A thread that modifies the shared data can invoke the `pthread_cond_signal()` function, thereby signaling one thread waiting on the condition variable. This is illustrated below:

```
pthread_mutex_lock(&mutex);
a = b;
pthread_cond_signal(&cond_var);
pthread_mutex_unlock(&mutex);
```

It is important to note that the call to `pthread_cond_signal()` does not release the mutex lock. It is the subsequent call to `pthread_mutex_unlock()` that releases the mutex. Once the mutex lock is released, the signaled thread becomes the owner of the mutex lock and returns control from the call to `pthread_cond_wait()`.

We provide several programming problems and projects at the end of this chapter that use Pthreads mutex locks and condition variables, as well as POSIX semaphores.

7.4 Synchronization in Java

The Java language and its API have provided rich support for thread synchronization since the origins of the language. In this section, we first cover Java monitors, Java's original synchronization mechanism. We then cover three additional mechanisms that were introduced in Release 1.5: reentrant locks, semaphores, and condition variables. We include these because they represent the most common locking and synchronization mechanisms. However, the Java API provides many features that we do not cover in this text—for example, support for atomic variables and the CAS instruction—and we encourage interested readers to consult the bibliography for more information.

7.4.1 Java Monitors

Java provides a monitor-like concurrency mechanism for thread synchronization. We illustrate this mechanism with the `BoundedBuffer` class (Figure 7.9), which implements a solution to the bounded-buffer problem wherein the producer and consumer invoke the `insert()` and `remove()` methods, respectively.

Every object in Java has associated with it a single lock. When a method is declared to be `synchronized`, calling the method requires owning the lock for the object. We declare a `synchronized` method by placing the `synchronized` keyword in the method definition, such as with the `insert()` and `remove()` methods in the `BoundedBuffer` class.

Invoking a `synchronized` method requires owning the lock on an object instance of `BoundedBuffer`. If the lock is already owned by another thread, the thread calling the `synchronized` method blocks and is placed in the **entry set** for the object's lock. The entry set represents the set of threads waiting for the lock to become available. If the lock is available when a `synchronized` method is called, the calling thread becomes the owner of the object's lock and can enter the method. The lock is released when the thread exits the method. If the entry set for the lock is not empty when the lock is released, the JVM

```
public class BoundedBuffer<E>
{
   private static final int BUFFER_SIZE = 5;

   private int count, in, out;
   private E[] buffer;

   public BoundedBuffer() {
      count = 0;
      in = 0;
      out = 0;
      buffer = (E[]) new Object[BUFFER_SIZE];
   }

   /* Producers call this method */
   public synchronized void insert(E item) {
      /* See Figure 7.11 */
   }

   /* Consumers call this method */
   public synchronized E remove() {
      /* See Figure 7.11 */
   }
}
```

Figure 7.9 Bounded buffer using Java synchronization.

arbitrarily selects a thread from this set to be the owner of the lock. (When we say "arbitrarily," we mean that the specification does not require that threads in this set be organized in any particular order. However, in practice, most virtual machines order threads in the entry set according to a FIFO policy.) Figure 7.10 illustrates how the entry set operates.

In addition to having a lock, every object also has associated with it a **wait set** consisting of a set of threads. This wait set is initially empty. When a thread enters a `synchronized` method, it owns the lock for the object. However, this thread may determine that it is unable to continue because a certain condition

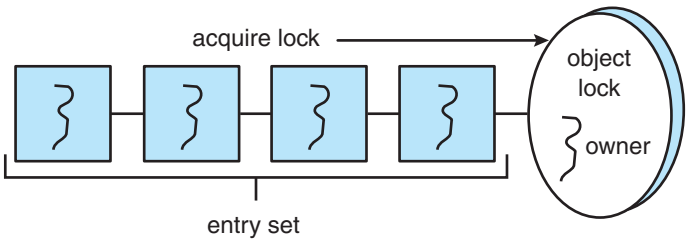

Figure 7.10 Entry set for a lock.

BLOCK SYNCHRONIZATION

The amount of time between when a lock is acquired and when it is released is defined as the **scope** of the lock. A `synchronized` method that has only a small percentage of its code manipulating shared data may yield a scope that is too large. In such an instance, it may be better to synchronize only the block of code that manipulates shared data than to synchronize the entire method. Such a design results in a smaller lock scope. Thus, in addition to declaring `synchronized` methods, Java also allows block synchronization, as illustrated below. Only the access to the critical-section code requires ownership of the object lock for the `this` object.

```
public void someMethod() {
   /* non-critical section */

   synchronized(this) {
      /* critical section */
   }

   /* remainder section */
}
```

has not been met. That will happen, for example, if the producer calls the `insert()` method and the buffer is full. The thread then will release the lock and wait until the condition that will allow it to continue is met.

When a thread calls the `wait()` method, the following happens:

1. The thread releases the lock for the object.
2. The state of the thread is set to blocked.
3. The thread is placed in the wait set for the object.

Consider the example in Figure 7.11. If the producer calls the `insert()` method and sees that the buffer is full, it calls the `wait()` method. This call releases the lock, blocks the producer, and puts the producer in the wait set for the object. Because the producer has released the lock, the consumer ultimately enters the `remove()` method, where it frees space in the buffer for the producer. Figure 7.12 illustrates the entry and wait sets for a lock. (Note that although `wait()` can throw an `InterruptedException`, we choose to ignore it for code clarity and simplicity.)

How does the consumer thread signal that the producer may now proceed? Ordinarily, when a thread exits a `synchronized` method, the departing thread releases only the lock associated with the object, possibly removing a thread from the entry set and giving it ownership of the lock. However, at the end of the `insert()` and `remove()` methods, we have a call to the method `notify()`. The call to `notify()`:

1. Picks an arbitrary thread `T` from the list of threads in the wait set

```
/* Producers call this method */
public synchronized void insert(E item) {
   while (count == BUFFER_SIZE) {
      try {
         wait();
      }
      catch (InterruptedException ie) { }
   }

   buffer[in] = item;
   in = (in + 1) % BUFFER_SIZE;
   count++;

   notify();
}

/* Consumers call this method */
public synchronized E remove() {
   E item;

   while (count == 0) {
      try {
         wait();
      }
      catch (InterruptedException ie) { }
   }

   item = buffer[out];
   out = (out + 1) % BUFFER_SIZE;
   count--;

   notify();

   return item;
}
```

Figure 7.11 `insert()` and `remove()` methods using `wait()` and `notify()`.

2. Moves T from the wait set to the entry set
3. Sets the state of T from blocked to runnable

T is now eligible to compete for the lock with the other threads. Once T has regained control of the lock, it returns from calling `wait()`, where it may check the value of `count` again. (Again, the selection of an *arbitrary* thread is according to the Java specification; in practice, most Java virtual machines order threads in the wait set according to a FIFO policy.)

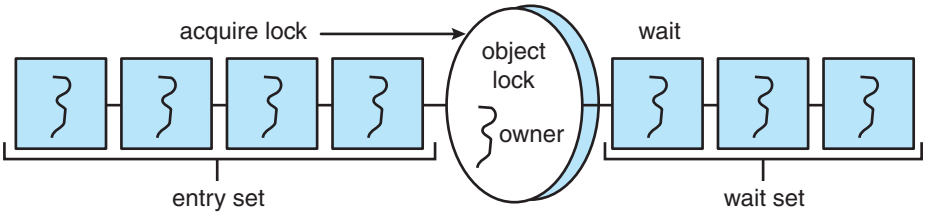

Figure 7.12 Entry and wait sets.

Next, we describe the `wait()` and `notify()` methods in terms of the methods shown in Figure 7.11. We assume that the buffer is full and the lock for the object is available.

- The producer calls the `insert()` method, sees that the lock is available, and enters the method. Once in the method, the producer determines that the buffer is full and calls `wait()`. The call to `wait()` releases the lock for the object, sets the state of the producer to blocked, and puts the producer in the wait set for the object.
- The consumer ultimately calls and enters the `remove()` method, as the lock for the object is now available. The consumer removes an item from the buffer and calls `notify()`. Note that the consumer still owns the lock for the object.
- The call to `notify()` removes the producer from the wait set for the object, moves the producer to the entry set, and sets the producer's state to runnable.
- The consumer exits the `remove()` method. Exiting this method releases the lock for the object.
- The producer tries to reacquire the lock and is successful. It resumes execution from the call to `wait()`. The producer tests the `while` loop, determines that room is available in the buffer, and proceeds with the remainder of the `insert()` method. If no thread is in the wait set for the object, the call to `notify()` is ignored. When the producer exits the method, it releases the lock for the object.

The `synchronized`, `wait()`, and `notify()` mechanisms have been part of Java since its origins. However, later revisions of the Java API introduced much more flexible and robust locking mechanisms, some of which we examine in the following sections.

7.4.2 Reentrant Locks

Perhaps the simplest locking mechanism available in the API is the `ReentrantLock`. In many ways, a `ReentrantLock` acts like the `synchronized` statement described in Section 7.4.1: a `ReentrantLock` is owned by a single thread and is used to provide mutually exclusive access to a shared resource. However, the `ReentrantLock` provides several additional features, such as setting a *fairness* parameter, which favors granting the lock to the longest-waiting thread. (Recall