thread**, to handle interactions with the application's GUI components. Typical interactions include *updating GUI components* or *processing user actions* such as mouse clicks. All tasks that require interaction with an application's GUI are placed in an *event queue* and are executed sequentially by the event dispatch thread.

Swing GUI components are not thread safe—they cannot be manipulated by multiple threads without the risk of incorrect results. Unlike the other examples presented in this chapter, thread safety in GUI applications is achieved not by synchronizing thread actions, but by *ensuring that Swing components are accessed from only a single thread*—the event dispatch thread. This technique is called **thread confinement**. Allowing just one thread to access non-thread-safe objects eliminates the possibility of corruption due to multiple threads accessing these objects concurrently.

Usually it's sufficient to perform simple calculations on the event dispatch thread in sequence with GUI component manipulations. If an application must perform a lengthy computation in response to a user interface interaction, the event dispatch thread cannot attend to other tasks in the event queue while the thread is tied up in that computation. This causes the GUI components to become unresponsive. It's preferable to handle a long-running computation in a separate thread, freeing the event dispatch thread to continue managing other GUI interactions. Of course, to update the GUI based on the computation's results, you must update the GUI from the event dispatch thread, rather than from the worker thread that performed the computation.

Class `SwingWorker`

Class `SwingWorker` (in package `javax.swing`) perform long-running computations in a worker thread and to update Swing components from the event dispatch thread based on the computations' results. `SwingWorker` implements the `Runnable` interface, meaning that *a `SwingWorker` object can be scheduled to execute in a separate thread*. The `SwingWorker` class provides several methods to simplify performing computations in a worker thread and making the results available for display in a GUI. Some common `SwingWorker` methods are described in Fig. 26.23.

Method	Description
`doInBackground`	Defines a long computation and is called in a worker thread.
`done`	Executes on the event dispatch thread when `doInBackground` returns.
`execute`	Schedules the `SwingWorker` object to be executed in a worker thread.
`get`	Waits for the computation to complete, then returns the result of the computation (i.e., the return value of `doInBackground`).
`publish`	Sends intermediate results from the `doInBackground` method to the `process` method for processing on the event dispatch thread.

Fig. 26.23 | Commonly used `SwingWorker` methods. (Part 1 of 2.)

Method	Description
`process`	Receives intermediate results from the `publish` method and processes these results on the event dispatch thread.
`setProgress`	Sets the progress property to notify any property change listeners on the event dispatch thread of progress bar updates.

Fig. 26.23 | Commonly used `SwingWorker` methods. (Part 2 of 2.)

26.11.1 Performing Computations in a Worker Thread

In the next example, the user enters a number *n* and the program gets the *n*th Fibonacci number, which we calculate using the recursive algorithm discussed in Section 18.4. Since the algorithm is time consuming for large values, we use a `SwingWorker` object to perform the calculation in a worker thread. The GUI also provides a separate set of components that get the next Fibonacci number in the sequence with each click of a button, beginning with `fibonacci(1)`. This set of components performs its short computation directly in the event dispatch thread. This program is capable of producing up to the 92nd Fibonacci number—subsequent values are outside the range that can be represented by a `long`. Recall that you can use class `BigInteger` to represent arbitrarily large integer values.

Class `BackgroundCalculator` (Fig. 26.24) performs the recursive Fibonacci calculation in a *worker thread*. This class extends `SwingWorker` (line 8), overriding the methods `doInBackground` and `done`. Method `doInBackground` (lines 21–24) computes the *n*th Fibonacci number in a worker thread and returns the result. Method `done` (lines 27–43) displays the result in a `JLabel`.

```
1  // Fig. 26.24: BackgroundCalculator.java
2  // SwingWorker subclass for calculating Fibonacci numbers
3  // in a background thread.
4  import javax.swing.SwingWorker;
5  import javax.swing.JLabel;
6  import java.util.concurrent.ExecutionException;
7
8  public class BackgroundCalculator extends SwingWorker< Long, Object >
9  {
10    private final int n; // Fibonacci number to calculate
11    private final JLabel resultJLabel; // JLabel to display the result
12
13    // constructor
14    public BackgroundCalculator( int number, JLabel label )
15    {
16       n = number;
17       resultJLabel = label;
18    } // end BackgroundCalculator constructor
```

Fig. 26.24 | `SwingWorker` subclass for calculating Fibonacci numbers in a background thread. (Part 1 of 2.)

```
19
20     // long-running code to be run in a worker thread
21     public Long doInBackground()
22     {
23        return nthFib = fibonacci( n );
24     } // end method doInBackground
25
26     // code to run on the event dispatch thread when doInBackground returns
27     protected void done()
28     {
29        try
30        {
31           // get the result of doInBackground and display it
32           resultJLabel.setText( get().toString() );
33        } // end try
34        catch ( InterruptedException ex )
35        {
36           resultJLabel.setText( "Interrupted while waiting for results." );
37        } // end catch
38        catch ( ExecutionException ex )
39        {
40           resultJLabel.setText(
41              "Error encountered while performing calculation." );
42        } // end catch
43     } // end method done
44
45     // recursive method fibonacci; calculates nth Fibonacci number
46     public long fibonacci( long number )
47     {
48        if ( number == 0 || number == 1 )
49           return number;
50        else
51           return fibonacci( number - 1 ) + fibonacci( number - 2 );
52     } // end method fibonacci
53  } // end class BackgroundCalculator
```

Fig. 26.24 | `SwingWorker` subclass for calculating Fibonacci numbers in a background thread. (Part 2 of 2.)

`SwingWorker` is a *generic class*. In line 8, the first type parameter is `Long` and the second is `Object`. The first type parameter indicates the type returned by the `doInBackground` method; the second indicates the type that's passed between the `publish` and `process` methods to handle intermediate results. Since we do not use `publish` and `process` in this example, we simply use `Object` as the second type parameter. We discuss `publish` and `process` in Section 26.11.2.

A `BackgroundCalculator` object can be instantiated from a class that controls a GUI. A `BackgroundCalculator` maintains instance variables for an integer that represents the Fibonacci number to be calculated and a `JLabel` that displays the results of the calculation (lines 10–11). The `BackgroundCalculator` constructor (lines 14–18) initializes these instance variables with the arguments that are passed to the constructor.

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Any GUI components that will be manipulated by `SwingWorker` methods, such as components that will be updated from methods `process` or `done`, should be passed to the `SwingWorker` subclass's constructor and stored in the subclass object. This gives these methods access to the GUI components they'll manipulate.

When method `execute` is called on a `BackgroundCalculator` object, the object is scheduled for execution in a worker thread. Method `doInBackground` is called from the worker thread and invokes the `fibonacci` method (lines 46–52), passing instance variable `n` as an argument (line 23). Method `fibonacci` uses recursion to compute the Fibonacci of `n`. When `fibonacci` returns, method `doInBackground` returns the result.

After `doInBackground` returns, method `done` is called from the event dispatch thread. This method attempts to set the result `JLabel` to the return value of `doInBackground` by calling method `get` to retrieve this return value (line 32). Method `get` waits for the result to be ready if necessary, but since we call it from method `done`, the computation will be complete before `get` is called. Lines 34–37 catch `InterruptedException` if the current thread is interrupted while waiting for `get` to return. This exception will not occur in this example since the calculation will have already completed by the time `get` is called. Lines 38–42 catch `ExecutionException`, which is thrown if an exception occurs during the computation.

Class `FibonacciNumbers`

Class `FibonacciNumbers` (Fig. 26.25) displays a window containing two sets of GUI components—one set to compute a Fibonacci number in a worker thread and another to get the next Fibonacci number in response to the user's clicking a `JButton`. The constructor (lines 38–109) places these components in separate titled `JPanels`. Lines 46–47 and 78–79 add two `JLabels`, a `JTextField` and a `JButton` to the `workerJPanel` to allow the user to enter an integer whose Fibonacci number will be calculated by the `BackgroundWorker`. Lines 84–85 and 103 add two `JLabels` and a `JButton` to the event dispatch thread panel to allow the user to get the next Fibonacci number in the sequence. Instance variables `n1` and `n2` contain the previous two Fibonacci numbers in the sequence and are initialized to `0` and `1`, respectively (lines 29–30). Instance variable `count` stores the most recently computed sequence number and is initialized to `1` (line 31). The two `JLabels` display `count` and `n2` initially, so that the user will see the text `Fibonacci of 1: 1` in the `eventThreadJPanel` when the GUI starts.

```
1  // Fig. 26.25: FibonacciNumbers.java
2  // Using SwingWorker to perform a long calculation with
3  // results displayed in a GUI.
4  import java.awt.GridLayout;
5  import java.awt.event.ActionEvent;
6  import java.awt.event.ActionListener;
7  import javax.swing.JButton;
8  import javax.swing.JFrame;
9  import javax.swing.JPanel;
```

Fig. 26.25 | Using `SwingWorker` to perform a long calculation with results displayed in a GUI. (Part 1 of 4.)

```
10 import javax.swing.JLabel;
11 import javax.swing.JTextField;
12 import javax.swing.border.TitledBorder;
13 import javax.swing.border.LineBorder;
14 import java.awt.Color;
15 import java.util.concurrent.ExecutionException;
16
17 public class FibonacciNumbers extends JFrame
18 {
19    // components for calculating the Fibonacci of a user-entered number
20    private final JPanel workerJPanel =
21       new JPanel( new GridLayout( 2, 2, 5, 5 ) );
22    private final JTextField numberJTextField = new JTextField();
23    private final JButton goJButton = new JButton( "Go" );
24    private final JLabel fibonacciJLabel = new JLabel();
25
26    // components and variables for getting the next Fibonacci number
27    private final JPanel eventThreadJPanel =
28       new JPanel( new GridLayout( 2, 2, 5, 5 ) );
29    private long n1 = 0; // initialize with first Fibonacci number
30    private long n2 = 1; // initialize with second Fibonacci number
31    private int count = 1; // current Fibonacci number to display
32    private final JLabel nJLabel = new JLabel( "Fibonacci of 1: " );
33    private final JLabel nFibonacciJLabel =
34       new JLabel( String.valueOf( n2 ) );
35    private final JButton nextNumberJButton = new JButton( "Next Number" );
36
37    // constructor
38    public FibonacciNumbers()
39    {
40       super( "Fibonacci Numbers" );
41       setLayout( new GridLayout( 2, 1, 10, 10 ) );
42
43       // add GUI components to the SwingWorker panel
44       workerJPanel.setBorder( new TitledBorder(
45          new LineBorder( Color.BLACK ), "With SwingWorker" ) );
46       workerJPanel.add( new JLabel( "Get Fibonacci of:" ) );
47       workerJPanel.add( numberJTextField );
48       goJButton.addActionListener(
49          new ActionListener()
50          {
51             public void actionPerformed( ActionEvent event )
52             {
53                int n;
54
55                try
56                {
57                   // retrieve user's input as an integer
58                   n = Integer.parseInt( numberJTextField.getText() );
59                } // end try
60                catch( NumberFormatException ex )
61                {
```

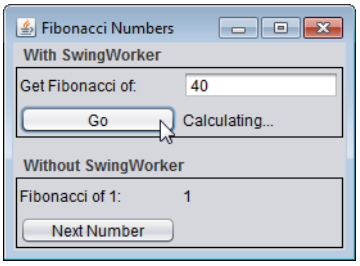
Fig. 26.25 | Using `SwingWorker` to perform a long calculation with results displayed in a GUI. (Part 2 of 4.)

```
62                   // display an error message if the user did not
63                   // enter an integer
64                   fibonacciJLabel.setText( "Enter an integer." );
65                   return;
66                } // end catch
67
68                // indicate that the calculation has begun
69                fibonacciJLabel.setText( "Calculating..." );
70
71                // create a task to perform calculation in background
72                BackgroundCalculator task =
73                   new BackgroundCalculator( n, fibonacciJLabel );
74                task.execute(); // execute the task
75             } // end method actionPerformed
76          } // end anonymous inner class
77       ); // end call to addActionListener
78       workerJPanel.add( goJButton );
79       workerJPanel.add( fibonacciJLabel );
80
81       // add GUI components to the event-dispatching thread panel
82       eventThreadJPanel.setBorder( new TitledBorder(
83          new LineBorder( Color.BLACK ), "Without SwingWorker" ) );
84       eventThreadJPanel.add( nJLabel );
85       eventThreadJPanel.add( nFibonacciJLabel );
86       nextNumberJButton.addActionListener(
87          new ActionListener()
88          {
89             public void actionPerformed( ActionEvent event )
90             {
91                // calculate the Fibonacci number after n2
92                long temp = n1 + n2;
93                n1 = n2;
94                n2 = temp;
95                ++count;
96
97                // display the next Fibonacci number
98                nJLabel.setText( "Fibonacci of " + count + ": " );
99                nFibonacciJLabel.setText( String.valueOf( n2 ) );
100            } // end method actionPerformed
101         } // end anonymous inner class
102      ); // end call to addActionListener
103      eventThreadJPanel.add( nextNumberJButton );
104
105      add( workerJPanel );
106      add( eventThreadJPanel );
107      setSize( 275, 200 );
108      setVisible( true );
109   } // end constructor
110
111   // main method begins program execution
112   public static void main( String[] args )
113   {
```

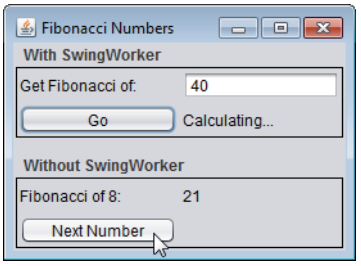
Fig. 26.25 | Using `SwingWorker` to perform a long calculation with results displayed in a GUI. (Part 3 of 4.)

```
114         FibonacciNumbers application = new FibonacciNumbers();
115         application.setDefaultCloseOperation( EXIT_ON_CLOSE );
116      } // end main
117   } // end class FibonacciNumbers
```

a) Begin calculating Fibonacci of 40 in the background



b) Calculating other Fibonacci values while Fibonacci of 40 continues calculating



c) Fibonacci of 40 calculation finishes

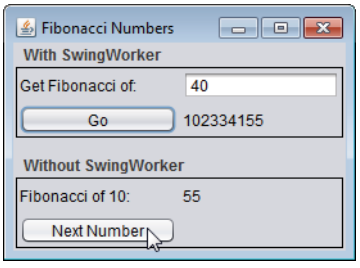


Fig. 26.25 | Using `SwingWorker` to perform a long calculation with results displayed in a GUI. (Part 4 of 4.)

Lines 48–77 register the event handler for the `goJButton`. If the user clicks this `JButton`, line 58 gets the value entered in the `numberJTextField` and attempts to parse it as an integer. Lines 72–73 create a new `BackgroundCalculator` object, passing in the user-entered value and the `fibonacciJLabel` that's used to display the calculation's results. Line 74 calls method `execute` on the `BackgroundCalculator`, scheduling it for execution in a separate worker thread. Method `execute` does not wait for the `BackgroundCalculator` to finish executing. It returns immediately, allowing the GUI to continue processing other events while the computation is performed.

If the user clicks the `nextNumberJButton` in the `eventThreadJPanel`, the event handler registered in lines 86–102 executes.Lines 92–95 add the previous two Fibonacci numbers stored in `n1` and `n2` to determine the next number in the sequence, update `n1` and `n2` to their new values and increment `count`. Then lines 98–99 update the GUI to display the next number. The code for these calculations is in method `actionPerformed`, so they're performed on the *event dispatch thread*. Handling such short computations in the event dispatch thread does not cause the GUI to become unresponsive, as with the recursive algorithm for calculating the Fibonacci of a large number. Because the longer Fibonacci computation is performed in a separate worker thread using the `SwingWorker`, it's possible to get the next Fibonacci number while the recursive computation is still in progress.

26.11.2 Processing Intermediate Results with SwingWorker

We've presented an example that uses the `SwingWorker` class to execute a long process in a *background thread* and update the GUI when the process is finished. We now present an example of updating the GUI with intermediate results before the long process completes. Figure 26.26 presents class `PrimeCalculator`, which extends `SwingWorker` to compute the first *n* prime numbers in a *worker thread*. In addition to the `doInBackground` and `done` methods used in the previous example, this class uses `SwingWorker` methods `publish`, `process` and `setProgress`. In this example, method `publish` sends prime numbers to method `process` as they're found, method `process` displays these primes in a GUI component and method `setProgress` updates the progress property. We later show how to use this property to update a `JProgressBar`.

```
1  // Fig. 26.26: PrimeCalculator.java
2  // Calculates the first n primes, displaying them as they are found.
3  import javax.swing.JTextArea;
4  import javax.swing.JLabel;
5  import javax.swing.JButton;
6  import javax.swing.SwingWorker;
7  import java.util.Arrays;
8  import java.util.Random;
9  import java.util.List;
10 import java.util.concurrent.CancellationException;
11 import java.util.concurrent.ExecutionException;
12
13 public class PrimeCalculator extends SwingWorker< Integer, Integer >
14 {
15    private final Random generator = new Random();
16    private final JTextArea intermediateJTextArea; // displays found primes
17    private final JButton getPrimesJButton;
18    private final JButton cancelJButton;
19    private final JLabel statusJLabel; // displays status of calculation
20    private final boolean[] primes; // boolean array for finding primes
21
22    // constructor
23    public PrimeCalculator( int max, JTextArea intermediate, JLabel status,
24       JButton getPrimes, JButton cancel )
25    {
26       intermediateJTextArea = intermediate;
27       statusJLabel = status;
28       getPrimesJButton = getPrimes;
29       cancelJButton = cancel;
30       primes = new boolean[ max ];
31
32       // initialize all prime array values to true
33       Arrays.fill( primes, true );
34    } // end constructor
35
36    // finds all primes up to max using the Sieve of Eratosthenes
37    public Integer doInBackground()
38    {
```

Fig. 26.26 | Calculates the first *n* primes, displaying them as they are found. (Part 1 of 3.)

```
39          int count = 0; // the number of primes found
40
41          // starting at the third value, cycle through the array and put
42          // false as the value of any greater number that is a multiple
43          for ( int i = 2; i < primes.length; i++ )
44          {
45             if ( isCancelled() ) // if calculation has been canceled
46                return count;
47             else
48             {
49                setProgress( 100 * ( i + 1 ) / primes.length );
50
51                try
52                {
53                   Thread.sleep( generator.nextInt( 5 ) );
54                } // end try
55                catch ( InterruptedException ex )
56                {
57                   statusJLabel.setText( "Worker thread interrupted" );
58                   return count;
59                } // end catch
60
61                if ( primes[ i ] ) // i is prime
62                {
63                   publish( i ); // make i available for display in prime list
64                   ++count;
65
66                   for ( int j = i + i; j < primes.length; j += i )
67                      primes[ j ] = false; // i is not prime
68                } // end if
69             } // end else
70          } // end for
71
72          return count;
73       } // end method doInBackground
74
75       // displays published values in primes list
76       protected void process( List< Integer > publishedVals )
77       {
78          for ( int i = 0; i < publishedVals.size(); i++ )
79             intermediateJTextArea.append( publishedVals.get( i ) + "\n" );
80       } // end method process
81
82       // code to execute when doInBackground completes
83       protected void done()
84       {
85          getPrimesJButton.setEnabled( true ); // enable Get Primes button
86          cancelJButton.setEnabled( false ); // disable Cancel button
87
88          int numPrimes;
89
90          try
91          {
```

Fig. 26.26 | Calculates the first *n* primes, displaying them as they are found. (Part 2 of 3.)

```
92            numPrimes = get(); // retrieve doInBackground return value
93         } // end try
94         catch ( InterruptedException ex )
95         {
96            statusJLabel.setText( "Interrupted while waiting for results." );
97            return;
98         } // end catch
99         catch ( ExecutionException ex )
100        {
101           statusJLabel.setText( "Error performing computation." );
102           return;
103        } // end catch
104        catch ( CancellationException ex )
105        {
106           statusJLabel.setText( "Cancelled." );
107           return;
108        } // end catch
109
110        statusJLabel.setText( "Found " + numPrimes + " primes." );
111     } // end method done
112  } // end class PrimeCalculator
```

Fig. 26.26 | Calculates the first *n* primes, displaying them as they are found. (Part 3 of 3.)

Class `PrimeCalculator` extends `SwingWorker` (line 13), with the first type parameter indicating the return type of method `doInBackground` and the second indicating the type of intermediate results passed between methods `publish` and `process`. In this case, both type parameters are `Integer`s. The constructor (lines 23–34) takes as arguments an integer that indicates the upper limit of the prime numbers to locate, a `JTextArea` used to display primes in the GUI, one `JButton` for initiating a calculation and one for canceling it, and a `JLabel` used to display the status of the calculation.

Sieve of Eratosthenes

Line 33 initializes the elements of the `boolean` array `primes` to `true` with `Arrays` method `fill`. `PrimeCalculator` uses this array and the **Sieve of Eratosthenes** algorithm (described in Exercise 7.27) to find all primes less than `max`. The Sieve of Eratosthenes takes a list of integers and, beginning with the first prime number, filters out all multiples of that prime. It then moves to the next prime, which will be the next number that's not yet filtered out, and eliminates all of its multiples. It continues until the end of the list is reached and all nonprimes have been filtered out. Algorithmically, we begin with element `2` of the `boolean` array and set the cells corresponding to all values that are multiples of 2 to `false` to indicate that they're divisible by 2 and thus not prime. We then move to the next array element, check whether it's `true`, and if so set all of its multiples to `false` to indicate that they're divisible by the current index. When the whole array has been traversed in this way, all indices that contain `true` are prime, as they have no divisors.

Method `doInBackground`

In method `doInBackground` (lines 37–73), the control variable `i` for the loop (lines 43–70) controls the current index for implementing the Sieve of Eratosthenes. Line 45 calls the inherited `SwingWorker` method **`isCancelled`** to determine whether the user has

clicked the **Cancel** button. If `isCancelled` returns `true`, method `doInBackground` returns the number of primes found so far (line 46) without finishing the computation.

If the calculation isn't canceled, line 49 calls `setProgress` to update the percentage of the array that's been traversed so far. Line 53 puts the currently executing thread to sleep for up to 4 milliseconds. We discuss the reason for this shortly. Line 61 tests whether the element of array `primes` at the current index is `true` (and thus prime). If so, line 63 passes the index to method `publish` so that it can be displayed as an intermediate result in the GUI and line 64 increments the number of primes found. Lines 66–67 set all multiples of the current index to `false` to indicate that they're not prime. When the entire array has been traversed, line 72 returns the number of primes found.

Method `process`

Lines 76–80 declare method `process`, which executes in the event dispatch thread and receives its argument `publishedVals` from method `publish`. The passing of values between `publish` in the worker thread and `process` in the event dispatch thread is asynchronous; `process` might not be invoked for every call to `publish`. All `Integers` published since the last call to `process` are received as a `List` by method `process`. Lines 78–79 iterate through this list and display the published values in a `JTextArea`. Because the computation in method `doInBackground` progresses quickly, publishing values often, updates to the `JTextArea` can pile up on the event dispatch thread, causing the GUI to become sluggish. In fact, when searching for a large number of primes, the *event dispatch thread* may receive so many requests in quick succession to update the `JTextArea` that it *runs out of memory in its event queue*. This is why we put the worker thread to sleep for a few milliseconds between calls to `publish`. The calculation is slowed just enough to allow the event dispatch thread to keep up with requests to update the `JTextArea` with new primes, enabling the GUI to update smoothly and remain responsive.

Method `done`

Lines 83–111 define method `done`. When the calculation is finished or canceled, method `done` enables the **Get Primes** button and disables the **Cancel** button (lines 85–86). Line 92 gets the return value—the number of primes found—from method `doInBackground`. Lines 94–108 catch the exceptions thrown by method `get` and display an appropriate message in the `statusJLabel`. If no exceptions occur, line 110 sets the `statusJLabel` to indicate the number of primes found.

Class `FindPrimes`

Class `FindPrimes` (Fig. 26.27) displays a `JTextField` that allows the user to enter a number, a `JButton` to begin finding all primes less than that number and a `JTextArea` to display the primes. A `JButton` allows the user to cancel the calculation, and a `JProgressBar` indicates the calculation's progress. The `FindPrimes` constructor (lines 32–125) sets up the application's GUI.

Lines 42–94 register the event handler for the `getPrimesJButton`. When the user clicks this `JButton`, lines 47–49 reset the `JProgressBar` and clear the `displayPrimesJTextArea` and the `statusJLabel`. Lines 53–63 parse the value in the `JTextField` and display an error message if the value is not an integer. Lines 66–68 construct a new `PrimeCalculator` object, passing as arguments the integer the user entered, the `displayPrimesJTextArea` for displaying the primes, the `statusJLabel` and the two `JButtons`.

```
1  // Fig 26.27: FindPrimes.java
2  // Using a SwingWorker to display prime numbers and update a JProgressBar
3  // while the prime numbers are being calculated.
4  import javax.swing.JFrame;
5  import javax.swing.JTextField;
6  import javax.swing.JTextArea;
7  import javax.swing.JButton;
8  import javax.swing.JProgressBar;
9  import javax.swing.JLabel;
10 import javax.swing.JPanel;
11 import javax.swing.JScrollPane;
12 import javax.swing.ScrollPaneConstants;
13 import java.awt.BorderLayout;
14 import java.awt.GridLayout;
15 import java.awt.event.ActionListener;
16 import java.awt.event.ActionEvent;
17 import java.util.concurrent.ExecutionException;
18 import java.beans.PropertyChangeListener;
19 import java.beans.PropertyChangeEvent;
20
21 public class FindPrimes extends JFrame
22 {
23    private final JTextField highestPrimeJTextField = new JTextField();
24    private final JButton getPrimesJButton = new JButton( "Get Primes" );
25    private final JTextArea displayPrimesJTextArea = new JTextArea();
26    private final JButton cancelJButton = new JButton( "Cancel" );
27    private final JProgressBar progressJProgressBar = new JProgressBar();
28    private final JLabel statusJLabel = new JLabel();
29    private PrimeCalculator calculator;
30
31    // constructor
32    public FindPrimes()
33    {
34       super( "Finding Primes with SwingWorker" );
35       setLayout( new BorderLayout() );
36
37       // initialize panel to get a number from the user
38       JPanel northJPanel = new JPanel();
39       northJPanel.add( new JLabel( "Find primes less than: " ) );
40       highestPrimeJTextField.setColumns( 5 );
41       northJPanel.add( highestPrimeJTextField );
42       getPrimesJButton.addActionListener(
43          new ActionListener()
44          {
45             public void actionPerformed( ActionEvent e )
46             {
47                progressJProgressBar.setValue( 0 ); // reset JProgressBar
48                displayPrimesJTextArea.setText( "" ); // clear JTextArea
49                statusJLabel.setText( "" ); // clear JLabel
50
51                int number; // search for primes up through this value
```

Fig. 26.27 | Using a `SwingWorker` to display prime numbers and update a `JProgressBar` while the prime numbers are being calculated. (Part 1 of 3.)

```
52
53                try
54                {
55                   // get user input
56                   number = Integer.parseInt(
57                      highestPrimeJTextField.getText() );
58                } // end try
59                catch ( NumberFormatException ex )
60                {
61                   statusJLabel.setText( "Enter an integer." );
62                   return;
63                } // end catch
64
65                // construct a new PrimeCalculator object
66                calculator = new PrimeCalculator( number,
67                   displayPrimesJTextArea, statusJLabel, getPrimesJButton,
68                   cancelJButton );
69
70                // listen for progress bar property changes
71                calculator.addPropertyChangeListener(
72                   new PropertyChangeListener()
73                   {
74                      public void propertyChange( PropertyChangeEvent e )
75                      {
76                         // if the changed property is progress,
77                         // update the progress bar
78                         if ( e.getPropertyName().equals( "progress" ) )
79                         {
80                            int newValue = ( Integer ) e.getNewValue();
81                            progressJProgressBar.setValue( newValue );
82                         } // end if
83                      } // end method propertyChange
84                   } // end anonymous inner class
85                ); // end call to addPropertyChangeListener
86
87                // disable Get Primes button and enable Cancel button
88                getPrimesJButton.setEnabled( false );
89                cancelJButton.setEnabled( true );
90
91                calculator.execute(); // execute the PrimeCalculator object
92             } // end method ActionPerformed
93          } // end anonymous inner class
94       ); // end call to addActionListener
95       northJPanel.add( getPrimesJButton );
96
97       // add a scrollable JList to display results of calculation
98       displayPrimesJTextArea.setEditable( false );
99       add( new JScrollPane( displayPrimesJTextArea,
100         ScrollPaneConstants.VERTICAL_SCROLLBAR_ALWAYS,
101         ScrollPaneConstants.HORIZONTAL_SCROLLBAR_NEVER ) );
102
```

Fig. 26.27 | Using a `SwingWorker` to display prime numbers and update a `JProgressBar` while the prime numbers are being calculated. (Part 2 of 3.)

```
103         // initialize a panel to display cancelJButton,
104         // progressJProgressBar, and statusJLabel
105         JPanel southJPanel = new JPanel( new GridLayout( 1, 3, 10, 10 ) );
106         cancelJButton.setEnabled( false );
107         cancelJButton.addActionListener(
108            new ActionListener()
109            {
110               public void actionPerformed( ActionEvent e )
111               {
112                  calculator.cancel( true ); // cancel the calculation
113               } // end method ActionPerformed
114            } // end anonymous inner class
115         ); // end call to addActionListener
116         southJPanel.add( cancelJButton );
117         progressJProgressBar.setStringPainted( true );
118         southJPanel.add( progressJProgressBar );
119         southJPanel.add( statusJLabel );
120
121         add( northJPanel, BorderLayout.NORTH );
122         add( southJPanel, BorderLayout.SOUTH );
123         setSize( 350, 300 );
124         setVisible( true );
125      } // end constructor
126
127      // main method begins program execution
128      public static void main( String[] args )
129      {
130         FindPrimes application = new FindPrimes();
131         application.setDefaultCloseOperation( EXIT_ON_CLOSE );
132      } // end main
133   } // end class FindPrimes
```

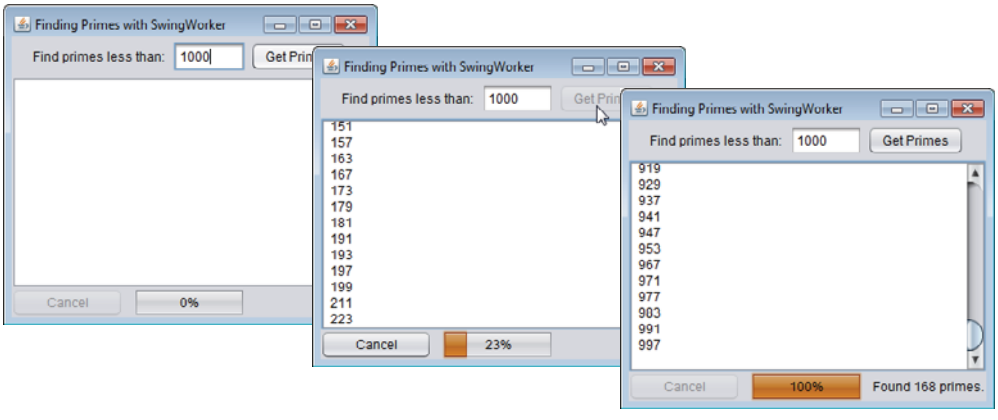


Fig. 26.27 | Using a `SwingWorker` to display prime numbers and update a `JProgressBar` while the prime numbers are being calculated. (Part 3 of 3.)

Lines 71–85 register a `PropertyChangeListener` for the `PrimeCalculator` object. **`PropertyChangeListener`** is an interface from package `java.beans` that defines a single method, `propertyChange`. Every time method `setProgress` is invoked on a `PrimeCalcu-`

lator, the PrimeCalculator generates a PropertyChangeEvent to indicate that the progress property has changed. Method propertyChange listens for these events. Line 78 tests whether a given PropertyChangeEvent indicates a change to the progress property. If so, line 80 gets the new value of the property and line 81 updates the JProgressBar with the new progress property value.

The **Get Primes** JButton is disabled (line 88) so only one calculation that updates the GUI can execute at a time, and the **Cancel** JButton is enabled (line 89) to allow the user to stop the computation before it completes. Line 91 executes the PrimesCalculator to begin finding primes. If the user clicks the cancelJButton, the event handler registered at lines 107–115 calls PrimeCalculator's method **cancel** (line 112), which is inherited from class SwingWorker, and the calculation returns early. The argument true to method cancel indicates that the thread performing the task should be interrupted in an attempt to cancel the task.

26.12 Interfaces Callable and Future

Interface Runnable provides only the most basic functionality for multithreaded programming. In fact, this interface has several limitations. Suppose a Runnable encounters a problem and tries to throw a *checked* exception. The run method is not declared to throw any exceptions, so the problem must be handled within the Runnable—the exception *cannot* be passed to the calling thread. Now suppose a Runnable is performing a long calculation and the application wants to retrieve the result of that calculation. The run method cannot return a value, so the application must use shared data to pass the value back to the calling thread. This also involves the overhead of synchronizing access to the data. The developers of the concurrency APIs recognized these limitations and created a new interface to fix them. The **Callable** interface (of package java.util.concurrent) declares a single method named **call**. This interface is designed to be similar to the Runnable interface—allowing an action to be performed concurrently in a separate thread—but the call method allows the thread to return a value or to throw a *checked* exception.

An application that creates a Callable likely wants to run it concurrently with other Runnables and Callables. The ExecutorService interface provides method **submit**, which will execute a Callable passed in as its argument. The submit method returns an object of type **Future** (of package java.util.concurrent), which is an interface that represents the executing Callable. The Future interface declares method **get** to return the result of the Callable and provides other methods to manage a Callable's execution.

26.13 Java SE 7: Fork/Join Framework

Java SE 7's concurrency APIs include the new fork/join framework, which helps programmers parallelize algorithms. The framework is beyond the scope of this book. Experts tell us that most Java programmers will benefit by this framework being used "behind the scenes" in the Java API and other third party libraries.

The fork/join framework is particularly well suited to divide-and-conquer-style algorithms, such as the merge sort that we implemented in Section 19.3.3. Recall that the recursive algorithm sorts an array by *splitting* it into two equal-sized subarrays, *sorting* each subarray, then *merging* them into one larger array. Each subarray is sorted by performing the same algorithm on the subarray. For algorithms like merge sort, the fork/join frame-

work can be used to create parallel tasks so that they can be distributed across multiple processors and be truly performed in parallel—the details of assigning the parallel tasks to different processors are handled for you by the framework.

To learn more about the fork/join framework and Java multithreading in general, please visit the sites listed in our Java Multithreading Resource Center at

```
www.deitel.com/JavaMultithreading
```

26.14 Wrap-Up

In this chapter, you learned that concurrency has historically been implemented with operating-system primitives available only to experienced systems programmers, but that Java makes concurrency available to you through the language and APIs. You also learned that the JVM itself creates threads to run a program, and that it also can create threads to perform housekeeping tasks such as garbage collection.

We discussed the life cycle of a thread and the states that a thread may occupy during its lifetime. Next, we presented the interface `Runnable`, which is used to specify a task that can execute concurrently with other tasks. This interface's `run` method is invoked by the thread executing the task. We showed how to execute a `Runnable` object by associating it with an object of class `Thread`. Then we showed how to use the `Executor` interface to manage the execution of `Runnable` objects via thread pools, which can reuse existing threads to eliminate the overhead of creating a new thread for each task and can improve performance by optimizing the number of threads to ensure that the processor stays busy.

You learned that when multiple threads share an object and one or more of them modify that object, indeterminate results may occur unless access to the shared object is managed properly. We showed you how to solve this problem via thread synchronization, which coordinates access to shared data by multiple concurrent threads. You learned several techniques for performing synchronization—first with the built-in class `ArrayBlockingQueue` (which handles *all* the synchronization details for you), then with Java's built-in monitors and the `synchronized` keyword, and finally with interfaces `Lock` and `Condition`.

We discussed the fact that Swing GUIs are not thread safe, so all interactions with and modifications to the GUI must be performed in the event dispatch thread. We also discussed the problems associated with performing long-running calculations in the event dispatch thread. Then we showed how you can use the `SwingWorker` class to perform long-running calculations in worker threads. You learned how to display the results of a `SwingWorker` in a GUI when the calculation completed and how to display intermediate results while the calculation was still in process.

Finally, we discussed the `Callable` and `Future` interfaces, which enable you to execute tasks that return results and to obtain those results, respectively. We use the multithreading techniques introduced in this chapter again in Chapter 27, Networking, to help build multithreaded servers that can interact with multiple clients concurrently.

Summary

Section 26.1 Introduction

- Historically, concurrency (p. 1046) has been implemented with operating-system primitives available only to experienced systems programmers.

- The Ada programming language made concurrency primitives widely available.
- Java makes concurrency available to you through the language and APIs.
- The JVM creates threads to run a program and for housekeeping tasks such as garbage collection.

Section 26.2 Thread States: Life Cycle of a Thread

- A new thread begins its life cycle in the *new* state (p. 1048). When the program starts the thread, it's placed in the *runnable* state. A thread in the *runnable* state is considered to be executing its task.
- A *runnable* thread transitions to the *waiting* state (p. 1048) to wait for another thread to perform a task. A *waiting* thread transitions to *runnable* when another thread notifies it to continue executing.
- A *runnable* thread can enter the *timed waiting* state (p. 1048) for a specified interval of time, transitioning back to *runnable* when that time interval expires or when the event it's waiting for occurs.
- A *runnable* thread can transition to the *timed waiting* state if it provides an optional wait interval when it's waiting for another thread to perform a task. Such a thread will return to the *runnable* state when it's notified by another thread or when the timed interval expires.
- A sleeping thread (p. 1049) remains in the *timed waiting* state for a designated period of time, after which it returns to the *runnable* state.
- A *runnable* thread transitions to the *blocked* state (p. 1049) when it attempts to perform a task that cannot be completed immediately and the thread must temporarily wait until that task completes. At that point, the *blocked* thread transitions to the *runnable* state, so it can resume execution.
- A *runnable* thread enters the *terminated* state (p. 1049) when it successfully completes its task or otherwise terminates (perhaps due to an error).
- At the operating-system level, the *runnable* state (p. 1048) encompasses two separate states. When a thread first transitions to the *runnable* state from the *new* state, it's in the *ready* state (p. 1049). A *ready* thread enters the *running* state (p. 1049) when the operating system dispatches it.
- Most operating systems allot a quantum (p. 1049) or timeslice in which a thread performs its task. When this expires, the thread returns to the *ready* state and another thread is assigned to the processor.
- Thread scheduling determines which thread to dispatch based on thread priorities.
- The job of an operating system's thread scheduler (p. 1050) is to determine which thread runs next.
- When a higher-priority thread enters the *ready* state, the operating system generally preempts the currently *running* thread (an operation known as preemptive scheduling; p. 1050).
- Depending on the operating system, higher-priority threads could postpone—possibly indefinitely (p. 1050)—the execution of lower-priority threads.

Section 26.3 Creating and Executing Threads with `Executor` Framework

- A `Runnable` (p. 1051) object represents a task that can execute concurrently with other tasks.
- Interface `Runnable` declares method `run` (p. 1051) in which you place the code that defines the task to perform. The thread executing a `Runnable` calls method `run` to perform the task.
- A program will not terminate until its last thread completes execution.
- You cannot predict the order in which threads will be scheduled, even if you know the order in which they were created and started.
- It's recommended that you use the `Executor` interface (p. 1051) to manage the execution of `Runnable` objects. An `Executor` object typically creates and manages a group of threads—called a thread pool (p. 1051).
- `Executors` (p. 1051) can reuse existing threads and can improve performance by optimizing the number of threads to ensure that the processor stays busy.

- `Executor` method `execute` (p. 1051) receives a `Runnable` and assigns it to an available thread in a thread pool. If there are none, the `Executor` creates a new thread or waits for one to become available.
- Interface `ExecutorService` (of package `java.util.concurrent`; p. 1051) extends interface `Executor` and declares other methods for managing the life cycle of an `Executor`.
- An object that implements the `ExecutorService` interface can be created using `static` methods declared in class `Executors` (of package `java.util.concurrent`).
- `Executors` method `newCachedThreadPool` (p. 1052) returns an `ExecutorService` that creates new threads as they're needed by the application.
- `ExecutorService` method `execute` executes its `Runnable` sometime in the future. The method returns immediately from each invocation—the program does not wait for each task to finish.
- `ExecutorService` method `shutdown` (p. 1054) notifies the `ExecutorService` to stop accepting new tasks, but continues executing existing tasks and terminates when those tasks complete execution.

Section 26.4 Thread Synchronization

- Thread synchronization (p. 1054) coordinates access to shared data by multiple concurrent threads.
- By synchronizing threads, you can ensure that each thread accessing a shared object excludes all other threads from doing so simultaneously—this is called mutual exclusion (p. 1054).
- A common way to perform synchronization is to use Java's built-in monitors. Every object has a monitor and a monitor lock (p. 1055). The monitor ensures that its object's monitor lock is held by a maximum of only one thread at any time, and thus can be used to enforce mutual exclusion.
- If an operation requires the executing thread to hold a lock while the operation is performed, a thread must acquire the lock (p. 1055) before it can proceed with the operation. Any other threads attempting to perform an operation that requires the same lock will be *blocked* until the first thread releases the lock, at which point the *blocked* threads may attempt to acquire the lock.
- To specify that a thread must hold a monitor lock to execute a block of code, the code should be placed in a `synchronized` statement (p. 1055). Such code is said to be guarded by the monitor lock (p. 1055).
- The `synchronized` statements are declared using the `synchronized` keyword:

```
synchronized ( object )
{
   statements
} // end synchronized statement
```

  where *object* is the object whose monitor lock will be acquired; *object* is normally `this` if it's the object in which the `synchronized` statement appears.
- Java also allows `synchronized` methods (p. 1055). Before executing, a non-`static` `synchronized` method must acquire the lock on the object that's used to call the method. Similary, a `static` `synchronized` method must acquire the lock on the class that's used to call the method.
- `ExecutorService` method `awaitTermination` (p. 1058) forces a program to wait for threads to terminate. It returns control to its caller either when all tasks executing in the `ExecutorService` complete or when the specified timeout elapses. If all tasks complete before the timeout elapses, the method returns `true`; otherwise, it returns `false`.
- You can simulate atomicity (p. 1060) by ensuring that only one thread performs a set of operations at a time. Atomicity can be achieved with `synchronized` statements or `synchronized` methods.
- When you share immutable data across threads, you should declare the corresponding data fields `final` to indicate that variables' values will not change after they're initialized.

Section 26.5 Producer/Consumer Relationship without Synchronization

- In a multithreaded producer/consumer relationship (p. 1062), a producer thread generates data and places it in a shared object called a buffer. A consumer thread reads data from the buffer.
- Operations on a buffer data shared by a producer and a consumer should proceed only if the buffer is in the correct state. If the buffer is not full, the producer may produce; if the buffer is not empty, the consumer may consume. If the buffer is full when the producer attempts to write into it, the producer must wait until there's space. If the buffer is empty or the previous value was already read, the consumer must wait for new data to become available.

Section 26.6 Producer/Consumer Relationship: `ArrayBlockingQueue`

- `ArrayBlockingQueue` (p. 1070) is a fully implemented buffer class from package `java.util.concurrent` that implements the `BlockingQueue` interface.
- An `ArrayBlockingQueue` can implement a shared buffer in a producer/consumer relationship. Method `put` (p. 1070) places an element at the end of the `BlockingQueue`, waiting if the queue is full. Method `take` (p. 1070) removes an element from the head of the `BlockingQueue`, waiting if the queue is empty.
- `ArrayBlockingQueue` stores shared data in an array that's sized with an argument passed to the constructor. Once created, an `ArrayBlockingQueue` is fixed in size.

Section 26.7 Producer/Consumer Relationship with Synchronization

- You can implement a shared buffer yourself using the `synchronized` keyword and `Object` methods `wait` (p. 1073), `notify` and `notifyAll`.
- A thread can call `Object` method `wait` to release an object's monitor lock, and wait in the *waiting* state while the other threads try to enter the object's `synchronized` statement(s) or method(s).
- When a thread executing a `synchronized` statement (or method) completes or satisfies the condition on which another thread may be waiting, it can call `Object` method `notify` (p. 1073) to allow a waiting thread to transition to the *runnable* state. At this point, the thread that was transitioned can attempt to reacquire the monitor lock on the object.
- If a thread calls `notifyAll` (p. 1073), then all the threads waiting for the monitor lock become eligible to reacquire the lock (that is, they all transition to the *runnable* state).

Section 26.8 Producer/Consumer Relationship: Bounded Buffers

- You cannot make assumptions about the relative speeds of concurrent threads.
- A bounded buffer (p. 1080) can be used to minimize the amount of waiting time for threads that share resources and operate at the same average speeds. If the producer temporarily produces values faster than the consumer can consume them, the producer can write additional values into the extra buffer space (if any are available). If the consumer consumes faster than the producer produces new values, the consumer can read additional values (if there are any) from the buffer.
- The key to using a bounded buffer with a producer and consumer that operate at about the same speed is to provide the buffer with enough locations to handle the anticipated "extra" production.
- The simplest way to implement a bounded buffer is to use an `ArrayBlockingQueue` for the buffer so that all of the synchronization details are handled for you.

Section 26.9 Producer/Consumer Relationship: The `Lock` and `Condition` Interfaces

- The `Lock` and `Condition` interfaces (p. 1087) give programmers more precise control over thread synchronization, but are more complicated to use.
- Any object can contain a reference to an object that implements the `Lock` interface (of package `java.util.concurrent.locks`). A thread calls the `Lock`'s `lock` method (p. 1086) to acquire the

lock. Once a `Lock` has been obtained by one thread, the `Lock` object will not allow another thread to obtain the `Lock` until the first thread releases the `Lock` (by calling the `Lock`'s `unlock` method; p. 1086).

- If several threads are trying to call method `lock` on the same `Lock` object at the same time, only one thread can obtain the lock—the others are placed in the *waiting* state. When a thread calls `unlock`, the object's lock is released and a waiting thread attempting to lock the object proceeds.
- Class `ReentrantLock` (p. 1087) is a basic implementation of the `Lock` interface.
- The `ReentrantLock` constructor takes a `boolean` that specifies whether the lock has a fairness policy (p. 1087). If `true`, the `ReentrantLock`'s fairness policy is "the longest-waiting thread will acquire the lock when it's available"—this prevents indefinite postponement. If the argument is set to `false`, there's no guarantee as to which waiting thread will acquire the lock when it's available.
- If a thread that owns a `Lock` determines that it cannot continue with its task until some condition is satisfied, the thread can wait on a condition object (p. 1087). Using `Lock` objects allows you to explicitly declare the condition objects on which a thread may need to wait.
- `Condition` (p. 1087) objects are associated with a specific `Lock` and are created by calling `Lock` method `newCondition`, which returns a `Condition` object. To wait on a `Condition`, the thread can call the `Condition`'s `await` method. This immediately releases the associated `Lock` and places the thread in the *waiting* state for that `Condition`. Other threads can then try to obtain the `Lock`.
- When a *runnable* thread completes a task and determines that a *waiting* thread can now continue, the *runnable* thread can call `Condition` method `signal` to allow a thread in that `Condition`'s *waiting* state to return to the *runnable* state. At this point, the thread that transitioned from the *waiting* state to the *runnable* state can attempt to reacquire the `Lock`.
- If multiple threads are in a `Condition`'s *waiting* state when `signal` is called, the default implementation of `Condition` signals the longest-waiting thread to transition to the *runnable* state.
- If a thread calls `Condition` method `signalAll`, then all the threads waiting for that condition transition to the *runnable* state and become eligible to reacquire the `Lock`.
- When a thread is finished with a shared object, it must call method `unlock` to release the `Lock`.
- `Lock`s allow you to interrupt waiting threads or to specify a timeout for waiting to acquire a lock—not possible with `synchronized`. Also, a `Lock` object is not constrained to be acquired and released in the same block of code, which is the case with the `synchronized` keyword.
- `Condition` objects allow you to specify multiple conditions on which threads may wait. Thus, it's possible to indicate to waiting threads that a specific condition object is now true by calling that `Condition` object's `signal` or `signallAll` methods (p. 1087). With `synchronized`, there's no way to explicitly state the condition on which threads are waiting.

Section 26.11 Multithreading with GUI

- The event dispatch thread (p. 1095) handles interactions with the application's GUI components. All tasks that interact with the GUI are placed in an event queue and executed sequentially by this thread.
- Swing GUI components are not thread safe. Thread safety is achieved by ensuring that Swing components are accessed from only the event dispatch thread.
- Performing a lengthy computation in response to a user interface interaction ties up the event dispatch thread, preventing it from attending to other tasks and causing the GUI components to become unresponsive. Long-running computations should be handled in separate threads.
- You can extend generic class `SwingWorker` (p. 1095; package `javax.swing`), which implements `Runnable`, to perform long-running computations in a worker thread and to update Swing components from the event dispatch thread based on the computations' results. You override its

`doInBackground` and `done` methods. Method `doInBackground` performs the computation and returns the result. Method `done` displays the results in the GUI.

- Class `SwingWorker`'s first type parameter indicates the type returned by the `doInBackground` method; the second indicates the type that's passed between the `publish` and `process` methods to handle intermediate results.
- Method `doInBackground` is called from a worker thread. After `doInBackground` returns, method `done` is called from the event dispatch thread to display the results.
- An `ExecutionException` is thrown if an exception occurs during the computation.
- `SwingWorker` method `publish` repeatedly sends intermediate results to method `process`, which displays the results in a GUI component. Method `setProgress` updates the progress property.
- Method `process` executes in the event dispatch thread and receives data from method `publish`. The passing of values between `publish` in the worker thread and `process` in the event dispatch thread is asynchronous; `process` is not necessarily invoked for every call to `publish`.
- `PropertyChangeListener` (p. 1108) is an interface from package `java.beans` that defines a single method, `propertyChange`. Every time method `setProgress` is invoked, a `PropertyChangeEvent` is generated to indicate that the progress property has changed.

Section 26.12 Interfaces `Callable` and `Future`

- The `Callable` (p. 1109) interface (of package `java.util.concurrent`) declares a single method named `call` that allows the thread to return a value or to throw a checked exception.
- `ExecutorService` method `submit` (p. 1109) executes a `Callable` passed in as its argument.
- Method `submit` returns an object of type `Future` (of package `java.util.concurrent`) that represents the executing `Callable`. Interface `Future` (p. 1109) declares method `get` to return the result of the `Callable` and provides other methods to manage a `Callable`'s execution.

Section 26.13 Java SE 7: Fork/Join Framework

- Java SE 7's concurrency APIs include the new fork/join framework, which helps programmers parallelize algorithms. The fork/join framework particularly well suited to divide-and-conquer-style algorithms, like the merge sort.

Self-Review Exercises

26.1 Fill in the blanks in each of the following statements:

a) A thread enters the *terminated* state when _____.

b) To pause for a designated number of milliseconds and resume execution, a thread should call method _____ of class _____.

c) Method _____ of class `Condition` moves a single thread in an object's *waiting* state to the *runnable* state.

d) Method _____ of class `Condition` moves every thread in an object's *waiting* state to the *runnable* state.

e) A(n) _____ thread enters the _____ state when it completes its task or otherwise terminates.

f) A *runnable* thread can enter the _____ state for a specified interval of time.

g) At the operating-system level, the *runnable* state actually encompasses two separate states, _____ and _____.

h) `Runnable`s are executed using a class that implements the _____ interface.

i) `ExecutorService` method _____ ends each thread in an `ExecutorService` as soon as it finishes executing its current `Runnable`, if any.

j) A thread can call method _____ on a `Condition` object to release the associated `Lock` and place that thread in the _____ state.
k) In a(n) _____ relationship, the _____ generates data and stores it in a shared object, and the _____ reads data from the shared object.
l) Class _____ implements the `BlockingQueue` interface using an array.
m) Keyword _____ indicates that only one thread at a time should execute on an object.

26.2 State whether each of the following is *true* or *false*. If *false*, explain why.
a) A thread is not *runnable* if it has terminated.
b) Some operating systems use timeslicing with threads. Therefore, they can enable threads to preempt threads of the same priority.
c) When the thread's quantum expires, the thread returns to the *running* state as the operating system assigns it to a processor.
d) On a single-processor system without timeslicing, each thread in a set of equal-priority threads (with no other threads present) runs to completion before other threads of equal priority get a chance to execute.

Answers to Self-Review Exercises

26.1 a) its `run` method ends. b) `sleep`, `Thread`. c) `signal`. d) `signalAll`. e) *runnable*, *terminated*. f) *timed waiting*. g) *ready*, *running*. h) `Executor`. i) `shutdown`. j) `await`, *waiting*. k) producer/consumer, producer, consumer. l) `ArrayBlockingQueue`. m) `synchronized`.

26.2 a) True. b) False. Timeslicing allows a thread to execute until its timeslice (or quantum) expires. Then other threads of equal priority can execute. c) False. When a thread's quantum expires, the thread returns to the *ready* state and the operating system assigns to the processor another thread. d) True.

Exercises

26.3 ***(True or False)*** State whether each of the following is *true* or *false*. If *false*, explain why.
a) Method `sleep` does not consume processor time while a thread sleeps.
b) Declaring a method `synchronized` guarantees that deadlock cannot occur.
c) Once a `ReentrantLock` has been obtained by a thread, the `ReentrantLock` object will not allow another thread to obtain the lock until the first thread releases it.
d) Swing components are thread safe.

26.4 ***(Multithreading Terms)*** Define each of the following terms.
a) thread
b) multithreading
c) *runnable* state
d) *timed waiting* state
e) preemptive scheduling
f) `Runnable` interface
g) `notifyAll` method
h) producer/consumer relationship
i) quantum

26.5 ***(Multithreading Terms)*** Discuss each of the following terms in the context of Java's threading mechanisms:
a) `synchronized`
b) producer
c) consumer

d) `wait`
e) `notify`
f) `Lock`
g) `Condition`

26.6 *(Blocked State)* List the reasons for entering the *blocked* state. For each of these, describe how the program will normally leave the *blocked* state and enter the *runnable* state.

26.7 *(Deadlock and Indefinite Postponement)* Two problems that can occur in systems that allow threads to wait are deadlock, in which one or more threads will wait forever for an event that cannot occur, and indefinite postponement, in which one or more threads will be delayed for some unpredictably long time. Give an example of how each of these problems can occur in multithreaded Java programs.

26.8 *(Bouncing Ball)* Write a program that bounces a blue ball inside a `JPanel`. The ball should begin moving with a `mousePressed` event. When the ball hits the edge of the `JPanel`, it should bounce off the edge and continue in the opposite direction. The ball should be updated using a `Runnable`.

26.9 *(Bouncing Balls)* Modify the program in Exercise 26.8 to add a new ball each time the user clicks the mouse. Provide for a minimum of 20 balls. Randomly choose the color for each new ball.

26.10 *(Bouncing Balls with Shadows)* Modify the program in Exercise 26.9 to add shadows. As a ball moves, draw a solid black oval at the bottom of the `JPanel`. You may consider adding a 3-D effect by increasing or decreasing the size of each ball when it hits the edge of the `JPanel`.

26.11 *(Circular Buffer with `Lock`s and `Condition`s)* Reimplement the example in Section 26.8 using the `Lock` and `Condition` concepts presented in Section 26.9.