opened. Similarly, all output is performed just before the program terminates, when the program results must be written to a single file. Between start-up and termination, the program is entirely CPU-bound. Your task is to improve the performance of this application by multithreading it. The application runs on a system that uses the one-to-one threading model (each user thread maps to a kernel thread).

- How many threads will you create to perform the input and output? Explain.
- How many threads will you create for the CPU-intensive portion of the application? Explain.

4.17 Consider the following code segment:

```
pid_t pid;

pid = fork();
if (pid == 0) { /* child process */
   fork();
   thread_create( . . .);
}
fork();
```

a. How many unique processes are created?

b. How many unique threads are created?

4.18 As described in Section 4.7.2, Linux does not distinguish between processes and threads. Instead, Linux treats both in the same way, allowing a task to be more akin to a process or a thread depending on the set of flags passed to the `clone()` system call. However, other operating systems, such as Windows, treat processes and threads differently. Typically, such systems use a notation in which the data structure for a process contains pointers to the separate threads belonging to the process. Contrast these two approaches for modeling processes and threads within the kernel.

4.19 The program shown in Figure 4.23 uses the Pthreads API. What would be the output from the program at `LINE C` and `LINE P`?

4.20 Consider a multicore system and a multithreaded program written using the many-to-many threading model. Let the number of user-level threads in the program be greater than the number of processing cores in the system. Discuss the performance implications of the following scenarios.

a. The number of kernel threads allocated to the program is less than the number of processing cores.

b. The number of kernel threads allocated to the program is equal to the number of processing cores.

c. The number of kernel threads allocated to the program is greater than the number of processing cores but less than the number of user-level threads.

```
#include <pthread.h>
#include <stdio.h>

int value = 0;
void *runner(void *param); /* the thread */

int main(int argc, char *argv[])
{
pid_t pid;
pthread_t tid;
pthread_attr_t attr;

   pid = fork();

   if (pid == 0) { /* child process */
      pthread_attr_init(&attr);
      pthread_create(&tid,&attr,runner,NULL);
      pthread_join(tid,NULL);
      printf("CHILD: value = %d",value); /* LINE C */
   }
   else if (pid > 0) { /* parent process */
      wait(NULL);
      printf("PARENT: value = %d",value); /* LINE P */
   }
}

void *runner(void *param) {
   value = 5;
   pthread_exit(0);
}
```

Figure 4.22 C program for Exercise 4.19.

4.21 Pthreads provides an API for managing thread cancellation. The `pthread_setcancelstate()` function is used to set the cancellation state. Its prototype appears as follows:

```
pthread_setcancelstate(int state, int *oldstate)
```

The two possible values for the state are `PTHREAD_CANCEL_ENABLE` and `PTHREAD_CANCEL_DISABLE`.

Using the code segment shown in Figure 4.24, provide examples of two operations that would be suitable to perform between the calls to disable and enable thread cancellation.

```
int oldstate;

pthread_setcancelstate(PTHREAD_CANCEL_DISABLE, &oldstate);

/* What operations would be performed here? */

pthread_setcancelstate(PTHREAD_CANCEL_ENABLE, &oldstate);
```

Figure 4.23 C program for Exercise 4.21.

Programming Problems

4.22 Write a multithreaded program that calculates various statistical values for a list of numbers. This program will be passed a series of numbers on the command line and will then create three separate worker threads. One thread will determine the average of the numbers, the second will determine the maximum value, and the third will determine the minimum value. For example, suppose your program is passed the integers

90 81 78 95 79 72 85

The program will report

```
The average value is 82
The minimum value is 72
The maximum value is 95
```

The variables representing the average, minimum, and maximum values will be stored globally. The worker threads will set these values, and the parent thread will output the values once the workers have exited. (We could obviously expand this program by creating additional threads that determine other statistical values, such as median and standard deviation.)

4.23 Write a multithreaded program that outputs prime numbers. This program should work as follows: The user will run the program and will enter a number on the command line. The program will then create a separate thread that outputs all the prime numbers less than or equal to the number entered by the user.

4.24 An interesting way of calculating π is to use a technique known as ***Monte Carlo***, which involves randomization. This technique works as follows:

Suppose you have a circle inscribed within a square, as shown in Figure 4.25. (Assume that the radius of this circle is 1.)

- First, generate a series of random points as simple (x, y) coordinates. These points must fall within the Cartesian coordinates that bound the square. Of the total number of random points that are generated, some will occur within the circle.
- Next, estimate π by performing the following calculation:

$$\pi = 4 \times \textit{(number of points in circle)} \ / \ \textit{(total number of points)}$$

Write a multithreaded version of this algorithm that creates a separate thread to generate a number of random points. The thread will count the number of points that occur within the circle and store that result in a global variable. When this thread has exited, the parent thread will calculate and output the estimated value of π. It is worth experimenting with the number of random points generated. As a general rule, the greater the number of points, the closer the approximation to π.

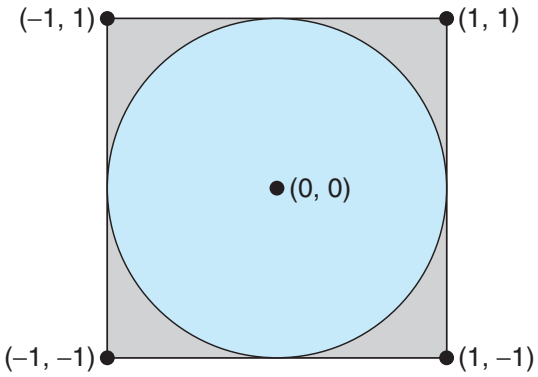


Figure 4.25 Monte Carlo technique for calculating π.

In the source-code download for this text, you will find a sample program that provides a technique for generating random numbers, as well as determining if the random (x, y) point occurs within the circle.

Readers interested in the details of the Monte Carlo method for estimating π should consult the bibliography at the end of this chapter. In Chapter 6, we modify this exercise using relevant material from that chapter.

4.25 Repeat Exercise 4.24, but instead of using a separate thread to generate random points, use OpenMP to parallelize the generation of points. Be careful not to place the calculation of π in the parallel region, since you want to calculate π only once.

4.26 Modify the socket-based date server (Figure 3.27) in Chapter 3 so that the server services each client request in a separate thread.

4.27 The Fibonacci sequence is the series of numbers $0, 1, 1, 2, 3, 5, 8, \ldots$. Formally, it can be expressed as:

$$fib_0 = 0$$
$$fib_1 = 1$$
$$fib_n = fib_{n-1} + fib_{n-2}$$

Write a multithreaded program that generates the Fibonacci sequence. This program should work as follows: On the command line, the user will enter the number of Fibonacci numbers that the program is to generate. The program will then create a separate thread that will generate the Fibonacci numbers, placing the sequence in data that can be shared by the threads (an array is probably the most convenient data structure). When the thread finishes execution, the parent thread will output the sequence generated by the child thread. Because the parent thread cannot begin outputting the Fibonacci sequence until the child thread finishes, the parent thread will have to wait for the child thread to finish. Use the techniques described in Section 4.4 to meet this requirement.

4.28 Modify programming problem Exercise 3.20 from Chapter 3, which asks you to design a pid manager. This modification will consist of writing a

multithreaded program that tests your solution to Exercise 3.20. You will create a number of threads—for example, 100—and each thread will request a pid, sleep for a random period of time, and then release the pid. (Sleeping for a random period of time approximates the typical pid usage in which a pid is assigned to a new process, the process executes and then terminates, and the pid is released on the process's termination.) On UNIX and Linux systems, sleeping is accomplished through the `sleep()` function, which is passed an integer value representing the number of seconds to sleep. This problem will be modified in Chapter 7.

4.29 Exercise 3.25 in Chapter 3 involves designing an echo server using the Java threading API. This server is single-threaded, meaning that the server cannot respond to concurrent echo clients until the current client exits. Modify the solution to Exercise 3.25 so that the echo server services each client in a separate request.

Programming Projects

Project 1—Sudoku Solution Validator

A ***Sudoku*** puzzle uses a 9×9 grid in which each column and row, as well as each of the nine 3×3 subgrids, must contain all of the digits $1 \cdots 9$. Figure 4.26 presents an example of a valid Sudoku puzzle. This project consists of designing a multithreaded application that determines whether the solution to a Sudoku puzzle is valid.

There are several different ways of multithreading this application. One suggested strategy is to create threads that check the following criteria:

- A thread to check that each column contains the digits 1 through 9
- A thread to check that each row contains the digits 1 through 9

6	2	4	5	3	9	1	8	7
5	1	9	7	2	8	6	3	4
8	3	7	6	1	4	2	9	5
1	4	3	8	6	5	7	2	9
9	5	8	2	4	7	3	6	1
7	6	2	3	9	1	4	5	8
3	7	1	9	5	6	8	4	2
4	9	6	1	8	2	5	7	3
2	8	5	4	7	3	9	1	6

Figure 4.26 Solution to a 9×9 Sudoku puzzle.

- Nine threads to check that each of the 3×3 subgrids contains the digits 1 through 9

This would result in a total of eleven separate threads for validating a Sudoku puzzle. However, you are welcome to create even more threads for this project. For example, rather than creating one thread that checks all nine columns, you could create nine separate threads and have each of them check one column.

I. Passing Parameters to Each Thread

The parent thread will create the worker threads, passing each worker the location that it must check in the Sudoku grid. This step will require passing several parameters to each thread. The easiest approach is to create a data structure using a `struct`. For example, a structure to pass the row and column where a thread must begin validating would appear as follows:

```
/* structure for passing data to threads */
typedef struct
{
   int row;
   int column;
} parameters;
```

Both Pthreads and Windows programs will create worker threads using a strategy similar to that shown below:

```
parameters *data = (parameters *) malloc(sizeof(parameters));
data->row = 1;
data->column = 1;
/* Now create the thread passing it data as a parameter */
```

The `data` pointer will be passed to either the `pthread_create()` (Pthreads) function or the `CreateThread()` (Windows) function, which in turn will pass it as a parameter to the function that is to run as a separate thread.

II. Returning Results to the Parent Thread

Each worker thread is assigned the task of determining the validity of a particular region of the Sudoku puzzle. Once a worker has performed this check, it must pass its results back to the parent. One good way to handle this is to create an array of integer values that is visible to each thread. The i^{th} index in this array corresponds to the i^{th} worker thread. If a worker sets its corresponding value to 1, it is indicating that its region of the Sudoku puzzle is valid. A value of 0 indicates otherwise. When all worker threads have completed, the parent thread checks each entry in the result array to determine if the Sudoku puzzle is valid.

Project 2—Multithreaded Sorting Application

Write a multithreaded sorting program that works as follows: A list of integers is divided into two smaller lists of equal size. Two separate threads (which we

will term ***sorting threads***) sort each sublist using a sorting algorithm of your choice. The two sublists are then merged by a third thread—a ***merging thread*** —which merges the two sublists into a single sorted list.

Because global data are shared across all threads, perhaps the easiest way to set up the data is to create a global array. Each sorting thread will work on one half of this array. A second global array of the same size as the unsorted integer array will also be established. The merging thread will then merge the two sublists into this second array. Graphically, this program is structured as in Figure 4.27.

This programming project will require passing parameters to each of the sorting threads. In particular, it will be necessary to identify the starting index from which each thread is to begin sorting. Refer to the instructions in Project 1 for details on passing parameters to a thread.

The parent thread will output the sorted array once all sorting threads have exited.

Project 3—Fork-Join Sorting Application

Implement the preceding project (Multithreaded Sorting Application) using Java's fork-join parallelism API. This project will be developed in two different versions. Each version will implement a different divide-and-conquer sorting algorithm:

1. Quicksort
2. Mergesort

The Quicksort implementation will use the Quicksort algorithm for dividing the list of elements to be sorted into a *left half* and a *right half* based on the

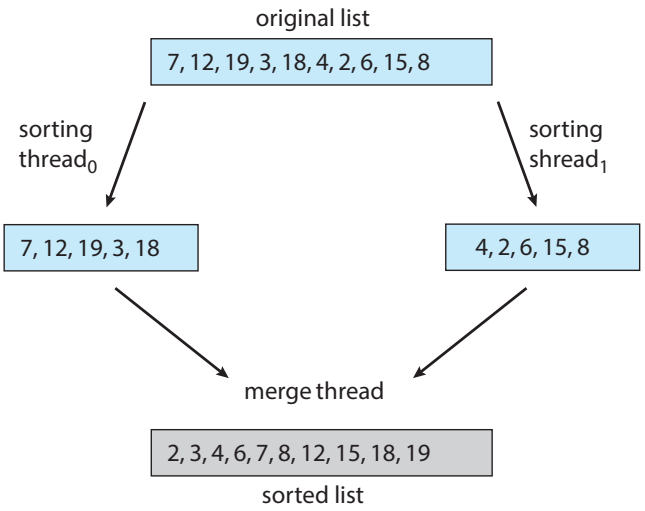


Figure 4.27 Multithreaded sorting.

position of the pivot value. The Mergesort algorithm will divide the list into two evenly sized halves. For both the Quicksort and Mergesort algorithms, when the list to be sorted falls within some threshold value (for example, the list is size 100 or fewer), directly apply a simple algorithm such as the Selection or Insertion sort. Most data structures texts describe these two well-known, divide-and-conquer sorting algorithms.

The class `SumTask` shown in Section 4.5.2.1 extends `RecursiveTask`, which is a result-bearing `ForkJoinTask`. As this assignment will involve sorting the array that is passed to the task, but not returning any values, you will instead create a class that extends `RecursiveAction`, a non result-bearing `ForkJoinTask` (see Figure 4.19).

The objects passed to each sorting algorithm are required to implement Java's `Comparable` interface, and this will need to be reflected in the class definition for each sorting algorithm. The source code download for this text includes Java code that provides the foundations for beginning this project.

CPU Scheduling

CPU scheduling is the basis of multiprogrammed operating systems. By switching the CPU among processes, the operating system can make the computer more productive. In this chapter, we introduce basic CPU-scheduling concepts and present several CPU-scheduling algorithms, including real-time systems. We also consider the problem of selecting an algorithm for a particular system.

In Chapter 4, we introduced threads to the process model. On modern operating systems it is kernel-level threads—not processes—that are in fact being scheduled by the operating system. However, the terms "process scheduling" and "thread scheduling" are often used interchangeably. In this chapter, we use ***process scheduling*** when discussing general scheduling concepts and ***thread scheduling*** to refer to thread-specific ideas.

Similarly, in Chapter 1 we describe how a ***core*** is the basic computational unit of a CPU, and that a process executes on a CPU's core. However, in many instances in this chapter, when we use the general terminology of scheduling a process to "run on a CPU", we are implying that the process is running on a CPU's core.

CHAPTER OBJECTIVES

- Describe various CPU scheduling algorithms.
- Assess CPU scheduling algorithms based on scheduling criteria.
- Explain the issues related to multiprocessor and multicore scheduling.
- Describe various real-time scheduling algorithms.
- Describe the scheduling algorithms used in the Windows, Linux, and Solaris operating systems.
- Apply modeling and simulations to evaluate CPU scheduling algorithms.
- Design a program that implements several different CPU scheduling algorithms.

5.1 Basic Concepts

In a system with a single CPU core, only one process can run at a time. Others must wait until the CPU's core is free and can be rescheduled. The objective of multiprogramming is to have some process running at all times, to maximize CPU utilization. The idea is relatively simple. A process is executed until it must wait, typically for the completion of some I/O request. In a simple computer system, the CPU then just sits idle. All this waiting time is wasted; no useful work is accomplished. With multiprogramming, we try to use this time productively. Several processes are kept in memory at one time. When one process has to wait, the operating system takes the CPU away from that process and gives the CPU to another process. This pattern continues. Every time one process has to wait, another process can take over use of the CPU. On a multicore system, this concept of keeping the CPU busy is extended to all processing cores on the system.

Scheduling of this kind is a fundamental operating-system function. Almost all computer resources are scheduled before use. The CPU is, of course, one of the primary computer resources. Thus, its scheduling is central to operating-system design.

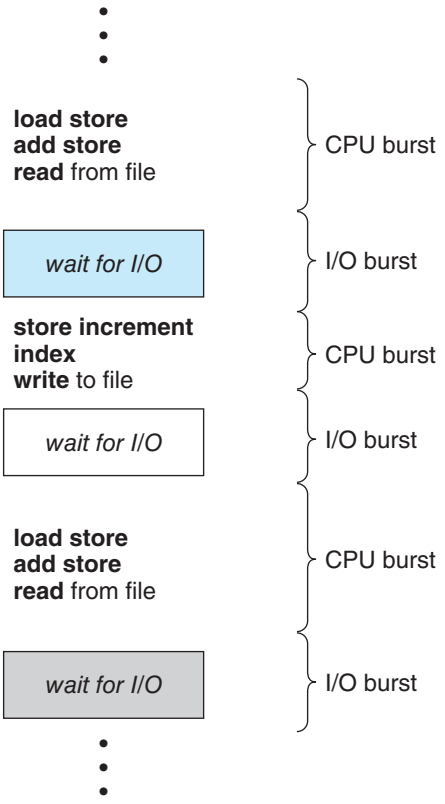


Figure 5.1 Alternating sequence of CPU and I/O bursts.

5.1.1 CPU–I/O Burst Cycle

The success of CPU scheduling depends on an observed property of processes: process execution consists of a **cycle** of CPU execution and I/O wait. Processes alternate between these two states. Process execution begins with a **CPU burst**. That is followed by an **I/O burst**, which is followed by another CPU burst, then another I/O burst, and so on. Eventually, the final CPU burst ends with a system request to terminate execution (Figure 5.1).

The durations of CPU bursts have been measured extensively. Although they vary greatly from process to process and from computer to computer, they tend to have a frequency curve similar to that shown in Figure 5.2. The curve is generally characterized as exponential or hyperexponential, with a large number of short CPU bursts and a small number of long CPU bursts. An I/O-bound program typically has many short CPU bursts. A CPU-bound program might have a few long CPU bursts. This distribution can be important when implementing a CPU-scheduling algorithm.

5.1.2 CPU Scheduler

Whenever the CPU becomes idle, the operating system must select one of the processes in the ready queue to be executed. The selection process is carried out by the **CPU scheduler**, which selects a process from the processes in memory that are ready to execute and allocates the CPU to that process.

Note that the ready queue is not necessarily a first-in, first-out (FIFO) queue. As we shall see when we consider the various scheduling algorithms, a ready queue can be implemented as a FIFO queue, a priority queue, a tree, or simply an unordered linked list. Conceptually, however, all the processes in the ready queue are lined up waiting for a chance to run on the CPU. The records in the queues are generally process control blocks (PCBs) of the processes.

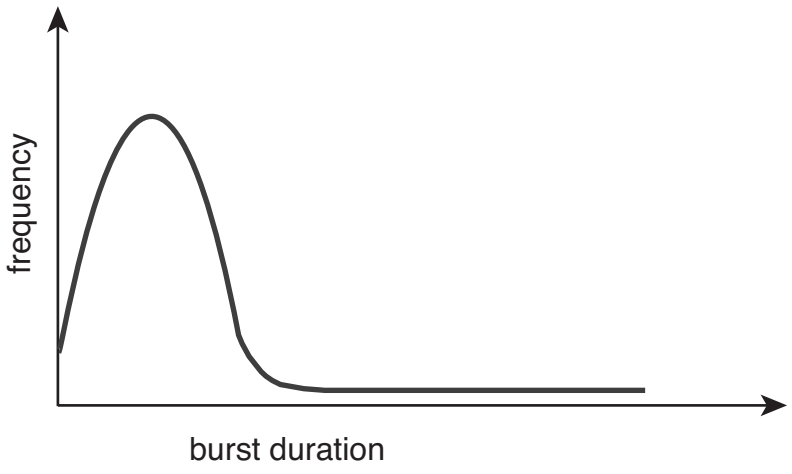


Figure 5.2 Histogram of CPU-burst durations.

5.1.3 Preemptive and Nonpreemptive Scheduling

CPU-scheduling decisions may take place under the following four circumstances:

1. When a process switches from the running state to the waiting state (for example, as the result of an I/O request or an invocation of `wait()` for the termination of a child process)
2. When a process switches from the running state to the ready state (for example, when an interrupt occurs)
3. When a process switches from the waiting state to the ready state (for example, at completion of I/O)
4. When a process terminates

For situations 1 and 4, there is no choice in terms of scheduling. A new process (if one exists in the ready queue) must be selected for execution. There is a choice, however, for situations 2 and 3.

When scheduling takes place only under circumstances 1 and 4, we say that the scheduling scheme is **nonpreemptive** or **cooperative**. Otherwise, it is **preemptive**. Under nonpreemptive scheduling, once the CPU has been allocated to a process, the process keeps the CPU until it releases it either by terminating or by switching to the waiting state. Virtually all modern operating systems including Windows, macOS, Linux, and UNIX use preemptive scheduling algorithms.

Unfortunately, preemptive scheduling can result in race conditions when data are shared among several processes. Consider the case of two processes that share data. While one process is updating the data, it is preempted so that the second process can run. The second process then tries to read the data, which are in an inconsistent state. This issue will be explored in detail in Chapter 6.

Preemption also affects the design of the operating-system kernel. During the processing of a system call, the kernel may be busy with an activity on behalf of a process. Such activities may involve changing important kernel data (for instance, I/O queues). What happens if the process is preempted in the middle of these changes and the kernel (or the device driver) needs to read or modify the same structure? Chaos ensues. As will be discussed in Section 6.2, operating-system kernels can be designed as either nonpreemptive or preemptive. A nonpreemptive kernel will wait for a system call to complete or for a process to block while waiting for I/O to complete to take place before doing a context switch. This scheme ensures that the kernel structure is simple, since the kernel will not preempt a process while the kernel data structures are in an inconsistent state. Unfortunately, this kernel-execution model is a poor one for supporting real-time computing, where tasks must complete execution within a given time frame. In Section 5.6, we explore scheduling demands of real-time systems. A preemptive kernel requires mechanisms such as mutex locks to prevent race conditions when accessing shared kernel data structures. Most modern operating systems are now fully preemptive when running in kernel mode.

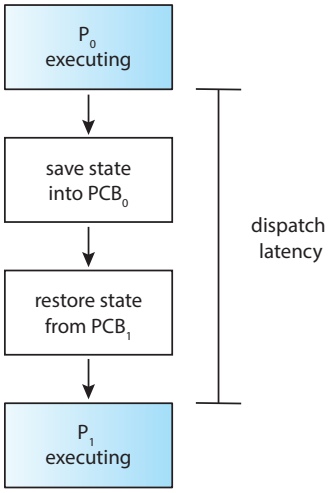


Figure 5.3 The role of the dispatcher.

Because interrupts can, by definition, occur at any time, and because they cannot always be ignored by the kernel, the sections of code affected by interrupts must be guarded from simultaneous use. The operating system needs to accept interrupts at almost all times. Otherwise, input might be lost or output overwritten. So that these sections of code are not accessed concurrently by several processes, they disable interrupts at entry and reenable interrupts at exit. It is important to note that sections of code that disable interrupts do not occur very often and typically contain few instructions.

5.1.4 Dispatcher

Another component involved in the CPU-scheduling function is the **dispatcher**. The dispatcher is the module that gives control of the CPU's core to the process selected by the CPU scheduler. This function involves the following:

- Switching context from one process to another
- Switching to user mode
- Jumping to the proper location in the user program to resume that program

The dispatcher should be as fast as possible, since it is invoked during every context switch. The time it takes for the dispatcher to stop one process and start another running is known as the **dispatch latency** and is illustrated in Figure 5.3.

An interesting question to consider is, how often do context switches occur? On a system-wide level, the number of context switches can be obtained by using the `vmstat` command that is available on Linux systems. Below is the output (which has been trimmed) from the command

```
vmstat 1 3
```

This command provides 3 lines of output over a 1-second delay:

```
------cpu-----
24
225
339
```

The first line gives the average number of context switches over 1 second since the system booted, and the next two lines give the number of context switches over two 1-second intervals. Since this machine booted, it has averaged 24 context switches per second. And in the past second, 225 context switches were made, with 339 context switches in the second prior to that.

We can also use the `/proc` file system to determine the number of context switches for a given process. For example, the contents of the file `/proc/2166/status` will list various statistics for the process with `pid = 2166`. The command

```
cat /proc/2166/status
```

provides the following trimmed output:

```
voluntary_ctxt_switches          150
nonvoluntary_ctxt_switches       8
```

This output shows the number of context switches over the lifetime of the process. Notice the distinction between ***voluntary*** and ***nonvoluntary*** context switches. A voluntary context switch occurs when a process has given up control of the CPU because it requires a resource that is currently unavailable (such as blocking for I/O.) A nonvoluntary context switch occurs when the CPU has been taken away from a process, such as when its time slice has expired or it has been preempted by a higher-priority process.

5.2 Scheduling Criteria

Different CPU-scheduling algorithms have different properties, and the choice of a particular algorithm may favor one class of processes over another. In choosing which algorithm to use in a particular situation, we must consider the properties of the various algorithms.

Many criteria have been suggested for comparing CPU-scheduling algorithms. Which characteristics are used for comparison can make a substantial difference in which algorithm is judged to be best. The criteria include the following:

- **CPU utilization**. We want to keep the CPU as busy as possible. Conceptually, CPU utilization can range from 0 to 100 percent. In a real system, it should range from 40 percent (for a lightly loaded system) to 90 percent (for a heavily loaded system). (CPU utilization can be obtained by using the `top` command on Linux, macOS, and UNIX systems.)
- **Throughput**. If the CPU is busy executing processes, then work is being done. One measure of work is the number of processes that are completed

per time unit, called **throughput**. For long processes, this rate may be one process over several seconds; for short transactions, it may be tens of processes per second.

- **Turnaround time**. From the point of view of a particular process, the important criterion is how long it takes to execute that process. The interval from the time of submission of a process to the time of completion is the turnaround time. Turnaround time is the sum of the periods spent waiting in the ready queue, executing on the CPU, and doing I/O.
- **Waiting time**. The CPU-scheduling algorithm does not affect the amount of time during which a process executes or does I/O. It affects only the amount of time that a process spends waiting in the ready queue. Waiting time is the sum of the periods spent waiting in the ready queue.
- **Response time**. In an interactive system, turnaround time may not be the best criterion. Often, a process can produce some output fairly early and can continue computing new results while previous results are being output to the user. Thus, another measure is the time from the submission of a request until the first response is produced. This measure, called response time, is the time it takes to start responding, not the time it takes to output the response.

It is desirable to maximize CPU utilization and throughput and to minimize turnaround time, waiting time, and response time. In most cases, we optimize the average measure. However, under some circumstances, we prefer to optimize the minimum or maximum values rather than the average. For example, to guarantee that all users get good service, we may want to minimize the maximum response time.

Investigators have suggested that, for interactive systems (such as a PC desktop or laptop system), it is more important to minimize the variance in the response time than to minimize the average response time. A system with reasonable and predictable response time may be considered more desirable than a system that is faster on the average but is highly variable. However, little work has been done on CPU-scheduling algorithms that minimize variance.

As we discuss various CPU-scheduling algorithms in the following section, we illustrate their operation. An accurate illustration should involve many processes, each a sequence of several hundred CPU bursts and I/O bursts. For simplicity, though, we consider only one CPU burst (in milliseconds) per process in our examples. Our measure of comparison is the average waiting time. More elaborate evaluation mechanisms are discussed in Section 5.8.

5.3 Scheduling Algorithms

CPU scheduling deals with the problem of deciding which of the processes in the ready queue is to be allocated the CPU's core. There are many different CPU-scheduling algorithms. In this section, we describe several of them. Although most modern CPU architectures have multiple processing cores, we describe these scheduling algorithms in the context of only one processing core available. That is, a single CPU that has a single processing core, thus the system is

capable of only running one process at a time. In Section 5.5 we discuss CPU scheduling in the context of multiprocessor systems.

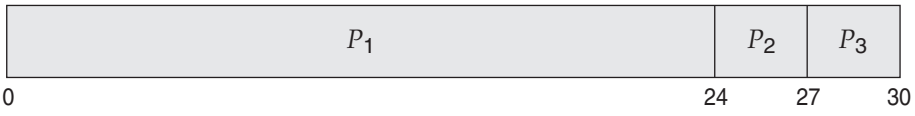
5.3.1 First-Come, First-Served Scheduling

By far the simplest CPU-scheduling algorithm is the **first-come first-serve** (**FCFS**) scheduling algorithm. With this scheme, the process that requests the CPU first is allocated the CPU first. The implementation of the FCFS policy is easily managed with a FIFO queue. When a process enters the ready queue, its PCB is linked onto the tail of the queue. When the CPU is free, it is allocated to the process at the head of the queue. The running process is then removed from the queue. The code for FCFS scheduling is simple to write and understand.

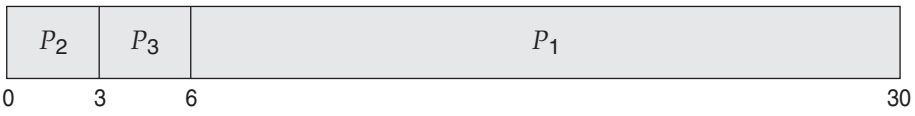
On the negative side, the average waiting time under the FCFS policy is often quite long. Consider the following set of processes that arrive at time 0, with the length of the CPU burst given in milliseconds:

Process	Burst Time
P_1	24
P_2	3
P_3	3

If the processes arrive in the order P_1, P_2, P_3, and are served in FCFS order, we get the result shown in the following **Gantt chart**, which is a bar chart that illustrates a particular schedule, including the start and finish times of each of the participating processes:



The waiting time is 0 milliseconds for process P_1, 24 milliseconds for process P_2, and 27 milliseconds for process P_3. Thus, the average waiting time is (0 + 24 + 27)/3 = 17 milliseconds. If the processes arrive in the order P_2, P_3, P_1, however, the results will be as shown in the following Gantt chart:



The average waiting time is now (6 + 0 + 3)/3 = 3 milliseconds. This reduction is substantial. Thus, the average waiting time under an FCFS policy is generally not minimal and may vary substantially if the processes' CPU burst times vary greatly.

In addition, consider the performance of FCFS scheduling in a dynamic situation. Assume we have one CPU-bound process and many I/O-bound processes. As the processes flow around the system, the following scenario may result. The CPU-bound process will get and hold the CPU. During this time, all the other processes will finish their I/O and will move into the ready queue, waiting for the CPU. While the processes wait in the ready queue, the I/O

devices are idle. Eventually, the CPU-bound process finishes its CPU burst and moves to an I/O device. All the I/O-bound processes, which have short CPU bursts, execute quickly and move back to the I/O queues. At this point, the CPU sits idle. The CPU-bound process will then move back to the ready queue and be allocated the CPU. Again, all the I/O processes end up waiting in the ready queue until the CPU-bound process is done. There is a **convoy effect** as all the other processes wait for the one big process to get off the CPU. This effect results in lower CPU and device utilization than might be possible if the shorter processes were allowed to go first.

Note also that the FCFS scheduling algorithm is nonpreemptive. Once the CPU has been allocated to a process, that process keeps the CPU until it releases the CPU, either by terminating or by requesting I/O. The FCFS algorithm is thus particularly troublesome for interactive systems, where it is important that each process get a share of the CPU at regular intervals. It would be disastrous to allow one process to keep the CPU for an extended period.

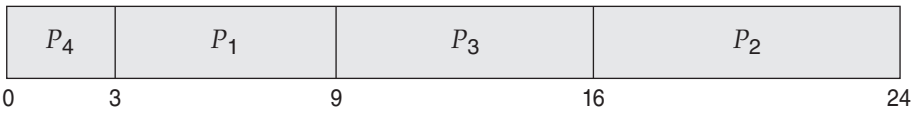
5.3.2 Shortest-Job-First Scheduling

A different approach to CPU scheduling is the **shortest-job-firs** (**SJF**) scheduling algorithm. This algorithm associates with each process the length of the process's next CPU burst. When the CPU is available, it is assigned to the process that has the smallest next CPU burst. If the next CPU bursts of two processes are the same, FCFS scheduling is used to break the tie. Note that a more appropriate term for this scheduling method would be the ***shortest-next-CPU-burst*** algorithm, because scheduling depends on the length of the next CPU burst of a process, rather than its total length. We use the term SJF because most people and textbooks use this term to refer to this type of scheduling.

As an example of SJF scheduling, consider the following set of processes, with the length of the CPU burst given in milliseconds:

Process	Burst Time
P_1	6
P_2	8
P_3	7
P_4	3

Using SJF scheduling, we would schedule these processes according to the following Gantt chart:



The waiting time is 3 milliseconds for process P_1, 16 milliseconds for process P_2, 9 milliseconds for process P_3, and 0 milliseconds for process P_4. Thus, the average waiting time is (3 + 16 + 9 + 0)/4 = 7 milliseconds. By comparison, if we were using the FCFS scheduling scheme, the average waiting time would be 10.25 milliseconds.

The SJF scheduling algorithm is provably optimal, in that it gives the minimum average waiting time for a given set of processes. Moving a short process

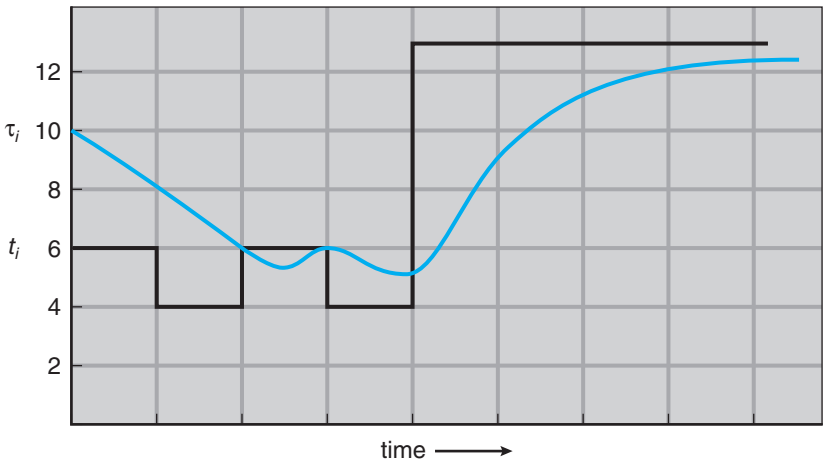
before a long one decreases the waiting time of the short process more than it increases the waiting time of the long process. Consequently, the average waiting time decreases.

Although the SJF algorithm is optimal, it cannot be implemented at the level of CPU scheduling, as there is no way to know the length of the next CPU burst. One approach to this problem is to try to approximate SJF scheduling. We may not know the length of the next CPU burst, but we may be able to predict its value. We expect that the next CPU burst will be similar in length to the previous ones. By computing an approximation of the length of the next CPU burst, we can pick the process with the shortest predicted CPU burst.

The next CPU burst is generally predicted as an **exponential average** of the measured lengths of previous CPU bursts. We can define the exponential average with the following formula. Let t_n be the length of the nth CPU burst, and let τ_{n+1} be our predicted value for the next CPU burst. Then, for α, $0 \leq \alpha \leq 1$, define

$$\tau_{n+1} = \alpha\, t_n + (1 - \alpha)\tau_n.$$

The value of t_n contains our most recent information, while τ_n stores the past history. The parameter α controls the relative weight of recent and past history in our prediction. If $\alpha = 0$, then $\tau_{n+1} = \tau_n$, and recent history has no effect (current conditions are assumed to be transient). If $\alpha = 1$, then $\tau_{n+1} = t_n$, and only the most recent CPU burst matters (history is assumed to be old and irrelevant). More commonly, $\alpha = 1/2$, so recent history and past history are equally weighted. The initial τ_0 can be defined as a constant or as an overall system average. Figure 5.4 shows an exponential average with $\alpha = 1/2$ and $\tau_0 = 10$.



CPU burst (t_i)	6	4	6	4	13	13	13	...
"guess" (τ_i)	10	8	6	6	5	9	11	12	...

Figure 5.4 Prediction of the length of the next CPU burst.

To understand the behavior of the exponential average, we can expand the formula for τ_{n+1} by substituting for τ_n to find

$$\tau_{n+1} = \alpha t_n + (1 - \alpha)\alpha t_{n-1} + \cdots + (1 - \alpha)^j \alpha t_{n-j} + \cdots + (1 - \alpha)^{n+1} \tau_0.$$

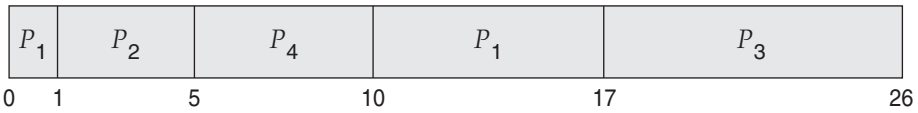
Typically, α is less than 1. As a result, $(1 - \alpha)$ is also less than 1, and each successive term has less weight than its predecessor.

The SJF algorithm can be either preemptive or nonpreemptive. The choice arises when a new process arrives at the ready queue while a previous process is still executing. The next CPU burst of the newly arrived process may be shorter than what is left of the currently executing process. A preemptive SJF algorithm will preempt the currently executing process, whereas a nonpreemptive SJF algorithm will allow the currently running process to finish its CPU burst. Preemptive SJF scheduling is sometimes called **shortest-remaining-time-firs** scheduling.

As an example, consider the following four processes, with the length of the CPU burst given in milliseconds:

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

If the processes arrive at the ready queue at the times shown and need the indicated burst times, then the resulting preemptive SJF schedule is as depicted in the following Gantt chart:



Process P_1 is started at time 0, since it is the only process in the queue. Process P_2 arrives at time 1. The remaining time for process P_1 (7 milliseconds) is larger than the time required by process P_2 (4 milliseconds), so process P_1 is preempted, and process P_2 is scheduled. The average waiting time for this example is $[(10 - 1) + (1 - 1) + (17 - 2) + (5 - 3)]/4 = 26/4 = 6.5$ milliseconds. Nonpreemptive SJF scheduling would result in an average waiting time of 7.75 milliseconds.

5.3.3 Round-Robin Scheduling

The **round-robin** (RR) scheduling algorithm is similar to FCFS scheduling, but preemption is added to enable the system to switch between processes. A small unit of time, called a **time quantum** or **time slice**, is defined. A time quantum is generally from 10 to 100 milliseconds in length. The ready queue is treated as a circular queue. The CPU scheduler goes around the ready queue, allocating the CPU to each process for a time interval of up to 1 time quantum.

To implement RR scheduling, we again treat the ready queue as a FIFO queue of processes. New processes are added to the tail of the ready queue.

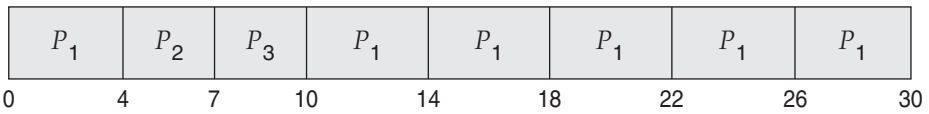
The CPU scheduler picks the first process from the ready queue, sets a timer to interrupt after 1 time quantum, and dispatches the process.

One of two things will then happen. The process may have a CPU burst of less than 1 time quantum. In this case, the process itself will release the CPU voluntarily. The scheduler will then proceed to the next process in the ready queue. If the CPU burst of the currently running process is longer than 1 time quantum, the timer will go off and will cause an interrupt to the operating system. A context switch will be executed, and the process will be put at the tail of the ready queue. The CPU scheduler will then select the next process in the ready queue.

The average waiting time under the RR policy is often long. Consider the following set of processes that arrive at time 0, with the length of the CPU burst given in milliseconds:

Process	Burst Time
P_1	24
P_2	3
P_3	3

If we use a time quantum of 4 milliseconds, then process P_1 gets the first 4 milliseconds. Since it requires another 20 milliseconds, it is preempted after the first time quantum, and the CPU is given to the next process in the queue, process P_2. Process P_2 does not need 4 milliseconds, so it quits before its time quantum expires. The CPU is then given to the next process, process P_3. Once each process has received 1 time quantum, the CPU is returned to process P_1 for an additional time quantum. The resulting RR schedule is as follows:



Let's calculate the average waiting time for this schedule. P_1 waits for 6 milliseconds ($10 - 4$), P_2 waits for 4 milliseconds, and P_3 waits for 7 milliseconds. Thus, the average waiting time is $17/3 = 5.66$ milliseconds.

In the RR scheduling algorithm, no process is allocated the CPU for more than 1 time quantum in a row (unless it is the only runnable process). If a process's CPU burst exceeds 1 time quantum, that process is preempted and is put back in the ready queue. The RR scheduling algorithm is thus preemptive.

If there are n processes in the ready queue and the time quantum is q, then each process gets $1/n$ of the CPU time in chunks of at most q time units. Each process must wait no longer than $(n - 1) \times q$ time units until its next time quantum. For example, with five processes and a time quantum of 20 milliseconds, each process will get up to 20 milliseconds every 100 milliseconds.

The performance of the RR algorithm depends heavily on the size of the time quantum. At one extreme, if the time quantum is extremely large, the RR policy is the same as the FCFS policy. In contrast, if the time quantum is extremely small (say, 1 millisecond), the RR approach can result in a large

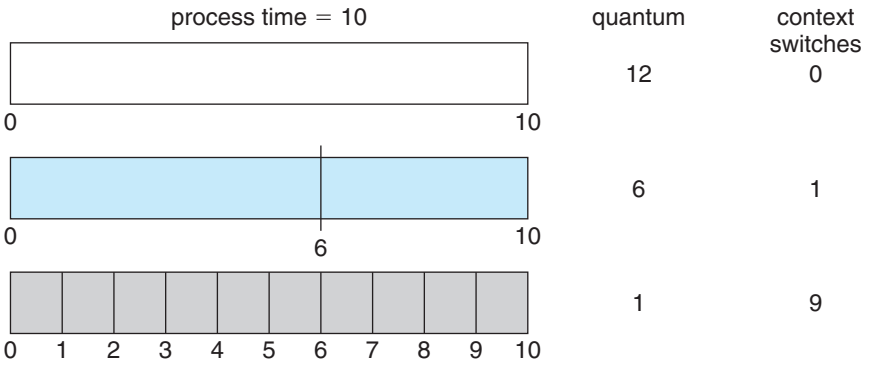


Figure 5.5 How a smaller time quantum increases context switches.

number of context switches. Assume, for example, that we have only one process of 10 time units. If the quantum is 12 time units, the process finishes in less than 1 time quantum, with no overhead. If the quantum is 6 time units, however, the process requires 2 quanta, resulting in a context switch. If the time quantum is 1 time unit, then nine context switches will occur, slowing the execution of the process accordingly (Figure 5.5).

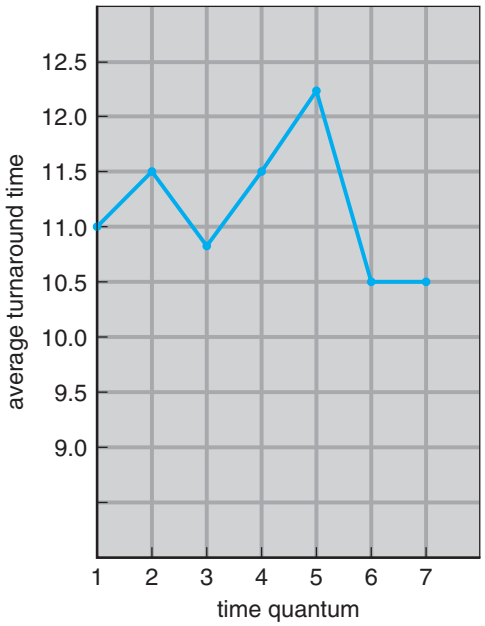
Thus, we want the time quantum to be large with respect to the context-switch time. If the context-switch time is approximately 10 percent of the time quantum, then about 10 percent of the CPU time will be spent in context switching. In practice, most modern systems have time quanta ranging from 10 to 100 milliseconds. The time required for a context switch is typically less than 10 microseconds; thus, the context-switch time is a small fraction of the time quantum.

Turnaround time also depends on the size of the time quantum. As we can see from Figure 5.6, the average turnaround time of a set of processes does not necessarily improve as the time-quantum size increases. In general, the average turnaround time can be improved if most processes finish their next CPU burst in a single time quantum. For example, given three processes of 10 time units each and a quantum of 1 time unit, the average turnaround time is 29. If the time quantum is 10, however, the average turnaround time drops to 20. If context-switch time is added in, the average turnaround time increases even more for a smaller time quantum, since more context switches are required.

Although the time quantum should be large compared with the context-switch time, it should not be too large. As we pointed out earlier, if the time quantum is too large, RR scheduling degenerates to an FCFS policy. A rule of thumb is that 80 percent of the CPU bursts should be shorter than the time quantum.

5.3.4 Priority Scheduling

The SJF algorithm is a special case of the general **priority-scheduling** algorithm. A priority is associated with each process, and the CPU is allocated to the



process	time
P_1	6
P_2	3
P_3	1
P_4	7

Figure 5.6 How turnaround time varies with the time quantum.

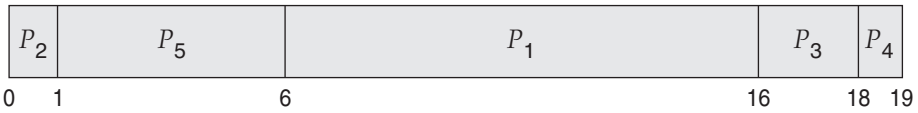
process with the highest priority. Equal-priority processes are scheduled in FCFS order. An SJF algorithm is simply a priority algorithm where the priority (p) is the inverse of the (predicted) next CPU burst. The larger the CPU burst, the lower the priority, and vice versa.

Note that we discuss scheduling in terms of ***high*** priority and ***low*** priority. Priorities are generally indicated by some fixed range of numbers, such as 0 to 7 or 0 to 4,095. However, there is no general agreement on whether 0 is the highest or lowest priority. Some systems use low numbers to represent low priority; others use low numbers for high priority. This difference can lead to confusion. In this text, we assume that low numbers represent high priority.

As an example, consider the following set of processes, assumed to have arrived at time 0 in the order $P_1, P_2, \cdots, P_5$, with the length of the CPU burst given in milliseconds:

Process	Burst Time	Priority
P_1	10	3
P_2	1	1
P_3	2	4
P_4	1	5
P_5	5	2

Using priority scheduling, we would schedule these processes according to the following Gantt chart:



The average waiting time is 8.2 milliseconds.

Priorities can be defined either internally or externally. Internally defined priorities use some measurable quantity or quantities to compute the priority of a process. For example, time limits, memory requirements, the number of open files, and the ratio of average I/O burst to average CPU burst have been used in computing priorities. External priorities are set by criteria outside the operating system, such as the importance of the process, the type and amount of funds being paid for computer use, the department sponsoring the work, and other, often political, factors.

Priority scheduling can be either preemptive or nonpreemptive. When a process arrives at the ready queue, its priority is compared with the priority of the currently running process. A preemptive priority scheduling algorithm will preempt the CPU if the priority of the newly arrived process is higher than the priority of the currently running process. A nonpreemptive priority scheduling algorithm will simply put the new process at the head of the ready queue.

A major problem with priority scheduling algorithms is **indefinit blocking**, or **starvation**. A process that is ready to run but waiting for the CPU can be considered blocked. A priority scheduling algorithm can leave some low-priority processes waiting indefinitely. In a heavily loaded computer system, a steady stream of higher-priority processes can prevent a low-priority process from ever getting the CPU. Generally, one of two things will happen. Either the process will eventually be run (at 2 A.M. Sunday, when the system is finally lightly loaded), or the computer system will eventually crash and lose all unfinished low-priority processes. (Rumor has it that when they shut down the IBM 7094 at MIT in 1973, they found a low-priority process that had been submitted in 1967 and had not yet been run.)

A solution to the problem of indefinite blockage of low-priority processes is **aging**. Aging involves gradually increasing the priority of processes that wait in the system for a long time. For example, if priorities range from 127 (low) to 0 (high), we could periodically (say, every second) increase the priority of a waiting process by 1. Eventually, even a process with an initial priority of 127 would have the highest priority in the system and would be executed. In fact, it would take a little over 2 minutes for a priority-127 process to age to a priority-0 process.

Another option is to combine round-robin and priority scheduling in such a way that the system executes the highest-priority process and runs processes with the same priority using round-robin scheduling. Let's illustrate with an example using the following set of processes, with the burst time in milliseconds:

Process	Burst Time	Priority
P_1	4	3
P_2	5	2
P_3	8	2
P_4	7	1
P_5	3	3

Using priority scheduling with round-robin for processes with equal priority, we would schedule these processes according to the following Gantt chart using a time quantum of 2 milliseconds:

In this example, process P_4 has the highest priority, so it will run to completion. Processes P_2 and P_3 have the next-highest priority, and they will execute in a round-robin fashion. Notice that when process P_2 finishes at time 16, process P_3 is the highest-priority process, so it will run until it completes execution. Now, only processes P_1 and P_5 remain, and as they have equal priority, they will execute in round-robin order until they complete.

5.3.5 Multilevel Queue Scheduling

With both priority and round-robin scheduling, all processes may be placed in a single queue, and the scheduler then selects the process with the highest priority to run. Depending on how the queues are managed, an $O(n)$ search may be necessary to determine the highest-priority process. In practice, it is often easier to have separate queues for each distinct priority, and priority scheduling simply schedules the process in the highest-priority queue. This is illustrated in Figure 5.7. This approach—known as **multilevel queue**—also works well when priority scheduling is combined with round-robin: if there are multiple processes in the highest-priority queue, they are executed in round-robin order. In the most generalized form of this approach, a priority is assigned statically to each process, and a process remains in the same queue for the duration of its runtime.

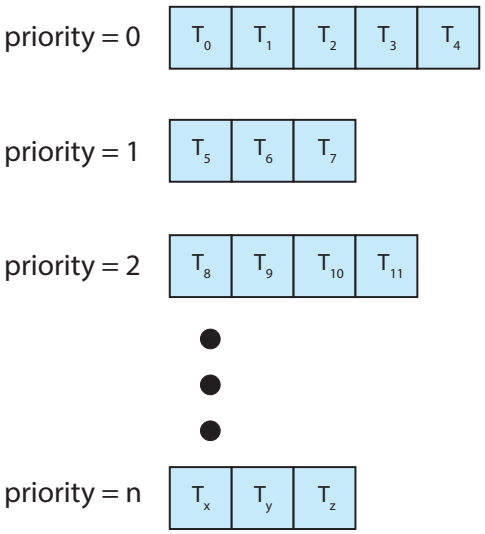


Figure 5.7 Separate queues for each priority.

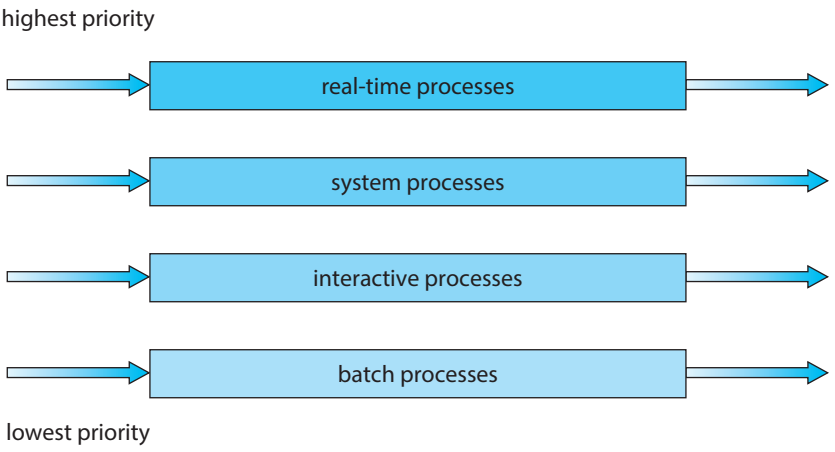


Figure 5.8 Multilevel queue scheduling.

A multilevel queue scheduling algorithm can also be used to partition processes into several separate queues based on the process type (Figure 5.8). For example, a common division is made between **foreground** (interactive) processes and **background** (batch) processes. These two types of processes have different response-time requirements and so may have different scheduling needs. In addition, foreground processes may have priority (externally defined) over background processes. Separate queues might be used for foreground and background processes, and each queue might have its own scheduling algorithm. The foreground queue might be scheduled by an RR algorithm, for example, while the background queue is scheduled by an FCFS algorithm.

In addition, there must be scheduling among the queues, which is commonly implemented as fixed-priority preemptive scheduling. For example, the real-time queue may have absolute priority over the interactive queue.

Let's look at an example of a multilevel queue scheduling algorithm with four queues, listed below in order of priority:

1. Real-time processes
2. System processes
3. Interactive processes
4. Batch processes

Each queue has absolute priority over lower-priority queues. No process in the batch queue, for example, could run unless the queues for real-time processes, system processes, and interactive processes were all empty. If an interactive process entered the ready queue while a batch process was running, the batch process would be preempted.

Another possibility is to time-slice among the queues. Here, each queue gets a certain portion of the CPU time, which it can then schedule among its various processes. For instance, in the foreground–background queue example, the foreground queue can be given 80 percent of the CPU time for RR scheduling

among its processes, while the background queue receives 20 percent of the CPU to give to its processes on an FCFS basis.

5.3.6 Multilevel Feedback Queue Scheduling

Normally, when the multilevel queue scheduling algorithm is used, processes are permanently assigned to a queue when they enter the system. If there are separate queues for foreground and background processes, for example, processes do not move from one queue to the other, since processes do not change their foreground or background nature. This setup has the advantage of low scheduling overhead, but it is inflexible.

The **multilevel feedback queue** scheduling algorithm, in contrast, allows a process to move between queues. The idea is to separate processes according to the characteristics of their CPU bursts. If a process uses too much CPU time, it will be moved to a lower-priority queue. This scheme leaves I/O-bound and interactive processes—which are typically characterized by short CPU bursts—in the higher-priority queues. In addition, a process that waits too long in a lower-priority queue may be moved to a higher-priority queue. This form of aging prevents starvation.

For example, consider a multilevel feedback queue scheduler with three queues, numbered from 0 to 2 (Figure 5.9). The scheduler first executes all processes in queue 0. Only when queue 0 is empty will it execute processes in queue 1. Similarly, processes in queue 2 will be executed only if queues 0 and 1 are empty. A process that arrives for queue 1 will preempt a process in queue 2. A process in queue 1 will in turn be preempted by a process arriving for queue 0.

An entering process is put in queue 0. A process in queue 0 is given a time quantum of 8 milliseconds. If it does not finish within this time, it is moved to the tail of queue 1. If queue 0 is empty, the process at the head of queue 1 is given a quantum of 16 milliseconds. If it does not complete, it is preempted and is put into queue 2. Processes in queue 2 are run on an FCFS basis but are run only when queues 0 and 1 are empty. To prevent starvation, a process that waits too long in a lower-priority queue may gradually be moved to a higher-priority queue.

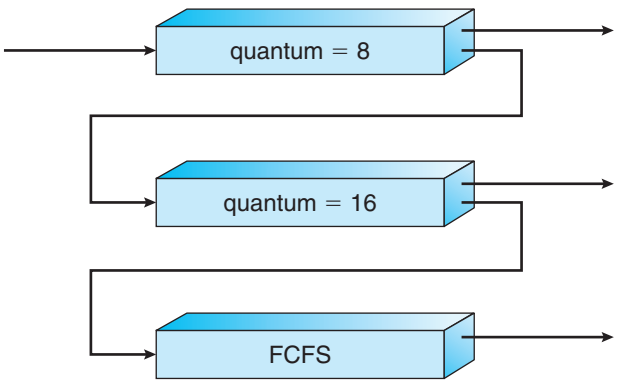


Figure 5.9 Multilevel feedback queues.

This scheduling algorithm gives highest priority to any process with a CPU burst of 8 milliseconds or less. Such a process will quickly get the CPU, finish its CPU burst, and go off to its next I/O burst. Processes that need more than 8 but less than 24 milliseconds are also served quickly, although with lower priority than shorter processes. Long processes automatically sink to queue 2 and are served in FCFS order with any CPU cycles left over from queues 0 and 1.

In general, a multilevel feedback queue scheduler is defined by the following parameters:

- The number of queues
- The scheduling algorithm for each queue
- The method used to determine when to upgrade a process to a higher-priority queue
- The method used to determine when to demote a process to a lower-priority queue
- The method used to determine which queue a process will enter when that process needs service

The definition of a multilevel feedback queue scheduler makes it the most general CPU-scheduling algorithm. It can be configured to match a specific system under design. Unfortunately, it is also the most complex algorithm, since defining the best scheduler requires some means by which to select values for all the parameters.

5.4 Thread Scheduling

In Chapter 4, we introduced threads to the process model, distinguishing between ***user-level*** and ***kernel-level*** threads. On most modern operating systems it is kernel-level threads—not processes—that are being scheduled by the operating system. User-level threads are managed by a thread library, and the kernel is unaware of them. To run on a CPU, user-level threads must ultimately be mapped to an associated kernel-level thread, although this mapping may be indirect and may use a lightweight process (LWP). In this section, we explore scheduling issues involving user-level and kernel-level threads and offer specific examples of scheduling for Pthreads.

5.4.1 Contention Scope

One distinction between user-level and kernel-level threads lies in how they are scheduled. On systems implementing the many-to-one (Section 4.3.1) and many-to-many (Section 4.3.3) models, the thread library schedules user-level threads to run on an available LWP. This scheme is known as **process-contention scope** (**PCS**), since competition for the CPU takes place among threads belonging to the same process. (When we say the thread library *schedules* user threads onto available LWPs, we do not mean that the threads are actually *running* on a CPU as that further requires the operating system to schedule the LWP's kernel thread onto a physical CPU core.) To decide which

kernel-level thread to schedule onto a CPU, the kernel uses **system-contention scope** (**SCS**). Competition for the CPU with SCS scheduling takes place among all threads in the system. Systems using the one-to-one model (Section 4.3.2), such as Windows and Linux schedule threads using only SCS.

Typically, PCS is done according to priority—the scheduler selects the runnable thread with the highest priority to run. User-level thread priorities are set by the programmer and are not adjusted by the thread library, although some thread libraries may allow the programmer to change the priority of a thread. It is important to note that PCS will typically preempt the thread currently running in favor of a higher-priority thread; however, there is no guarantee of time slicing (Section 5.3.3) among threads of equal priority.

5.4.2 Pthread Scheduling

We provided a sample POSIX Pthread program in Section 4.4.1, along with an introduction to thread creation with Pthreads. Now, we highlight the POSIX Pthread API that allows specifying PCS or SCS during thread creation. Pthreads identifies the following contention scope values:

- PTHREAD_SCOPE_PROCESS schedules threads using PCS scheduling.
- PTHREAD_SCOPE_SYSTEM schedules threads using SCS scheduling.

On systems implementing the many-to-many model, the PTHREAD_SCOPE_PROCESS policy schedules user-level threads onto available LWPs. The number of LWPs is maintained by the thread library, perhaps using scheduler activations (Section 4.6.5). The PTHREAD_SCOPE_SYSTEM scheduling policy will create and bind an LWP for each user-level thread on many-to-many systems, effectively mapping threads using the one-to-one policy.

The Pthread IPC (Interprocess Communication) provides two functions for setting—and getting—the contention scope policy:

- `pthread_attr_setscope(pthread_attr_t *attr, int scope)`
- `pthread_attr_getscope(pthread_attr_t *attr, int *scope)`

The first parameter for both functions contains a pointer to the attribute set for the thread. The second parameter for the `pthread_attr_setscope()` function is passed either the PTHREAD_SCOPE_SYSTEM or the PTHREAD_SCOPE_PROCESS value, indicating how the contention scope is to be set. In the case of `pthread_attr_getscope()`, this second parameter contains a pointer to an `int` value that is set to the current value of the contention scope. If an error occurs, each of these functions returns a nonzero value.

In Figure 5.10, we illustrate a Pthread scheduling API. The program first determines the existing contention scope and sets it to PTHREAD_SCOPE_SYSTEM. It then creates five separate threads that will run using the SCS scheduling policy. Note that on some systems, only certain contention scope values are allowed. For example, Linux and macOS systems allow only PTHREAD_SCOPE_SYSTEM.

```
#include <pthread.h>
#include <stdio.h>
#define NUM_THREADS 5

int main(int argc, char *argv[])
{
   int i, scope;
   pthread_t tid[NUM_THREADS];
   pthread_attr_t attr;

   /* get the default attributes */
   pthread_attr_init(&attr);

   /* first inquire on the current scope */
   if (pthread_attr_getscope(&attr, &scope) != 0)
      fprintf(stderr, "Unable to get scheduling scope\n");
   else {
      if (scope == PTHREAD_SCOPE_PROCESS)
       printf("PTHREAD_SCOPE_PROCESS");
      else if (scope == PTHREAD_SCOPE_SYSTEM)
       printf("PTHREAD_SCOPE_SYSTEM");
      else
       fprintf(stderr, "Illegal scope value.\n");
    }

   /* set the scheduling algorithm to PCS or SCS */
   pthread_attr_setscope(&attr, PTHREAD_SCOPE_SYSTEM);

   /* create the threads */
   for (i = 0; i < NUM_THREADS; i++)
       pthread_create(&tid[i],&attr,runner,NULL);

   /* now join on each thread */
   for (i = 0; i < NUM_THREADS; i++)
       pthread_join(tid[i], NULL);
}

/* Each thread will begin control in this function */
void *runner(void *param)
{
   /* do some work ... */

   pthread_exit(0);
}
```

Figure 5.10 Pthread scheduling API.

5.5 Multi-Processor Scheduling

Our discussion thus far has focused on the problems of scheduling the CPU in a system with a single processing core. If multiple CPUs are available, **load sharing**, where multiple threads may run in parallel, becomes possible, however scheduling issues become correspondingly more complex. Many possibilities have been tried; and as we saw with CPU scheduling with a single-core CPU, there is no one best solution.

Traditionally, the term **multiprocessor** referred to systems that provided multiple physical processors, where each processor contained one single-core CPU. However, the definition of multiprocessor has evolved significantly, and on modern computing systems, ***multiprocessor*** now applies to the following system architectures:

- Multicore CPUs
- Multithreaded cores
- NUMA systems
- Heterogeneous multiprocessing

Here, we discuss several concerns in multiprocessor scheduling in the context of these different architectures. In the first three examples we concentrate on systems in which the processors are identical—homogeneous—in terms of their functionality. We can then use any available CPU to run any process in the queue. In the last example we explore a system where the processors are not identical in their capabilities.

5.5.1 Approaches to Multiple-Processor Scheduling

One approach to CPU scheduling in a multiprocessor system has all scheduling decisions, I/O processing, and other system activities handled by a single processor — the master server. The other processors execute only user code. This **asymmetric multiprocessing** is simple because only one core accesses the system data structures, reducing the need for data sharing. The downfall of this approach is the master server becomes a potential bottleneck where overall system performance may be reduced.

The standard approach for supporting multiprocessors is **symmetric multiprocessing** (**SMP**), where each processor is self-scheduling. Scheduling proceeds by having the scheduler for each processor examine the ready queue and select a thread to run. Note that this provides two possible strategies for organizing the threads eligible to be scheduled:

1. All threads may be in a common ready queue.
2. Each processor may have its own private queue of threads.

These two strategies are contrasted in Figure 5.11. If we select the first option, we have a possible race condition on the shared ready queue and therefore must ensure that two separate processors do not choose to schedule the same thread and that threads are not lost from the queue. As discussed in

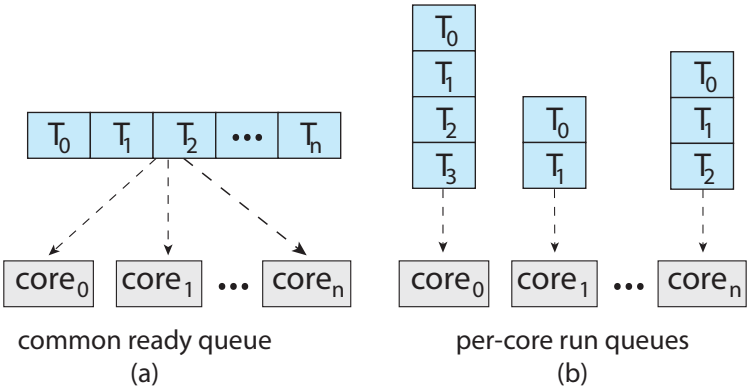


Figure 5.11 Organization of ready queues.

Chapter 6, we could use some form of locking to protect the common ready queue from this race condition. Locking would be highly contended, however, as all accesses to the queue would require lock ownership, and accessing the shared queue would likely be a performance bottleneck. The second option permits each processor to schedule threads from its private run queue and therefore does not suffer from the possible performance problems associated with a shared run queue. Thus, it is the most common approach on systems supporting SMP. Additionally, as described in Section 5.5.4, having private, per-processor run queues in fact may lead to more efficient use of cache memory. There are issues with per-processor run queues—most notably, workloads of varying sizes. However, as we shall see, balancing algorithms can be used to equalize workloads among all processors.

Virtually all modern operating systems support SMP, including Windows, Linux, and macOS as well as mobile systems including Android and iOS. In the remainder of this section, we discuss issues concerning SMP systems when designing CPU scheduling algorithms.

5.5.2 Multicore Processors

Traditionally, SMP systems have allowed several processes to run in parallel by providing multiple physical processors. However, most contemporary computer hardware now places multiple computing cores on the same physical chip, resulting in a **multicore processor**. Each core maintains its architectural state and thus appears to the operating system to be a separate logical CPU. SMP systems that use multicore processors are faster and consume less power than systems in which each CPU has its own physical chip.

Multicore processors may complicate scheduling issues. Let's consider how this can happen. Researchers have discovered that when a processor accesses memory, it spends a significant amount of time waiting for the data to become available. This situation, known as a **memory stall**, occurs primarily because modern processors operate at much faster speeds than memory. However, a memory stall can also occur because of a cache miss (accessing data that are not in cache memory). Figure 5.12 illustrates a memory stall. In this scenario, the processor can spend up to 50 percent of its time waiting for data to become available from memory.

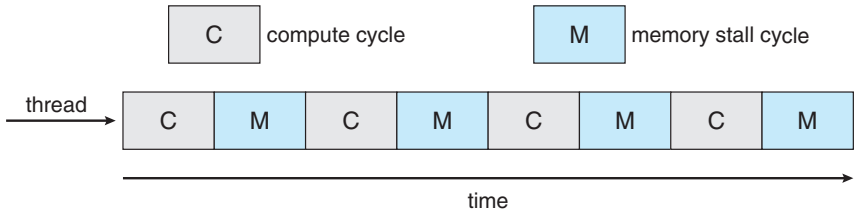


Figure 5.12 Memory stall.

To remedy this situation, many recent hardware designs have implemented multithreaded processing cores in which two (or more) **hardware threads** are assigned to each core. That way, if one hardware thread stalls while waiting for memory, the core can switch to another thread. Figure 5.13 illustrates a dual-threaded processing core on which the execution of thread 0 and the execution of thread 1 are interleaved. From an operating system perspective, each hardware thread maintains its architectural state, such as instruction pointer and register set, and thus appears as a logical CPU that is available to run a software thread. This technique—known as **chip multithreading** (CMT)—is illustrated in Figure 5.14. Here, the processor contains four computing cores, with each core containing two hardware threads. From the perspective of the operating system, there are eight logical CPUs.

Intel processors use the term **hyper-threading** (also known as **simultaneous multithreading** or SMT) to describe assigning multiple hardware threads to a single processing core. Contemporary Intel processors—such as the i7—support two threads per core, while the Oracle Sparc M7 processor supports eight threads per core, with eight cores per processor, thus providing the operating system with 64 logical CPUs.

In general, there are two ways to multithread a processing core: **coarse-grained** and **fine-graine** multithreading. With coarse-grained multithreading, a thread executes on a core until a long-latency event such as a memory stall occurs. Because of the delay caused by the long-latency event, the core must switch to another thread to begin execution. However, the cost of switching between threads is high, since the instruction pipeline must be flushed before the other thread can begin execution on the processor core. Once this new thread begins execution, it begins filling the pipeline with its instructions. Fine-grained (or interleaved) multithreading switches between threads at a much finer level of granularity—typically at the boundary of an instruction

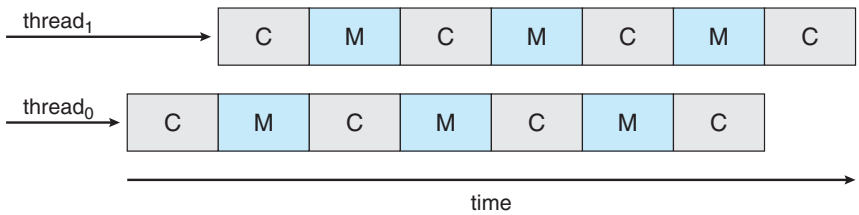


Figure 5.13 Multithreaded multicore system.

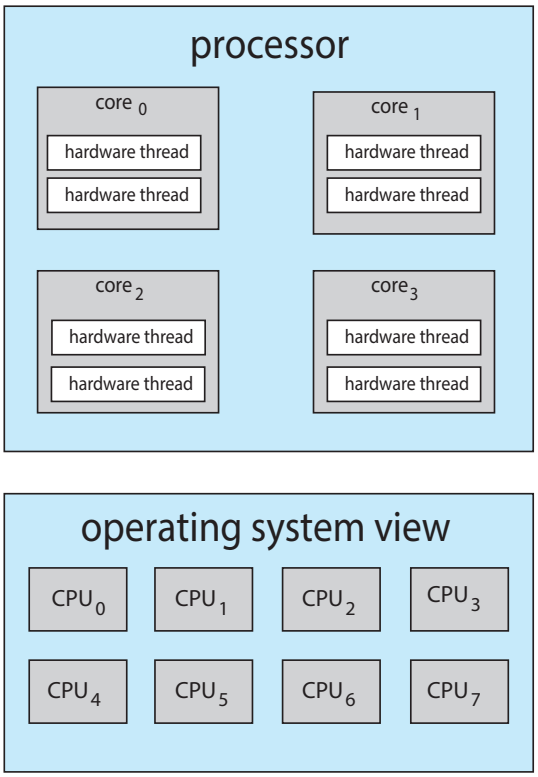


Figure 5.14 Chip multithreading.

cycle. However, the architectural design of fine-grained systems includes logic for thread switching. As a result, the cost of switching between threads is small.

It is important to note that the resources of the physical core (such as caches and pipelines) must be shared among its hardware threads, and therefore a processing core can only execute one hardware thread at a time. Consequently, a multithreaded, multicore processor actually requires two different levels of scheduling, as shown in Figure 5.15, which illustrates a dual-threaded processing core.

On one level are the scheduling decisions that must be made by the operating system as it chooses which software thread to run on each hardware thread (logical CPU). For all practical purposes, such decisions have been the primary focus of this chapter. Therefore, for this level of scheduling, the operating system may choose any scheduling algorithm, including those described in Section 5.3.

A second level of scheduling specifies how each core decides which hardware thread to run. There are several strategies to adopt in this situation. One approach is to use a simple round-robin algorithm to schedule a hardware thread to the processing core. This is the approach adopted by the UltraSPARC T3. Another approach is used by the Intel Itanium, a dual-core processor with two hardware-managed threads per core. Assigned to each hardware thread is a dynamic ***urgency*** value ranging from 0 to 7, with 0 representing the lowest urgency and 7 the highest. The Itanium identifies five different events that may

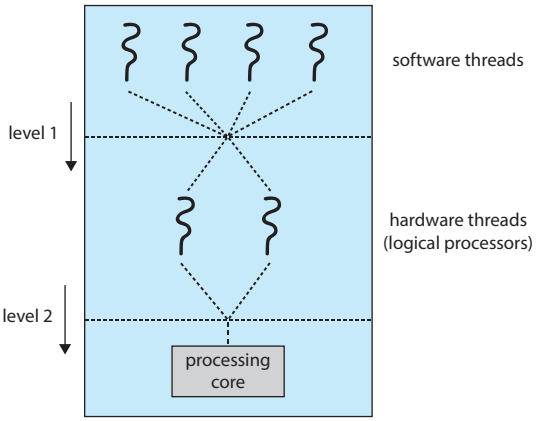


Figure 5.15 Two levels of scheduling.

trigger a thread switch. When one of these events occurs, the thread-switching logic compares the urgency of the two threads and selects the thread with the highest urgency value to execute on the processor core.

Note that the two different levels of scheduling shown in Figure 5.15 are not necessarily mutually exclusive. In fact, if the operating system scheduler (the first level) is made aware of the sharing of processor resources, it can make more effective scheduling decisions. As an example, assume that a CPU has two processing cores, and each core has two hardware threads. If two software threads are running on this system, they can be running either on the same core or on separate cores. If they are both scheduled to run on the same core, they have to share processor resources and thus are likely to proceed more slowly than if they were scheduled on separate cores. If the operating system is aware of the level of processor resource sharing, it can schedule software threads onto logical processors that do not share resources.

5.5.3 Load Balancing

On SMP systems, it is important to keep the workload balanced among all processors to fully utilize the benefits of having more than one processor. Otherwise, one or more processors may sit idle while other processors have high workloads, along with ready queues of threads awaiting the CPU. **Load balancing** attempts to keep the workload evenly distributed across all processors in an SMP system. It is important to note that load balancing is typically necessary only on systems where each processor has its own private ready queue of eligible threads to execute. On systems with a common run queue, load balancing is unnecessary, because once a processor becomes idle, it immediately extracts a runnable thread from the common ready queue.

There are two general approaches to load balancing: push migration and pull migration. With **push migration**, a specific task periodically checks the load on each processor and—if it finds an imbalance—evenly distributes the load by moving (or pushing) threads from overloaded to idle or less-busy processors. **Pull migration** occurs when an idle processor pulls a waiting task from a busy processor. Push and pull migration need not be mutually exclusive and are, in fact, often implemented in parallel on load-balancing systems. For

example, the Linux CFS scheduler (described in Section 5.7.1) and the ULE scheduler available for FreeBSD systems implement both techniques.

The concept of a "balanced load" may have different meanings. One view of a balanced load may require simply that all queues have approximately the same number of threads. Alternatively, balance may require an equal distribution of thread priorities across all queues. In addition, in certain situations, neither of these strategies may be sufficient. Indeed, they may work against the goals of the scheduling algorithm. (We leave further consideration of this as an exercise.)

5.5.4 Processor Affinity

Consider what happens to cache memory when a thread has been running on a specific processor. The data most recently accessed by the thread populate the cache for the processor. As a result, successive memory accesses by the thread are often satisfied in cache memory (known as a "warm cache"). Now consider what happens if the thread migrates to another processor—say, due to load balancing. The contents of cache memory must be invalidated for the first processor, and the cache for the second processor must be repopulated. Because of the high cost of invalidating and repopulating caches, most operating systems with SMP support try to avoid migrating a thread from one processor to another and instead attempt to keep a thread running on the same processor and take advantage of a warm cache. This is known as **processor affinit** —that is, a process has an affinity for the processor on which it is currently running.

The two strategies described in Section 5.5.1 for organizing the queue of threads available for scheduling have implications for processor affinity. If we adopt the approach of a common ready queue, a thread may be selected for execution by any processor. Thus, if a thread is scheduled on a new processor, that processor's cache must be repopulated. With private, per-processor ready queues, a thread is always scheduled on the same processor and can therefore benefit from the contents of a warm cache. Essentially, per-processor ready queues provide processor affinity for free!

Processor affinity takes several forms. When an operating system has a policy of attempting to keep a process running on the same processor—but not guaranteeing that it will do so—we have a situation known as **soft affinit** . Here, the operating system will attempt to keep a process on a single processor, but it is possible for a process to migrate between processors during load balancing. In contrast, some systems provide system calls that support **hard affinit** , thereby allowing a process to specify a subset of processors on which it can run. Many systems provide both soft and hard affinity. For example, Linux implements soft affinity, but it also provides the `sched_setaffinity()` system call, which supports hard affinity by allowing a thread to specify the set of CPUs on which it is eligible to run.

The main-memory architecture of a system can affect processor affinity issues as well. Figure 5.16 illustrates an architecture featuring non-uniform memory access (NUMA) where there are two physical processor chips each with their own CPU and local memory. Although a system interconnect allows all CPUs in a NUMA system to share one physical address space, a CPU has faster access to its local memory than to memory local to another CPU. If the operating system's CPU scheduler and memory-placement algorithms are ***NUMA-aware***

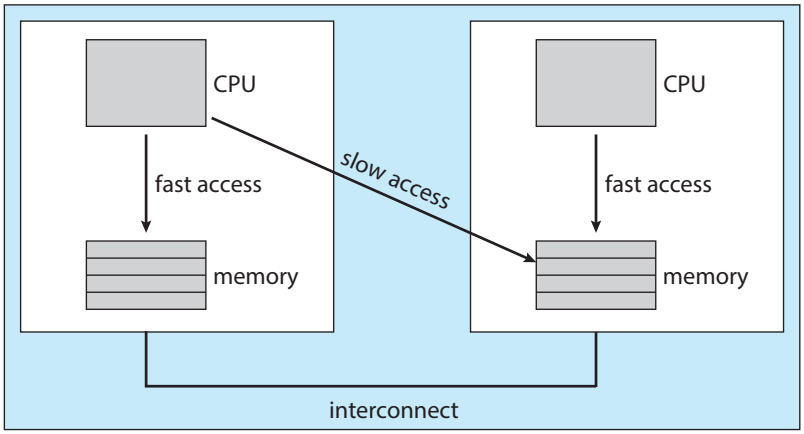


Figure 5.16 NUMA and CPU scheduling.

and work together, then a thread that has been scheduled onto a particular CPU can be allocated memory closest to where the CPU resides, thus providing the thread the fastest possible memory access.

Interestingly, load balancing often counteracts the benefits of processor affinity. That is, the benefit of keeping a thread running on the same processor is that the thread can take advantage of its data being in that processor's cache memory. Balancing loads by moving a thread from one processor to another removes this benefit. Similarly, migrating a thread between processors may incur a penalty on NUMA systems, where a thread may be moved to a processor that requires longer memory access times. In other words, there is a natural tension between load balancing and minimizing memory access times. Thus, scheduling algorithms for modern multicore NUMA systems have become quite complex. In Section 5.7.1, we examine the Linux CFS scheduling algorithm and explore how it balances these competing goals.

5.5.5 Heterogeneous Multiprocessing

In the examples we have discussed so far, all processors are identical in terms of their capabilities, thus allowing any thread to run on any processing core. The only difference being that memory access times may vary based upon load balancing and processor affinity policies, as well as on NUMA systems.

Although mobile systems now include multicore architectures, some systems are now designed using cores that run the same instruction set, yet vary in terms of their clock speed and power management, including the ability to adjust the power consumption of a core to the point of idling the core. Such systems are known as **heterogeneous multiprocessing** (HMP). Note this is not a form of asymmetric multiprocessing as described in Section 5.5.1 as both system and user tasks can run on any core. Rather, the intention behind HMP is to better manage power consumption by assigning tasks to certain cores based upon the specific demands of the task.

For ARM processors that support it, this type of architecture is known as **big.LITTLE** where higher-peformance ***big*** cores are combined with energy efficient ***LITTLE*** cores. ***Big*** cores consume greater energy and therefore should

only be used for short periods of time. Likewise, ***little*** cores use less energy and can therefore be used for longer periods.

There are several advantages to this approach. By combining a number of slower cores with faster ones, a CPU scheduler can assign tasks that do not require high performance, but may need to run for longer periods, (such as background tasks) to little cores, thereby helping to preserve a battery charge. Similarly, interactive applications which require more processing power, but may run for shorter durations, can be assigned to big cores. Additionally, if the mobile device is in a power-saving mode, energy-intensive big cores can be disabled and the system can rely solely on energy-efficient little cores. Windows 10 supports HMP scheduling by allowing a thread to select a scheduling policy that best supports its power management demands.

5.6 Real-Time CPU Scheduling

CPU scheduling for real-time operating systems involves special issues. In general, we can distinguish between soft real-time systems and hard real-time systems. **Soft real-time systems** provide no guarantee as to when a critical real-time process will be scheduled. They guarantee only that the process will be given preference over noncritical processes. **Hard real-time systems** have stricter requirements. A task must be serviced by its deadline; service after the deadline has expired is the same as no service at all. In this section, we explore several issues related to process scheduling in both soft and hard real-time operating systems.

5.6.1 Minimizing Latency

Consider the event-driven nature of a real-time system. The system is typically waiting for an event in real time to occur. Events may arise either in software —as when a timer expires—or in hardware—as when a remote-controlled vehicle detects that it is approaching an obstruction. When an event occurs, the system must respond to and service it as quickly as possible. We refer to **event latency** as the amount of time that elapses from when an event occurs to when it is serviced (Figure 5.17).

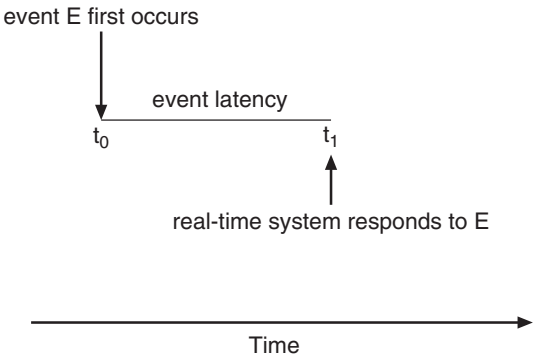


Figure 5.17 Event latency.

Usually, different events have different latency requirements. For example, the latency requirement for an antilock brake system might be 3 to 5 milliseconds. That is, from the time a wheel first detects that it is sliding, the system controlling the antilock brakes has 3 to 5 milliseconds to respond to and control the situation. Any response that takes longer might result in the automobile's veering out of control. In contrast, an embedded system controlling radar in an airliner might tolerate a latency period of several seconds.

Two types of latencies affect the performance of real-time systems:

1. Interrupt latency
2. Dispatch latency

Interrupt latency refers to the period of time from the arrival of an interrupt at the CPU to the start of the routine that services the interrupt. When an interrupt occurs, the operating system must first complete the instruction it is executing and determine the type of interrupt that occurred. It must then save the state of the current process before servicing the interrupt using the specific interrupt service routine (ISR). The total time required to perform these tasks is the interrupt latency (Figure 5.18).

Obviously, it is crucial for real-time operating systems to minimize interrupt latency to ensure that real-time tasks receive immediate attention. Indeed, for hard real-time systems, interrupt latency must not simply be minimized, it must be bounded to meet the strict requirements of these systems.

One important factor contributing to interrupt latency is the amount of time interrupts may be disabled while kernel data structures are being updated. Real-time operating systems require that interrupts be disabled for only very short periods of time.

The amount of time required for the scheduling dispatcher to stop one process and start another is known as **dispatch latency**. Providing real-time

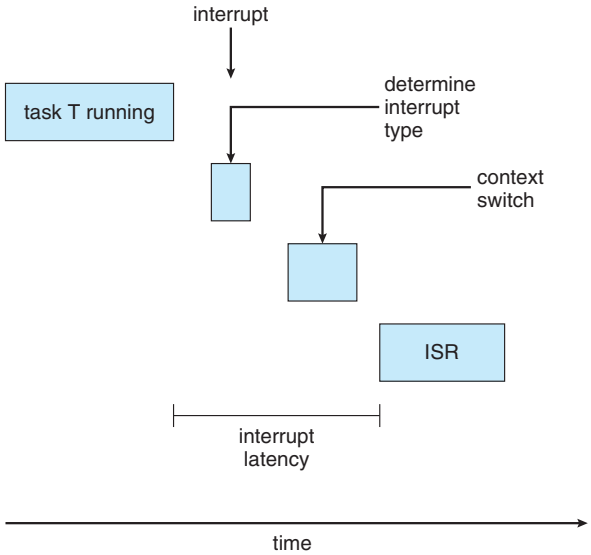


Figure 5.18 Interrupt latency.

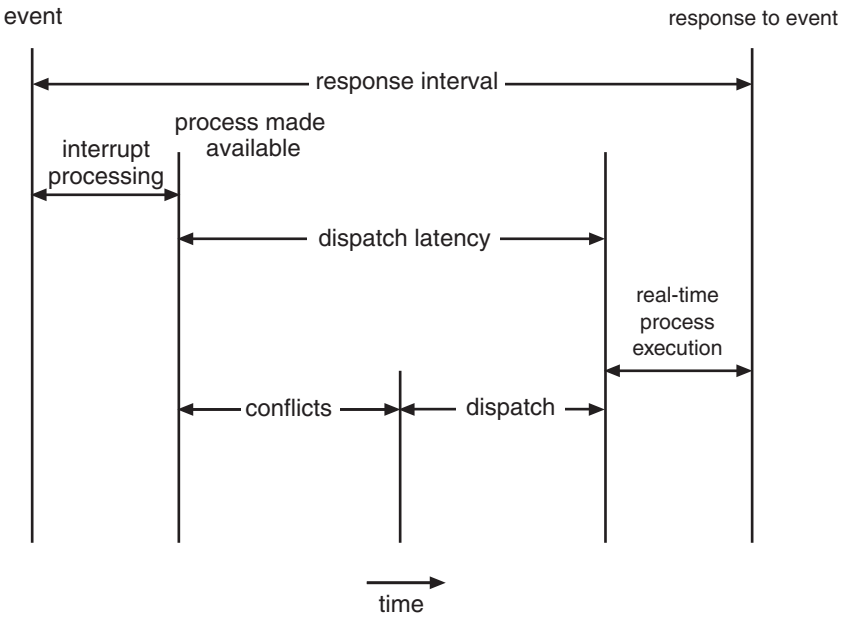


Figure 5.19 Dispatch latency.

tasks with immediate access to the CPU mandates that real-time operating systems minimize this latency as well. The most effective technique for keeping dispatch latency low is to provide preemptive kernels. For hard real-time systems, dispatch latency is typically measured in several microseconds.

In Figure 5.19, we diagram the makeup of dispatch latency. The **conflic phase** of dispatch latency has two components:

1. Preemption of any process running in the kernel
2. Release by low-priority processes of resources needed by a high-priority process

Following the conflict phase, the dispatch phase schedules the high-priority process onto an available CPU.

5.6.2 Priority-Based Scheduling

The most important feature of a real-time operating system is to respond immediately to a real-time process as soon as that process requires the CPU. As a result, the scheduler for a real-time operating system must support a priority-based algorithm with preemption. Recall that priority-based scheduling algorithms assign each process a priority based on its importance; more important tasks are assigned higher priorities than those deemed less important. If the scheduler also supports preemption, a process currently running on the CPU will be preempted if a higher-priority process becomes available to run.

Preemptive, priority-based scheduling algorithms are discussed in detail in Section 5.3.4, and Section 5.7 presents examples of the soft real-time scheduling features of the Linux, Windows, and Solaris operating systems. Each of these systems assigns real-time processes the highest scheduling priority. For

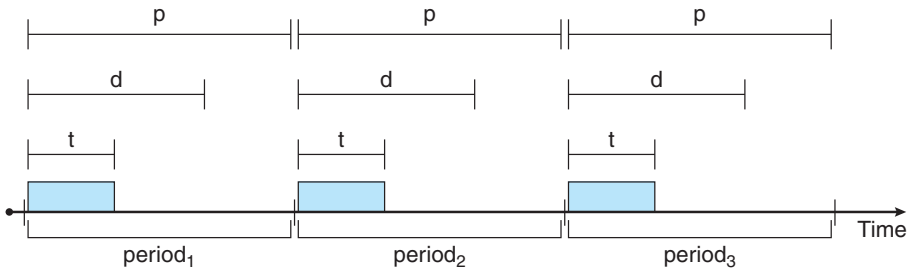


Figure 5.20 Periodic task.

example, Windows has 32 different priority levels. The highest levels—priority values 16 to 31—are reserved for real-time processes. Solaris and Linux have similar prioritization schemes.

Note that providing a preemptive, priority-based scheduler only guarantees soft real-time functionality. Hard real-time systems must further guarantee that real-time tasks will be serviced in accord with their deadline requirements, and making such guarantees requires additional scheduling features. In the remainder of this section, we cover scheduling algorithms appropriate for hard real-time systems.

Before we proceed with the details of the individual schedulers, however, we must define certain characteristics of the processes that are to be scheduled. First, the processes are considered **periodic**. That is, they require the CPU at constant intervals (periods). Once a periodic process has acquired the CPU, it has a fixed processing time t, a deadline d by which it must be serviced by the CPU, and a period p. The relationship of the processing time, the deadline, and the period can be expressed as $0 \leq t \leq d \leq p$. The **rate** of a periodic task is $1/p$. Figure 5.20 illustrates the execution of a periodic process over time. Schedulers can take advantage of these characteristics and assign priorities according to a process's deadline or rate requirements.

What is unusual about this form of scheduling is that a process may have to announce its deadline requirements to the scheduler. Then, using a technique known as an **admission-control** algorithm, the scheduler does one of two things. It either admits the process, guaranteeing that the process will complete on time, or rejects the request as impossible if it cannot guarantee that the task will be serviced by its deadline.

5.6.3 Rate-Monotonic Scheduling

The **rate-monotonic** scheduling algorithm schedules periodic tasks using a static priority policy with preemption. If a lower-priority process is running and a higher-priority process becomes available to run, it will preempt the lower-priority process. Upon entering the system, each periodic task is assigned a priority inversely based on its period. The shorter the period, the higher the priority; the longer the period, the lower the priority. The rationale behind this policy is to assign a higher priority to tasks that require the CPU more often. Furthermore, rate-monotonic scheduling assumes that the process-

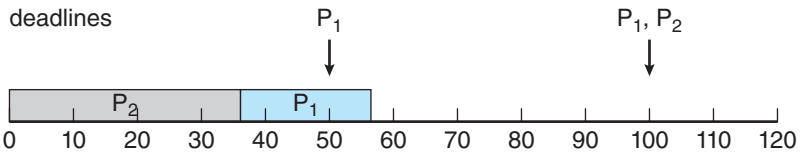


Figure 5.21 Scheduling of tasks when P_2 has a higher priority than P_1.

ing time of a periodic process is the same for each CPU burst. That is, every time a process acquires the CPU, the duration of its CPU burst is the same.

Let's consider an example. We have two processes, P_1 and P_2. The periods for P_1 and P_2 are 50 and 100, respectively—that is, $p_1 = 50$ and $p_2 = 100$. The processing times are $t_1 = 20$ for P_1 and $t_2 = 35$ for P_2. The deadline for each process requires that it complete its CPU burst by the start of its next period.

We must first ask ourselves whether it is possible to schedule these tasks so that each meets its deadlines. If we measure the CPU utilization of a process P_i as the ratio of its burst to its period—t_i/p_i—the CPU utilization of P_1 is $20/50 = 0.40$ and that of P_2 is $35/100 = 0.35$, for a total CPU utilization of 75 percent. Therefore, it seems we can schedule these tasks in such a way that both meet their deadlines and still leave the CPU with available cycles.

Suppose we assign P_2 a higher priority than P_1. The execution of P_1 and P_2 in this situation is shown in Figure 5.21. As we can see, P_2 starts execution first and completes at time 35. At this point, P_1 starts; it completes its CPU burst at time 55. However, the first deadline for P_1 was at time 50, so the scheduler has caused P_1 to miss its deadline.

Now suppose we use rate-monotonic scheduling, in which we assign P_1 a higher priority than P_2 because the period of P_1 is shorter than that of P_2. The execution of these processes in this situation is shown in Figure 5.22. P_1 starts first and completes its CPU burst at time 20, thereby meeting its first deadline. P_2 starts running at this point and runs until time 50. At this time, it is preempted by P_1, although it still has 5 milliseconds remaining in its CPU burst. P_1 completes its CPU burst at time 70, at which point the scheduler resumes P_2. P_2 completes its CPU burst at time 75, also meeting its first deadline. The system is idle until time 100, when P_1 is scheduled again.

Rate-monotonic scheduling is considered optimal in that if a set of processes cannot be scheduled by this algorithm, it cannot be scheduled by any other algorithm that assigns static priorities. Let's next examine a set of processes that cannot be scheduled using the rate-monotonic algorithm.

Assume that process P_1 has a period of $p_1 = 50$ and a CPU burst of $t_1 = 25$. For P_2, the corresponding values are $p_2 = 80$ and $t_2 = 35$. Rate-monotonic

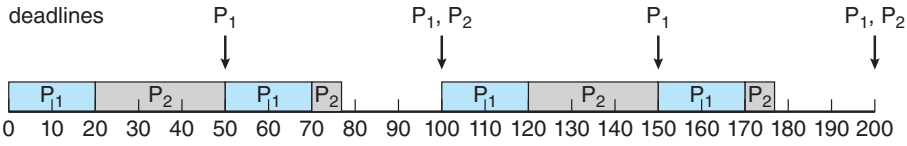


Figure 5.22 Rate-monotonic scheduling.

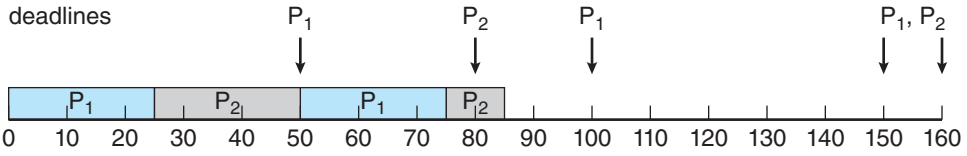


Figure 5.23 Missing deadlines with rate-monotonic scheduling.

scheduling would assign process P_1 a higher priority, as it has the shorter period. The total CPU utilization of the two processes is (25/50) + (35/80) = 0.94, and it therefore seems logical that the two processes could be scheduled and still leave the CPU with 6 percent available time. Figure 5.23 shows the scheduling of processes P_1 and P_2. Initially, P_1 runs until it completes its CPU burst at time 25. Process P_2 then begins running and runs until time 50, when it is preempted by P_1. At this point, P_2 still has 10 milliseconds remaining in its CPU burst. Process P_1 runs until time 75; consequently, P2 finishes its burst at time 85, after the deadline for completion of its CPU burst at time 80.

Despite being optimal, then, rate-monotonic scheduling has a limitation: CPU utilization is bounded, and it is not always possible to maximize CPU resources fully. The worst-case CPU utilization for scheduling N processes is

$$N(2^{1/N} - 1).$$

With one process in the system, CPU utilization is 100 percent, but it falls to approximately 69 percent as the number of processes approaches infinity. With two processes, CPU utilization is bounded at about 83 percent. Combined CPU utilization for the two processes scheduled in Figure 5.21 and Figure 5.22 is 75 percent; therefore, the rate-monotonic scheduling algorithm is guaranteed to schedule them so that they can meet their deadlines. For the two processes scheduled in Figure 5.23, combined CPU utilization is approximately 94 percent; therefore, rate-monotonic scheduling cannot guarantee that they can be scheduled so that they meet their deadlines.

5.6.4 Earliest-Deadline-First Scheduling

Earliest-deadline-firs (EDF) scheduling assigns priorities dynamically according to deadline. The earlier the deadline, the higher the priority; the later the deadline, the lower the priority. Under the EDF policy, when a process becomes runnable, it must announce its deadline requirements to the system. Priorities may have to be adjusted to reflect the deadline of the newly runnable process. Note how this differs from rate-monotonic scheduling, where priorities are fixed.

To illustrate EDF scheduling, we again schedule the processes shown in Figure 5.23, which failed to meet deadline requirements under rate-monotonic scheduling. Recall that P_1 has values of $p_1 = 50$ and $t_1 = 25$ and that P_2 has values of $p_2 = 80$ and $t_2 = 35$. The EDF scheduling of these processes is shown in Figure 5.24. Process P_1 has the earliest deadline, so its initial priority is higher than that of process P_2. Process P_2 begins running at the end of the CPU burst for P_1. However, whereas rate-monotonic scheduling allows P_1 to preempt P_2

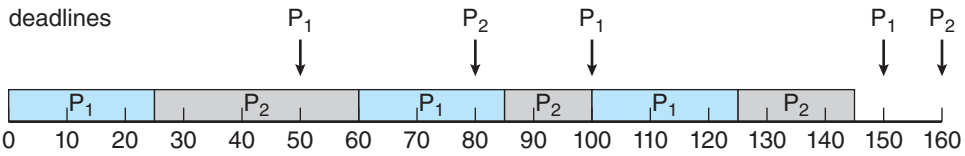


Figure 5.24 Earliest-deadline-first scheduling.

at the beginning of its next period at time 50, EDF scheduling allows process P_2 to continue running. P_2 now has a higher priority than P_1 because its next deadline (at time 80) is earlier than that of P_1 (at time 100). Thus, both P_1 and P_2 meet their first deadlines. Process P_1 again begins running at time 60 and completes its second CPU burst at time 85, also meeting its second deadline at time 100. P_2 begins running at this point, only to be preempted by P_1 at the start of its next period at time 100. P_2 is preempted because P_1 has an earlier deadline (time 150) than P_2 (time 160). At time 125, P_1 completes its CPU burst and P_2 resumes execution, finishing at time 145 and meeting its deadline as well. The system is idle until time 150, when P_1 is scheduled to run once again.

Unlike the rate-monotonic algorithm, EDF scheduling does not require that processes be periodic, nor must a process require a constant amount of CPU time per burst. The only requirement is that a process announce its deadline to the scheduler when it becomes runnable. The appeal of EDF scheduling is that it is theoretically optimal—theoretically, it can schedule processes so that each process can meet its deadline requirements and CPU utilization will be 100 percent. In practice, however, it is impossible to achieve this level of CPU utilization due to the cost of context switching between processes and interrupt handling.

5.6.5 Proportional Share Scheduling

Proportional share schedulers operate by allocating T shares among all applications. An application can receive N shares of time, thus ensuring that the application will have N/T of the total processor time. As an example, assume that a total of $T = 100$ shares is to be divided among three processes, A, B, and C. A is assigned 50 shares, B is assigned 15 shares, and C is assigned 20 shares. This scheme ensures that A will have 50 percent of total processor time, B will have 15 percent, and C will have 20 percent.

Proportional share schedulers must work in conjunction with an admission-control policy to guarantee that an application receives its allocated shares of time. An admission-control policy will admit a client requesting a particular number of shares only if sufficient shares are available. In our current example, we have allocated $50 + 15 + 20 = 85$ shares of the total of 100 shares. If a new process D requested 30 shares, the admission controller would deny D entry into the system.

5.6.6 POSIX Real-Time Scheduling

The POSIX standard also provides extensions for real-time computing—POSIX.1b. Here, we cover some of the POSIX API related to scheduling real-time threads. POSIX defines two scheduling classes for real-time threads:

- SCHED_FIFO
- SCHED_RR

SCHED_FIFO schedules threads according to a first-come, first-served policy using a FIFO queue as outlined in Section 5.3.1. However, there is no time slicing among threads of equal priority. Therefore, the highest-priority real-time thread at the front of the FIFO queue will be granted the CPU until it terminates or blocks. SCHED_RR uses a round-robin policy. It is similar to SCHED_FIFO except that it provides time slicing among threads of equal priority. POSIX provides an additional scheduling class—SCHED_OTHER—but its implementation is undefined and system specific; it may behave differently on different systems.

The POSIX API specifies the following two functions for getting and setting the scheduling policy:

- `pthread_attr_getschedpolicy(pthread_attr_t *attr, int *policy)`
- `pthread_attr_setschedpolicy(pthread_attr_t *attr, int policy)`

The first parameter to both functions is a pointer to the set of attributes for the thread. The second parameter is either (1) a pointer to an integer that is set to the current scheduling policy (for `pthread_attr_getsched_policy()`) or (2) an integer value (SCHED_FIFO, SCHED_RR, or SCHED_OTHER) for the `pthread_attr_setsched_policy()` function. Both functions return nonzero values if an error occurs.

In Figure 5.25, we illustrate a POSIX Pthread program using this API. This program first determines the current scheduling policy and then sets the scheduling algorithm to SCHED_FIFO.

5.7 Operating-System Examples

We turn next to a description of the scheduling policies of the Linux, Windows, and Solaris operating systems. It is important to note that we use the term ***process scheduling*** in a general sense here. In fact, we are describing the scheduling of ***kernel threads*** with Solaris and Windows systems and of ***tasks*** with the Linux scheduler.

5.7.1 Example: Linux Scheduling

Process scheduling in Linux has had an interesting history. Prior to Version 2.5, the Linux kernel ran a variation of the traditional UNIX scheduling algorithm. However, as this algorithm was not designed with SMP systems in mind, it did not adequately support systems with multiple processors. In addition, it resulted in poor performance for systems with a large number of runnable processes. With Version 2.5 of the kernel, the scheduler was overhauled to include a scheduling algorithm—known as $O(1)$—that ran in constant time regardless of the number of tasks in the system. The $O(1)$ scheduler also provided

```
#include <pthread.h>
#include <stdio.h>
#define NUM_THREADS 5

int main(int argc, char *argv[])
{
   int i, policy;
   pthread_t tid[NUM_THREADS];
   pthread_attr_t attr;

   /* get the default attributes */
   pthread_attr_init(&attr);

   /* get the current scheduling policy */
   if (pthread_attr_getschedpolicy(&attr, &policy) != 0)
      fprintf(stderr, "Unable to get policy.\n");
   else {
      if (policy == SCHED_OTHER)
       printf("SCHED_OTHER\n");
      else if (policy == SCHED_RR)
       printf("SCHED_RR\n");
      else if (policy == SCHED_FIFO)
       printf("SCHED_FIFO\n");
   }

   /* set the scheduling policy - FIFO, RR, or OTHER */
   if (pthread_attr_setschedpolicy(&attr, SCHED_FIFO) != 0)
      fprintf(stderr, "Unable to set policy.\n");

   /* create the threads */
   for (i = 0; i < NUM_THREADS; i++)
       pthread_create(&tid[i],&attr,runner,NULL);

   /* now join on each thread */
   for (i = 0; i < NUM_THREADS; i++)
      pthread_join(tid[i], NULL);
}

/* Each thread will begin control in this function */
void *runner(void *param)
{
   /* do some work ... */

   pthread_exit(0);
}
```

Figure 5.25 POSIX real-time scheduling API.

increased support for SMP systems, including processor affinity and load balancing between processors. However, in practice, although the *O*(1) scheduler delivered excellent performance on SMP systems, it led to poor response times for the interactive processes that are common on many desktop computer systems. During development of the 2.6 kernel, the scheduler was again revised; and in release 2.6.23 of the kernel, the ***Completely Fair Scheduler*** (CFS) became the default Linux scheduling algorithm.

Scheduling in the Linux system is based on **scheduling classes**. Each class is assigned a specific priority. By using different scheduling classes, the kernel can accommodate different scheduling algorithms based on the needs of the system and its processes. The scheduling criteria for a Linux server, for example, may be different from those for a mobile device running Linux. To decide which task to run next, the scheduler selects the highest-priority task belonging to the highest-priority scheduling class. Standard Linux kernels implement two scheduling classes: (1) a default scheduling class using the CFS scheduling algorithm and (2) a real-time scheduling class. We discuss each of these classes here. New scheduling classes can, of course, be added.

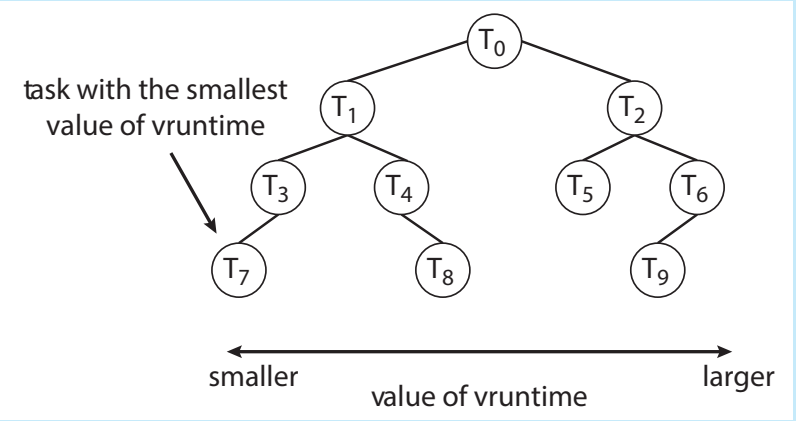
Rather than using strict rules that associate a relative priority value with the length of a time quantum, the CFS scheduler assigns a proportion of CPU processing time to each task. This proportion is calculated based on the **nice value** assigned to each task. Nice values range from −20 to +19, where a numerically lower nice value indicates a higher relative priority. Tasks with lower nice values receive a higher proportion of CPU processing time than tasks with higher nice values. The default nice value is 0. (The term ***nice*** comes from the idea that if a task increases its nice value from, say, 0 to +10, it is being nice to other tasks in the system by lowering its relative priority. In other words, nice processes finish last!) CFS doesn't use discrete values of time slices and instead identifies a **targeted latency**, which is an interval of time during which every runnable task should run at least once. Proportions of CPU time are allocated from the value of targeted latency. In addition to having default and minimum values, targeted latency can increase if the number of active tasks in the system grows beyond a certain threshold.

The CFS scheduler doesn't directly assign priorities. Rather, it records how long each task has run by maintaining the **virtual run time** of each task using the per-task variable `vruntime`. The virtual run time is associated with a decay factor based on the priority of a task: lower-priority tasks have higher rates of decay than higher-priority tasks. For tasks at normal priority (nice values of 0), virtual run time is identical to actual physical run time. Thus, if a task with default priority runs for 200 milliseconds, its `vruntime` will also be 200 milliseconds. However, if a lower-priority task runs for 200 milliseconds, its `vruntime` will be higher than 200 milliseconds. Similarly, if a higher-priority task runs for 200 milliseconds, its `vruntime` will be less than 200 milliseconds. To decide which task to run next, the scheduler simply selects the task that has the smallest `vruntime` value. In addition, a higher-priority task that becomes available to run can preempt a lower-priority task.

Let's examine the CFS scheduler in action: Assume that two tasks have the same nice values. One task is I/O-bound, and the other is CPU-bound. Typically, the I/O-bound task will run only for short periods before blocking for additional I/O, and the CPU-bound task will exhaust its time period whenever it has an opportunity to run on a processor. Therefore, the value of `vruntime` will

CFS PERFORMANCE

The Linux CFS scheduler provides an efficient algorithm for selecting which task to run next. Rather than using a standard queue data structure, each runnable task is placed in a red-black tree—a balanced binary search tree whose key is based on the value of `vruntime`. This tree is shown below.



When a task becomes runnable, it is added to the tree. If a task on the tree is not runnable (for example, if it is blocked while waiting for I/O), it is removed. Generally speaking, tasks that have been given less processing time (smaller values of `vruntime`) are toward the left side of the tree, and tasks that have been given more processing time are on the right side. According to the properties of a binary search tree, the leftmost node has the smallest key value, which for the sake of the CFS scheduler means that it is the task with the highest priority. Because the red-black tree is balanced, navigating it to discover the leftmost node will require $O(\log N)$ operations (where N is the number of nodes in the tree). However, for efficiency reasons, the Linux scheduler caches this value in the variable `rb_leftmost`, and thus determining which task to run next requires only retrieving the cached value.

eventually be lower for the I/O-bound task than for the CPU-bound task, giving the I/O-bound task higher priority than the CPU-bound task. At that point, if the CPU-bound task is executing when the I/O-bound task becomes eligible to run (for example, when I/O the task is waiting for becomes available), the I/O-bound task will preempt the CPU-bound task.

Linux also implements real-time scheduling using the POSIX standard as described in Section 5.6.6. Any task scheduled using either the SCHED_FIFO or the SCHED_RR real-time policy runs at a higher priority than normal (non-real-time) tasks. Linux uses two separate priority ranges, one for real-time tasks and a second for normal tasks. Real-time tasks are assigned static priorities within the range of 0 to 99, and normal tasks are assigned priorities from 100 to 139. These two ranges map into a global priority scheme wherein numerically lower values indicate higher relative priorities. Normal tasks are assigned a priority

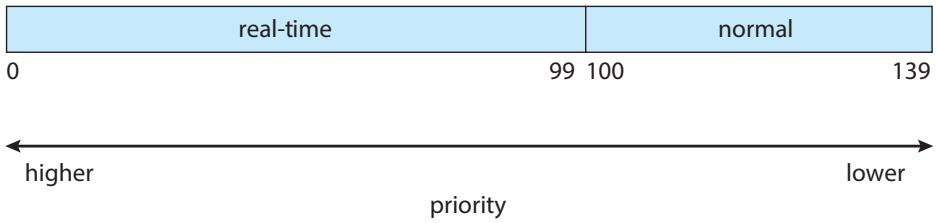


Figure 5.26 Scheduling priorities on a Linux system.

based on their nice values, where a value of −20 maps to priority 100 and a nice value of +19 maps to 139. This scheme is shown in Figure 5.26.

The CFS scheduler also supports load balancing, using a sophisticated technique that equalizes the load among processing cores yet is also NUMA-aware and minimizes the migration of threads. CFS defines the load of each thread as a combination of the thread's priority and its average rate of CPU utilization. Therefore, a thread that has a high priority, yet is mostly I/O-bound and requires little CPU usage, has a generally low load, similar to the load of a low-priority thread that has high CPU utilization. Using this metric, the load of a queue is the sum of the loads of all threads in the queue, and balancing is simply ensuring that all queues have approximately the same load.

As highlighted in Section 5.5.4, however, migrating a thread may result in a memory access penalty due to either having to invalidate cache contents or, on NUMA systems, incurring longer memory access times. To address this problem, Linux identifies a hierarchical system of scheduling domains. A **scheduling domain** is a set of CPU cores that can be balanced against one another. This idea is illustrated in Figure 5.27. The cores in each scheduling domain are grouped according to how they share the resources of the system. For example, although each core shown in Figure 5.27 may have its own level 1 (L1) cache, pairs of cores share a level 2 (L2) cache and are thus organized into separate $domain_0$ and $domain_1$. Likewise, these two domains may share a level 3 (L3) cache, and are therefore organized into a processor-level domain (also known as a **NUMA node**). Taking this one-step further, on a NUMA system,

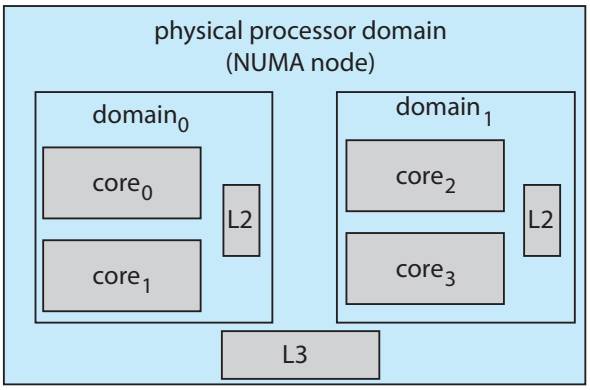


Figure 5.27 NUMA-aware load balancing with Linux CFS scheduler.

a larger system-level domain would combine separate processor-level NUMA nodes.

The general strategy behind CFS is to balance loads within domains, beginning at the lowest level of the hierarchy. Using Figure 5.27 as an example, initially a thread would only migrate between cores on the same domain (i.e. within $domain_0$ or $domain_1$.) Load balancing at the next level would occur between $domain_0$ and $domain_1$. CFS is reluctant to migrate threads between separate NUMA nodes if a thread would be moved farther from its local memory, and such migration would only occur under severe load imbalances. As a general rule, if the overall system is busy, CFS will not load-balance beyond the domain local to each core to avoid the memory latency penalties of NUMA systems.

5.7.2 Example: Windows Scheduling

Windows schedules threads using a priority-based, preemptive scheduling algorithm. The Windows scheduler ensures that the highest-priority thread will always run. The portion of the Windows kernel that handles scheduling is called the **dispatcher**. A thread selected to run by the dispatcher will run until it is preempted by a higher-priority thread, until it terminates, until its time quantum ends, or until it calls a blocking system call, such as for I/O. If a higher-priority real-time thread becomes ready while a lower-priority thread is running, the lower-priority thread will be preempted. This preemption gives a real-time thread preferential access to the CPU when the thread needs such access.

The dispatcher uses a 32-level priority scheme to determine the order of thread execution. Priorities are divided into two classes. The **variable class** contains threads having priorities from 1 to 15, and the **real-time class** contains threads with priorities ranging from 16 to 31. (There is also a thread running at priority 0 that is used for memory management.) The dispatcher uses a queue for each scheduling priority and traverses the set of queues from highest to lowest until it finds a thread that is ready to run. If no ready thread is found, the dispatcher will execute a special thread called the **idle thread**.

There is a relationship between the numeric priorities of the Windows kernel and the Windows API. The Windows API identifies the following six priority classes to which a process can belong:

- IDLE_PRIORITY_CLASS
- BELOW_NORMAL_PRIORITY_CLASS
- NORMAL_PRIORITY_CLASS
- ABOVE_NORMAL_PRIORITY_CLASS
- HIGH_PRIORITY_CLASS
- REALTIME_PRIORITY_CLASS

Processes are typically members of the NORMAL_PRIORITY_CLASS. A process belongs to this class unless the parent of the process was a member of the IDLE_PRIORITY_CLASS or unless another class was specified when the process was created. Additionally, the priority class of a process can be altered with

the `SetPriorityClass()` function in the Windows API. Priorities in all classes except the REALTIME_PRIORITY_CLASS are variable, meaning that the priority of a thread belonging to one of these classes can change.

A thread within a given priority class also has a relative priority. The values for relative priorities include:

- IDLE
- LOWEST
- BELOW_NORMAL
- NORMAL
- ABOVE_NORMAL
- HIGHEST
- TIME_CRITICAL

The priority of each thread is based on both the priority class it belongs to and its relative priority within that class. This relationship is shown in Figure 5.28. The values of the priority classes appear in the top row. The left column contains the values for the relative priorities. For example, if the relative priority of a thread in the ABOVE_NORMAL_PRIORITY_CLASS is NORMAL, the numeric priority of that thread is 10.

Furthermore, each thread has a base priority representing a value in the priority range for the class to which the thread belongs. By default, the base priority is the value of the NORMAL relative priority for that class. The base priorities for each priority class are as follows:

- REALTIME_PRIORITY_CLASS—24
- HIGH_PRIORITY_CLASS—13
- ABOVE_NORMAL_PRIORITY_CLASS—10
- NORMAL_PRIORITY_CLASS—8

	real-time	high	above normal	normal	below normal	idle priority
time-critical	31	15	15	15	15	15
highest	26	15	12	10	8	6
above normal	25	14	11	9	7	5
normal	24	13	10	8	6	4
below normal	23	12	9	7	5	3
lowest	22	11	8	6	4	2
idle	16	1	1	1	1	1

Figure 5.28 Windows thread priorities.

- BELOW_NORMAL_PRIORITY_CLASS—6
- IDLE_PRIORITY_CLASS—4

The initial priority of a thread is typically the base priority of the process the thread belongs to, although the `SetThreadPriority()` function in the Windows API can also be used to modify a thread's base priority.

When a thread's time quantum runs out, that thread is interrupted. If the thread is in the variable-priority class, its priority is lowered. The priority is never lowered below the base priority, however. Lowering the priority tends to limit the CPU consumption of compute-bound threads. When a variable-priority thread is released from a wait operation, the dispatcher boosts the priority. The amount of the boost depends on what the thread was waiting for. For example, a thread waiting for keyboard I/O would get a large increase, whereas a thread waiting for a disk operation would get a moderate one. This strategy tends to give good response times to interactive threads that are using the mouse and windows. It also enables I/O-bound threads to keep the I/O devices busy while permitting compute-bound threads to use spare CPU cycles in the background. This strategy is used by several operating systems, including UNIX. In addition, the window with which the user is currently interacting receives a priority boost to enhance its response time.

When a user is running an interactive program, the system needs to provide especially good performance. For this reason, Windows has a special scheduling rule for processes in the NORMAL_PRIORITY_CLASS. Windows distinguishes between the **foreground process** that is currently selected on the screen and the **background processes** that are not currently selected. When a process moves into the foreground, Windows increases the scheduling quantum by some factor—typically by 3. This increase gives the foreground process three times longer to run before a time-sharing preemption occurs.

Windows 7 introduced **user-mode scheduling** (**UMS**), which allows applications to create and manage threads independently of the kernel. Thus, an application can create and schedule multiple threads without involving the Windows kernel scheduler. For applications that create a large number of threads, scheduling threads in user mode is much more efficient than kernel-mode thread scheduling, as no kernel intervention is necessary.

Earlier versions of Windows provided a similar feature known as **fiber** , which allowed several user-mode threads (fibers) to be mapped to a single kernel thread. However, fibers were of limited practical use. A fiber was unable to make calls to the Windows API because all fibers had to share the thread environment block (TEB) of the thread on which they were running. This presented a problem if a Windows API function placed state information into the TEB for one fiber, only to have the information overwritten by a different fiber. UMS overcomes this obstacle by providing each user-mode thread with its own thread context.

In addition, unlike fibers, UMS is not intended to be used directly by the programmer. The details of writing user-mode schedulers can be very challenging, and UMS does not include such a scheduler. Rather, the schedulers come from programming language libraries that build on top of UMS. For example, Microsoft provides **Concurrency Runtime** (ConcRT), a concurrent programming framework for C++ that is designed for task-based parallelism

(Section 4.2) on multicore processors. ConcRT provides a user-mode scheduler together with facilities for decomposing programs into tasks, which can then be scheduled on the available processing cores.

Windows also supports scheduling on multiprocessor systems as described in Section 5.5 by attempting to schedule a thread on the most optimal processing core for that thread, which includes maintaining a thread's preferred as well as most recent processor. One technique used by Windows is to create sets of logical processors (known as **SMT sets**). On a hyper-threaded SMT system, hardware threads belonging to the same CPU core would also belong to the same SMT set. Logical processors are numbered, beginning from 0. As an example, a dual-threaded/quad-core system would contain eight logical processors, consisting of the four SMT sets: {0, 1}, {2, 3}, {4, 5}, and {6, 7}. To avoid cache memory access penalites highlighted in Section 5.5.4, the scheduler attempts to maintain a thread running on logical processors within the same SMT set.

To distribute loads across different logical processors, each thread is assigned an **ideal processor**, which is a number representing a thread's preferred processor. Each process has an initial seed value identifying the ideal CPU for a thread belonging to that process. This seed is incremented for each new thread created by that process, thereby distributing the load across different logical processors. On SMT systems, the increment for the next ideal processor is in the next SMT set. For example, on a dual-threaded/quad-core system, the ideal processors for threads in a specific process would be assigned 0, 2, 4, 6, 0, 2, ... To avoid the situation wherby the first thread for each process is assigned processor 0, processes are assigned different seed values, thereby distributing the load of threads across all physical processing cores in the system. Continuing our example from above, if the seed for a second process were 1, the ideal processors would be assigned in the order 1, 3, 5, 7, 1, 3, and so forth.

5.7.3 Example: Solaris Scheduling

Solaris uses priority-based thread scheduling. Each thread belongs to one of six classes:

1. Time sharing (TS)
2. Interactive (IA)
3. Real time (RT)
4. System (SYS)
5. Fair share (FSS)
6. Fixed priority (FP)

Within each class there are different priorities and different scheduling algorithms.

The default scheduling class for a process is time sharing. The scheduling policy for the time-sharing class dynamically alters priorities and assigns time slices of different lengths using a multilevel feedback queue. By default, there is an inverse relationship between priorities and time slices. The higher the

priority	time quantum	time quantum expired	return from sleep
0	200	0	50
5	200	0	50
10	160	0	51
15	160	5	51
20	120	10	52
25	120	15	52
30	80	20	53
35	80	25	54
40	40	30	55
45	40	35	56
50	40	40	58
55	40	45	58
59	20	49	59

Figure 5.29 Solaris dispatch table for time-sharing and interactive threads.

priority, the smaller the time slice; and the lower the priority, the larger the time slice. Interactive processes typically have a higher priority; CPU-bound processes, a lower priority. This scheduling policy gives good response time for interactive processes and good throughput for CPU-bound processes. The interactive class uses the same scheduling policy as the time-sharing class, but it gives windowing applications—such as those created by the KDE or GNOME window managers—a higher priority for better performance.

Figure 5.29 shows the simplified dispatch table for scheduling time-sharing and interactive threads. These two scheduling classes include 60 priority levels, but for brevity, we display only a handful. (To see the full dispatch table on a Solaris system or VM, run `dispadmin -c TS -g`.) The dispatch table shown in Figure 5.29 contains the following fields:

- **Priority**. The class-dependent priority for the time-sharing and interactive classes. A higher number indicates a higher priority.
- **Time quantum**. The time quantum for the associated priority. This illustrates the inverse relationship between priorities and time quanta: the lowest priority (priority 0) has the highest time quantum (200 milliseconds), and the highest priority (priority 59) has the lowest time quantum (20 milliseconds).
- **Time quantum expired**. The new priority of a thread that has used its entire time quantum without blocking. Such threads are considered CPU-intensive. As shown in the table, these threads have their priorities lowered.

- **Return from sleep**. The priority of a thread that is returning from sleeping (such as from waiting for I/O). As the table illustrates, when I/O is available for a waiting thread, its priority is boosted to between 50 and 59, supporting the scheduling policy of providing good response time for interactive processes.

Threads in the real-time class are given the highest priority. A real-time process will run before a process in any other class. This assignment allows a real-time process to have a guaranteed response from the system within a bounded period of time. In general, however, few processes belong to the real-time class.

Solaris uses the system class to run kernel threads, such as the scheduler and paging daemon. Once the priority of a system thread is established, it does not change. The system class is reserved for kernel use (user processes running in kernel mode are not in the system class).

The fixed-priority and fair-share classes were introduced with Solaris 9. Threads in the fixed-priority class have the same priority range as those in the time-sharing class; however, their priorities are not dynamically adjusted. The fair-share class uses CPU **shares** instead of priorities to make scheduling decisions. CPU shares indicate entitlement to available CPU resources and are allocated to a set of processes (known as a **project**).

Each scheduling class includes a set of priorities. However, the scheduler converts the class-specific priorities into global priorities and selects the thread with the highest global priority to run. The selected thread runs on the CPU until it (1) blocks, (2) uses its time slice, or (3) is preempted by a higher-priority thread. If there are multiple threads with the same priority, the scheduler uses a round-robin queue. Figure 5.30 illustrates how the six scheduling classes relate to one another and how they map to global priorities. Notice that the kernel maintains ten threads for servicing interrupts. These threads do not belong to any scheduling class and execute at the highest priority (160–169). As mentioned, Solaris has traditionally used the many-to-many model (Section 4.3.3) but switched to the one-to-one model (Section 4.3.2) beginning with Solaris 9.

5.8 Algorithm Evaluation

How do we select a CPU-scheduling algorithm for a particular system? As we saw in Section 5.3, there are many scheduling algorithms, each with its own parameters. As a result, selecting an algorithm can be difficult.

The first problem is defining the criteria to be used in selecting an algorithm. As we saw in Section 5.2, criteria are often defined in terms of CPU utilization, response time, or throughput. To select an algorithm, we must first define the relative importance of these elements. Our criteria may include several measures, such as these:

- Maximizing CPU utilization under the constraint that the maximum response time is 300 milliseconds

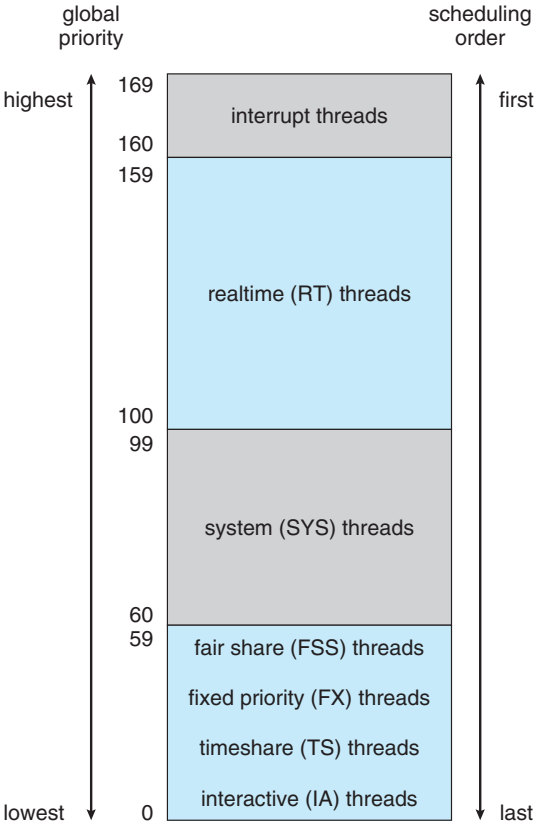


Figure 5.30 Solaris scheduling.

- Maximizing throughput such that turnaround time is (on average) linearly proportional to total execution time

Once the selection criteria have been defined, we want to evaluate the algorithms under consideration. We next describe the various evaluation methods we can use.

5.8.1 Deterministic Modeling

One major class of evaluation methods is **analytic evaluation**. Analytic evaluation uses the given algorithm and the system workload to produce a formula or number to evaluate the performance of the algorithm for that workload.

Deterministic modeling is one type of analytic evaluation. This method takes a particular predetermined workload and defines the performance of each algorithm for that workload. For example, assume that we have the workload shown below. All five processes arrive at time 0, in the order given, with the length of the CPU burst given in milliseconds:

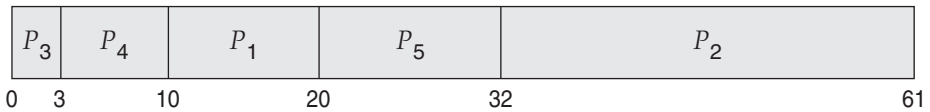
Process	Burst Time
P_1	10
P_2	29
P_3	3
P_4	7
P_5	12

Consider the FCFS, SJF, and RR (quantum = 10 milliseconds) scheduling algorithms for this set of processes. Which algorithm would give the minimum average waiting time?

For the FCFS algorithm, we would execute the processes as

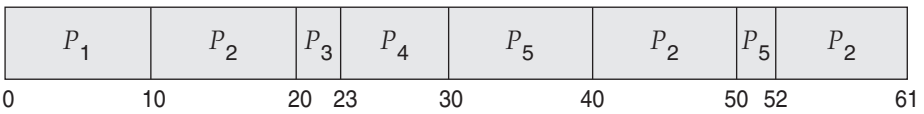
The waiting time is 0 milliseconds for process P_1, 10 milliseconds for process P_2, 39 milliseconds for process P_3, 42 milliseconds for process P_4, and 49 milliseconds for process P_5. Thus, the average waiting time is (0 + 10 + 39 + 42 + 49)/5 = 28 milliseconds.

With nonpreemptive SJF scheduling, we execute the processes as



The waiting time is 10 milliseconds for process P_1, 32 milliseconds for process P_2, 0 milliseconds for process P_3, 3 milliseconds for process P_4, and 20 milliseconds for process P_5. Thus, the average waiting time is (10 + 32 + 0 + 3 + 20)/5 = 13 milliseconds.

With the RR algorithm, we execute the processes as



The waiting time is 0 milliseconds for process P_1, 32 milliseconds for process P_2, 20 milliseconds for process P_3, 23 milliseconds for process P_4, and 40 milliseconds for process P_5. Thus, the average waiting time is (0 + 32 + 20 + 23 + 40)/5 = 23 milliseconds.

We can see that, in this case, the average waiting time obtained with the SJF policy is less than half that obtained with FCFS scheduling; the RR algorithm gives us an intermediate value.

Deterministic modeling is simple and fast. It gives us exact numbers, allowing us to compare the algorithms. However, it requires exact numbers for input, and its answers apply only to those cases. The main uses of deterministic modeling are in describing scheduling algorithms and providing examples. In cases where we are running the same program over and over again and can

measure the program's processing requirements exactly, we may be able to use deterministic modeling to select a scheduling algorithm. Furthermore, over a set of examples, deterministic modeling may indicate trends that can then be analyzed and proved separately. For example, it can be shown that, for the environment described (all processes and their times available at time 0), the SJF policy will always result in the minimum waiting time.

5.8.2 Queueing Models

On many systems, the processes that are run vary from day to day, so there is no static set of processes (or times) to use for deterministic modeling. What can be determined, however, is the distribution of CPU and I/O bursts. These distributions can be measured and then approximated or simply estimated. The result is a mathematical formula describing the probability of a particular CPU burst. Commonly, this distribution is exponential and is described by its mean. Similarly, we can describe the distribution of times when processes arrive in the system (the arrival-time distribution). From these two distributions, it is possible to compute the average throughput, utilization, waiting time, and so on for most algorithms.

The computer system is described as a network of servers. Each server has a queue of waiting processes. The CPU is a server with its ready queue, as is the I/O system with its device queues. Knowing arrival rates and service rates, we can compute utilization, average queue length, average wait time, and so on. This area of study is called **queueing-network analysis**.

As an example, let n be the average long-term queue length (excluding the process being serviced), let W be the average waiting time in the queue, and let λ be the average arrival rate for new processes in the queue (such as three processes per second). We expect that during the time W that a process waits, $\lambda \times W$ new processes will arrive in the queue. If the system is in a steady state, then the number of processes leaving the queue must be equal to the number of processes that arrive. Thus,

$$n = \lambda \times W.$$

This equation, known as **Little's formula**, is particularly useful because it is valid for any scheduling algorithm and arrival distribution. For example n could be the number of customers in a store.

We can use Little's formula to compute one of the three variables if we know the other two. For example, if we know that 7 processes arrive every second (on average) and that there are normally 14 processes in the queue, then we can compute the average waiting time per process as 2 seconds.

Queueing analysis can be useful in comparing scheduling algorithms, but it also has limitations. At the moment, the classes of algorithms and distributions that can be handled are fairly limited. The mathematics of complicated algorithms and distributions can be difficult to work with. Thus, arrival and service distributions are often defined in mathematically tractable—but unrealistic—ways. It is also generally necessary to make a number of independent assumptions, which may not be accurate. As a result of these difficulties, queueing models are often only approximations of real systems, and the accuracy of the computed results may be questionable.

5.8.3 Simulations

To get a more accurate evaluation of scheduling algorithms, we can use simulations. Running simulations involves programming a model of the computer system. Software data structures represent the major components of the system. The simulator has a variable representing a clock. As this variable's value is increased, the simulator modifies the system state to reflect the activities of the devices, the processes, and the scheduler. As the simulation executes, statistics that indicate algorithm performance are gathered and printed.

The data to drive the simulation can be generated in several ways. The most common method uses a random-number generator that is programmed to generate processes, CPU burst times, arrivals, departures, and so on, according to probability distributions. The distributions can be defined mathematically (uniform, exponential, Poisson) or empirically. If a distribution is to be defined empirically, measurements of the actual system under study are taken. The results define the distribution of events in the real system; this distribution can then be used to drive the simulation.

A distribution-driven simulation may be inaccurate, however, because of relationships between successive events in the real system. The frequency distribution indicates only how many instances of each event occur; it does not indicate anything about the order of their occurrence. To correct this problem, we can use **trace files**. We create a trace by monitoring the real system and recording the sequence of actual events (Figure 5.31). We then use this sequence to drive the simulation. Trace files provide an excellent way to compare two algorithms on exactly the same set of real inputs. This method can produce accurate results for its inputs.

Simulations can be expensive, often requiring many hours of computer time. A more detailed simulation provides more accurate results, but it also

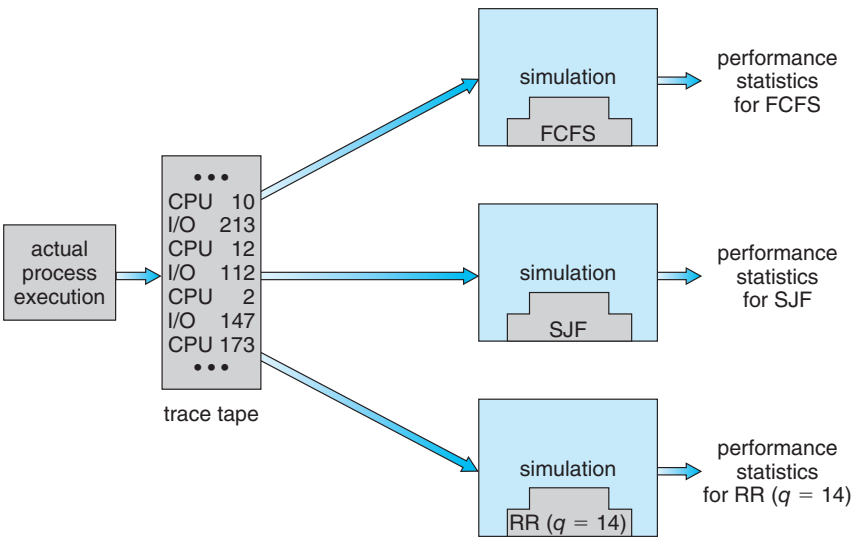


Figure 5.31 Evaluation of CPU schedulers by simulation.

takes more computer time. In addition, trace files can require large amounts of storage space. Finally, the design, coding, and debugging of the simulator can be a major task.

5.8.4 Implementation

Even a simulation is of limited accuracy. The only completely accurate way to evaluate a scheduling algorithm is to code it up, put it in the operating system, and see how it works. This approach puts the actual algorithm in the real system for evaluation under real operating conditions.

This method is not without expense. The expense is incurred in coding the algorithm and modifying the operating system to support it (along with its required data structures). There is also cost in testing the changes, usually in virtual machines rather than on dedicated hardware. **Regression testing** confirms that the changes haven't made anything worse, and haven't caused new bugs or caused old bugs to be recreated (for example because the algorithm being replaced solved some bug and changing it caused that bug to reoccur).

Another difficulty is that the environment in which the algorithm is used will change. The environment will change not only in the usual way, as new programs are written and the types of problems change, but also as a result of the performance of the scheduler. If short processes are given priority, then users may break larger processes into sets of smaller processes. If interactive processes are given priority over noninteractive processes, then users may switch to interactive use. This problem is usually addressed by using tools or scripts that encapsulate complete sets of actions, repeatedly using those tools, and using those tools while measuring the results (and detecting any problems they cause in the new environment).

Of course human or program behavior can attempt to circumvent scheduling algorithms. For example, researchers designed one system that classified interactive and noninteractive processes automatically by looking at the amount of terminal I/O. If a process did not input or output to the terminal in a 1-second interval, the process was classified as noninteractive and was moved to a lower-priority queue. In response to this policy, one programmer modified his programs to write an arbitrary character to the terminal at regular intervals of less than 1 second. The system gave his programs a high priority, even though the terminal output was completely meaningless.

In general, most flexible scheduling algorithms are those that can be altered by the system managers or by the users so that they can be tuned for a specific application or set of applications. A workstation that performs high-end graphical applications, for instance, may have scheduling needs different from those of a web server or file server. Some operating systems—particularly several versions of UNIX—allow the system manager to fine-tune the scheduling parameters for a particular system configuration. For example, Solaris provides the `dispadmin` command to allow the system administrator to modify the parameters of the scheduling classes described in Section 5.7.3.

Another approach is to use APIs that can modify the priority of a process or thread. The Java, POSIX, and Windows APIs provide such functions. The downfall of this approach is that performance-tuning a system or application most often does not result in improved performance in more general situations.

5.9 Summary

- CPU scheduling is the task of selecting a waiting process from the ready queue and allocating the CPU to it. The CPU is allocated to the selected process by the dispatcher.
- Scheduling algorithms may be either preemptive (where the CPU can be taken away from a process) or nonpreemptive (where a process must voluntarily relinquish control of the CPU). Almost all modern operating systems are preemptive.
- Scheduling algorithms can be evaluated according to the following five criteria: (1) CPU utilization, (2) throughput, (3) turnaround time, (4) waiting time, and (5) response time.
- First-come, first-served (FCFS) scheduling is the simplest scheduling algorithm, but it can cause short processes to wait for very long processes.
- Shortest-job-first (SJF) scheduling is provably optimal, providing the shortest average waiting time. Implementing SJF scheduling is difficult, however, because predicting the length of the next CPU burst is difficult.
- Round-robin (RR) scheduling allocates the CPU to each process for a time quantum. If the process does not relinquish the CPU before its time quantum expires, the process is preempted, and another process is scheduled to run for a time quantum.
- Priority scheduling assigns each process a priority, and the CPU is allocated to the process with the highest priority. Processes with the same priority can be scheduled in FCFS order or using RR scheduling.
- Multilevel queue scheduling partitions processes into several separate queues arranged by priority, and the scheduler executes the processes in the highest-priority queue. Different scheduling algorithms may be used in each queue.
- Multilevel feedback queues are similar to multilevel queues, except that a process may migrate between different queues.
- Multicore processors place one or more CPUs on the same physical chip, and each CPU may have more than one hardware thread. From the perspective of the operating system, each hardware thread appears to be a logical CPU.
- Load balancing on multicore systems equalizes loads between CPU cores, although migrating threads between cores to balance loads may invalidate cache contents and therefore may increase memory access times.
- Soft real-time scheduling gives priority to real-time tasks over non-real-time tasks. Hard real-time scheduling provides timing guarantees for real-time tasks,
- Rate-monotonic real-time scheduling schedules periodic tasks using a static priority policy with preemption.

- Earliest-deadline-first (EDF) scheduling assigns priorities according to deadline. The earlier the deadline, the higher the priority; the later the deadline, the lower the priority.
- Proportional share scheduling allocates T shares among all applications. If an application is allocated N shares of time, it is ensured of having N/T of the total processor time.
- Linux uses the completely fair scheduler (CFS), which assigns a proportion of CPU processing time to each task. The proportion is based on the virtual runtime (`vruntime`) value associated with each task.
- Windows scheduling uses a preemptive, 32-level priority scheme to determine the order of thread scheduling.
- Solaris identifies six unique scheduling classes that are mapped to a global priority. CPU-intensive threads are generally assigned lower priorities (and longer time quantums), and I/O-bound threads are usually assigned higher priorities (with shorter time quantums.)
- Modeling and simulations can be used to evaluate a CPU scheduling algorithm.

Practice Exercises

5.1 A CPU-scheduling algorithm determines an order for the execution of its scheduled processes. Given n processes to be scheduled on one processor, how many different schedules are possible? Give a formula in terms of n.

5.2 Explain the difference between preemptive and nonpreemptive scheduling.

5.3 Suppose that the following processes arrive for execution at the times indicated. Each process will run for the amount of time listed. In answering the questions, use nonpreemptive scheduling, and base all decisions on the information you have at the time the decision must be made.

Process	Arrival Time	Burst Time
P_1	0.0	8
P_2	0.4	4
P_3	1.0	1

a. What is the average turnaround time for these processes with the FCFS scheduling algorithm?

b. What is the average turnaround time for these processes with the SJF scheduling algorithm?

c. The SJF algorithm is supposed to improve performance, but notice that we chose to run process P_1 at time 0 because we did not know that two shorter processes would arrive soon. Compute what the

average turnaround time will be if the CPU is left idle for the first 1 unit and then SJF scheduling is used. Remember that processes P_1 and P_2 are waiting during this idle time, so their waiting time may increase. This algorithm could be known as ***future-knowledge scheduling***.

5.4 Consider the following set of processes, with the length of the CPU burst time given in milliseconds:

Process	Burst Time	Priority
P_1	2	2
P_2	1	1
P_3	8	4
P_4	4	2
P_5	5	3

The processes are assumed to have arrived in the order P_1, P_2, P_3, P_4, P_5, all at time 0.

a. Draw four Gantt charts that illustrate the execution of these processes using the following scheduling algorithms: FCFS, SJF, nonpreemptive priority (a larger priority number implies a higher priority), and RR (quantum = 2).

b. What is the turnaround time of each process for each of the scheduling algorithms in part a?

c. What is the waiting time of each process for each of these scheduling algorithms?

d. Which of the algorithms results in the minimum average waiting time (over all processes)?

5.5 The following processes are being scheduled using a preemptive, round-robin scheduling algorithm.

Process	Priority	Burst	Arrival
P_1	40	20	0
P_2	30	25	25
P_3	30	25	30
P_4	35	15	60
P_5	5	10	100
P_6	10	10	105

Each process is assigned a numerical priority, with a higher number indicating a higher relative priority. In addition to the processes listed below, the system also has an **idle task** (which consumes no CPU resources and is identified as P_{idle}). This task has priority 0 and is scheduled whenever the system has no other available processes to run. The length of a

time quantum is 10 units. If a process is preempted by a higher-priority process, the preempted process is placed at the end of the queue.

a. Show the scheduling order of the processes using a Gantt chart.

b. What is the turnaround time for each process?

c. What is the waiting time for each process?

d. What is the CPU utilization rate?

5.6 What advantage is there in having different time-quantum sizes at different levels of a multilevel queueing system?

5.7 Many CPU-scheduling algorithms are parameterized. For example, the RR algorithm requires a parameter to indicate the time slice. Multilevel feedback queues require parameters to define the number of queues, the scheduling algorithms for each queue, the criteria used to move processes between queues, and so on.

These algorithms are thus really sets of algorithms (for example, the set of RR algorithms for all time slices, and so on). One set of algorithms may include another (for example, the FCFS algorithm is the RR algorithm with an infinite time quantum). What (if any) relation holds between the following pairs of algorithm sets?

a. Priority and SJF

b. Multilevel feedback queues and FCFS

c. Priority and FCFS

d. RR and SJF

5.8 Suppose that a CPU scheduling algorithm favors those processes that have used the least processor time in the recent past. Why will this algorithm favor I/O-bound programs and yet not permanently starve CPU-bound programs?

5.9 Distinguish between PCS and SCS scheduling.

5.10 The traditional UNIX scheduler enforces an inverse relationship between priority numbers and priorities: the higher the number, the lower the priority. The scheduler recalculates process priorities once per second using the following function:

Priority = (recent CPU usage / 2) + base

where base = 60 and *recent CPU usage* refers to a value indicating how often a process has used the CPU since priorities were last recalculated.

Assume that recent CPU usage for process P_1 is 40, for process P_2 is 18, and for process P_3 is 10. What will be the new priorities for these three processes when priorities are recalculated? Based on this information, does the traditional UNIX scheduler raise or lower the relative priority of a CPU-bound process?

Further Reading

Scheduling policies used in the UNIX FreeBSD 5.2 are presented by [McKusick et al. (2015)]; The Linux CFS scheduler is further described in https://www.ibm.com/developerworks/library/l-completely-fair-scheduler/. Solaris scheduling is described by [Mauro and McDougall (2007)]. [Russinovich et al. (2017)] discusses scheduling in Windows internals. [Butenhof (1997)] and [Lewis and Berg (1998)] describe scheduling in Pthreads systems. Multicore scheduling is examined in [McNairy and Bhatia (2005)], [Kongetira et al. (2005)], and [Siddha et al. (2007)] .

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Chapter 5 Exercises

5.11 Of these two types of programs:

a. I/O-bound

b. CPU-bound

which is more likely to have voluntary context switches, and which is more likely to have nonvoluntary context switches? Explain your answer.

5.12 Discuss how the following pairs of scheduling criteria conflict in certain settings.

a. CPU utilization and response time

b. Average turnaround time and maximum waiting time

c. I/O device utilization and CPU utilization

5.13 One technique for implementing **lottery scheduling** works by assigning processes lottery tickets, which are used for allocating CPU time. Whenever a scheduling decision has to be made, a lottery ticket is chosen at random, and the process holding that ticket gets the CPU. The BTV operating system implements lottery scheduling by holding a lottery 50 times each second, with each lottery winner getting 20 milliseconds of CPU time (20 milliseconds × 50 = 1 second). Describe how the BTV scheduler can ensure that higher-priority threads receive more attention from the CPU than lower-priority threads.

5.14 Most scheduling algorithms maintain a **run queue**, which lists processes eligible to run on a processor. On multicore systems, there are two general options: (1) each processing core has its own run queue, or (2) a single run queue is shared by all processing cores. What are the advantages and disadvantages of each of these approaches?

5.15 Consider the exponential average formula used to predict the length of the next CPU burst. What are the implications of assigning the following values to the parameters used by the algorithm?

a. $\alpha = 0$ and $\tau_0 = 100$ milliseconds

b. $\alpha = 0.99$ and $\tau_0 = 10$ milliseconds

5.16 A variation of the round-robin scheduler is the **regressive round-robin** scheduler. This scheduler assigns each process a time quantum and a priority. The initial value of a time quantum is 50 milliseconds. However, every time a process has been allocated the CPU and uses its entire time quantum (does not block for I/O), 10 milliseconds is added to its time quantum, and its priority level is boosted. (The time quantum for a process can be increased to a maximum of 100 milliseconds.) When a process blocks before using its entire time quantum, its time quantum is reduced by 5 milliseconds, but its priority remains the same. What type of process (CPU-bound or I/O-bound) does the regressive round-robin scheduler favor? Explain.

5.17 Consider the following set of processes, with the length of the CPU burst given in milliseconds:

Process	Burst Time	Priority
P_1	5	4
P_2	3	1
P_3	1	2
P_4	7	2
P_5	4	3

The processes are assumed to have arrived in the order P_1, P_2, P_3, P_4, P_5, all at time 0.

a. Draw four Gantt charts that illustrate the execution of these processes using the following scheduling algorithms: FCFS, SJF, nonpreemptive priority (a larger priority number implies a higher priority), and RR (quantum = 2).

b. What is the turnaround time of each process for each of the scheduling algorithms in part a?

c. What is the waiting time of each process for each of these scheduling algorithms?

d. Which of the algorithms results in the minimum average waiting time (over all processes)?

5.18 The following processes are being scheduled using a preemptive, priority-based, round-robin scheduling algorithm.

Process	Priority	Burst	Arrival
P_1	8	15	0
P_2	3	20	0
P_3	4	20	20
P_4	4	20	25
P_5	5	5	45
P_6	5	15	55

Each process is assigned a numerical priority, with a higher number indicating a higher relative priority. The scheduler will execute the highest-priority process. For processes with the same priority, a round-robin scheduler will be used with a time quantum of 10 units. If a process is preempted by a higher-priority process, the preempted process is placed at the end of the queue.

a. Show the scheduling order of the processes using a Gantt chart.

b. What is the turnaround time for each process?

c. What is the waiting time for each process?

5.19 The `nice` command is used to set the nice value of a process on Linux, as well as on other UNIX systems. Explain why some systems may allow any user to assign a process a nice value >= 0 yet allow only the root (or administrator) user to assign nice values < 0.

5.20 Which of the following scheduling algorithms could result in starvation?

a. First-come, first-served

b. Shortest job first

c. Round robin

d. Priority

5.21 Consider a variant of the RR scheduling algorithm in which the entries in the ready queue are pointers to the PCBs.

a. What would be the effect of putting two pointers to the same process in the ready queue?

b. What would be two major advantages and two disadvantages of this scheme?

c. How would you modify the basic RR algorithm to achieve the same effect without the duplicate pointers?

5.22 Consider a system running ten I/O-bound tasks and one CPU-bound task. Assume that the I/O-bound tasks issue an I/O operation once for every millisecond of CPU computing and that each I/O operation takes 10 milliseconds to complete. Also assume that the context-switching overhead is 0.1 millisecond and that all processes are long-running tasks. Describe the CPU utilization for a round-robin scheduler when:

a. The time quantum is 1 millisecond

b. The time quantum is 10 milliseconds

5.23 Consider a system implementing multilevel queue scheduling. What strategy can a computer user employ to maximize the amount of CPU time allocated to the user's process?

5.24 Consider a preemptive priority scheduling algorithm based on dynamically changing priorities. Larger priority numbers imply higher priority. When a process is waiting for the CPU (in the ready queue, but not running), its priority changes at a rate α. When it is running, its priority changes at a rate β. All processes are given a priority of 0 when they enter the ready queue. The parameters α and β can be set to give many different scheduling algorithms.

a. What is the algorithm that results from $\beta > \alpha > 0$?

b. What is the algorithm that results from $\alpha < \beta < 0$?

5.25 Explain the how the following scheduling algorithms discriminate either in favor of or against short processes:

a. FCFS

b. RR

c. Multilevel feedback queues

5.26 Describe why a shared ready queue might suffer from performance problems in an SMP environment.

5.27 Consider a load-balancing algorithm that ensures that each queue has approximately the same number of threads, independent of priority. How effectively would a priority-based scheduling algorithm handle this situation if one run queue had all high-priority threads and a second queue had all low-priority threads?

5.28 Assume that an SMP system has private, per-processor run queues. When a new process is created, it can be placed in either the same queue as the parent process or a separate queue.

a. What are the benefits of placing the new process in the same queue as its parent?

b. What are the benefits of placing the new process in a different queue?

5.29 Assume that a thread has blocked for network I/O and is eligible to run again. Describe why a NUMA-aware scheduling algorithm should reschedule the thread on the same CPU on which it previously ran.

5.30 Using the Windows scheduling algorithm, determine the numeric priority of each of the following threads.

a. A thread in the REALTIME_PRIORITY_CLASS with a relative priority of NORMAL

b. A thread in the ABOVE_NORMAL_PRIORITY_CLASS with a relative priority of HIGHEST

c. A thread in the BELOW_NORMAL_PRIORITY_CLASS with a relative priority of ABOVE_NORMAL

5.31 Assuming that no threads belong to the REALTIME_PRIORITY_CLASS and that none may be assigned a TIME_CRITICAL priority, what combination of priority class and priority corresponds to the highest possible relative priority in Windows scheduling?

5.32 Consider the scheduling algorithm in the Solaris operating system for time-sharing threads.

a. What is the time quantum (in milliseconds) for a thread with priority 15? With priority 40?

b. Assume that a thread with priority 50 has used its entire time quantum without blocking. What new priority will the scheduler assign this thread?

c. Assume that a thread with priority 20 blocks for I/O before its time quantum has expired. What new priority will the scheduler assign this thread?

5.33 Assume that two tasks, A and B, are running on a Linux system. The nice values of A and B are -5 and $+5$, respectively. Using the CFS scheduler as a guide, describe how the respective values of `vruntime` vary between the two processes given each of the following scenarios:

- Both A and B are CPU-bound.
- A is I/O-bound, and B is CPU-bound.
- A is CPU-bound, and B is I/O-bound.

5.34 Provide a specific circumstance that illustrates where rate-monotonic scheduling is inferior to earliest-deadline-first scheduling in meeting real-time process deadlines?

5.35 Consider two processes, P_1 and P_2, where $p_1 = 50$, $t_1 = 25$, $p_2 = 75$, and $t_2 = 30$.

a. Can these two processes be scheduled using rate-monotonic scheduling? Illustrate your answer using a Gantt chart such as the ones in Figure 5.21–Figure 5.24.

b. Illustrate the scheduling of these two processes using earliest-deadline-first (EDF) scheduling.

5.36 Explain why interrupt and dispatch latency times must be bounded in a hard real-time system.

5.37 Describe the advantages of using heterogeneous multiprocessing in a mobile system.

Programming Projects

Scheduling Algorithms

This project involves implementing several different process scheduling algorithms. The scheduler will be assigned a predefined set of tasks and will schedule the tasks based on the selected scheduling algorithm. Each task is assigned a priority and CPU burst. The following scheduling algorithms will be implemented:

- First-come, first-served (FCFS), which schedules tasks in the order in which they request the CPU.
- Shortest-job-first (SJF), which schedules tasks in order of the length of the tasks' next CPU burst.
- Priority scheduling, which schedules tasks based on priority.
- Round-robin (RR) scheduling, where each task is run for a time quantum (or for the remainder of its CPU burst).
- Priority with round-robin, which schedules tasks in order of priority and uses round-robin scheduling for tasks with equal priority.

Priorities range from 1 to 10, where a higher numeric value indicates a higher relative priority. For round-robin scheduling, the length of a time quantum is 10 milliseconds.

I. Implementation

The implementation of this project may be completed in either C or Java, and program files supporting both of these languages are provided in the source code download for the text. These supporting files read in the schedule of tasks, insert the tasks into a list, and invoke the scheduler.

The schedule of tasks has the form [*task name*] [*priority*] [*CPU burst*], with the following example format:

```
T1, 4, 20
T2, 2, 25
T3, 3, 25
T4, 3, 15
T5, 10, 10
```

Thus, task `T1` has priority 4 and a CPU burst of 20 milliseconds, and so forth. It is assumed that all tasks arrive at the same time, so your scheduler algorithms do not have to support higher-priority processes preempting processes with lower priorities. In addition, tasks do not have to be placed into a queue or list in any particular order.

There are a few different strategies for organizing the list of tasks, as first presented in Section 5.1.2. One approach is to place all tasks in a single unordered list, where the strategy for task selection depends on the scheduling

algorithm. For example, SJF scheduling would search the list to find the task with the shortest next CPU burst. Alternatively, a list could be ordered according to scheduling criteria (that is, by priority). One other strategy involves having a separate queue for each unique priority, as shown in Figure 5.7. These approaches are briefly discussed in Section 5.3.6. It is also worth highlighting that we are using the terms ***list*** and ***queue*** somewhat interchangeably. However, a queue has very specific FIFO functionality, whereas a list does not have such strict insertion and deletion requirements. You are likely to find the functionality of a general list to be more suitable when completing this project.

II. C Implementation Details

The file `driver.c` reads in the schedule of tasks, inserts each task into a linked list, and invokes the process scheduler by calling the `schedule()` function. The `schedule()` function executes each task according to the specified scheduling algorithm. Tasks selected for execution on the CPU are determined by the `pickNextTask()` function and are executed by invoking the `run()` function defined in the `CPU.c` file. A `Makefile` is used to determine the specific scheduling algorithm that will be invoked by `driver`. For example, to build the FCFS scheduler, we would enter

```
make fcfs
```

and would execute the scheduler (using the schedule of tasks `schedule.txt`) as follows:

```
./fcfs schedule.txt
```

Refer to the `README` file in the source code download for further details. Before proceeding, be sure to familiarize yourself with the source code provided as well as the `Makefile`.

III. Java Implementation Details

The file `Driver.java` reads in the schedule of tasks, inserts each task into a Java `ArrayList`, and invokes the process scheduler by calling the `schedule()` method. The following interface identifies a generic scheduling algorithm, which the five different scheduling algorithms will implement:

```
public interface Algorithm
{
   // Implementation of scheduling algorithm
   public void schedule();

   // Selects the next task to be scheduled
   public Task pickNetTask();
}
```

The `schedule()` method obtains the next task to be run on the CPU by invoking the `pickNextTask()` method and then executes this `Task` by calling the `static run()` method in the `CPU.java` class.

The program is run as follows:

```
java Driver fcfs schedule.txt
```

Refer to the README file in the source code download for further details. Before proceeding, be sure to familiarize yourself with all Java source files provided in the source code download.

IV. Further Challenges

Two additional challenges are presented for this project:

1. Each task provided to the scheduler is assigned a unique task (tid). If a scheduler is running in an SMP environment where each CPU is separately running its own scheduler, there is a possible race condition on the variable that is used to assign task identifiers. Fix this race condition using an atomic integer.

   On Linux and macOS systems, the __sync_fetch_and_add() function can be used to atomically increment an integer value. As an example, the following code sample atomically increments value by 1:

   ```
   int value = 0;
   __sync_fetch_and_add(&value,1);
   ```

   Refer to the Java API for details on how to use the AtomicInteger class for Java programs.

2. Calculate the average turnaround time, waiting time, and response time for each of the scheduling algorithms.

Part Three

Process Synchronization

A system typically consists of several (perhaps hundreds or even thousands) of threads running either concurrently or in parallel. Threads often share user data. Meanwhile, the operating system continuously updates various data structures to support multiple threads. A *race condition* exists when access to shared data is not controlled, possibly resulting in corrupt data values.

Process synchronization involves using tools that control access to shared data to avoid race conditions. These tools must be used carefully, as their incorrect use can result in poor system performance, including deadlock.

Synchronization Tools

A **cooperating process** is one that can affect or be affected by other processes executing in the system. Cooperating processes can either directly share a logical address space (that is, both code and data) or be allowed to share data only through shared memory or message passing. Concurrent access to shared data may result in data inconsistency, however. In this chapter, we discuss various mechanisms to ensure the orderly execution of cooperating processes that share a logical address space, so that data consistency is maintained.

CHAPTER OBJECTIVES

- Describe the critical-section problem and illustrate a race condition.
- Illustrate hardware solutions to the critical-section problem using memory barriers, compare-and-swap operations, and atomic variables.
- Demonstrate how mutex locks, semaphores, monitors, and condition variables can be used to solve the critical-section problem.
- Evaluate tools that solve the critical-section problem in low-, moderate-, and high-contention scenarios.

6.1 Background

We've already seen that processes can execute concurrently or in parallel. Section 3.2.2 introduced the role of process scheduling and described how the CPU scheduler switches rapidly between processes to provide concurrent execution. This means that one process may only partially complete execution before another process is scheduled. In fact, a process may be interrupted at any point in its instruction stream, and the processing core may be assigned to execute instructions of another process. Additionally, Section 4.2 introduced parallel execution, in which two instruction streams (representing different processes) execute simultaneously on separate processing cores. In this chapter, we explain how concurrent or parallel execution can contribute to issues involving the integrity of data shared by several processes.

Let's consider an example of how this can happen. In Chapter 3, we developed a model of a system consisting of cooperating sequential processes or threads, all running asynchronously and possibly sharing data. We illustrated this model with the producer–consumer problem, which is a representative paradigm of many operating system functions. Specifically, in Section 3.5, we described how a bounded buffer could be used to enable processes to share memory.

We now return to our consideration of the bounded buffer. As we pointed out, our original solution allowed at most `BUFFER_SIZE – 1` items in the buffer at the same time. Suppose we want to modify the algorithm to remedy this deficiency. One possibility is to add an integer variable, `count`, initialized to 0. `count` is incremented every time we add a new item to the buffer and is decremented every time we remove one item from the buffer. The code for the producer process can be modified as follows:

```
while (true) {
     /* produce an item in next_produced */

     while (count == BUFFER_SIZE)
        ; /* do nothing */

     buffer[in] = next_produced;
     in = (in + 1) % BUFFER_SIZE;
     count++;
}
```

The code for the consumer process can be modified as follows:

```
while (true) {
     while (count == 0)
        ; /* do nothing */

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

     /* consume the item in next_consumed */
}
```

Although the producer and consumer routines shown above are correct separately, they may not function correctly when executed concurrently. As an illustration, suppose that the value of the variable `count` is currently 5 and that the producer and consumer processes concurrently execute the statements "`count++`" and "`count--`". Following the execution of these two statements, the value of the variable `count` may be 4, 5, or 6! The only correct result, though, is `count == 5`, which is generated correctly if the producer and consumer execute separately.

We can show that the value of `count` may be incorrect as follows. Note that the statement "`count++`" may be implemented in machine language (on a typical machine) as follows:

$$\begin{aligned} register_1 &= \texttt{count} \\ register_1 &= register_1 + 1 \\ \texttt{count} &= register_1 \end{aligned}$$

where $register_1$ is one of the local CPU registers. Similarly, the statement "`count--`" is implemented as follows:

$$\begin{aligned} register_2 &= \texttt{count} \\ register_2 &= register_2 - 1 \\ \texttt{count} &= register_2 \end{aligned}$$

where again $register_2$ is one of the local CPU registers. Even though $register_1$ and $register_2$ may be the same physical register, remember that the contents of this register will be saved and restored by the interrupt handler (Section 1.2.3).

The concurrent execution of "`count++`" and "`count--`" is equivalent to a sequential execution in which the lower-level statements presented previously are interleaved in some arbitrary order (but the order within each high-level statement is preserved). One such interleaving is the following:

T_0:	*producer*	execute	$register_1 = \texttt{count}$	$\{register_1 = 5\}$
T_1:	*producer*	execute	$register_1 = register_1 + 1$	$\{register_1 = 6\}$
T_2:	*consumer*	execute	$register_2 = \texttt{count}$	$\{register_2 = 5\}$
T_3:	*consumer*	execute	$register_2 = register_2 - 1$	$\{register_2 = 4\}$
T_4:	*producer*	execute	$\texttt{count} = register_1$	$\{count = 6\}$
T_5:	*consumer*	execute	$\texttt{count} = register_2$	$\{count = 4\}$

Notice that we have arrived at the incorrect state "`count == 4`", indicating that four buffers are full, when, in fact, five buffers are full. If we reversed the order of the statements at T_4 and T_5, we would arrive at the incorrect state "`count == 6`".

We would arrive at this incorrect state because we allowed both processes to manipulate the variable `count` concurrently. A situation like this, where several processes access and manipulate the same data concurrently and the outcome of the execution depends on the particular order in which the access takes place, is called a **race condition**. To guard against the race condition above, we need to ensure that only one process at a time can be manipulating the variable `count`. To make such a guarantee, we require that the processes be synchronized in some way.

Situations such as the one just described occur frequently in operating systems as different parts of the system manipulate resources. Furthermore, as we have emphasized in earlier chapters, the prominence of multicore systems has brought an increased emphasis on developing multithreaded applications. In such applications, several threads—which are quite possibly sharing data—are running in parallel on different processing cores. Clearly, we want any changes that result from such activities not to interfere with one

another. Because of the importance of this issue, we devote a major portion of this chapter to **process synchronization** and **coordination** among cooperating processes.

6.2 The Critical-Section Problem

We begin our consideration of process synchronization by discussing the so-called critical-section problem. Consider a system consisting of n processes $\{P_0, P_1, ..., P_{n-1}\}$. Each process has a segment of code, called a **critical section**, in which the process may be accessing — and updating — data that is shared with at least one other process. The important feature of the system is that, when one process is executing in its critical section, no other process is allowed to execute in its critical section. That is, no two processes are executing in their critical sections at the same time. The ***critical-section problem*** is to design a protocol that the processes can use to synchronize their activity so as to cooperatively share data. Each process must request permission to enter its critical section. The section of code implementing this request is the **entry section**. The critical section may be followed by an **exit section**. The remaining code is the **remainder section**. The general structure of a typical process is shown in Figure 6.1. The entry section and exit section are enclosed in boxes to highlight these important segments of code.

A solution to the critical-section problem must satisfy the following three requirements:

1. **Mutual exclusion**. If process P_i is executing in its critical section, then no other processes can be executing in their critical sections.
2. **Progress**. If no process is executing in its critical section and some processes wish to enter their critical sections, then only those processes that are not executing in their remainder sections can participate in deciding which will enter its critical section next, and this selection cannot be postponed indefinitely.

```
while (true) {

    entry section

        critical section

    exit section

        remainder section

}
```

Figure 6.1 General structure of a typical process.

3. **Bounded waiting**. There exists a bound, or limit, on the number of times that other processes are allowed to enter their critical sections after a process has made a request to enter its critical section and before that request is granted.

We assume that each process is executing at a nonzero speed. However, we can make no assumption concerning the relative speed of the n processes.

At a given point in time, many kernel-mode processes may be active in the operating system. As a result, the code implementing an operating system (***kernel code***) is subject to several possible race conditions. Consider as an example a kernel data structure that maintains a list of all open files in the system. This list must be modified when a new file is opened or closed (adding the file to the list or removing it from the list). If two processes were to open files simultaneously, the separate updates to this list could result in a race condition.

Another example is illustrated in Figure 6.2. In this situation, two processes, P_0 and P_1, are creating child processes using the `fork()` system call. Recall from Section 3.3.1 that `fork()` returns the process identifier of the newly created process to the parent process. In this example, there is a race condition on the variable kernel variable `next_available_pid` which represents the value of the next available process identifier. Unless mutual exclusion is provided, it is possible the same process identifier number could be assigned to two separate processes.

Other kernel data structures that are prone to possible race conditions include structures for maintaining memory allocation, for maintaining process lists, and for interrupt handling. It is up to kernel developers to ensure that the operating system is free from such race conditions.

The critical-section problem could be solved simply in a single-core environment if we could prevent interrupts from occurring while a shared variable was being modified. In this way, we could be sure that the current sequence

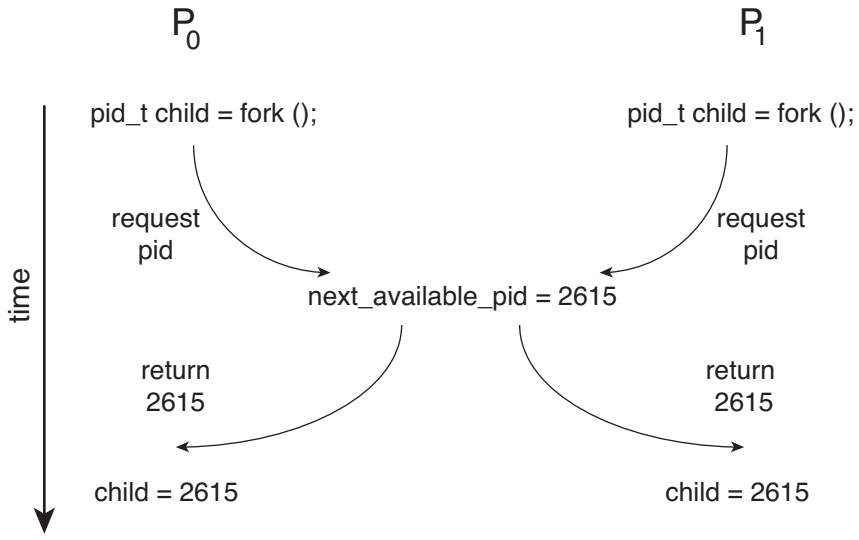

Figure 6.2 Race condition when assigning a pid.

of instructions would be allowed to execute in order without preemption. No other instructions would be run, so no unexpected modifications could be made to the shared variable.

Unfortunately, this solution is not as feasible in a multiprocessor environment. Disabling interrupts on a multiprocessor can be time consuming, since the message is passed to all the processors. This message passing delays entry into each critical section, and system efficiency decreases. Also consider the effect on a system's clock if the clock is kept updated by interrupts.

Two general approaches are used to handle critical sections in operating systems: **preemptive kernels** and **nonpreemptive kernels**. A preemptive kernel allows a process to be preempted while it is running in kernel mode. A nonpreemptive kernel does not allow a process running in kernel mode to be preempted; a kernel-mode process will run until it exits kernel mode, blocks, or voluntarily yields control of the CPU.

Obviously, a nonpreemptive kernel is essentially free from race conditions on kernel data structures, as only one process is active in the kernel at a time. We cannot say the same about preemptive kernels, so they must be carefully designed to ensure that shared kernel data are free from race conditions. Preemptive kernels are especially difficult to design for SMP architectures, since in these environments it is possible for two kernel-mode processes to run simultaneously on different CPU cores.

Why, then, would anyone favor a preemptive kernel over a nonpreemptive one? A preemptive kernel may be more responsive, since there is less risk that a kernel-mode process will run for an arbitrarily long period before relinquishing the processor to waiting processes. (Of course, this risk can also be minimized by designing kernel code that does not behave in this way.) Furthermore, a preemptive kernel is more suitable for real-time programming, as it will allow a real-time process to preempt a process currently running in the kernel.

6.3 Peterson's Solution

Next, we illustrate a classic software-based solution to the critical-section problem known as **Peterson's solution**. Because of the way modern computer architectures perform basic machine-language instructions, such as `load` and `store`, there are no guarantees that Peterson's solution will work correctly on such architectures. However, we present the solution because it provides a good algorithmic description of solving the critical-section problem and illustrates some of the complexities involved in designing software that addresses the requirements of mutual exclusion, progress, and bounded waiting.

Peterson's solution is restricted to two processes that alternate execution between their critical sections and remainder sections. The processes are numbered P_0 and P_1. For convenience, when presenting P_i, we use P_j to denote the other process; that is, `j` equals $1 - $ `i`.

Peterson's solution requires the two processes to share two data items:

```
int turn;
boolean flag[2];
```

```
while (true) {
    flag[i] = true;
    turn = j;
    while (flag[j] && turn == j)
        ;

        /* critical section */

    flag[i] = false;

        /*remainder section */
}
```

Figure 6.3 The structure of process P_i in Peterson's solution.

The variable `turn` indicates whose turn it is to enter its critical section. That is, if `turn == i`, then process P_i is allowed to execute in its critical section. The `flag` array is used to indicate if a process is ready to enter its critical section. For example, if `flag[i]` is `true`, P_i is ready to enter its critical section. With an explanation of these data structures complete, we are now ready to describe the algorithm shown in Figure 6.3.

To enter the critical section, process P_i first sets `flag[i]` to be `true` and then sets `turn` to the value `j`, thereby asserting that if the other process wishes to enter the critical section, it can do so. If both processes try to enter at the same time, `turn` will be set to both `i` and `j` at roughly the same time. Only one of these assignments will last; the other will occur but will be overwritten immediately. The eventual value of `turn` determines which of the two processes is allowed to enter its critical section first.

We now prove that this solution is correct. We need to show that:

1. Mutual exclusion is preserved.
2. The progress requirement is satisfied.
3. The bounded-waiting requirement is met.

To prove property 1, we note that each P_i enters its critical section only if either `flag[j] == false` or `turn == i`. Also note that, if both processes can be executing in their critical sections at the same time, then `flag[0] == flag[1] == true`. These two observations imply that P_0 and P_1 could not have successfully executed their `while` statements at about the same time, since the value of `turn` can be either 0 or 1 but cannot be both. Hence, one of the processes—say, P_j—must have successfully executed the `while` statement, whereas P_i had to execute at least one additional statement ("`turn == j`"). However, at that time, `flag[j] == true` and `turn == j`, and this condition will persist as long as P_j is in its critical section; as a result, mutual exclusion is preserved.

To prove properties 2 and 3, we note that a process P_i can be prevented from entering the critical section only if it is stuck in the `while` loop with the condition `flag[j] == true` and `turn == j`; this loop is the only one possible. If P_j is not ready to enter the critical section, then `flag[j] == false`, and P_i can enter its critical section. If P_j has set `flag[j]` to `true` and is also executing in its `while` statement, then either `turn == i` or `turn == j`. If `turn == i`, then P_i will enter the critical section. If `turn == j`, then P_j will enter the critical section. However, once P_j exits its critical section, it will reset `flag[j]` to `false`, allowing P_i to enter its critical section. If P_j resets `flag[j]` to `true`, it must also set `turn` to `i`. Thus, since P_i does not change the value of the variable `turn` while executing the `while` statement, P_i will enter the critical section (progress) after at most one entry by P_j (bounded waiting).

As mentioned at the beginning of this section, Peterson's solution is not guaranteed to work on modern computer architectures for the primary reason that, to improve system performance, processors and/or compilers may reorder read and write operations that have no dependencies. For a single-threaded application, this reordering is immaterial as far as program correctness is concerned, as the final values are consistent with what is expected. (This is similar to balancing a checkbook—the actual order in which credit and debit operations are performed is unimportant, because the final balance will still be the same.) But for a multithreaded application with shared data, the reordering of instructions may render inconsistent or unexpected results.

As an example, consider the following data that are shared between two threads:

```
boolean flag = false;
int x = 0;
```

where Thread 1 performs the statements

```
while (!flag)
   ;
print x;
```

and Thread 2 performs

```
x = 100;
flag = true;
```

The expected behavior is, of course, that Thread 1 outputs the value 100 for variable `x`. However, as there are no data dependencies between the variables `flag` and `x`, it is possible that a processor may reorder the instructions for Thread 2 so that `flag` is assigned `true` before assignment of `x = 100`. In this situation, it is possible that Thread 1 would output 0 for variable `x`. Less obvious is that the processor may also reorder the statements issued by Thread 1 and load the variable `x` before loading the value of `flag`. If this were to occur, Thread 1 would output 0 for variable `x` even if the instructions issued by Thread 2 were not reordered.

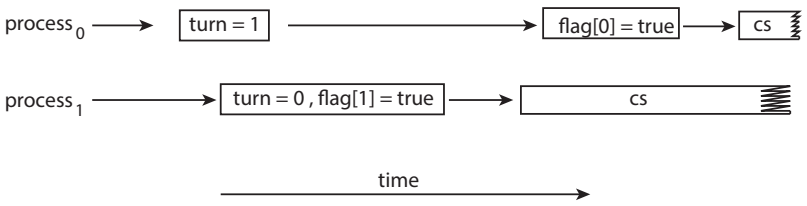

Figure 6.4 The effects of instruction reordering in Peterson's solution.

How does this affect Peterson's solution? Consider what happens if the assignments of the first two statements that appear in the entry section of Peterson's solution in Figure 6.3 are reordered; it is possible that both threads may be active in their critical sections at the same time, as shown in Figure 6.4.

As you will see in the following sections, the only way to preserve mutual exclusion is by using proper synchronization tools. Our discussion of these tools begins with primitive support in hardware and proceeds through abstract, high-level, software-based APIs available to both kernel developers and application programmers.

6.4 Hardware Support for Synchronization

We have just described one software-based solution to the critical-section problem. (We refer to it as a ***software-based*** solution because the algorithm involves no special support from the operating system or specific hardware instructions to ensure mutual exclusion.) However, as discussed, software-based solutions are not guaranteed to work on modern computer architectures. In this section, we present three hardware instructions that provide support for solving the critical-section problem. These primitive operations can be used directly as synchronization tools, or they can be used to form the foundation of more abstract synchronization mechanisms.

6.4.1 Memory Barriers

In Section 6.3, we saw that a system may reorder instructions, a policy that can lead to unreliable data states. How a computer architecture determines what memory guarantees it will provide to an application program is known as its **memory model**. In general, a memory model falls into one of two categories:

1. **Strongly ordered**, where a memory modification on one processor is immediately visible to all other processors.
2. **Weakly ordered**, where modifications to memory on one processor may not be immediately visible to other processors.

Memory models vary by processor type, so kernel developers cannot make any assumptions regarding the visibility of modifications to memory on a shared-memory multiprocessor. To address this issue, computer architectures provide instructions that can *force* any changes in memory to be propagated to all other processors, thereby ensuring that memory modifications are visible to

threads running on other processors. Such instructions are known as **memory barriers** or **memory fences**. When a memory barrier instruction is performed, the system ensures that all loads and stores are completed before any subsequent load or store operations are performed. Therefore, even if instructions were reordered, the memory barrier ensures that the store operations are completed in memory and visible to other processors before future load or store operations are performed.

Let's return to our most recent example, in which reordering of instructions could have resulted in the wrong output, and use a memory barrier to ensure that we obtain the expected output.

If we add a memory barrier operation to Thread 1

```
while (!flag)
   memory_barrier();
print x;
```

we guarantee that the value of `flag` is loaded before the value of `x`.

Similarly, if we place a memory barrier between the assignments performed by Thread 2

```
x = 100;
memory_barrier();
flag = true;
```

we ensure that the assignment to `x` occurs before the assignment to `flag`.

With respect to Peterson's solution, we could place a memory barrier between the first two assignment statements in the entry section to avoid the reordering of operations shown in Figure 6.4. Note that memory barriers are considered very low-level operations and are typically only used by kernel developers when writing specialized code that ensures mutual exclusion.

6.4.2 Hardware Instructions

Many modern computer systems provide special hardware instructions that allow us either to test and modify the content of a word or to swap the contents of two words **atomically**—that is, as one uninterruptible unit. We can use these special instructions to solve the critical-section problem in a relatively simple manner. Rather than discussing one specific instruction for one specific machine, we abstract the main concepts behind these types of instructions by describing the `test_and_set()` and `compare_and_swap()` instructions.

```
boolean test_and_set(boolean *target) {
   boolean rv = *target;
   *target = true;

   return rv;
}
```

Figure 6.5 The definition of the atomic `test_and_set()` instruction.

```
do {
   while (test_and_set(&lock))
      ; /* do nothing */

      /* critical section */

   lock = false;

      /* remainder section */
} while (true);
```

Figure 6.6 Mutual-exclusion implementation with `test_and_set()`.

The `test_and_set()` instruction can be defined as shown in Figure 6.5. The important characteristic of this instruction is that it is executed atomically. Thus, if two `test_and_set()` instructions are executed simultaneously (each on a different core), they will be executed sequentially in some arbitrary order. If the machine supports the `test_and_set()` instruction, then we can implement mutual exclusion by declaring a boolean variable `lock`, initialized to `false`. The structure of process P_i is shown in Figure 6.6.

The `compare_and_swap()` instruction (CAS), just like the `test_and_set()` instruction, operates on two words atomically, but uses a different mechanism that is based on swapping the content of two words.

The CAS instruction operates on three operands and is defined in Figure 6.7. The operand `value` is set to `new_value` only if the expression `(*value == expected)` is true. Regardless, CAS always returns the original value of the variable `value`. The important characteristic of this instruction is that it is executed atomically. Thus, if two CAS instructions are executed simultaneously (each on a different core), they will be executed sequentially in some arbitrary order.

Mutual exclusion using CAS can be provided as follows: A global variable (`lock`) is declared and is initialized to 0. The first process that invokes `compare_and_swap()` will set `lock` to 1. It will then enter its critical section,

```
int compare_and_swap(int *value, int expected, int new_value) {
   int temp = *value;

   if (*value == expected)
      *value = new_value;

   return temp;
}
```

Figure 6.7 The definition of the atomic `compare_and_swap()` instruction.

```
while (true) {
   while (compare_and_swap(&lock, 0, 1) != 0)
      ; /* do nothing */

      /* critical section */

   lock = 0;

      /* remainder section */
}
```

Figure 6.8 Mutual exclusion with the `compare_and_swap()` instruction.

because the original value of `lock` was equal to the expected value of 0. Subsequent calls to `compare_and_swap()` will not succeed, because `lock` now is not equal to the expected value of 0. When a process exits its critical section, it sets `lock` back to 0, which allows another process to enter its critical section. The structure of process P_i is shown in Figure 6.8.

Although this algorithm satisfies the mutual-exclusion requirement, it does not satisfy the bounded-waiting requirement. In Figure 6.9, we present

```
while (true) {
   waiting[i] = true;
   key = 1;
   while (waiting[i] && key == 1)
      key = compare_and_swap(&lock,0,1);
   waiting[i] = false;

      /* critical section */

   j = (i + 1) % n;
   while ((j != i) && !waiting[j])
      j = (j + 1) % n;

   if (j == i)
      lock = 0;
   else
      waiting[j] = false;

      /* remainder section */
}
```

Figure 6.9 Bounded-waiting mutual exclusion with `compare_and_swap()`.

MAKING COMPARE-AND-SWAP ATOMIC

On Intel x86 architectures, the assembly language statement `cmpxchg` is used to implement the `compare_and_swap()` instruction. To enforce atomic execution, the `lock` prefix is used to lock the bus while the destination operand is being updated. The general form of this instruction appears as:

```
lock cmpxchg <destination operand>, <source operand>
```

another algorithm using the `compare_and_swap()` instruction that satisfies all the critical-section requirements. The common data structures are

```
boolean waiting[n];
int lock;
```

The elements in the `waiting` array are initialized to `false`, and `lock` is initialized to 0. To prove that the mutual-exclusion requirement is met, we note that process P_i can enter its critical section only if either `waiting[i] == false` or `key == 0`. The value of `key` can become 0 only if the `compare_and_swap()` is executed. The first process to execute the `compare_and_swap()` will find `key == 0`; all others must wait. The variable `waiting[i]` can become `false` only if another process leaves its critical section; only one `waiting[i]` is set to `false`, maintaining the mutual-exclusion requirement.

To prove that the progress requirement is met, we note that the arguments presented for mutual exclusion also apply here, since a process exiting the critical section either sets `lock` to 0 or sets `waiting[j]` to `false`. Both allow a process that is waiting to enter its critical section to proceed.

To prove that the bounded-waiting requirement is met, we note that, when a process leaves its critical section, it scans the array `waiting` in the cyclic ordering ($i + 1, i + 2, \ldots, n - 1, 0, \ldots, i - 1$). It designates the first process in this ordering that is in the entry section (`waiting[j] == true`) as the next one to enter the critical section. Any process waiting to enter its critical section will thus do so within $n - 1$ turns.

Details describing the implementation of the atomic `test_and_set()` and `compare_and_swap()` instructions are discussed more fully in books on computer architecture.

6.4.3 Atomic Variables

Typically, the `compare_and_swap()` instruction is not used directly to provide mutual exclusion. Rather, it is used as a basic building block for constructing other tools that solve the critical-section problem. One such tool is an **atomic variable**, which provides atomic operations on basic data types such as integers and booleans. We know from Section 6.1 that incrementing or decrementing an integer value may produce a race condition. Atomic variables can be used in to ensure mutual exclusion in situations where there may be a data race on a single variable while it is being updated, as when a counter is incremented.

Most systems that support atomic variables provide special atomic data types as well as functions for accessing and manipulating atomic variables.

These functions are often implemented using `compare_and_swap()` operations. As an example, the following increments the atomic integer `sequence`:

```
increment(&sequence);
```

where the `increment()` function is implemented using the CAS instruction:

```
void increment(atomic_int *v)
{
   int temp;

   do {
      temp = *v;
   }
   while (temp != compare_and_swap(v, temp, temp+1));
}
```

It is important to note that although atomic variables provide atomic updates, they do not entirely solve race conditions in all circumstances. For example, in the bounded-buffer problem described in Section 6.1, we could use an atomic integer for `count`. This would ensure that the updates to `count` were atomic. However, the producer and consumer processes also have `while` loops whose condition depends on the value of `count`. Consider a situation in which the buffer is currently empty and two consumers are looping while waiting for `count` > 0. If a producer entered one item in the buffer, both consumers could exit their `while` loops (as `count` would no longer be equal to 0) and proceed to consume, even though the value of `count` was only set to 1.

Atomic variables are commonly used in operating systems as well as concurrent applications, although their use is often limited to single updates of shared data such as counters and sequence generators. In the following sections, we explore more robust tools that address race conditions in more generalized situations.

6.5 Mutex Locks

The hardware-based solutions to the critical-section problem presented in Section 6.4 are complicated as well as generally inaccessible to application programmers. Instead, operating-system designers build higher-level software tools to solve the critical-section problem. The simplest of these tools is the **mutex lock**. (In fact, the term *mutex* is short for *mut*ual *ex*clusion.) We use the mutex lock to protect critical sections and thus prevent race conditions. That is, a process must acquire the lock before entering a critical section; it releases the lock when it exits the critical section. The `acquire()` function acquires the lock, and the `release()` function releases the lock, as illustrated in Figure 6.10.

A mutex lock has a boolean variable `available` whose value indicates if the lock is available or not. If the lock is available, a call to `acquire()` succeeds, and the lock is then considered unavailable. A process that attempts to acquire an unavailable lock is blocked until the lock is released.

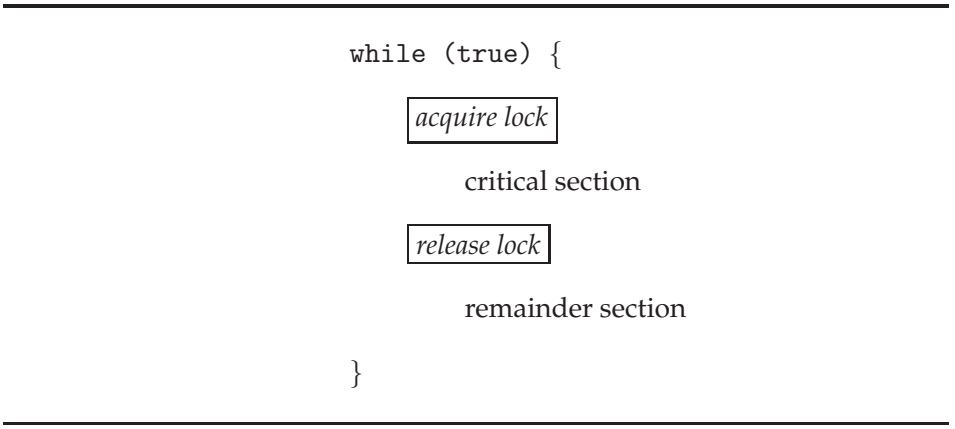

Figure 6.10 Solution to the critical-section problem using mutex locks.

The definition of `acquire()` is as follows:

```
acquire() {
    while (!available)
       ; /* busy wait */
    available = false;
}
```

The definition of `release()` is as follows:

```
release() {
   available = true;
}
```

Calls to either `acquire()` or `release()` must be performed atomically. Thus, mutex locks can be implemented using the CAS operation described in Section 6.4, and we leave the description of this technique as an exercise.

LOCK CONTENTION

Locks are either contended or uncontended. A lock is considered **contended** if a thread blocks while trying to acquire the lock. If a lock is available when a thread attempts to acquire it, the lock is considered **uncontended**. Contended locks can experience either ***high contention*** (a relatively large number of threads attempting to acquire the lock) or ***low contention*** (a relatively small number of threads attempting to acquire the lock.) Unsurprisingly, highly contended locks tend to decrease overall performance of concurrent applications.

WHAT IS MEANT BY "SHORT DURATION"?

Spinlocks are often identified as the locking mechanism of choice on multiprocessor systems when the lock is to be held for a short duration. But what exactly constitutes a *short duration*? Given that waiting on a lock requires two context switches—a context switch to move the thread to the waiting state and a second context switch to restore the waiting thread once the lock becomes available—the general rule is to use a spinlock if the lock will be held for a duration of less than two context switches.

The main disadvantage of the implementation given here is that it requires **busy waiting**. While a process is in its critical section, any other process that tries to enter its critical section must loop continuously in the call to `acquire()`. This continual looping is clearly a problem in a real multiprogramming system, where a single CPU core is shared among many processes. Busy waiting also wastes CPU cycles that some other process might be able to use productively. (In Section 6.6, we examine a strategy that avoids busy waiting by temporarily putting the waiting process to sleep and then awakening it once the lock becomes available.)

The type of mutex lock we have been describing is also called a **spinlock** because the process "spins" while waiting for the lock to become available. (We see the same issue with the code examples illustrating the `compare_and_swap()` instruction.) Spinlocks do have an advantage, however, in that no context switch is required when a process must wait on a lock, and a context switch may take considerable time. In certain circumstances on multicore systems, spinlocks are in fact the preferable choice for locking. If a lock is to be held for a short duration, one thread can "spin" on one processing core while another thread performs its critical section on another core. On modern multicore computing systems, spinlocks are widely used in many operating systems.

In Chapter 7 we examine how mutex locks can be used to solve classical synchronization problems. We also discuss how mutex locks and spinlocks are used in several operating systems, as well as in Pthreads.

6.6 Semaphores

Mutex locks, as we mentioned earlier, are generally considered the simplest of synchronization tools. In this section, we examine a more robust tool that can behave similarly to a mutex lock but can also provide more sophisticated ways for processes to synchronize their activities.

A **semaphore** `S` is an integer variable that, apart from initialization, is accessed only through two standard atomic operations: `wait()` and `signal()`. Semaphores were introduced by the Dutch computer scientist Edsger Dijkstra, and such, the `wait()` operation was originally termed `P` (from the Dutch

proberen, "to test"); `signal()` was originally called `V` (from *verhogen,* "to increment"). The definition of `wait()` is as follows:

```
wait(S) {
    while (S <= 0)
       ; // busy wait
    S--;
}
```

The definition of `signal()` is as follows:

```
signal(S) {
    S++;
}
```

All modifications to the integer value of the semaphore in the `wait()` and `signal()` operations must be executed atomically. That is, when one process modifies the semaphore value, no other process can simultaneously modify that same semaphore value. In addition, in the case of `wait(S)`, the testing of the integer value of `S` ($S \leq 0$), as well as its possible modification (`S--`), must be executed without interruption. We shall see how these operations can be implemented in Section 6.6.2. First, let's see how semaphores can be used.

6.6.1 Semaphore Usage

Operating systems often distinguish between counting and binary semaphores. The value of a **counting semaphore** can range over an unrestricted domain. The value of a **binary semaphore** can range only between 0 and 1. Thus, binary semaphores behave similarly to mutex locks. In fact, on systems that do not provide mutex locks, binary semaphores can be used instead for providing mutual exclusion.

Counting semaphores can be used to control access to a given resource consisting of a finite number of instances. The semaphore is initialized to the number of resources available. Each process that wishes to use a resource performs a `wait()` operation on the semaphore (thereby decrementing the count). When a process releases a resource, it performs a `signal()` operation (incrementing the count). When the count for the semaphore goes to 0, all resources are being used. After that, processes that wish to use a resource will block until the count becomes greater than 0.

We can also use semaphores to solve various synchronization problems. For example, consider two concurrently running processes: P_1 with a statement S_1 and P_2 with a statement S_2. Suppose we require that S_2 be executed only after S_1 has completed. We can implement this scheme readily by letting P_1 and P_2 share a common semaphore `synch`, initialized to 0. In process P_1, we insert the statements

```
S1;
signal(synch);
```

In process P_2, we insert the statements

```
wait(synch);
S2;
```

Because `synch` is initialized to 0, P_2 will execute S_2 only after P_1 has invoked `signal(synch)`, which is after statement S_1 has been executed.

6.6.2 Semaphore Implementation

Recall that the implementation of mutex locks discussed in Section 6.5 suffers from busy waiting. The definitions of the `wait()` and `signal()` semaphore operations just described present the same problem. To overcome this problem, we can modify the definition of the `wait()` and `signal()` operations as follows: When a process executes the `wait()` operation and finds that the semaphore value is not positive, it must wait. However, rather than engaging in busy waiting, the process can suspend itself. The suspend operation places a process into a waiting queue associated with the semaphore, and the state of the process is switched to the waiting state. Then control is transferred to the CPU scheduler, which selects another process to execute.

A process that is suspended, waiting on a semaphore `S`, should be restarted when some other process executes a `signal()` operation. The process is restarted by a `wakeup()` operation, which changes the process from the waiting state to the ready state. The process is then placed in the ready queue. (The CPU may or may not be switched from the running process to the newly ready process, depending on the CPU-scheduling algorithm.)

To implement semaphores under this definition, we define a semaphore as follows:

```
typedef struct {
    int value;
    struct process *list;
} semaphore;
```

Each semaphore has an integer `value` and a list of processes `list`. When a process must wait on a semaphore, it is added to the list of processes. A `signal()` operation removes one process from the list of waiting processes and awakens that process.

Now, the `wait()` semaphore operation can be defined as

```
wait(semaphore *S) {
        S->value--;
        if (S->value < 0) {
            add this process to S->list;
            sleep();
        }
}
```

and the `signal()` semaphore operation can be defined as

```
signal(semaphore *S) {
        S->value++;
        if (S->value <= 0) {
                remove a process P from S->list;
                wakeup(P);
        }
}
```

The `sleep()` operation suspends the process that invokes it. The `wakeup(P)` operation resumes the execution of a suspended process `P`. These two operations are provided by the operating system as basic system calls.

Note that in this implementation, semaphore values may be negative, whereas semaphore values are never negative under the classical definition of semaphores with busy waiting. If a semaphore value is negative, its magnitude is the number of processes waiting on that semaphore. This fact results from switching the order of the decrement and the test in the implementation of the `wait()` operation.

The list of waiting processes can be easily implemented by a link field in each process control block (PCB). Each semaphore contains an integer value and a pointer to a list of PCBs. One way to add and remove processes from the list so as to ensure bounded waiting is to use a FIFO queue, where the semaphore contains both head and tail pointers to the queue. In general, however, the list can use any queuing strategy. Correct usage of semaphores does not depend on a particular queuing strategy for the semaphore lists.

As mentioned, it is critical that semaphore operations be executed atomically. We must guarantee that no two processes can execute `wait()` and `signal()` operations on the same semaphore at the same time. This is a critical-section problem, and in a single-processor environment, we can solve it by simply inhibiting interrupts during the time the `wait()` and `signal()` operations are executing. This scheme works in a single-processor environment because, once interrupts are inhibited, instructions from different processes cannot be interleaved. Only the currently running process executes until interrupts are reenabled and the scheduler can regain control.

In a multicore environment, interrupts must be disabled on every processing core. Otherwise, instructions from different processes (running on different cores) may be interleaved in some arbitrary way. Disabling interrupts on every core can be a difficult task and can seriously diminish performance. Therefore, SMP systems must provide alternative techniques—such as `compare_and_swap()` or spinlocks—to ensure that `wait()` and `signal()` are performed atomically.

It is important to admit that we have not completely eliminated busy waiting with this definition of the `wait()` and `signal()` operations. Rather, we have moved busy waiting from the entry section to the critical sections of application programs. Furthermore, we have limited busy waiting to the critical sections of the `wait()` and `signal()` operations, and these sections are short (if properly coded, they should be no more than about ten instructions). Thus, the critical section is almost never occupied, and busy waiting occurs

rarely, and then for only a short time. An entirely different situation exists with application programs whose critical sections may be long (minutes or even hours) or may almost always be occupied. In such cases, busy waiting is extremely inefficient.

6.7 Monitors

Although semaphores provide a convenient and effective mechanism for process synchronization, using them incorrectly can result in timing errors that are difficult to detect, since these errors happen only if particular execution sequences take place, and these sequences do not always occur.

We have seen an example of such errors in the use of a count in our solution to the producer–consumer problem (Section 6.1). In that example, the timing problem happened only rarely, and even then the `count` value appeared to be reasonable—off by only 1. Nevertheless, the solution is obviously not an acceptable one. It is for this reason that mutex locks and semaphores were introduced in the first place.

Unfortunately, such timing errors can still occur when either mutex locks or semaphores are used. To illustrate how, we review the semaphore solution to the critical-section problem. All processes share a binary semaphore variable `mutex`, which is initialized to 1. Each process must execute `wait(mutex)` before entering the critical section and `signal(mutex)` afterward. If this sequence is not observed, two processes may be in their critical sections simultaneously. Next, we list several difficulties that may result. Note that these difficulties will arise even if a ***single*** process is not well behaved. This situation may be caused by an honest programming error or an uncooperative programmer.

- Suppose that a program interchanges the order in which the `wait()` and `signal()` operations on the semaphore `mutex` are executed, resulting in the following execution:

```
signal(mutex);
    ...
  critical section
    ...
wait(mutex);
```

  In this situation, several processes may be executing in their critical sections simultaneously, violating the mutual-exclusion requirement. This error may be discovered only if several processes are simultaneously active in their critical sections. Note that this situation may not always be reproducible.

- Suppose that a program replaces `signal(mutex)` with `wait(mutex)`. That is, it executes

```
wait(mutex);
    ...
  critical section
    ...
wait(mutex);
```

In this case, the process will permanently block on the second call to `wait()`, as the semaphore is now unavailable.

- Suppose that a process omits the `wait(mutex)`, or the `signal(mutex)`, or both. In this case, either mutual exclusion is violated or the process will permanently block.

These examples illustrate that various types of errors can be generated easily when programmers use semaphores or mutex locks incorrectly to solve the critical-section problem. One strategy for dealing with such errors is to incorporate simple synchronization tools as high-level language constructs. In this section, we describe one fundamental high-level synchronization construct—the **monitor** type.

6.7.1 Monitor Usage

An **abstract data type**—or ADT—encapsulates data with a set of functions to operate on that data that are independent of any specific implementation of the ADT. A ***monitor type*** is an ADT that includes a set of programmer-defined operations that are provided with mutual exclusion within the monitor. The monitor type also declares the variables whose values define the state of an

```
monitor monitor name
{
   /* shared variable declarations */

   function P1 ( . . . ) {
      . . .
   }

   function P2 ( . . . ) {
      . . .
   }

         .
         .
         .
   function Pn ( . . . ) {
      . . .
   }

   initialization_code ( . . . ) {
      . . .
   }
}
```

Figure 6.11 Pseudocode syntax of a monitor.

instance of that type, along with the bodies of functions that operate on those variables. The syntax of a monitor type is shown in Figure 6.11. The representation of a monitor type cannot be used directly by the various processes. Thus, a function defined within a monitor can access only those variables declared locally within the monitor and its formal parameters. Similarly, the local variables of a monitor can be accessed by only the local functions.

The monitor construct ensures that only one process at a time is active within the monitor. Consequently, the programmer does not need to code this synchronization constraint explicitly (Figure 6.12). However, the monitor construct, as defined so far, is not sufficiently powerful for modeling some synchronization schemes. For this purpose, we need to define additional synchronization mechanisms. These mechanisms are provided by the `condition` construct. A programmer who needs to write a tailor-made synchronization scheme can define one or more variables of type *condition*:

```
condition x, y;
```

The only operations that can be invoked on a condition variable are `wait()` and `signal()`. The operation

```
x.wait();
```

means that the process invoking this operation is suspended until another process invokes

```
x.signal();
```

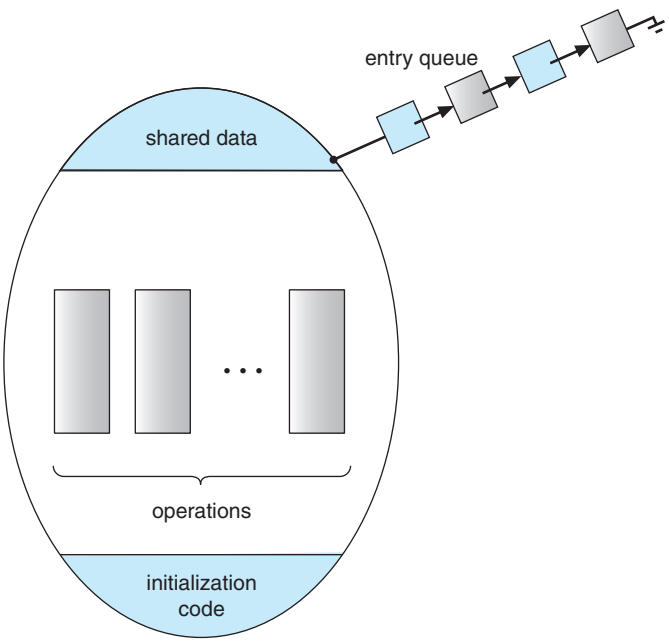

Figure 6.12 Schematic view of a monitor.

The `x.signal()` operation resumes exactly one suspended process. If no process is suspended, then the `signal()` operation has no effect; that is, the state of `x` is the same as if the operation had never been executed (Figure 6.13). Contrast this operation with the `signal()` operation associated with semaphores, which always affects the state of the semaphore.

Now suppose that, when the `x.signal()` operation is invoked by a process P, there exists a suspended process Q associated with condition `x`. Clearly, if the suspended process Q is allowed to resume its execution, the signaling process P must wait. Otherwise, both P and Q would be active simultaneously within the monitor. Note, however, that conceptually both processes can continue with their execution. Two possibilities exist:

1. **Signal and wait**. P either waits until Q leaves the monitor or waits for another condition.
2. **Signal and continue**. Q either waits until P leaves the monitor or waits for another condition.

There are reasonable arguments in favor of adopting either option. On the one hand, since P was already executing in the monitor, the ***signal-and-continue*** method seems more reasonable. On the other, if we allow thread P to continue, then by the time Q is resumed, the logical condition for which Q was waiting may no longer hold. A compromise between these two choices exists as well: when thread P executes the signal operation, it immediately leaves the monitor. Hence, Q is immediately resumed.

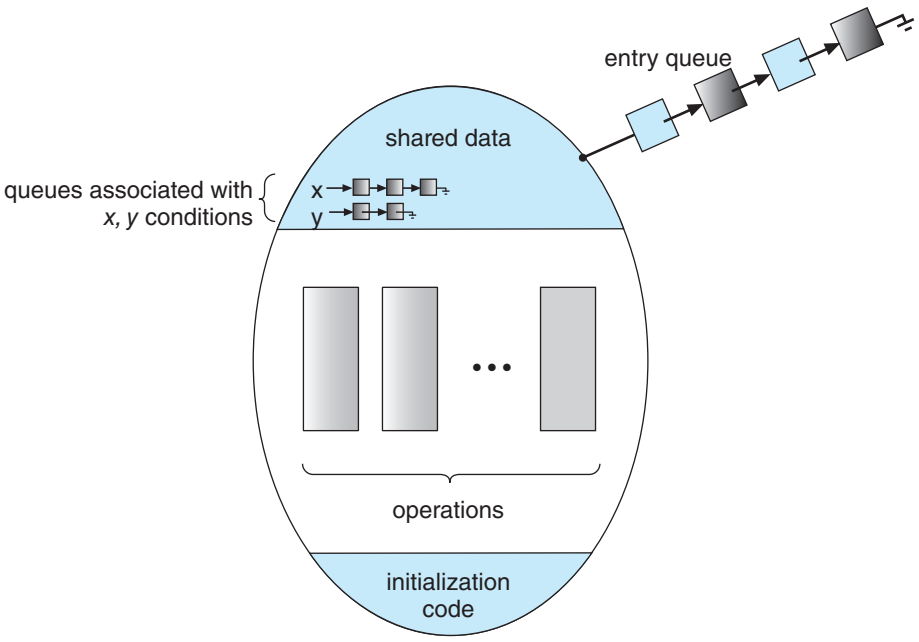

Figure 6.13 Monitor with condition variables.

Many programming languages have incorporated the idea of the monitor as described in this section, including Java and C#. Other languages—such as Erlang—provide concurrency support using a similar mechanism.

6.7.2 Implementing a Monitor Using Semaphores

We now consider a possible implementation of the monitor mechanism using semaphores. For each monitor, a binary semaphore `mutex` (initialized to 1) is provided to ensure mutual exclusion. A process must execute `wait(mutex)` before entering the monitor and must execute `signal(mutex)` after leaving the monitor.

We will use the signal-and-wait scheme in our implementation. Since a signaling process must wait until the resumed process either leaves or waits, an additional binary semaphore, `next`, is introduced, initialized to 0. The signaling processes can use `next` to suspend themselves. An integer variable `next_count` is also provided to count the number of processes suspended on `next`. Thus, each external function `F` is replaced by

```
wait(mutex);
    ...
  body of F
    ...
if (next_count > 0)
  signal(next);
else
  signal(mutex);
```

Mutual exclusion within a monitor is ensured.

We can now describe how condition variables are implemented as well. For each condition `x`, we introduce a binary semaphore `x_sem` and an integer variable `x_count`, both initialized to 0. The operation `x.wait()` can now be implemented as

```
x_count++;
if (next_count > 0)
  signal(next);
else
  signal(mutex);
wait(x_sem);
x_count--;
```

The operation `x.signal()` can be implemented as

```
if (x_count > 0) {
  next_count++;
  signal(x_sem);
  wait(next);
  next_count--;
}
```

This implementation is applicable to the definitions of monitors given by both Hoare and Brinch-Hansen (see the bibliographical notes at the end of the chapter). In some cases, however, the generality of the implementation is

```
monitor ResourceAllocator
{
   boolean busy;
   condition x;

   void acquire(int time) {
      if (busy)
         x.wait(time);
      busy = true;
   }

   void release() {
      busy = false;
      x.signal();
   }

   initialization_code() {
      busy = false;
   }
}
```

Figure 6.14 A monitor to allocate a single resource.

unnecessary, and a significant improvement in efficiency is possible. We leave this problem to you in Exercise 6.27.

6.7.3 Resuming Processes within a Monitor

We turn now to the subject of process-resumption order within a monitor. If several processes are suspended on condition `x`, and an `x.signal()` operation is executed by some process, then how do we determine which of the suspended processes should be resumed next? One simple solution is to use a first-come, first-served (FCFS) ordering, so that the process that has been waiting the longest is resumed first. In many circumstances, however, such a simple scheduling scheme is not adequate. In these circumstances, the **conditional-wait** construct can be used. This construct has the form

```
x.wait(c);
```

where `c` is an integer expression that is evaluated when the `wait()` operation is executed. The value of `c`, which is called a **priority number**, is then stored with the name of the process that is suspended. When `x.signal()` is executed, the process with the smallest priority number is resumed next.

To illustrate this new mechanism, consider the `ResourceAllocator` monitor shown in Figure 6.14, which controls the allocation of a single resource among competing processes. Each process, when requesting an allocation of this resource, specifies the maximum time it plans to use the resource. The monitor allocates the resource to the process that has the shortest time-allocation

request. A process that needs to access the resource in question must observe the following sequence:

```
R.acquire(t);
    ...
  access the resource;
    ...
R.release();
```

where R is an instance of type ResourceAllocator.

Unfortunately, the monitor concept cannot guarantee that the preceding access sequence will be observed. In particular, the following problems can occur:

- A process might access a resource without first gaining access permission to the resource.
- A process might never release a resource once it has been granted access to the resource.
- A process might attempt to release a resource that it never requested.
- A process might request the same resource twice (without first releasing the resource).

The same difficulties are encountered with the use of semaphores, and these difficulties are similar in nature to those that encouraged us to develop the monitor constructs in the first place. Previously, we had to worry about the correct use of semaphores. Now, we have to worry about the correct use of higher-level programmer-defined operations, with which the compiler can no longer assist us.

One possible solution to the current problem is to include the resource-access operations within the ResourceAllocator monitor. However, using this solution will mean that scheduling is done according to the built-in monitor-scheduling algorithm rather than the one we have coded.

To ensure that the processes observe the appropriate sequences, we must inspect all the programs that make use of the ResourceAllocator monitor and its managed resource. We must check two conditions to establish the correctness of this system. First, user processes must always make their calls on the monitor in a correct sequence. Second, we must be sure that an uncooperative process does not simply ignore the mutual-exclusion gateway provided by the monitor and try to access the shared resource directly, without using the access protocols. Only if these two conditions can be ensured can we guarantee that no time-dependent errors will occur and that the scheduling algorithm will not be defeated.

Although this inspection may be possible for a small, static system, it is not reasonable for a large system or a dynamic system. This access-control problem can be solved only through the use of the additional mechanisms that are described in Chapter 17.

6.8 Liveness

One consequence of using synchronization tools to coordinate access to critical sections is the possibility that a process attempting to enter its critical section will wait indefinitely. Recall that in Section 6.2, we outlined three criteria that solutions to the critical-section problem must satisfy. Indefinite waiting violates two of these—the progress and bounded-waiting criteria.

Liveness refers to a set of properties that a system must satisfy to ensure that processes make progress during their execution life cycle. A process waiting indefinitely under the circumstances just described is an example of a "liveness failure."

There are many different forms of liveness failure; however, all are generally characterized by poor performance and responsiveness. A very simple example of a liveness failure is an infinite loop. A busy wait loop presents the *possibility* of a liveness failure, especially if a process may loop an arbitrarily long period of time. Efforts at providing mutual exclusion using tools such as mutex locks and semaphores can often lead to such failures in concurrent programming. In this section, we explore two situations that can lead to liveness failures.

6.8.1 Deadlock

The implementation of a semaphore with a waiting queue may result in a situation where two or more processes are waiting indefinitely for an event that can be caused only by one of the waiting processes. The event in question is the execution of a `signal()` operation. When such a state is reached, these processes are said to be **deadlocked**.

To illustrate this, consider a system consisting of two processes, P_0 and P_1, each accessing two semaphores, `S` and `Q`, set to the value 1:

P_0	P_1
`wait(S);`	`wait(Q);`
`wait(Q);`	`wait(S);`
.	.
.	.
.	.
`signal(S);`	`signal(Q);`
`signal(Q);`	`signal(S);`

Suppose that P_0 executes `wait(S)` and then P_1 executes `wait(Q)`. When P_0 executes `wait(Q)`, it must wait until P_1 executes `signal(Q)`. Similarly, when P_1 executes `wait(S)`, it must wait until P_0 executes `signal(S)`. Since these `signal()` operations cannot be executed, P_0 and P_1 are deadlocked.

We say that a set of processes is in a deadlocked state when *every process in the set is waiting for an event that can be caused only by another process in the set*. The "events" with which we are mainly concerned here are the acquisition and release of resources such as mutex locks and semaphores. Other types of events may result in deadlocks, as we show in more detail in Chapter 8. In

that chapter, we describe various mechanisms for dealing with the deadlock problem, as well as other forms of liveness failures.

6.8.2 Priority Inversion

A scheduling challenge arises when a higher-priority process needs to read or modify kernel data that are currently being accessed by a lower-priority process—or a chain of lower-priority processes. Since kernel data are typically protected with a lock, the higher-priority process will have to wait for a lower-priority one to finish with the resource. The situation becomes more complicated if the lower-priority process is preempted in favor of another process with a higher priority.

As an example, assume we have three processes—L, M, and H—whose priorities follow the order $L < M < H$. Assume that process H requires a semaphore S, which is currently being accessed by process L. Ordinarily, process H would wait for L to finish using resource S. However, now suppose that process M becomes runnable, thereby preempting process L. Indirectly, a process with a lower priority—process M—has affected how long process H must wait for L to relinquish resource S.

This liveness problem is known as **priority inversion**, and it can occur only in systems with more than two priorities. Typically, priority inversion is avoided by implementing a **priority-inheritance protocol**. According to this protocol, all processes that are accessing resources needed by a higher-priority process inherit the higher priority until they are finished with the resources in question. When they are finished, their priorities revert to their original values. In the example above, a priority-inheritance protocol would allow process L to temporarily inherit the priority of process H, thereby preventing process M from preempting its execution. When process L had finished using resource S, it would relinquish its inherited priority from H and assume its original priority. Because resource S would now be available, process H—not M—would run next.

6.9 Evaluation

We have described several different synchronization tools that can be used to solve the critical-section problem. Given correct implementation and usage, these tools can be used effectively to ensure mutual exclusion as well as address liveness issues. With the growth of concurrent programs that leverage the power of modern multicore computer systems, increasing attention is being paid to the performance of synchronization tools. Trying to identify when to use which tool, however, can be a daunting challenge. In this section, we present some simple strategies for determining when to use specific synchronization tools.

The hardware solutions outlined in Section 6.4 are considered very low level and are typically used as the foundations for constructing other synchronization tools, such as mutex locks. However, there has been a recent focus on using the CAS instruction to construct **lock-free** algorithms that provide protection from race conditions without requiring the overhead of locking. Although these lock-free solutions are gaining popularity due to low overhead

PRIORITY INVERSION AND THE MARS PATHFINDER

Priority inversion can be more than a scheduling inconvenience. On systems with tight time constraints—such as real-time systems—priority inversion can cause a process to take longer than it should to accomplish a task. When that happens, other failures can cascade, resulting in system failure.

Consider the Mars Pathfinder, a NASA space probe that landed a robot, the Sojourner rover, on Mars in 1997 to conduct experiments. Shortly after the Sojourner began operating, it started to experience frequent computer resets. Each reset reinitialized all hardware and software, including communications. If the problem had not been solved, the Sojourner would have failed in its mission.

The problem was caused by the fact that one high-priority task, "bc_dist," was taking longer than expected to complete its work. This task was being forced to wait for a shared resource that was held by the lower-priority "ASI/MET" task, which in turn was preempted by multiple medium-priority tasks. The "bc_dist" task would stall waiting for the shared resource, and ultimately the "bc_sched" task would discover the problem and perform the reset. The Sojourner was suffering from a typical case of priority inversion.

The operating system on the Sojourner was the VxWorks real-time operating system, which had a global variable to enable priority inheritance on all semaphores. After testing, the variable was set on the Sojourner (on Mars!), and the problem was solved.

A full description of the problem, its detection, and its solution was written by the software team lead and is available at http://research.microsoft.com/en-us/um/people/mbj/mars_pathfinder/authoritative_account.html.

and ability to scale, the algorithms themselves are often difficult to develop and test. (In the exercises at the end of this chapter, we ask you to evaluate the correctness of a lock-free stack.)

CAS-based approaches are considered an *optimistic* approach—you optimistically first update a variable and then use collision detection to see if another thread is updating the variable concurrently. If so, you repeatedly retry the operation until it is successfully updated without conflict. Mutual-exclusion locking, in contrast, is considered a *pessimistic* strategy; you assume another thread is concurrently updating the variable, so you pessimistically acquire the lock before making any updates.

The following guidelines identify general rules concerning performance differences between CAS-based synchronization and traditional synchronization (such as mutex locks and semaphores) under varying contention loads:

- **Uncontended**. Although both options are generally fast, CAS protection will be somewhat faster than traditional synchronization.
- **Moderate contention**. CAS protection will be faster—possibly much faster—than traditional synchronization.

- **High contention**. Under very highly contended loads, traditional synchronization will ultimately be faster than CAS-based synchronization.

Moderate contention is particularly interesting to examine. In this scenario, the CAS operation succeeds most of the time, and when it fails, it will iterate through the loop shown in Figure 6.8 only a few times before ultimately succeeding. By comparison, with mutual-exclusion locking, *any* attempt to acquire a contended lock will result in a more complicated—and time-intensive—code path that suspends a thread and places it on a wait queue, requiring a context switch to another thread.

The choice of a mechanism that addresses race conditions can also greatly affect system performance. For example, atomic integers are much lighter weight than traditional locks, and are generally more appropriate than mutex locks or semaphores for single updates to shared variables such as counters. We also see this in the design of operating systems where spinlocks are used on multiprocessor systems when locks are held for short durations. In general, mutex locks are simpler and require less overhead than semaphores and are preferable to binary semaphores for protecting access to a critical section. However, for some uses—such as controlling access to a finite number of resources—a counting semaphore is generally more appropriate than a mutex lock. Similarly, in some instances, a reader–writer lock may be preferred over a mutex lock, as it allows a higher degree of concurrency (that is, multiple readers).

The appeal of higher-level tools such as monitors and condition variables is based on their simplicity and ease of use. However, such tools may have significant overhead and, depending on their implementation, may be less likely to scale in highly contended situations.

Fortunately, there is much ongoing research toward developing scalable, efficient tools that address the demands of concurrent programming. Some examples include:

- Designing compilers that generate more efficient code.
- Developing languages that provide support for concurrent programming.
- Improving the performance of existing libraries and APIs.

In the next chapter, we examine how various operating systems and APIs available to developers implement the synchronization tools presented in this chapter.

6.10 Summary

- A race condition occurs when processes have concurrent access to shared data and the final result depends on the particular order in which concurrent accesses occur. Race conditions can result in corrupted values of shared data.
- A critical section is a section of code where shared data may be manipulated and a possible race condition may occur. The critical-section problem

is to design a protocol whereby processes can synchronize their activity to cooperatively share data.

- A solution to the critical-section problem must satisfy the following three requirements: (1) mutual exclusion, (2) progress, and (3) bounded waiting. Mutual exclusion ensures that only one process at a time is active in its critical section. Progress ensures that programs will cooperatively determine what process will next enter its critical section. Bounded waiting limits how much time a program will wait before it can enter its critical section.
- Software solutions to the critical-section problem, such as Peterson's solution, do not work well on modern computer architectures.
- Hardware support for the critical-section problem includes memory barriers; hardware instructions, such as the compare-and-swap instruction; and atomic variables.
- A mutex lock provides mutual exclusion by requiring that a process acquire a lock before entering a critical section and release the lock on exiting the critical section.
- Semaphores, like mutex locks, can be used to provide mutual exclusion. However, whereas a mutex lock has a binary value that indicates if the lock is available or not, a semaphore has an integer value and can therefore be used to solve a variety of synchronization problems.
- A monitor is an abstract data type that provides a high-level form of process synchronization. A monitor uses condition variables that allow processes to wait for certain conditions to become true and to signal one another when conditions have been set to true.
- Solutions to the critical-section problem may suffer from liveness problems, including deadlock.
- The various tools that can be used to solve the critical-section problem as well as to synchronize the activity of processes can be evaluated under varying levels of contention. Some tools work better under certain contention loads than others.

Practice Exercises

6.1 In Section 6.4, we mentioned that disabling interrupts frequently can affect the system's clock. Explain why this can occur and how such effects can be minimized.

6.2 What is the meaning of the term ***busy waiting***? What other kinds of waiting are there in an operating system? Can busy waiting be avoided altogether? Explain your answer.

6.3 Explain why spinlocks are not appropriate for single-processor systems yet are often used in multiprocessor systems.

6.4 Show that, if the `wait()` and `signal()` semaphore operations are not executed atomically, then mutual exclusion may be violated.

6.5 Illustrate how a binary semaphore can be used to implement mutual exclusion among *n* processes.

6.6 Race conditions are possible in many computer systems. Consider a banking system that maintains an account balance with two functions: `deposit(amount)` and `withdraw(amount)`. These two functions are passed the `amount` that is to be deposited or withdrawn from the bank account balance. Assume that a husband and wife share a bank account. Concurrently, the husband calls the `withdraw()` function, and the wife calls `deposit()`. Describe how a race condition is possible and what might be done to prevent the race condition from occurring.

Further Reading

The mutual-exclusion problem was first discussed in a classic paper by [Dijkstra (1965)]. The semaphore concept was suggested by [Dijkstra (1965)]. The monitor concept was developed by [Brinch-Hansen (1973)]. [Hoare (1974)] gave a complete description of the monitor.

For more on the Mars Pathfinder problem see http://research.microsoft.com/en-us/um/people/mbj/mars_pathfinder/authoritative_account.html

A thorough discussion of memory barriers and cache memory is presented in [Mckenney (2010)]. [Herlihy and Shavit (2012)] presents details on several issues related to multiprocessor programming, including memory models and compare-and-swap instructions. [Bahra (2013)] examines nonblocking algorithms on modern multicore systems.

Bibliography

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Chapter 6 Exercises

6.7 The pseudocode of Figure 6.15 illustrates the basic `push()` and `pop()` operations of an array-based stack. Assuming that this algorithm could be used in a concurrent environment, answer the following questions:

a. What data have a race condition?

b. How could the race condition be fixed?

6.8 Race conditions are possible in many computer systems. Consider an online auction system where the current highest bid for each item must be maintained. A person who wishes to bid on an item calls the `bid(amount)` function, which compares the amount being bid to the current highest bid. If the amount exceeds the current highest bid, the highest bid is set to the new amount. This is illustrated below:

```
void bid(double amount) {
   if (amount > highestBid)
      highestBid = amount;
}
```

```
push(item) {
   if (top < SIZE) {
      stack[top] = item;
      top++;
   }
   else
      ERROR
}

pop() {
   if (!is_empty()) {
      top--;
      return stack[top];
   }
   else
      ERROR
}

is_empty() {
   if (top == 0)
      return true;
   else
      return false;
}
```

Figure 6.16 Array-based stack for Exercise 6.12.

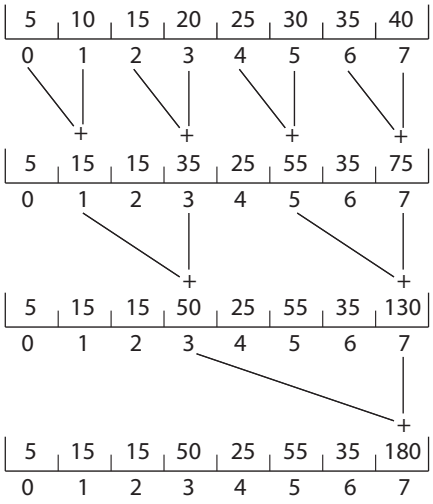

Figure 6.17 Summing an array as a series of partial sums for Exercise 6.14.

Describe how a race condition is possible in this situation and what might be done to prevent the race condition from occurring.

6.9 The following program example can be used to sum the array `values` of size *N* elements in parallel on a system containing *N* computing cores (there is a separate processor for each array element):

```
for j = 1 to log_2(N) {
   for k = 1 to N {
      if ((k + 1) % pow(2,j) == 0) {
         values[k] += values[k - pow(2,(j-1))]
      }
   }
}
```

This has the effect of summing the elements in the array as a series of partial sums, as shown in Figure 6.16. After the code has executed, the sum of all elements in the array is stored in the last array location. Are there any race conditions in the above code example? If so, identify where they occur and illustrate with an example. If not, demonstrate why this algorithm is free from race conditions.

6.10 The `compare_and_swap()` instruction can be used to design lock-free data structures such as stacks, queues, and lists. The program example shown in Figure 6.17 presents a possible solution to a lock-free stack using CAS instructions, where the stack is represented as a linked list of `Node` elements with `top` representing the top of the stack. Is this implementation free from race conditions?

```
typedef struct node {
   value_t data;
   struct node *next;
} Node;

Node *top; // top of stack

void push(value_t item) {
   Node *old_node;
   Node *new_node;

   new_node = malloc(sizeof(Node));
   new_node->data = item;

   do {
      old_node = top;
      new_node->next = old_node;
   }
   while (compare_and_swap(top,old_node,new_node) != old_node);
}

value_t pop() {
   Node *old_node;
   Node *new_node;

   do {
      old_node = top;
      if (old_node == NULL)
         return NULL;
      new_node = old_node->next;
   }
   while (compare_and_swap(top,old_node,new_node) != old_node);

   return old_node->data;
}
```

Figure 6.18 Lock-free stack for Exercise 6.15.

6.11 One approach for using `compare_and_swap()` for implementing a spinlock is as follows:

```
void lock_spinlock(int *lock) {
   while (compare_and_swap(lock, 0, 1) != 0)
      ; /* spin */
}
```

A suggested alternative approach is to use the "compare and compare-and-swap" idiom, which checks the status of the lock before invoking the

`compare_and_swap()` operation. (The rationale behind this approach is to invoke `compare_and_swap()`only if the lock is currently available.) This strategy is shown below:

```
void lock_spinlock(int *lock) {
{
   while (true) {
      if (*lock == 0) {
         /* lock appears to be available */

         if (!compare_and_swap(lock, 0, 1))
            break;
      }
   }
}
```

Does this "compare and compare-and-swap" idiom work appropriately for implementing spinlocks? If so, explain. If not, illustrate how the integrity of the lock is compromised.

6.12 Some semaphore implementations provide a function `getValue()` that returns the current value of a semaphore. This function may, for instance, be invoked prior to calling `wait()` so that a process will only call `wait()` if the value of the semaphore is > 0, thereby preventing blocking while waiting for the semaphore. For example:

```
if (getValue(&sem) > 0)
   wait(&sem);
```

Many developers argue against such a function and discourage its use. Describe a potential problem that could occur when using the function `getValue()` in this scenario.

6.13 The first known correct software solution to the critical-section problem for two processes was developed by Dekker. The two processes, P_0 and P_1, share the following variables:

```
boolean flag[2]; /* initially false */
int turn;
```

The structure of process P_i (`i` == 0 or 1) is shown in Figure 6.18. The other process is P_j (`j` == 1 or 0). Prove that the algorithm satisfies all three requirements for the critical-section problem.

6.14 The first known correct software solution to the critical-section problem for n processes with a lower bound on waiting of $n - 1$ turns was presented by Eisenberg and McGuire. The processes share the following variables:

```
enum pstate {idle, want_in, in_cs};
pstate flag[n];
int turn;
```

```
while (true) {
   flag[i] = true;

   while (flag[j]) {
      if (turn == j) {
         flag[i] = false;
         while (turn == j)
            ; /* do nothing */
         flag[i] = true;
      }
   }

      /* critical section */

   turn = j;
   flag[i] = false;

      /* remainder section */
}
```

Figure 6.19 The structure of process P_i in Dekker's algorithm.

All the elements of `flag` are initially `idle`. The initial value of `turn` is immaterial (between 0 and `n-1`). The structure of process P_i is shown in Figure 6.19. Prove that the algorithm satisfies all three requirements for the critical-section problem.

6.15 Explain why implementing synchronization primitives by disabling interrupts is not appropriate in a single-processor system if the synchronization primitives are to be used in user-level programs.

6.16 Consider how to implement a mutex lock using the `compare_and_swap()` instruction. Assume that the following structure defining the mutex lock is available:

```
typedef struct {
     int available;
} lock;
```

The value `(available == 0)` indicates that the lock is available, and a value of 1 indicates that the lock is unavailable. Using this `struct`, illustrate how the following functions can be implemented using the `compare_and_swap()` instruction:

- `void acquire(lock *mutex)`
- `void release(lock *mutex)`

Be sure to include any initialization that may be necessary.

```
while (true) {
   while (true) {
      flag[i] = want_in;
      j = turn;

      while (j != i) {
         if (flag[j] != idle) {
            j = turn;
         else
            j = (j + 1) % n;
      }

      flag[i] = in_cs;
      j = 0;

      while ( (j < n) && (j == i || flag[j] != in_cs))
         j++;

      if ( (j >= n) && (turn == i || flag[turn] == idle))
         break;
   }

      /* critical section */

   j = (turn + 1) % n;

   while (flag[j] == idle)
      j = (j + 1) % n;

   turn = j;
   flag[i] = idle;

      /* remainder section */
}
```

Figure 6.20 The structure of process P_i in Eisenberg and McGuire's algorithm.

6.17 Explain why interrupts are not appropriate for implementing synchronization primitives in multiprocessor systems.

6.18 The implementation of mutex locks provided in Section 6.5 suffers from busy waiting. Describe what changes would be necessary so that a process waiting to acquire a mutex lock would be blocked and placed into a waiting queue until the lock became available.

6.19 Assume that a system has multiple processing cores. For each of the following scenarios, describe which is a better locking mechanism—a

spinlock or a mutex lock where waiting processes sleep while waiting for the lock to become available:

- The lock is to be held for a short duration.
- The lock is to be held for a long duration.
- A thread may be put to sleep while holding the lock.

6.20 Assume that a context switch takes T time. Suggest an upper bound (in terms of T) for holding a spinlock. If the spinlock is held for any longer, a mutex lock (where waiting threads are put to sleep) is a better alternative.

6.21 A multithreaded web server wishes to keep track of the number of requests it services (known as ***hits***). Consider the two following strategies to prevent a race condition on the variable `hits`. The first strategy is to use a basic mutex lock when updating `hits`:

```
int hits;
mutex_lock hit_lock;

hit_lock.acquire();
hits++;
hit_lock.release();
```

A second strategy is to use an atomic integer:

```
atomic_t hits;
atomic_inc(&hits);
```

Explain which of these two strategies is more efficient.

6.22 Consider the code example for allocating and releasing processes shown in Figure 6.20.

a. Identify the race condition(s).

b. Assume you have a mutex lock named `mutex` with the operations `acquire()` and `release()`. Indicate where the locking needs to be placed to prevent the race condition(s).

c. Could we replace the integer variable

```
int number_of_processes = 0
```

with the atomic integer

```
atomic_t number_of_processes = 0
```

to prevent the race condition(s)?

6.23 Servers can be designed to limit the number of open connections. For example, a server may wish to have only N socket connections at any point in time. As soon as N connections are made, the server will not accept another incoming connection until an existing connection is

```
#define MAX_PROCESSES 255
int number_of_processes = 0;

/* the implementation of fork() calls this function */
int allocate_process() {
int new_pid;

   if (number_of_processes == MAX_PROCESSES)
      return -1;
   else {
      /* allocate necessary process resources */
      ++number_of_processes;

      return new_pid;
   }
}

/* the implementation of exit() calls this function */
void release_process() {
    /* release process resources */
    --number_of_processes;
}
```

Figure 6.21 Allocating and releasing processes for Exercise 6.27.

released. Illustrate how semaphores can be used by a server to limit the number of concurrent connections.

6.24 In Section 6.7, we use the following illustration as an incorrect use of semaphores to solve the critical-section problem:

```
wait(mutex);
   ...
critical section
   ...
wait(mutex);
```

Explain why this is an example of a liveness failure.

6.25 Demonstrate that monitors and semaphores are equivalent to the degree that they can be used to implement solutions to the same types of synchronization problems.

6.26 Describe how the `signal()` operation associated with monitors differs from the corresponding operation defined for semaphores.

6.27 Suppose the `signal()` statement can appear only as the last statement in a monitor function. Suggest how the implementation described in Section 6.7 can be simplified in this situation.

6.28 Consider a system consisting of processes $P_1, P_2, ..., P_n$, each of which has a unique priority number. Write a monitor that allocates three identical printers to these processes, using the priority numbers for deciding the order of allocation.

6.29 A file is to be shared among different processes, each of which has a unique number. The file can be accessed simultaneously by several processes, subject to the following constraint: the sum of all unique numbers associated with all the processes currently accessing the file must be less than n. Write a monitor to coordinate access to the file.

6.30 When a signal is performed on a condition inside a monitor, the signaling process can either continue its execution or transfer control to the process that is signaled. How would the solution to the preceding exercise differ with these two different ways in which signaling can be performed?

6.31 Design an algorithm for a monitor that implements an alarm clock that enables a calling program to delay itself for a specified number of time units (*ticks*). You may assume the existence of a real hardware clock that invokes a function `tick()` in your monitor at regular intervals.

6.32 Discuss ways in which the priority inversion problem could be addressed in a real-time system. Also discuss whether the solutions could be implemented within the context of a proportional share scheduler.

Programming Problems

6.33 Assume that a finite number of resources of a single resource type must be managed. Processes may ask for a number of these resources and will return them once finished. As an example, many commercial software packages provide a given number of ***licenses***, indicating the number of applications that may run concurrently. When the application is started, the license count is decremented. When the application is terminated, the license count is incremented. If all licenses are in use, requests to start the application are denied. Such a request will be granted only when an existing license holder terminates the application and a license is returned.

The following program segment is used to manage a finite number of instances of an available resource. The maximum number of resources and the number of available resources are declared as follows:

```
#define MAX_RESOURCES 5
int available_resources = MAX_RESOURCES;
```

When a process wishes to obtain a number of resources, it invokes the `decrease_count()` function:

```
/* decrease available_resources by count resources */
/* return 0 if sufficient resources available, */
/* otherwise return -1 */
int decrease_count(int count) {
   if (available_resources < count)
      return -1;
   else {
      available_resources -= count;

      return 0;
   }
}
```

When a process wants to return a number of resources, it calls the `increase_count()` function:

```
/* increase available_resources by count */
int increase_count(int count) {
   available_resources += count;

   return 0;
}
```

The preceding program segment produces a race condition. Do the following:

a. Identify the data involved in the race condition.

b. Identify the location (or locations) in the code where the race condition occurs.

c. Using a semaphore or mutex lock, fix the race condition. It is permissible to modify the `decrease_count()` function so that the calling process is blocked until sufficient resources are available.

6.34 The `decrease_count()` function in the previous exercise currently returns 0 if sufficient resources are available and −1 otherwise. This leads to awkward programming for a process that wishes to obtain a number of resources:

```
while (decrease_count(count) == -1)
  ;
```

Rewrite the resource-manager code segment using a monitor and condition variables so that the `decrease_count()` function suspends the process until sufficient resources are available. This will allow a process to invoke `decrease_count()` by simply calling

```
decrease_count(count);
```

The process will return from this function call only when sufficient resources are available.

Synchronization Examples

In Chapter 6, we presented the critical-section problem and focused on how race conditions can occur when multiple concurrent processes share data. We went on to examine several tools that address the critical-section problem by preventing race conditions from occurring. These tools ranged from low-level hardware solutions (such as memory barriers and the compare-and-swap operation) to increasingly higher-level tools (from mutex locks to semaphores to monitors). We also discussed various challenges in designing applications that are free from race conditions, including liveness hazards such as deadlocks. In this chapter, we apply the tools presented in Chapter 6 to several classic synchronization problems. We also explore the synchronization mechanisms used by the Linux, UNIX, and Windows operating systems, and we describe API details for both Java and POSIX systems.

CHAPTER OBJECTIVES

- Explain the bounded-buffer, readers–writers, and dining–philosophers synchronization problems.
- Describe specific tools used by Linux and Windows to solve process synchronization problems.
- Illustrate how POSIX and Java can be used to solve process synchronization problems.
- Design and develop solutions to process synchronization problems using POSIX and Java APIs.

7.1 Classic Problems of Synchronization

In this section, we present a number of synchronization problems as examples of a large class of concurrency-control problems. These problems are used for testing nearly every newly proposed synchronization scheme. In our solutions to the problems, we use semaphores for synchronization, since that is the

```
while (true) {
      . . .
   /* produce an item in next_produced */
      . . .
   wait(empty);
   wait(mutex);
      . . .
   /* add next_produced to the buffer */
      . . .
   signal(mutex);
   signal(full);
}
```

Figure 7.1 The structure of the producer process.

traditional way to present such solutions. However, actual implementations of these solutions could use mutex locks in place of binary semaphores.

7.1.1 The Bounded-Buffer Problem

The *bounded-buffer problem* was introduced in Section 6.1; it is commonly used to illustrate the power of synchronization primitives. Here, we present a general structure of this scheme without committing ourselves to any particular implementation. We provide a related programming project in the exercises at the end of the chapter.

In our problem, the producer and consumer processes share the following data structures:

```
int n;
semaphore mutex = 1;
semaphore empty = n;
semaphore full = 0
```

We assume that the pool consists of `n` buffers, each capable of holding one item. The `mutex` binary semaphore provides mutual exclusion for accesses to the buffer pool and is initialized to the value 1. The `empty` and `full` semaphores count the number of empty and full buffers. The semaphore `empty` is initialized to the value `n`; the semaphore `full` is initialized to the value 0.

The code for the producer process is shown in Figure 7.1, and the code for the consumer process is shown in Figure 7.2. Note the symmetry between the producer and the consumer. We can interpret this code as the producer producing full buffers for the consumer or as the consumer producing empty buffers for the producer.

7.1.2 The Readers–Writers Problem

Suppose that a database is to be shared among several concurrent processes. Some of these processes may want only to read the database, whereas others may want to update (that is, read and write) the database. We distinguish

```
while (true) {
   wait(full);
   wait(mutex);
      . . .
   /* remove an item from buffer to next_consumed */
      . . .
   signal(mutex);
   signal(empty);
      . . .
   /* consume the item in next_consumed */
      . . .
}
```

Figure 7.2 The structure of the consumer process.

between these two types of processes by referring to the former as ***readers*** and to the latter as ***writers***. Obviously, if two readers access the shared data simultaneously, no adverse effects will result. However, if a writer and some other process (either a reader or a writer) access the database simultaneously, chaos may ensue.

To ensure that these difficulties do not arise, we require that the writers have exclusive access to the shared database while writing to the database. This synchronization problem is referred to as the **readers–writers problem**. Since it was originally stated, it has been used to test nearly every new synchronization primitive.

The readers–writers problem has several variations, all involving priorities. The simplest one, referred to as the ***first*** readers–writers problem, requires that no reader be kept waiting unless a writer has already obtained permission to use the shared object. In other words, no reader should wait for other readers to finish simply because a writer is waiting. The ***second*** readers–writers problem requires that, once a writer is ready, that writer perform its write as soon as possible. In other words, if a writer is waiting to access the object, no new readers may start reading.

A solution to either problem may result in starvation. In the first case, writers may starve; in the second case, readers may starve. For this reason, other variants of the problem have been proposed. Next, we present a solution to the first readers–writers problem. See the bibliographical notes at the end of the chapter for references describing starvation-free solutions to the second readers–writers problem.

In the solution to the first readers–writers problem, the reader processes share the following data structures:

```
semaphore rw_mutex = 1;
semaphore mutex = 1;
int read_count = 0;
```

The binary semaphores `mutex` and `rw_mutex` are initialized to 1; `read_count` is a counting semaphore initialized to 0. The semaphore `rw_mutex`

```
while (true) {
   wait(rw_mutex);
      . . .
   /* writing is performed */
      . . .
   signal(rw_mutex);
}
```

Figure 7.3 The structure of a writer process.

is common to both reader and writer processes. The `mutex` semaphore is used to ensure mutual exclusion when the variable `read_count` is updated. The `read_count` variable keeps track of how many processes are currently reading the object. The semaphore `rw_mutex` functions as a mutual exclusion semaphore for the writers. It is also used by the first or last reader that enters or exits the critical section. It is not used by readers that enter or exit while other readers are in their critical sections.

The code for a writer process is shown in Figure 7.3; the code for a reader process is shown in Figure 7.4. Note that, if a writer is in the critical section and n readers are waiting, then one reader is queued on `rw_mutex`, and $n - 1$ readers are queued on `mutex`. Also observe that, when a writer executes `signal(rw_mutex)`, we may resume the execution of either the waiting readers or a single waiting writer. The selection is made by the scheduler.

The readers–writers problem and its solutions have been generalized to provide **reader–writer** locks on some systems. Acquiring a reader–writer lock requires specifying the mode of the lock: either *read* or *write* access. When a

```
while (true) {
   wait(mutex);
   read_count++;
   if (read_count == 1)
      wait(rw_mutex);
   signal(mutex);
      . . .
   /* reading is performed */
      . . .
   wait(mutex);
   read_count--;
   if (read_count == 0)
      signal(rw_mutex);
   signal(mutex);
}
```

Figure 7.4 The structure of a reader process.

process wishes only to read shared data, it requests the reader–writer lock in read mode. A process wishing to modify the shared data must request the lock in write mode. Multiple processes are permitted to concurrently acquire a reader–writer lock in read mode, but only one process may acquire the lock for writing, as exclusive access is required for writers.

Reader–writer locks are most useful in the following situations:

- In applications where it is easy to identify which processes only read shared data and which processes only write shared data.
- In applications that have more readers than writers. This is because reader–writer locks generally require more overhead to establish than semaphores or mutual-exclusion locks. The increased concurrency of allowing multiple readers compensates for the overhead involved in setting up the reader–writer lock.

7.1.3 The Dining-Philosophers Problem

Consider five philosophers who spend their lives thinking and eating. The philosophers share a circular table surrounded by five chairs, each belonging to one philosopher. In the center of the table is a bowl of rice, and the table is laid with five single chopsticks (Figure 7.5). When a philosopher thinks, she does not interact with her colleagues. From time to time, a philosopher gets hungry and tries to pick up the two chopsticks that are closest to her (the chopsticks that are between her and her left and right neighbors). A philosopher may pick up only one chopstick at a time. Obviously, she cannot pick up a chopstick that is already in the hand of a neighbor. When a hungry philosopher has both her chopsticks at the same time, she eats without releasing the chopsticks. When she is finished eating, she puts down both chopsticks and starts thinking again.

The **dining-philosophers problem** is considered a classic synchronization problem neither because of its practical importance nor because computer scientists dislike philosophers but because it is an example of a large class of concurrency-control problems. It is a simple representation of the need

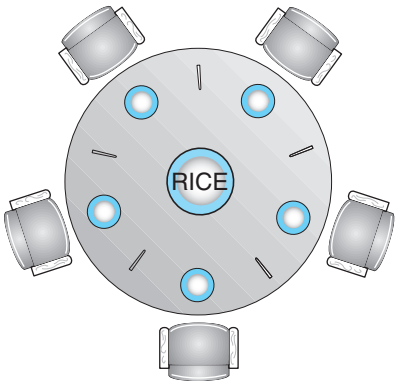

Figure 7.5 The situation of the dining philosophers.

```
while (true) {
   wait(chopstick[i]);
   wait(chopstick[(i+1) % 5]);
      . . .
   /* eat for a while */
      . . .
   signal(chopstick[i]);
   signal(chopstick[(i+1) % 5]);
      . . .
   /* think for awhile */
      . . .
}
```

Figure 7.6 The structure of philosopher *i*.

to allocate several resources among several processes in a deadlock-free and starvation-free manner.

7.1.3.1 Semaphore Solution

One simple solution is to represent each chopstick with a semaphore. A philosopher tries to grab a chopstick by executing a `wait()` operation on that semaphore. She releases her chopsticks by executing the `signal()` operation on the appropriate semaphores. Thus, the shared data are

```
semaphore chopstick[5];
```

where all the elements of `chopstick` are initialized to 1. The structure of philosopher *i* is shown in Figure 7.6.

Although this solution guarantees that no two neighbors are eating simultaneously, it nevertheless must be rejected because it could create a deadlock. Suppose that all five philosophers become hungry at the same time and each grabs her left chopstick. All the elements of `chopstick` will now be equal to 0. When each philosopher tries to grab her right chopstick, she will be delayed forever.

Several possible remedies to the deadlock problem are the following:

- Allow at most four philosophers to be sitting simultaneously at the table.
- Allow a philosopher to pick up her chopsticks only if both chopsticks are available (to do this, she must pick them up in a critical section).
- Use an asymmetric solution—that is, an odd-numbered philosopher picks up first her left chopstick and then her right chopstick, whereas an even-numbered philosopher picks up her right chopstick and then her left chopstick.

In Section 6.7, we present a solution to the dining-philosophers problem that ensures freedom from deadlocks. Note, however, that any satisfactory solution to the dining-philosophers problem must guard against the possibility

that one of the philosophers will starve to death. A deadlock-free solution does not necessarily eliminate the possibility of starvation.

7.1.3.2 Monitor Solution

Next, we illustrate monitor concepts by presenting a deadlock-free solution to the dining-philosophers problem. This solution imposes the restriction that a philosopher may pick up her chopsticks only if both of them are available. To code this solution, we need to distinguish among three states in which we may find a philosopher. For this purpose, we introduce the following data structure:

```
enum {THINKING, HUNGRY, EATING} state[5];
```

Philosopher *i* can set the variable `state[i] = EATING` only if her two neighbors are not eating: (`state[(i+4) % 5] != EATING`) and (`state[(i+1) % 5] != EATING`).

We also need to declare

```
condition self[5];
```

This allows philosopher *i* to delay herself when she is hungry but is unable to obtain the chopsticks she needs.

We are now in a position to describe our solution to the dining-philosophers problem. The distribution of the chopsticks is controlled by the monitor `DiningPhilosophers`, whose definition is shown in Figure 7.7. Each philosopher, before starting to eat, must invoke the operation `pickup()`. This act may result in the suspension of the philosopher process. After the successful completion of the operation, the philosopher may eat. Following this, the philosopher invokes the `putdown()` operation. Thus, philosopher *i* must invoke the operations `pickup()` and `putdown()` in the following sequence:

```
DiningPhilosophers.pickup(i);
                ...
                eat
                ...
DiningPhilosophers.putdown(i);
```

It is easy to show that this solution ensures that no two neighbors are eating simultaneously and that no deadlocks will occur. As we already noted, however, it is possible for a philosopher to starve to death. We do not present a solution to this problem but rather leave it as an exercise for you.

7.2 Synchronization within the Kernel

We next describe the synchronization mechanisms provided by the Windows and Linux operating systems. These two operating systems provide good examples of different approaches to synchronizing the kernel, and as you will

```
monitor DiningPhilosophers
{
   enum {THINKING, HUNGRY, EATING} state[5];
   condition self[5];

   void pickup(int i) {
      state[i] = HUNGRY;
      test(i);
      if (state[i] != EATING)
         self[i].wait();
   }

   void putdown(int i) {
      state[i] = THINKING;
      test((i + 4) % 5);
      test((i + 1) % 5);
   }

   void test(int i) {
      if ((state[(i + 4) % 5] != EATING) &&
       (state[i] == HUNGRY) &&
       (state[(i + 1) % 5] != EATING)) {
         state[i] = EATING;
         self[i].signal();
      }
   }

   initialization_code() {
      for (int i = 0; i < 5; i++)
         state[i] = THINKING;
    }
}
```

Figure 7.7 A monitor solution to the dining-philosophers problem.

see, the synchronization mechanisms available in these systems differ in subtle yet significant ways.

7.2.1 Synchronization in Windows

The Windows operating system is a multithreaded kernel that provides support for real-time applications and multiple processors. When the Windows kernel accesses a global resource on a single-processor system, it temporarily masks interrupts for all interrupt handlers that may also access the global resource. On a multiprocessor system, Windows protects access to global resources using spinlocks, although the kernel uses spinlocks only to protect short code segments. Furthermore, for reasons of efficiency, the kernel ensures that a thread will never be preempted while holding a spinlock.

For thread synchronization outside the kernel, Windows provides **dispatcher objects**. Using a dispatcher object, threads synchronize according to several different mechanisms, including mutex locks, semaphores, events, and timers. The system protects shared data by requiring a thread to gain ownership of a mutex to access the data and to release ownership when it is finished. Semaphores behave as described in Section 6.6. **Events** are similar to condition variables; that is, they may notify a waiting thread when a desired condition occurs. Finally, timers are used to notify one (or more than one) thread that a specified amount of time has expired.

Dispatcher objects may be in either a signaled state or a nonsignaled state. An object in a **signaled state** is available, and a thread will not block when acquiring the object. An object in a **nonsignaled state** is not available, and a thread will block when attempting to acquire the object. We illustrate the state transitions of a mutex lock dispatcher object in Figure 7.8.

A relationship exists between the state of a dispatcher object and the state of a thread. When a thread blocks on a nonsignaled dispatcher object, its state changes from ready to waiting, and the thread is placed in a waiting queue for that object. When the state for the dispatcher object moves to signaled, the kernel checks whether any threads are waiting on the object. If so, the kernel moves one thread—or possibly more—from the waiting state to the ready state, where they can resume executing. The number of threads the kernel selects from the waiting queue depends on the type of dispatcher object for which each thread is waiting. The kernel will select only one thread from the waiting queue for a mutex, since a mutex object may be "owned" by only a single thread. For an event object, the kernel will select all threads that are waiting for the event.

We can use a mutex lock as an illustration of dispatcher objects and thread states. If a thread tries to acquire a mutex dispatcher object that is in a nonsignaled state, that thread will be suspended and placed in a waiting queue for the mutex object. When the mutex moves to the signaled state (because another thread has released the lock on the mutex), the thread waiting at the front of the queue will be moved from the waiting state to the ready state and will acquire the mutex lock.

A **critical-section object** is a user-mode mutex that can often be acquired and released without kernel intervention. On a multiprocessor system, a critical-section object first uses a spinlock while waiting for the other thread to release the object. If it spins too long, the acquiring thread will then allocate a kernel mutex and yield its CPU. Critical-section objects are particularly efficient because the kernel mutex is allocated only when there is contention for the object. In practice, there is very little contention, so the savings are significant.

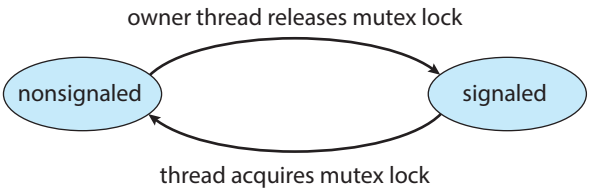

Figure 7.8 Mutex dispatcher object.

We provide a programming project at the end of this chapter that uses mutex locks and semaphores in the Windows API.

7.2.2 Synchronization in Linux

Prior to Version 2.6, Linux was a nonpreemptive kernel, meaning that a process running in kernel mode could not be preempted—even if a higher-priority process became available to run. Now, however, the Linux kernel is fully preemptive, so a task can be preempted when it is running in the kernel.

Linux provides several different mechanisms for synchronization in the kernel. As most computer architectures provide instructions for atomic versions of simple math operations, the simplest synchronization technique within the Linux kernel is an atomic integer, which is represented using the opaque data type `atomic_t`. As the name implies, all math operations using atomic integers are performed without interruption. To illustrate, consider a program that consists of an atomic integer `counter` and an integer `value`.

```
atomic_t counter;
int value;
```

The following code illustrates the effect of performing various atomic operations:

Atomic Operation	*Effect*
`atomic_set(&counter,5);`	`counter = 5`
`atomic_add(10,&counter);`	`counter = counter + 10`
`atomic_sub(4,&counter);`	`counter = counter - 4`
`atomic_inc(&counter);`	`counter = counter + 1`
`value = atomic_read(&counter);`	`value = 12`

Atomic integers are particularly efficient in situations where an integer variable—such as a counter—needs to be updated, since atomic operations do not require the overhead of locking mechanisms. However, their use is limited to these sorts of scenarios. In situations where there are several variables contributing to a possible race condition, more sophisticated locking tools must be used.

Mutex locks are available in Linux for protecting critical sections within the kernel. Here, a task must invoke the `mutex_lock()` function prior to entering a critical section and the `mutex_unlock()` function after exiting the critical section. If the mutex lock is unavailable, a task calling `mutex_lock()` is put into a sleep state and is awakened when the lock's owner invokes `mutex_unlock()`.

Linux also provides spinlocks and semaphores (as well as reader–writer versions of these two locks) for locking in the kernel. On SMP machines, the fundamental locking mechanism is a spinlock, and the kernel is designed so that the spinlock is held only for short durations. On single-processor machines, such as embedded systems with only a single processing core, spinlocks are inappropriate for use and are replaced by enabling and disabling kernel preemption. That is, on systems with a single processing core, rather than holding a spinlock, the kernel disables kernel preemption; and rather than releasing the spinlock, it enables kernel preemption. This is summarized below:

Single Processor	Multiple Processors
Disable kernel preemption	Acquire spin lock
Enable kernel preemption	Release spin lock

In the Linux kernel, both spinlocks and mutex locks are *nonrecursive*, which means that if a thread has acquired one of these locks, it cannot acquire the same lock a second time without first releasing the lock. Otherwise, the second attempt at acquiring the lock will block.

Linux uses an interesting approach to disable and enable kernel preemption. It provides two simple system calls—`preempt_disable()` and `preempt_enable()`—for disabling and enabling kernel preemption. The kernel is not preemptible, however, if a task running in the kernel is holding a lock. To enforce this rule, each task in the system has a `thread-info` structure containing a counter, `preempt_count`, to indicate the number of locks being held by the task. When a lock is acquired, `preempt_count` is incremented. It is decremented when a lock is released. If the value of `preempt_count` for the task currently running in the kernel is greater than 0, it is not safe to preempt the kernel, as this task currently holds a lock. If the count is 0, the kernel can safely be interrupted (assuming there are no outstanding calls to `preempt_disable()`).

Spinlocks—along with enabling and disabling kernel preemption—are used in the kernel only when a lock (or disabling kernel preemption) is held for a short duration. When a lock must be held for a longer period, semaphores or mutex locks are appropriate for use.

7.3 POSIX Synchronization

The synchronization methods discussed in the preceding section pertain to synchronization within the kernel and are therefore available only to kernel developers. In contrast, the POSIX API is available for programmers at the user level and is not part of any particular operating-system kernel. (Of course, it must ultimately be implemented using tools provided by the host operating system.)

In this section, we cover mutex locks, semaphores, and condition variables that are available in the Pthreads and POSIX APIs. These APIs are widely used for thread creation and synchronization by developers on UNIX, Linux, and macOS systems.

7.3.1 POSIX Mutex Locks

Mutex locks represent the fundamental synchronization technique used with Pthreads. A mutex lock is used to protect critical sections of code—that is, a thread acquires the lock before entering a critical section and releases it upon exiting the critical section. Pthreads uses the `pthread_mutex_t` data type for mutex locks. A mutex is created with the `pthread_mutex_init()` function. The first parameter is a pointer to the mutex. By passing `NULL` as a second parameter, we initialize the mutex to its default attributes. This is illustrated below:

```
#include <pthread.h>

pthread_mutex_t mutex;

/* create and initialize the mutex lock */
pthread_mutex_init(&mutex,NULL);
```

The mutex is acquired and released with the `pthread_mutex_lock()` and `pthread_mutex_unlock()` functions. If the mutex lock is unavailable when `pthread_mutex_lock()` is invoked, the calling thread is blocked until the owner invokes `pthread_mutex_unlock()`. The following code illustrates protecting a critical section with mutex locks:

```
/* acquire the mutex lock */
pthread_mutex_lock(&mutex);

/* critical section */

/* release the mutex lock */
pthread_mutex_unlock(&mutex);
```

All mutex functions return a value of 0 with correct operation; if an error occurs, these functions return a nonzero error code.

7.3.2 POSIX Semaphores

Many systems that implement Pthreads also provide semaphores, although semaphores are not part of the POSIX standard and instead belong to the POSIX SEM extension. POSIX specifies two types of semaphores—**named** and **unnamed**. Fundamentally, the two are quite similar, but they differ in terms of how they are created and shared between processes. Because both techniques are common, we discuss both here. Beginning with Version 2.6 of the kernel, Linux systems provide support for both named and unnamed semaphores.

7.3.2.1 POSIX Named Semaphores

The function `sem_open()` is used to create and open a POSIX named sempahore:

```
#include <semaphore.h>
sem_t *sem;

/* Create the semaphore and initialize it to 1 */
sem = sem_open("SEM", O_CREAT, 0666, 1);
```

In this instance, we are naming the semaphore `SEM`. The `O_CREAT` flag indicates that the semaphore will be created if it does not already exist. Additionally, the semaphore has read and write access for other processes (via the parameter `0666`) and is initialized to 1.

The advantage of named semaphores is that multiple unrelated processes can easily use a common semaphore as a synchronization mechanism by

simply referring to the semaphore's name. In the example above, once the semaphore SEM has been created, subsequent calls to sem_open() (with the same parameters) by other processes return a descriptor to the existing semaphore.

In Section 6.6, we described the classic wait() and signal() semaphore operations. POSIX declares these operations sem_wait() and sem_post(), respectively. The following code sample illustrates protecting a critical section using the named semaphore created above:

```
/* acquire the semaphore */
sem_wait(sem);

/* critical section */

/* release the semaphore */
sem_post(sem);
```

Both Linux and macOS systems provide POSIX named semaphores.

7.3.2.2 POSIX Unnamed Semaphores

An unnamed semaphore is created and initialized using the sem_init() function, which is passed three parameters:

1. A pointer to the semaphore
2. A flag indicating the level of sharing
3. The semaphore's initial value

and is illusrated in the following programming example:

```
#include <semaphore.h>
sem_t sem;

/* Create the semaphore and initialize it to 1 */
sem_init(&sem, 0, 1);
```

In this example, by passing the flag 0, we are indicating that this semaphore can be shared only by threads belonging to the process that created the semaphore. (If we supplied a nonzero value, we could allow the semaphore to be shared between separate processes by placing it in a region of shared memory.) In addition, we initialize the semaphore to the value 1.

POSIX unnamed semaphores use the same sem_wait() and sem_post() operations as named semaphores. The following code sample illustrates protecting a critical section using the unnamed semaphore created above:

```
/* acquire the semaphore */
sem_wait(&sem);

/* critical section */

/* release the semaphore */
sem_post(&sem);
```

Just like mutex locks, all semaphore functions return 0 when successful and nonzero when an error condition occurs.

7.3.3 POSIX Condition Variables

Condition variables in Pthreads behave similarly to those described in Section 6.7. However, in that section, condition variables are used within the context of a monitor, which provides a locking mechanism to ensure data integrity. Since Pthreads is typically used in C programs—and since C does not have a monitor— we accomplish locking by associating a condition variable with a mutex lock.

Condition variables in Pthreads use the `pthread_cond_t` data type and are initialized using the `pthread_cond_init()` function. The following code creates and initializes a condition variable as well as its associated mutex lock:

```
pthread_mutex_t mutex;
pthread_cond_t cond_var;

pthread_mutex_init(&mutex,NULL);
pthread_cond_init(&cond_var,NULL);
```

The `pthread_cond_wait()` function is used for waiting on a condition variable. The following code illustrates how a thread can wait for the condition `a == b` to become true using a Pthread condition variable:

```
pthread_mutex_lock(&mutex);
while (a != b)
     pthread_cond_wait(&cond_var, &mutex);

pthread_mutex_unlock(&mutex);
```

The mutex lock associated with the condition variable must be locked before the `pthread_cond_wait()` function is called, since it is used to protect the data in the conditional clause from a possible race condition. Once this lock is acquired, the thread can check the condition. If the condition is not true, the thread then invokes `pthread_cond_wait()`, passing the mutex lock and the condition variable as parameters. Calling `pthread_cond_wait()` releases the mutex lock, thereby allowing another thread to access the shared data and possibly update its value so that the condition clause evaluates to true. (To protect against program errors, it is important to place the conditional clause within a loop so that the condition is rechecked after being signaled.)

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

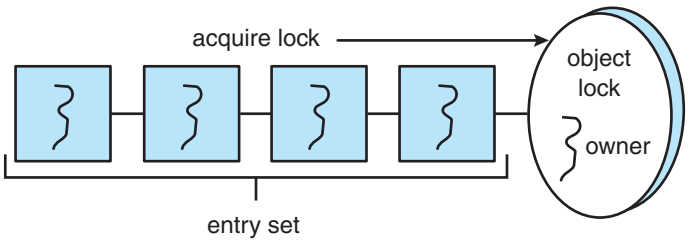

Figure 7.10 Entry set for a lock.

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.)

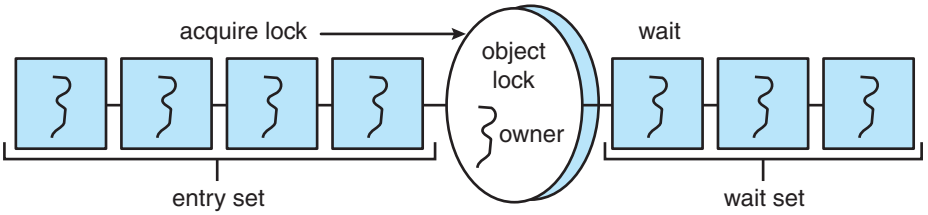

Figure 7.12 Entry and wait sets.

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

that the specification for the JVM does not indicate that threads in the wait set for an object lock are to be ordered in any specific fashion.)

A thread acquires a `ReentrantLock` lock by invoking its `lock()` method. If the lock is available—or if the thread invoking `lock()` already owns it, which is why it is termed *reentrant*—`lock()` assigns the invoking thread lock ownership and returns control. If the lock is unavailable, the invoking thread blocks until it is ultimately assigned the lock when its owner invokes `unlock()`. `ReentrantLock` implements the `Lock` interface; it is used as follows:

```
Lock key = new ReentrantLock();

key.lock();
try {
   /* critical section */
}
finally {
   key.unlock();
}
```

The programming idiom of using `try` and `finally` requires a bit of explanation. If the lock is acquired via the `lock()` method, it is important that the lock be similarly released. By enclosing `unlock()` in a `finally` clause, we ensure that the lock is released once the critical section completes or if an exception occurs within the `try` block. Notice that we do not place the call to `lock()` within the `try` clause, as `lock()` does not throw any checked exceptions. Consider what happens if we place `lock()` within the `try` clause and an unchecked exception occurs when `lock()` is invoked (such as `OutofMemoryError`): The `finally` clause triggers the call to `unlock()`, which then throws the unchecked `IllegalMonitorStateException`, as the lock was never acquired. This `IllegalMonitorStateException` replaces the unchecked exception that occurred when `lock()` was invoked, thereby obscuring the reason why the program initially failed.

Whereas a `ReentrantLock` provides mutual exclusion, it may be too conservative a strategy if multiple threads only read, but do not write, shared data. (We described this scenario in Section 7.1.2.) To address this need, the Java API also provides a `ReentrantReadWriteLock`, which is a lock that allows multiple concurrent readers but only one writer.

7.4.3 Semaphores

The Java API also provides a counting semaphore, as described in Section 6.6. The constructor for the semaphore appears as

```
Semaphore(int value);
```

where `value` specifies the initial value of the semaphore (a negative value is allowed). The `acquire()` method throws an `InterruptedException` if the acquiring thread is interrupted. The following example illustrates using a semaphore for mutual exclusion:

```
Semaphore sem = new Semaphore(1);

try {
   sem.acquire();
   /* critical section */
}
catch (InterruptedException ie) { }
finally {
   sem.release();
}
```

Notice that we place the call to `release()` in the `finally` clause to ensure that the semaphore is released.

7.4.4 Condition Variables

The last utility we cover in the Java API is the condition variable. Just as the `ReentrantLock` is similar to Java's `synchronized` statement, condition variables provide functionality similar to the `wait()` and `notify()` methods. Therefore, to provide mutual exclusion, a condition variable must be associated with a reentrant lock.

We create a condition variable by first creating a `ReentrantLock` and invoking its `newCondition()` method, which returns a `Condition` object representing the condition variable for the associated `ReentrantLock`. This is illustrated in the following statements:

```
Lock key = new ReentrantLock();
Condition condVar = key.newCondition();
```

Once the condition variable has been obtained, we can invoke its `await()` and `signal()` methods, which function in the same way as the `wait()` and `signal()` commands described in Section 6.7.

Recall that with monitors as described in Section 6.7, the `wait()` and `signal()` operations can be applied to ***named*** condition variables, allowing a thread to wait for a specific condition or to be notified when a specific condition has been met. At the language level, Java does not provide support for named condition variables. Each Java monitor is associated with just one unnamed condition variable, and the `wait()` and `notify()` operations described in Section 7.4.1 apply only to this single condition variable. When a Java thread is awakened via `notify()`, it receives no information as to why it was awakened; it is up to the reactivated thread to check for itself whether the condition for which it was waiting has been met. Condition variables remedy this by allowing a specific thread to be notified.

We illustrate with the following example: Suppose we have five threads, numbered 0 through 4, and a shared variable `turn` indicating which thread's turn it is. When a thread wishes to do work, it calls the `doWork()` method in Figure 7.13, passing its thread number. Only the thread whose value of `threadNumber` matches the value of `turn` can proceed; other threads must wait their turn.

```
/* threadNumber is the thread that wishes to do some work */
public void doWork(int threadNumber)
{
   lock.lock();

   try {
      /**
       * If it's not my turn, then wait
       * until I'm signaled.
       */
      if (threadNumber != turn)
        condVars[threadNumber].await();

      /**
       * Do some work for awhile ...
       */

      /**
       * Now signal to the next thread.
       */
      turn = (turn + 1) % 5;
      condVars[turn].signal();
   }
   catch (InterruptedException ie) { }
   finally {
      lock.unlock();
   }
}
```

Figure 7.13 Example using Java condition variables.

We also must create a `ReentrantLock` and five condition variables (representing the conditions the threads are waiting for) to signal the thread whose turn is next. This is shown below:

```
Lock lock = new ReentrantLock();
Condition[] condVars = new Condition[5];

for (int i = 0; i < 5; i++)
   condVars[i] = lock.newCondition();
```

When a thread enters `doWork()`, it invokes the `await()` method on its associated condition variable if its `threadNumber` is not equal to `turn`, only to resume when it is signaled by another thread. After a thread has completed its work, it signals the condition variable associated with the thread whose turn follows.

It is important to note that `doWork()` does not need to be declared `synchronized`, as the `ReentrantLock` provides mutual exclusion. When a thread

invokes `await()` on the condition variable, it releases the associated `ReentrantLock`, allowing another thread to acquire the mutual exclusion lock. Similarly, when `signal()` is invoked, only the condition variable is signaled; the lock is released by invoking `unlock()`.

7.5 Alternative Approaches

With the emergence of multicore systems has come increased pressure to develop concurrent applications that take advantage of multiple processing cores. However, concurrent applications present an increased risk of race conditions and liveness hazards such as deadlock. Traditionally, techniques such as mutex locks, semaphores, and monitors have been used to address these issues, but as the number of processing cores increases, it becomes increasingly difficult to design multithreaded applications that are free from race conditions and deadlock. In this section, we explore various features provided in both programming languages and hardware that support the design of thread-safe concurrent applications.

7.5.1 Transactional Memory

Quite often in computer science, ideas from one area of study can be used to solve problems in other areas. The concept of **transactional memory** originated in database theory, for example, yet it provides a strategy for process synchronization. A **memory transaction** is a sequence of memory read–write operations that are atomic. If all operations in a transaction are completed, the memory transaction is committed. Otherwise, the operations must be aborted and rolled back. The benefits of transactional memory can be obtained through features added to a programming language.

Consider an example. Suppose we have a function `update()` that modifies shared data. Traditionally, this function would be written using mutex locks (or semaphores) such as the following:

```
void update ()
{
   acquire();

   /* modify shared data */

   release();
}
```

However, using synchronization mechanisms such as mutex locks and semaphores involves many potential problems, including deadlock. Additionally, as the number of threads increases, traditional locking doesn't scale as well, because the level of contention among threads for lock ownership becomes very high.

As an alternative to traditional locking methods, new features that take advantage of transactional memory can be added to a programming language. In our example, suppose we add the construct `atomic{S}`, which ensures that

the operations in S execute as a transaction. This allows us to rewrite the update() function as follows:

```
void update ()
{
   atomic {
      /* modify shared data */
   }
}
```

The advantage of using such a mechanism rather than locks is that the transactional memory system—not the developer—is responsible for guaranteeing atomicity. Additionally, because no locks are involved, deadlock is not possible. Furthermore, a transactional memory system can identify which statements in atomic blocks can be executed concurrently, such as concurrent read access to a shared variable. It is, of course, possible for a programmer to identify these situations and use reader–writer locks, but the task becomes increasingly difficult as the number of threads within an application grows.

Transactional memory can be implemented in either software or hardware. **Software transactional memory** (**STM**), as the name suggests, implements transactional memory exclusively in software—no special hardware is needed. STM works by inserting instrumentation code inside transaction blocks. The code is inserted by a compiler and manages each transaction by examining where statements may run concurrently and where specific low-level locking is required. **Hardware transactional memory** (**HTM**) uses hardware cache hierarchies and cache coherency protocols to manage and resolve conflicts involving shared data residing in separate processors' caches. HTM requires no special code instrumentation and thus has less overhead than STM. However, HTM does require that existing cache hierarchies and cache coherency protocols be modified to support transactional memory.

Transactional memory has existed for several years without widespread implementation. However, the growth of multicore systems and the associated emphasis on concurrent and parallel programming have prompted a significant amount of research in this area on the part of both academics and commercial software and hardware vendors.

7.5.2 OpenMP

In Section 4.5.2, we provided an overview of OpenMP and its support of parallel programming in a shared-memory environment. Recall that OpenMP includes a set of compiler directives and an API. Any code following the compiler directive `#pragma omp parallel` is identified as a parallel region and is performed by a number of threads equal to the number of processing cores in the system. The advantage of OpenMP (and similar tools) is that thread creation and management are handled by the OpenMP library and are not the responsibility of application developers.

Along with its `#pragma omp parallel` compiler directive, OpenMP provides the compiler directive `#pragma omp critical`, which specifies the code region following the directive as a critical section in which only one thread may be active at a time. In this way, OpenMP provides support for ensuring that threads do not generate race conditions.

As an example of the use of the critical-section compiler directive, first assume that the shared variable `counter` can be modified in the `update()` function as follows:

```
void update(int value)
{
   counter += value;
}
```

If the `update()` function can be part of—or invoked from—a parallel region, a race condition is possible on the variable `counter`.

The critical-section compiler directive can be used to remedy this race condition and is coded as follows:

```
void update(int value)
{
   #pragma omp critical
   {
      counter += value;
   }
}
```

The critical-section compiler directive behaves much like a binary semaphore or mutex lock, ensuring that only one thread at a time is active in the critical section. If a thread attempts to enter a critical section when another thread is currently active in that section (that is, ***owns*** the section), the calling thread is blocked until the owner thread exits. If multiple critical sections must be used, each critical section can be assigned a separate name, and a rule can specify that no more than one thread may be active in a critical section of the same name simultaneously.

An advantage of using the critical-section compiler directive in OpenMP is that it is generally considered easier to use than standard mutex locks. However, a disadvantage is that application developers must still identify possible race conditions and adequately protect shared data using the compiler directive. Additionally, because the critical-section compiler directive behaves much like a mutex lock, deadlock is still possible when two or more critical sections are identified.

7.5.3 Functional Programming Languages

Most well-known programming languages—such as C, C++, Java, and C#—are known as **imperative** (or **procedural**) languages. Imperative languages are used for implementing algorithms that are state-based. In these languages, the flow of the algorithm is crucial to its correct operation, and state is represented with variables and other data structures. Of course, program state is mutable, as variables may be assigned different values over time.

With the current emphasis on concurrent and parallel programming for multicore systems, there has been greater focus on **functional** programming languages, which follow a programming paradigm much different from that offered by imperative languages. The fundamental difference between imperative and functional languages is that functional languages do not maintain state. That is, once a variable has been defined and assigned a value, its value

is immutable—it cannot change. Because functional languages disallow mutable state, they need not be concerned with issues such as race conditions and deadlocks. Essentially, most of the problems addressed in this chapter are nonexistent in functional languages.

Several functional languages are presently in use, and we briefly mention two of them here: Erlang and Scala. The Erlang language has gained significant attention because of its support for concurrency and the ease with which it can be used to develop applications that run on parallel systems. Scala is a functional language that is also object-oriented. In fact, much of the syntax of Scala is similar to the popular object-oriented languages Java and C#. Readers interested in Erlang and Scala, and in further details about functional languages in general, are encouraged to consult the bibliography at the end of this chapter for additional references.

7.6 Summary

- Classic problems of process synchronization include the bounded-buffer, readers–writers, and dining-philosophers problems. Solutions to these problems can be developed using the tools presented in Chapter 6, including mutex locks, semaphores, monitors, and condition variables.
- Windows uses dispatcher objects as well as events to implement process synchronization tools.
- Linux uses a variety of approaches to protect against race conditions, including atomic variables, spinlocks, and mutex locks.
- The POSIX API provides mutex locks, semaphores, and condition variables. POSIX provides two forms of semaphores: named and unnamed. Several unrelated processes can easily access the same named semaphore by simply referring to its name. Unnamed semaphores cannot be shared as easily, and require placing the semaphore in a region of shared memory.
- Java has a rich library and API for synchronization. Available tools include monitors (which are provided at the language level) as well as reentrant locks, semaphores, and condition variables (which are supported by the API).
- Alternative approaches to solving the critical-section problem include transactional memory, OpenMP, and functional languages. Functional languages are particularly intriguing, as they offer a different programming paradigm from procedural languages. Unlike procedural languages, functional languages do not maintain state and therefore are generally immune from race conditions and critical sections.

Practice Exercises

7.1 Explain why Windows and Linux implement multiple locking mechanisms. Describe the circumstances under which they use spinlocks, mutex locks, semaphores, and condition variables. In each case, explain why the mechanism is needed.

7.2 Windows provides a lightweight synchronization tool called **slim reader–writer** locks. Whereas most implementations of reader–writer locks favor either readers or writers, or perhaps order waiting threads using a FIFO policy, slim reader–writer locks favor neither readers nor writers, nor are waiting threads ordered in a FIFO queue. Explain the benefits of providing such a synchronization tool.

7.3 Describe what changes would be necessary to the producer and consumer processes in Figure 7.1 and Figure 7.2 so that a mutex lock could be used instead of a binary semaphore.

7.4 Describe how deadlock is possible with the dining-philosophers problem.

7.5 Explain the difference between signaled and non-signaled states with Windows dispatcher objects.

7.6 Assume `val` is an atomic integer in a Linux system. What is the value of `val` after the following operations have been completed?

```
atomic_set(&val,10);
atomic_sub(8,&val);
atomic_inc(&val);
atomic_inc(&val);
atomic_add(6,&val);
atomic_sub(3,&val);
```

Further Reading

Details of Windows synchronization can be found in [Solomon and Russinovich (2000)]. [Love (2010)] describes synchronization in the Linux kernel. [Hart (2005)] describes thread synchronization using Windows. [Breshears (2009)] and [Pacheco (2011)] provide detailed coverage of synchronization issues in relation to parallel programming. Details on using OpenMP can be found at http://openmp.org. Both [Oaks (2014)] and [Goetz et al. (2006)] contrast traditional synchronization and CAS-based strategies in Java.

Bibliography

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Chapter 7 Exercises

7.7 Describe two kernel data structures in which race conditions are possible. Be sure to include a description of how a race condition can occur.

7.8 The Linux kernel has a policy that a process cannot hold a spinlock while attempting to acquire a semaphore. Explain why this policy is in place.

7.9 Design an algorithm for a bounded-buffer monitor in which the buffers (portions) are embedded within the monitor itself.

7.10 The strict mutual exclusion within a monitor makes the bounded-buffer monitor of Exercise 7.14 mainly suitable for small portions.

a. Explain why this is true.

b. Design a new scheme that is suitable for larger portions.

7.11 Discuss the tradeoff between fairness and throughput of operations in the readers–writers problem. Propose a method for solving the readers–writers problem without causing starvation.

7.12 Explain why the call to the `lock()` method in a Java `ReentrantLock` is not placed in the `try` clause for exception handling, yet the call to the `unlock()` method is placed in a `finally` clause.

7.13 Explain the difference between software and hardware transactional memory.

Programming Problems

7.14 Exercise 3.20 required you to design a PID manager that allocated a unique process identifier to each process. Exercise 4.28 required you to modify your solution to Exercise 3.20 by writing a program that created a number of threads that requested and released process identifiers. Using mutex locks, modify your solution to Exercise 4.28 by ensuring that the data structure used to represent the availability of process identifiers is safe from race conditions.

7.15 In Exercise 4.27, you wrote a program to generate the Fibonacci sequence. The program required the parent thread to wait for the child thread to finish its execution before printing out the computed values. If we let the parent thread access the Fibonacci numbers as soon as they were computed by the child thread—rather than waiting for the child thread to terminate—what changes would be necessary to the solution for this exercise? Implement your modified solution.

7.16 The C program `stack-ptr.c` (available in the source-code download) contains an implementation of a stack using a linked list. An example of its use is as follows:

```
StackNode *top = NULL;
push(5, &top);
push(10, &top);
push(15, &top);

int value = pop(&top);
value = pop(&top);
value = pop(&top);
```

This program currently has a race condition and is not appropriate for a concurrent environment. Using Pthreads mutex locks (described in Section 7.3.1), fix the race condition.

7.17 Exercise 4.24 asked you to design a multithreaded program that estimated π using the Monte Carlo technique. In that exercise, you were asked to create a single thread that generated random points, storing the result in a global variable. Once that thread exited, the parent thread performed the calculation that estimated the value of π. Modify that program so that you create several threads, each of which generates random points and determines if the points fall within the circle. Each thread will have to update the global count of all points that fall within the circle. Protect against race conditions on updates to the shared global variable by using mutex locks.

7.18 Exercise 4.25 asked you to design a program using OpenMP that estimated π using the Monte Carlo technique. Examine your solution to that program looking for any possible race conditions. If you identify a race condition, protect against it using the strategy outlined in Section 7.5.2.

7.19 A **barrier** is a tool for synchronizing the activity of a number of threads. When a thread reaches a **barrier point**, it cannot proceed until all other

threads have reached this point as well. When the last thread reaches the barrier point, all threads are released and can resume concurrent execution.

Assume that the barrier is initialized to *N*—the number of threads that must wait at the barrier point:

```
init(N);
```

Each thread then performs some work until it reaches the barrier point:

```
/* do some work for awhile */

barrier_point();

/* do some work for awhile */
```

Using either the POSIX or Java synchronization tools described in this chapter, construct a barrier that implements the following API:

- `int init(int n)`—Initializes the barrier to the specified size.
- `int barrier_point(void)`—Identifies the barrier point. All threads are released from the barrier when the last thread reaches this point.

The return value of each function is used to identify error conditions. Each function will return 0 under normal operation and will return −1 if an error occurs. A testing harness is provided in the source-code download to test your implementation of the barrier.

Programming Projects

Project 1—Designing a Thread Pool

Thread pools were introduced in Section 4.5.1. When thread pools are used, a task is submitted to the pool and executed by a thread from the pool. Work is submitted to the pool using a queue, and an available thread removes work from the queue. If there are no available threads, the work remains queued until one becomes available. If there is no work, threads await notification until a task becomes available.

This project involves creating and managing a thread pool, and it may be completed using either Pthreds and POSIX synchronization or Java. Below we provide the details relevant to each specific technology.

I. POSIX

The POSIX version of this project will involve creating a number of threads using the Pthreads API as well as using POSIX mutex locks and semaphores for synchronization.

The Client

Users of the thread pool will utilize the following API:

- `void pool_init()`—Initializes the thread pool.
- `int pool_submit(void (*somefunction)(void *p), void *p)`—where `somefunction` is a pointer to the function that will be executed by a thread from the pool and `p` is a parameter passed to the function.
- `void pool_shutdown(void)`—Shuts down the thread pool once all tasks have completed.

We provide an example program `client.c` in the source code download that illustrates how to use the thread pool using these functions.

Implementation of the Thread Pool

In the source code download we provide the C source file `threadpool.c` as a partial implementation of the thread pool. You will need to implement the functions that are called by client users, as well as several additional functions that support the internals of the thread pool. Implementation will involve the following activities:

1. The `pool_init()` function will create the threads at startup as well as initialize mutual-exclusion locks and semaphores.
2. The `pool_submit()` function is partially implemented and currently places the function to be executed—as well as its data— into a `task` struct. The `task` struct represents work that will be completed by a thread in the pool. `pool_submit()` will add these tasks to the queue by invoking the `enqueue()` function, and worker threads will call `dequeue()` to retrieve work from the queue. The queue may be implemented statically (using arrays) or dynamically (using a linked list).

   The `pool_init()` function has an `int` return value that is used to indicate if the task was successfully submitted to the pool (0 indicates success, 1 indicates failure). If the queue is implemented using arrays, `pool_init()` will return 1 if there is an attempt to submit work and the queue is full. If the queue is implemented as a linked list, `pool_init()` should always return 0 unless a memory allocation error occurs.
3. The `worker()` function is executed by each thread in the pool, where each thread will wait for available work. Once work becomes available, the thread will remove it from the queue and invoke `execute()` to run the specified function.

   A semaphore can be used for notifying a waiting thread when work is submitted to the thread pool. Either named or unnamed semaphores may be used. Refer to Section 7.3.2 for further details on using POSIX semaphores.

4. A mutex lock is necessary to avoid race conditions when accessing or modifying the queue. (Section 7.3.1 provides details on Pthreads mutex locks.)
5. The `pool_shutdown()` function will cancel each worker thread and then wait for each thread to terminate by calling `pthread_join()`. Refer to Section 4.6.3 for details on POSIX thread cancellation. (The semaphore operation `sem_wait()` is a cancellation point that allows a thread waiting on a semaphore to be cancelled.)

Refer to the source-code download for additional details on this project. In particular, the `README` file describes the source and header files, as well as the `Makefile` for building the project.

II. Java

The Java version of this project may be completed using Java synchronization tools as described in Section 7.4. Synchronization may depend on either (a) monitors using `synchronized/wait()/notify()` (Section 7.4.1) or (b) semaphores and reentrant locks (Section 7.4.2 and Section 7.4.3). Java threads are described in Section 4.4.3.

Implementation of the Thread Pool

Your thread pool will implement the following API:

- `ThreadPool()`—Create a default-sized thread pool.
- `ThreadPool(int size)`—Create a thread pool of size `size`.
- `void add(Runnable task)`—Add a task to be performed by a thread in the pool.
- `void shutdown()`—Stop all threads in the pool.

We provide the Java source file `ThreadPool.java` as a partial implementation of the thread pool in the source code download. You will need to implement the methods that are called by client users, as well as several additional methods that support the internals of the thread pool. Implementation will involve the following activities:

1. The constructor will first create a number of idle threads that await work.
2. Work will be submitted to the pool via the `add()` method, which adds a task implementing the `Runnable` interface. The `add()` method will place the `Runnable` task into a queue (you may use an available structure from the Java API such as `java.util.List`).
3. Once a thread in the pool becomes available for work, it will check the queue for any `Runnable` tasks. If there is such a task, the idle thread will remove the task from the queue and invoke its `run()` method. If the queue is empty, the idle thread will wait to be notified when work

becomes available. (The `add()` method may implement notification using either `notify()` or semaphore operations when it places a `Runnable` task into the queue to possibly awaken an idle thread awaiting work.)

4. The `shutdown()` method will stop all threads in the pool by invoking their `interrupt()` method. This, of course, requires that `Runnable` tasks being executed by the thread pool check their interruption status (Section 4.6.3).

Refer to the source-code download for additional details on this project. In particular, the README file describes the Java source files, as well as further details on Java thread interruption.

Project 2—The Sleeping Teaching Assistant

A university computer science department has a teaching assistant (TA) who helps undergraduate students with their programming assignments during regular office hours. The TA's office is rather small and has room for only one desk with a chair and computer. There are three chairs in the hallway outside the office where students can sit and wait if the TA is currently helping another student. When there are no students who need help during office hours, the TA sits at the desk and takes a nap. If a student arrives during office hours and finds the TA sleeping, the student must awaken the TA to ask for help. If a student arrives and finds the TA currently helping another student, the student sits on one of the chairs in the hallway and waits. If no chairs are available, the student will come back at a later time.

Using POSIX threads, mutex locks, and semaphores, implement a solution that coordinates the activities of the TA and the students. Details for this assignment are provided below.

The Students and the TA

Using Pthreads (Section 4.4.1), begin by creating n students where each student will run as a separate thread. The TA will run as a separate thread as well. Student threads will alternate between programming for a period of time and seeking help from the TA. If the TA is available, they will obtain help. Otherwise, they will either sit in a chair in the hallway or, if no chairs are available, will resume programming and will seek help at a later time. If a student arrives and notices that the TA is sleeping, the student must notify the TA using a semaphore. When the TA finishes helping a student, the TA must check to see if there are students waiting for help in the hallway. If so, the TA must help each of these students in turn. If no students are present, the TA may return to napping.

Perhaps the best option for simulating students programming—as well as the TA providing help to a student—is to have the appropriate threads sleep for a random period of time.

Coverage of POSIX mutex locks and semaphores is provided in Section 7.3. Consult that section for details.

Project 3—The Dining-Philosophers Problem

In Section 7.1.3, we provide an outline of a solution to the dining-philosophers problem using monitors. This project involves implementing a solution to this problem using either POSIX mutex locks and condition variables or Java condition variables. Solutions will be based on the algorithm illustrated in Figure 7.7.

Both implementations will require creating five philosophers, each identified by a number 0 . . 4. Each philosopher will run as a separate thread. Philosophers alternate between thinking and eating. To simulate both activities, have each thread sleep for a random period between one and three seconds.

I. POSIX

Thread creation using Pthreads is covered in Section 4.4.1. When a philosopher wishes to eat, she invokes the function

```
pickup_forks(int philosopher_number)
```

where `philosopher_number` identifies the number of the philosopher wishing to eat. When a philosopher finishes eating, she invokes

```
return_forks(int philosopher_number)
```

Your implementation will require the use of POSIX condition variables, which are covered in Section 7.3.

II. Java

When a philosopher wishes to eat, she invokes the method `takeForks(philosopherNumber)`, where `philosopherNumber` identifies the number of the philosopher wishing to eat. When a philosopher finishes eating, she invokes `returnForks(philosopherNumber)`.

Your solution will implement the following interface:

```
public interface DiningServer
{
   /* Called by a philosopher when it wishes to eat */
   public void takeForks(int philosopherNumber);

   /* Called by a philosopher when it is finished eating */
   public void returnForks(int philosopherNumber);
}
```

It will require the use of Java condition variables, which are covered in Section 7.4.4.

Project 4—The Producer–Consumer Problem

In Section 7.1.1, we presented a semaphore-based solution to the producer–consumer problem using a bounded buffer. In this project, you will design a programming solution to the bounded-buffer problem using the producer and consumer processes shown in Figures 5.9 and 5.10. The solution presented in Section 7.1.1 uses three semaphores: `empty` and `full`, which count the number of empty and full slots in the buffer, and `mutex`, which is a binary (or mutual-exclusion) semaphore that protects the actual insertion or removal of items in the buffer. For this project, you will use standard counting semaphores for `empty` and `full` and a mutex lock, rather than a binary semaphore, to represent `mutex`. The producer and consumer—running as separate threads—will move items to and from a buffer that is synchronized with the `empty`, `full`, and `mutex` structures. You can solve this problem using either Pthreads or the Windows API.

The Buffer

Internally, the buffer will consist of a fixed-size array of type `buffer_item` (which will be defined using a `typedef`). The array of `buffer_item` objects will be manipulated as a circular queue. The definition of `buffer_item`, along with the size of the buffer, can be stored in a header file such as the following:

```
/* buffer.h */
typedef int buffer_item;
#define BUFFER_SIZE 5
```

The buffer will be manipulated with two functions, `insert_item()` and `remove_item()`, which are called by the producer and consumer threads, respectively. A skeleton outlining these functions appears in Figure 7.14.

The `insert_item()` and `remove_item()` functions will synchronize the producer and consumer using the algorithms outlined in Figure 7.1 and Figure 7.2. The buffer will also require an initialization function that initializes the mutual-exclusion object `mutex` along with the `empty` and `full` semaphores.

The `main()` function will initialize the buffer and create the separate producer and consumer threads. Once it has created the producer and consumer threads, the `main()` function will sleep for a period of time and, upon awakening, will terminate the application. The `main()` function will be passed three parameters on the command line:

1. How long to sleep before terminating
2. The number of producer threads
3. The number of consumer threads

A skeleton for this function appears in Figure 7.15.

```
#include "buffer.h"

/* the buffer */
buffer_item buffer[BUFFER_SIZE];

int insert_item(buffer_item item) {
   /* insert item into buffer
    return 0 if successful, otherwise
    return -1 indicating an error condition */
}

int remove_item(buffer_item *item) {
   /* remove an object from buffer
    placing it in item
    return 0 if successful, otherwise
    return -1 indicating an error condition */
}
```

Figure 7.14 Outline of buffer operations.

The Producer and Consumer Threads

The producer thread will alternate between sleeping for a random period of time and inserting a random integer into the buffer. Random numbers will be produced using the `rand()` function, which produces random integers between 0 and RAND_MAX. The consumer will also sleep for a random period of time and, upon awakening, will attempt to remove an item from the buffer. An outline of the producer and consumer threads appears in Figure 7.16.

```
#include "buffer.h"

int main(int argc, char *argv[]) {
  /* 1. Get command line arguments argv[1],argv[2],argv[3] */
  /* 2. Initialize buffer */
  /* 3. Create producer thread(s) */
  /* 4. Create consumer thread(s) */
  /* 5. Sleep */
  /* 6. Exit */
}
```

Figure 7.15 Outline of skeleton program.

```
#include <stdlib.h> /* required for rand() */
#include "buffer.h"

void *producer(void *param) {
   buffer_item item;

   while (true) {
      /* sleep for a random period of time */
      sleep(...);
      /* generate a random number */
      item = rand();
      if (insert_item(item))
         fprintf("report error condition");
      else
         printf("producer produced %d\n",item);
}

void *consumer(void *param) {
   buffer_item item;

   while (true) {
      /* sleep for a random period of time */
      sleep(...);
      if (remove_item(&item))
         fprintf("report error condition");
      else
         printf("consumer consumed %d\n",item);
}
```

Figure 7.16 An outline of the producer and consumer threads.

As noted earlier, you can solve this problem using either Pthreads or the Windows API. In the following sections, we supply more information on each of these choices.

Pthreads Thread Creation and Synchronization

Creating threads using the Pthreads API is discussed in Section 4.4.1. Coverage of mutex locks and semaphores using Pthreads is provided in Section 7.3. Refer to those sections for specific instructions on Pthreads thread creation and synchronization.

Windows Threads

Section 4.4.2 discusses thread creation using the Windows API. Refer to that section for specific instructions on creating threads.

Windows Mutex Locks

Mutex locks are a type of dispatcher object, as described in Section 7.2.1. The following illustrates how to create a mutex lock using the `CreateMutex()` function:

```
#include <windows.h>

HANDLE Mutex;
Mutex = CreateMutex(NULL, FALSE, NULL);
```

The first parameter refers to a security attribute for the mutex lock. By setting this attribute to `NULL`, we prevent any children of the process from creating this mutex lock to inherit the handle of the lock. The second parameter indicates whether the creator of the mutex lock is the lock's initial owner. Passing a value of `FALSE` indicates that the thread creating the mutex is not the initial owner. (We shall soon see how mutex locks are acquired.) The third parameter allows us to name the mutex. However, because we provide a value of `NULL`, we do not name the mutex. If successful, `CreateMutex()` returns a `HANDLE` to the mutex lock; otherwise, it returns `NULL`.

In Section 7.2.1, we identified dispatcher objects as being either ***signaled*** or ***nonsignaled***. A signaled dispatcher object (such as a mutex lock) is available for ownership. Once it is acquired, it moves to the nonsignaled state. When it is released, it returns to signaled.

Mutex locks are acquired by invoking the `WaitForSingleObject()` function. The function is passed the `HANDLE` to the lock along with a flag indicating how long to wait. The following code demonstrates how the mutex lock created above can be acquired:

```
WaitForSingleObject(Mutex, INFINITE);
```

The parameter value `INFINITE` indicates that we will wait an infinite amount of time for the lock to become available. Other values could be used that would allow the calling thread to time out if the lock did not become available within a specified time. If the lock is in a signaled state, `WaitForSingleObject()` returns immediately, and the lock becomes nonsignaled. A lock is released (moves to the signaled state) by invoking `ReleaseMutex()`—for example, as follows:

```
ReleaseMutex(Mutex);
```

Windows Semaphores

Semaphores in the Windows API are dispatcher objects and thus use the same signaling mechanism as mutex locks. Semaphores are created as follows:

```
#include <windows.h>

HANDLE Sem;
Sem = CreateSemaphore(NULL, 1, 5, NULL);
```

The first and last parameters identify a security attribute and a name for the semaphore, similar to what we described for mutex locks. The second and third parameters indicate the initial value and maximum value of the semaphore. In this instance, the initial value of the semaphore is 1, and its maximum value is 5. If successful, `CreateSemaphore()` returns a `HANDLE` to the mutex lock; otherwise, it returns `NULL`.

Semaphores are acquired with the same `WaitForSingleObject()` function as mutex locks. We acquire the semaphore `Sem` created in this example by using the following statement:

```
WaitForSingleObject(Sem, INFINITE);
```

If the value of the semaphore is > 0, the semaphore is in the signaled state and thus is acquired by the calling thread. Otherwise, the calling thread blocks indefinitely—as we are specifying `INFINITE`—until the semaphore returns to the signaled state.

The equivalent of the `signal()` operation for Windows semaphores is the `ReleaseSemaphore()` function. This function is passed three parameters:

1. The HANDLE of the semaphore
2. How much to increase the value of the semaphore
3. A pointer to the previous value of the semaphore

We can use the following statement to increase `Sem` by 1:

```
ReleaseSemaphore(Sem, 1, NULL);
```

Both `ReleaseSemaphore()` and `ReleaseMutex()` return a nonzero value if successful and 0 otherwise.

CHAPTER 8

Deadlocks

In a multiprogramming environment, several threads may compete for a finite number of resources. A thread requests resources; if the resources are not available at that time, the thread enters a waiting state. Sometimes, a waiting thread can never again change state, because the resources it has requested are held by other waiting threads. This situation is called a **deadlock**. We discussed this issue briefly in Chapter 6 as a form of liveness failure. There, we defined deadlock as a situation in which *every process in a set of processes is waiting for an event that can be caused only by another process in the set*.

Perhaps the best illustration of a deadlock can be drawn from a law passed by the Kansas legislature early in the 20th century. It said, in part: "When two trains approach each other at a crossing, both shall come to a full stop and neither shall start up again until the other has gone."

In this chapter, we describe methods that application developers as well as operating-system programmers can use to prevent or deal with deadlocks. Although some applications can identify programs that may deadlock, operating systems typically do not provide deadlock-prevention facilities, and it remains the responsibility of programmers to ensure that they design deadlock-free programs. Deadlock problems—as well as other liveness failures—are becoming more challenging as demand continues for increased concurrency and parallelism on multicore systems.

CHAPTER OBJECTIVES

- Illustrate how deadlock can occur when mutex locks are used.
- Define the four necessary conditions that characterize deadlock.
- Identify a deadlock situation in a resource allocation graph.
- Evaluate the four different approaches for preventing deadlocks.
- Apply the banker's algorithm for deadlock avoidance.
- Apply the deadlock detection algorithm.
- Evaluate approaches for recovering from deadlock.

8.1 System Model

A system consists of a finite number of resources to be distributed among a number of competing threads. The resources may be partitioned into several types (or classes), each consisting of some number of identical instances. CPU cycles, files, and I/O devices (such as network interfaces and DVD drives) are examples of resource types. If a system has four CPUs, then the resource type *CPU* has four instances. Similarly, the resource type *network* may have two instances. If a thread requests an instance of a resource type, the allocation of ***any*** instance of the type should satisfy the request. If it does not, then the instances are not identical, and the resource type classes have not been defined properly.

The various synchronization tools discussed in Chapter 6, such as mutex locks and semaphores, are also system resources; and on contemporary computer systems, they are the most common sources of deadlock. However, definition is not a problem here. A lock is typically associated with a specific data structure—that is, one lock may be used to protect access to a queue, another to protect access to a linked list, and so forth. For that reason, each instance of a lock is typically assigned its own resource class.

Note that throughout this chapter we discuss kernel resources, but threads may use resources from other processes (for example, via interprocess communication), and those resource uses can also result in deadlock. Such deadlocks are not the concern of the kernel and thus not described here.

A thread must request a resource before using it and must release the resource after using it. A thread may request as many resources as it requires to carry out its designated task. Obviously, the number of resources requested may not exceed the total number of resources available in the system. In other words, a thread cannot request two network interfaces if the system has only one.

Under the normal mode of operation, a thread may utilize a resource in only the following sequence:

1. **Request**. The thread requests the resource. If the request cannot be granted immediately (for example, if a mutex lock is currently held by another thread), then the requesting thread must wait until it can acquire the resource.
2. **Use**. The thread can operate on the resource (for example, if the resource is a mutex lock, the thread can access its critical section).
3. **Release**. The thread releases the resource.

The request and release of resources may be system calls, as explained in Chapter 2. Examples are the `request()` and `release()` of a device, `open()` and `close()` of a file, and `allocate()` and `free()` memory system calls. Similarly, as we saw in Chapter 6, request and release can be accomplished through the `wait()` and `signal()` operations on semaphores and through `acquire()` and `release()` of a mutex lock. For each use of a kernel-managed resource by a thread, the operating system checks to make sure that the thread has requested and has been allocated the resource. A system table records whether each resource is free or allocated. For each resource that is allocated,

the table also records the thread to which it is allocated. If a thread requests a resource that is currently allocated to another thread, it can be added to a queue of threads waiting for this resource.

A set of threads is in a deadlocked state when every thread in the set is waiting for an event that can be caused only by another thread in the set. The events with which we are mainly concerned here are resource acquisition and release. The resources are typically logical (for example, mutex locks, semaphores, and files); however, other types of events may result in deadlocks, including reading from a network interface or the IPC (interprocess communication) facilities discussed in Chapter 3.

To illustrate a deadlocked state, we refer back to the dining-philosophers problem from Section 7.1.3. In this situation, resources are represented by chopsticks. If all the philosophers get hungry at the same time, and each philosopher grabs the chopstick on her left, there are no longer any available chopsticks. Each philosopher is then blocked waiting for her right chopstick to become available.

Developers of multithreaded applications must remain aware of the possibility of deadlocks. The locking tools presented in Chapter 6 are designed to avoid race conditions. However, in using these tools, developers must pay careful attention to how locks are acquired and released. Otherwise, deadlock can occur, as described next.

8.2 Deadlock in Multithreaded Applications

Prior to examining how deadlock issues can be identified and managed, we first illustrate how deadlock can occur in a multithreaded Pthread program using POSIX mutex locks. The `pthread_mutex_init()` function initializes an unlocked mutex. Mutex locks are acquired and released using `pthread_mutex_lock()` and `pthread_mutex_unlock()`, respectively. If a thread attempts to acquire a locked mutex, the call to `pthread_mutex_lock()` blocks the thread until the owner of the mutex lock invokes `pthread_mutex_unlock()`.

Two mutex locks are created and initialized in the following code example:

```
pthread_mutex_t first_mutex;
pthread_mutex_t second_mutex;

pthread_mutex_init(&first_mutex,NULL);
pthread_mutex_init(&second_mutex,NULL);
```

Next, two threads—`thread_one` and `thread_two`—are created, and both these threads have access to both mutex locks. `thread_one` and `thread_two` run in the functions `do_work_one()` and `do_work_two()`, respectively, as shown in Figure 8.1.

In this example, `thread_one` attempts to acquire the mutex locks in the order (1) `first_mutex`, (2) `second_mutex`. At the same time, `thread_two` attempts to acquire the mutex locks in the order (1) `second_mutex`, (2) `first_mutex`. Deadlock is possible if `thread_one` acquires `first_mutex` while `thread_two` acquires `second_mutex`.

```
/* thread_one runs in this function */
void *do_work_one(void *param)
{
   pthread_mutex_lock(&first_mutex);
   pthread_mutex_lock(&second_mutex);
   /**
    * Do some work
    */
   pthread_mutex_unlock(&second_mutex);
   pthread_mutex_unlock(&first_mutex);

   pthread_exit(0);
}

/* thread_two runs in this function */
void *do_work_two(void *param)
{
   pthread_mutex_lock(&second_mutex);
   pthread_mutex_lock(&first_mutex);
   /**
    * Do some work
    */
   pthread_mutex_unlock(&first_mutex);
   pthread_mutex_unlock(&second_mutex);

   pthread_exit(0);
}
```

Figure 8.1 Deadlock example.

Note that, even though deadlock is possible, it will not occur if `thread_one` can acquire and release the mutex locks for `first_mutex` and `second_mutex` before `thread_two` attempts to acquire the locks. And, of course, the order in which the threads run depends on how they are scheduled by the CPU scheduler. This example illustrates a problem with handling deadlocks: it is difficult to identify and test for deadlocks that may occur only under certain scheduling circumstances.

8.2.1 Livelock

Livelock is another form of liveness failure. It is similar to deadlock; both prevent two or more threads from proceeding, but the threads are unable to proceed for different reasons. Whereas deadlock occurs when every thread in a set is blocked waiting for an event that can be caused only by another thread in the set, livelock occurs when a thread continuously attempts an action that fails. Livelock is similar to what sometimes happens when two people attempt to pass in a hallway: One moves to his right, the other to her left, still obstructing each other's progress. Then he moves to his left, and she moves

to her right, and so forth. They aren't blocked, but they aren't making any progress.

Livelock can be illustrated with the Pthreads `pthread_mutex_trylock()` function, which attempts to acquire a mutex lock without blocking. The code example in Figure 8.2 rewrites the example from Figure 8.1 so that it now uses `pthread_mutex_trylock()`. This situation can lead to livelock if `thread_one` acquires `first_mutex`, followed by `thread_two` acquiring `second_mutex`. Each thread then invokes `pthread_mutex_trylock()`, which fails, releases their respective locks, and repeats the same actions indefinitely.

Livelock typically occurs when threads retry failing operations at the same time. It thus can generally be avoided by having each thread retry the failing operation at random times. This is precisely the approach taken by Ethernet networks when a network collision occurs. Rather than trying to retransmit a packet immediately after a collision occurs, a host involved in a collision will *backoff* a random period of time before attempting to transmit again.

Livelock is less common than deadlock but nonetheless is a challenging issue in designing concurrent applications, and like deadlock, it may only occur under specific scheduling circumstances.

8.3 Deadlock Characterization

In the previous section we illustrated how deadlock could occur in multithreaded programming using mutex locks. We now look more closely at conditions that characterize deadlock.

8.3.1 Necessary Conditions

A deadlock situation can arise if the following four conditions hold simultaneously in a system:

1. **Mutual exclusion**. At least one resource must be held in a nonsharable mode; that is, only one thread at a time can use the resource. If another thread requests that resource, the requesting thread must be delayed until the resource has been released.
2. **Hold and wait**. A thread must be holding at least one resource and waiting to acquire additional resources that are currently being held by other threads.
3. **No preemption**. Resources cannot be preempted; that is, a resource can be released only voluntarily by the thread holding it, after that thread has completed its task.
4. **Circular wait**. A set $\{T_0, T_1, ..., T_n\}$ of waiting threads must exist such that T_0 is waiting for a resource held by T_1, T_1 is waiting for a resource held by T_2, ..., T_{n-1} is waiting for a resource held by T_n, and T_n is waiting for a resource held by T_0.

We emphasize that all four conditions must hold for a deadlock to occur. The circular-wait condition implies the hold-and-wait condition, so the four

```
/* thread_one runs in this function */
void *do_work_one(void *param)
{
   int done = 0;

   while (!done) {
      pthread_mutex_lock(&first_mutex);
      if (pthread_mutex_trylock(&second_mutex)) {
         /**
          * Do some work
          */
         pthread_mutex_unlock(&second_mutex);
         pthread_mutex_unlock(&first_mutex);
         done = 1;
      }
      else
         pthread_mutex_unlock(&first_mutex);
   }

   pthread_exit(0);
}

/* thread_two runs in this function */
void *do_work_two(void *param)
{
   int done = 0;

   while (!done) {
      pthread_mutex_lock(&second_mutex);
      if (pthread_mutex_trylock(&first_mutex)) {
         /**
          * Do some work
          */
         pthread_mutex_unlock(&first_mutex);
         pthread_mutex_unlock(&second_mutex);
         done = 1;
      }
      else
         pthread_mutex_unlock(&second_mutex);
   }

   pthread_exit(0);
}
```

Figure 8.2 Livelock example.

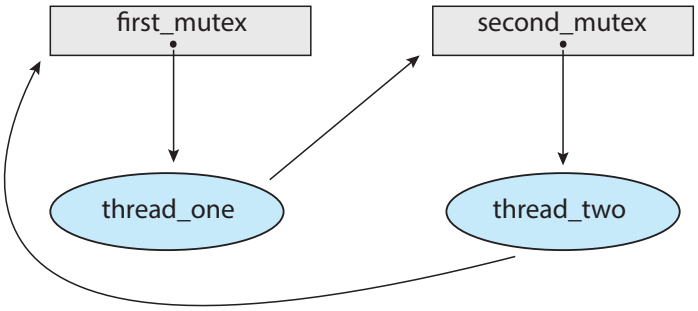

Figure 8.3 Resource-allocation graph for program in Figure 8.1.

conditions are not completely independent. We shall see in Section 8.5, however, that it is useful to consider each condition separately.

8.3.2 Resource-Allocation Graph

Deadlocks can be described more precisely in terms of a directed graph called a **system resource-allocation graph**. This graph consists of a set of vertices V and a set of edges E. The set of vertices V is partitioned into two different types of nodes: $T = \{T_1, T_2, ..., T_n\}$, the set consisting of all the active threads in the system, and $R = \{R_1, R_2, ..., R_m\}$, the set consisting of all resource types in the system.

A directed edge from thread T_i to resource type R_j is denoted by $T_i \rightarrow R_j$; it signifies that thread T_i has requested an instance of resource type R_j and is currently waiting for that resource. A directed edge from resource type R_j to thread T_i is denoted by $R_j \rightarrow T_i$; it signifies that an instance of resource type R_j has been allocated to thread T_i. A directed edge $T_i \rightarrow R_j$ is called a **request edge**; a directed edge $R_j \rightarrow T_i$ is called an **assignment edge**.

Pictorially, we represent each thread T_i as a circle and each resource type R_j as a rectangle. As a simple example, the resource allocation graph shown in Figure 8.3 illustrates the deadlock situation from the program in Figure 8.1. Since resource type R_j may have more than one instance, we represent each such instance as a dot within the rectangle. Note that a request edge points only to the rectangle R_j, whereas an assignment edge must also designate one of the dots in the rectangle.

When thread T_i requests an instance of resource type R_j, a request edge is inserted in the resource-allocation graph. When this request can be fulfilled, the request edge is ***instantaneously*** transformed to an assignment edge. When the thread no longer needs access to the resource, it releases the resource. As a result, the assignment edge is deleted.

The resource-allocation graph shown in Figure 8.4 depicts the following situation.

- The sets T, R, and E:
  - $T = \{T_1, T_2, T_3\}$
  - $R = \{R_1, R_2, R_3, R_4\}$

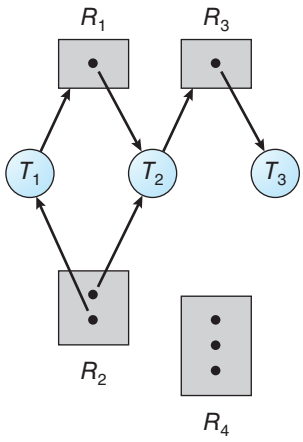

Figure 8.4 Resource-allocation graph.

- $E = \{T_1 \rightarrow R_1, T_2 \rightarrow R_3, R_1 \rightarrow T_2, R_2 \rightarrow T_2, R_2 \rightarrow T_1, R_3 \rightarrow T_3\}$

- Resource instances:
  - One instance of resource type R_1
  - Two instances of resource type R_2
  - One instance of resource type R_3
  - Three instances of resource type R_4

- Thread states:
  - Thread T_1 is holding an instance of resource type R_2 and is waiting for an instance of resource type R_1.
  - Thread T_2 is holding an instance of R_1 and an instance of R_2 and is waiting for an instance of R_3.
  - Thread T_3 is holding an instance of R_3.

Given the definition of a resource-allocation graph, it can be shown that, if the graph contains no cycles, then no thread in the system is deadlocked. If the graph does contain a cycle, then a deadlock may exist.

If each resource type has exactly one instance, then a cycle implies that a deadlock has occurred. If the cycle involves only a set of resource types, each of which has only a single instance, then a deadlock has occurred. Each thread involved in the cycle is deadlocked. In this case, a cycle in the graph is both a necessary and a sufficient condition for the existence of deadlock.

If each resource type has several instances, then a cycle does not necessarily imply that a deadlock has occurred. In this case, a cycle in the graph is a necessary but not a sufficient condition for the existence of deadlock.

To illustrate this concept, we return to the resource-allocation graph depicted in Figure 8.4. Suppose that thread T_3 requests an instance of resource type R_2. Since no resource instance is currently available, we add a request

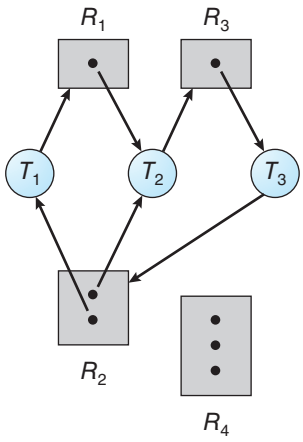

Figure 8.5 Resource-allocation graph with a deadlock.

edge $T_3 \rightarrow R_2$ to the graph (Figure 8.5). At this point, two minimal cycles exist in the system:

$$T_1 \rightarrow R_1 \rightarrow T_2 \rightarrow R_3 \rightarrow T_3 \rightarrow R_2 \rightarrow T_1$$
$$T_2 \rightarrow R_3 \rightarrow T_3 \rightarrow R_2 \rightarrow T_2$$

Threads T_1, T_2, and T_3 are deadlocked. Thread T_2 is waiting for the resource R_3, which is held by thread T_3. Thread T_3 is waiting for either thread T_1 or thread T_2 to release resource R_2. In addition, thread T_1 is waiting for thread T_2 to release resource R_1.

Now consider the resource-allocation graph in Figure 8.6. In this example, we also have a cycle:

$$T_1 \rightarrow R_1 \rightarrow T_3 \rightarrow R_2 \rightarrow T_1$$

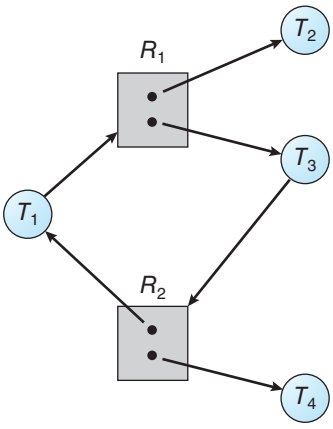

Figure 8.6 Resource-allocation graph with a cycle but no deadlock.

However, there is no deadlock. Observe that thread T_4 may release its instance of resource type R_2. That resource can then be allocated to T_3, breaking the cycle.

In summary, if a resource-allocation graph does not have a cycle, then the system is ***not*** in a deadlocked state. If there is a cycle, then the system ***may*** or ***may not*** be in a deadlocked state. This observation is important when we deal with the deadlock problem.

8.4 Methods for Handling Deadlocks

Generally speaking, we can deal with the deadlock problem in one of three ways:

- We can ignore the problem altogether and pretend that deadlocks never occur in the system.
- We can use a protocol to prevent or avoid deadlocks, ensuring that the system will ***never*** enter a deadlocked state.
- We can allow the system to enter a deadlocked state, detect it, and recover.

The first solution is the one used by most operating systems, including Linux and Windows. It is then up to kernel and application developers to write programs that handle deadlocks, typically using approaches outlined in the second solution. Some systems—such as databases—adopt the third solution, allowing deadlocks to occur and then managing the recovery.

Next, we elaborate briefly on the three methods for handling deadlocks. Then, in Section 8.5 through Section 8.8, we present detailed algorithms. Before proceeding, we should mention that some researchers have argued that none of the basic approaches alone is appropriate for the entire spectrum of resource-allocation problems in operating systems. The basic approaches can be combined, however, allowing us to select an optimal approach for each class of resources in a system.

To ensure that deadlocks never occur, the system can use either a deadlock-prevention or a deadlock-avoidance scheme. **Deadlock prevention** provides a set of methods to ensure that at least one of the necessary conditions (Section 8.3.1) cannot hold. These methods prevent deadlocks by constraining how requests for resources can be made. We discuss these methods in Section 8.5.

Deadlock avoidance requires that the operating system be given additional information in advance concerning which resources a thread will request and use during its lifetime. With this additional knowledge, the operating system can decide for each request whether or not the thread should wait. To decide whether the current request can be satisfied or must be delayed, the system must consider the resources currently available, the resources currently allocated to each thread, and the future requests and releases of each thread. We discuss these schemes in Section 8.6.

If a system does not employ either a deadlock-prevention or a deadlock-avoidance algorithm, then a deadlock situation may arise. In this environment, the system can provide an algorithm that examines the state of the system to determine whether a deadlock has occurred and an algorithm to recover from

the deadlock (if a deadlock has indeed occurred). We discuss these issues in Section 8.7 and Section 8.8.

In the absence of algorithms to detect and recover from deadlocks, we may arrive at a situation in which the system is in a deadlocked state yet has no way of recognizing what has happened. In this case, the undetected deadlock will cause the system's performance to deteriorate, because resources are being held by threads that cannot run and because more and more threads, as they make requests for resources, will enter a deadlocked state. Eventually, the system will stop functioning and will need to be restarted manually.

Although this method may not seem to be a viable approach to the deadlock problem, it is nevertheless used in most operating systems, as mentioned earlier. Expense is one important consideration. Ignoring the possibility of deadlocks is cheaper than the other approaches. Since in many systems, deadlocks occur infrequently (say, once per month), the extra expense of the other methods may not seem worthwhile.

In addition, methods used to recover from other liveness conditions, such as livelock, may be used to recover from deadlock. In some circumstances, a system is suffering from a liveness failure but is not in a deadlocked state. We see this situation, for example, with a real-time thread running at the highest priority (or any thread running on a nonpreemptive scheduler) and never returning control to the operating system. The system must have manual recovery methods for such conditions and may simply use those techniques for deadlock recovery.

8.5 Deadlock Prevention

As we noted in Section 8.3.1, for a deadlock to occur, each of the four necessary conditions must hold. By ensuring that at least one of these conditions cannot hold, we can *prevent* the occurrence of a deadlock. We elaborate on this approach by examining each of the four necessary conditions separately.

8.5.1 Mutual Exclusion

The mutual-exclusion condition must hold. That is, at least one resource must be nonsharable. Sharable resources do not require mutually exclusive access and thus cannot be involved in a deadlock. Read-only files are a good example of a sharable resource. If several threads attempt to open a read-only file at the same time, they can be granted simultaneous access to the file. A thread never needs to wait for a sharable resource. In general, however, we cannot prevent deadlocks by denying the mutual-exclusion condition, because some resources are intrinsically nonsharable. For example, a mutex lock cannot be simultaneously shared by several threads.

8.5.2 Hold and Wait

To ensure that the hold-and-wait condition never occurs in the system, we must guarantee that, whenever a thread requests a resource, it does not hold any other resources. One protocol that we can use requires each thread to request and be allocated all its resources before it begins execution. This is, of course,

impractical for most applications due to the dynamic nature of requesting resources.

An alternative protocol allows a thread to request resources only when it has none. A thread may request some resources and use them. Before it can request any additional resources, it must release all the resources that it is currently allocated.

Both these protocols have two main disadvantages. First, resource utilization may be low, since resources may be allocated but unused for a long period. For example, a thread may be allocated a mutex lock for its entire execution, yet only require it for a short duration. Second, starvation is possible. A thread that needs several popular resources may have to wait indefinitely, because at least one of the resources that it needs is always allocated to some other thread.

8.5.3 No Preemption

The third necessary condition for deadlocks is that there be no preemption of resources that have already been allocated. To ensure that this condition does not hold, we can use the following protocol. If a thread is holding some resources and requests another resource that cannot be immediately allocated to it (that is, the thread must wait), then all resources the thread is currently holding are preempted. In other words, these resources are implicitly released. The preempted resources are added to the list of resources for which the thread is waiting. The thread will be restarted only when it can regain its old resources, as well as the new ones that it is requesting.

Alternatively, if a thread requests some resources, we first check whether they are available. If they are, we allocate them. If they are not, we check whether they are allocated to some other thread that is waiting for additional resources. If so, we preempt the desired resources from the waiting thread and allocate them to the requesting thread. If the resources are neither available nor held by a waiting thread, the requesting thread must wait. While it is waiting, some of its resources may be preempted, but only if another thread requests them. A thread can be restarted only when it is allocated the new resources it is requesting and recovers any resources that were preempted while it was waiting.

This protocol is often applied to resources whose state can be easily saved and restored later, such as CPU registers and database transactions. It cannot generally be applied to such resources as mutex locks and semaphores, precisely the type of resources where deadlock occurs most commonly.

8.5.4 Circular Wait

The three options presented thus far for deadlock prevention are generally impractical in most situations. However, the fourth and final condition for deadlocks — the circular-wait condition — presents an opportunity for a practical solution by invalidating one of the necessary conditions. One way to ensure that this condition never holds is to impose a total ordering of all resource types and to require that each thread requests resources in an increasing order of enumeration.

To illustrate, we let $R = \{R_1, R_2, ..., R_m\}$ be the set of resource types. We assign to each resource type a unique integer number, which allows us to

compare two resources and to determine whether one precedes another in our ordering. Formally, we define a one-to-one function $F: R \rightarrow N$, where N is the set of natural numbers. We can accomplish this scheme in an application program by developing an ordering among all synchronization objects in the system. For example, the lock ordering in the Pthread program shown in Figure 8.1 could be

$$F(\texttt{first\_mutex}) = 1$$
$$F(\texttt{second\_mutex}) = 5$$

We can now consider the following protocol to prevent deadlocks: Each thread can request resources only in an increasing order of enumeration. That is, a thread can initially request an instance of a resource—say, R_i. After that, the thread can request an instance of resource R_j if and only if $F(R_j) > F(R_i)$. For example, using the function defined above, a thread that wants to use both `first_mutex` and `second_mutex` at the same time must first request `first_mutex` and then `second_mutex`. Alternatively, we can require that a thread requesting an instance of resource R_j must have released any resources R_i such that $F(R_i) \geq F(R_j)$. Note also that if several instances of the same resource type are needed, a ***single*** request for all of them must be issued.

If these two protocols are used, then the circular-wait condition cannot hold. We can demonstrate this fact by assuming that a circular wait exists (proof by contradiction). Let the set of threads involved in the circular wait be $\{T_0, T_1, ..., T_n\}$, where T_i is waiting for a resource R_i, which is held by thread T_{i+1}. (Modulo arithmetic is used on the indexes, so that T_n is waiting for a resource R_n held by T_0.) Then, since thread T_{i+1} is holding resource R_i while requesting resource R_{i+1}, we must have $F(R_i) < F(R_{i+1})$ for all i. But this condition means that $F(R_0) < F(R_1) < ... < F(R_n) < F(R_0)$. By transitivity, $F(R_0) < F(R_0)$, which is impossible. Therefore, there can be no circular wait.

Keep in mind that developing an ordering, or hierarchy, does not in itself prevent deadlock. It is up to application developers to write programs that follow the ordering. However, establishing a lock ordering can be difficult, especially on a system with hundreds—or thousands—of locks. To address this challenge, many Java developers have adopted the strategy of using the method `System.identityHashCode(Object)` (which returns the default hash code value of the `Object` parameter it has been passed) as the function for ordering lock acquisition.

It is also important to note that imposing a lock ordering does not guarantee deadlock prevention if locks can be acquired dynamically. For example, assume we have a function that transfers funds between two accounts. To prevent a race condition, each account has an associated mutex lock that is obtained from a `get_lock()` function such as that shown in Figure 8.7. Deadlock is possible if two threads simultaneously invoke the `transaction()` function, transposing different accounts. That is, one thread might invoke

```
transaction(checking_account, savings_account, 25.0)
```

and another might invoke

```
transaction(savings_account, checking_account, 50.0)
```

```
void transaction(Account from, Account to, double amount)
{
   mutex lock1, lock2;
   lock1 = get_lock(from);
   lock2 = get_lock(to);

   acquire(lock1);
      acquire(lock2);

         withdraw(from, amount);
         deposit(to, amount);

      release(lock2);
   release(lock1);
}
```

Figure 8.7 Deadlock example with lock ordering.

8.6 Deadlock Avoidance

Deadlock-prevention algorithms, as discussed in Section 8.5, prevent deadlocks by limiting how requests can be made. The limits ensure that at least one of the necessary conditions for deadlock cannot occur. Possible side effects of preventing deadlocks by this method, however, are low device utilization and reduced system throughput.

An alternative method for avoiding deadlocks is to require additional information about how resources are to be requested. For example, in a system with resources $R1$ and $R2$, the system might need to know that thread P will request first $R1$ and then $R2$ before releasing both resources, whereas thread Q will request $R2$ and then $R1$. With this knowledge of the complete sequence of requests and releases for each thread, the system can decide for each request whether or not the thread should wait in order to avoid a possible future deadlock. Each request requires that in making this decision the system consider the resources currently available, the resources currently allocated to each thread, and the future requests and releases of each thread.

The various algorithms that use this approach differ in the amount and type of information required. The simplest and most useful model requires that each thread declare the ***maximum number*** of resources of each type that it may need. Given this a priori information, it is possible to construct an algorithm that ensures that the system will never enter a deadlocked state. A deadlock-avoidance algorithm dynamically examines the resource-allocation state to ensure that a circular-wait condition can never exist. The resource-allocation ***state*** is defined by the number of available and allocated resources and the maximum demands of the threads. In the following sections, we explore two deadlock-avoidance algorithms.

LINUX LOCKDEP TOOL

Although ensuring that resources are acquired in the proper order is the responsibility of kernel and application developers, certain software can be used to verify that locks are acquired in the proper order. To detect possible deadlocks, Linux provides `lockdep`, a tool with rich functionality that can be used to verify locking order in the kernel. `lockdep` is designed to be enabled on a running kernel as it monitors usage patterns of lock acquisitions and releases against a set of rules for acquiring and releasing locks. Two examples follow, but note that `lockdep` provides significantly more functionality than what is described here:

- The order in which locks are acquired is dynamically maintained by the system. If `lockdep` detects locks being acquired out of order, it reports a possible deadlock condition.
- In Linux, spinlocks can be used in interrupt handlers. A possible source of deadlock occurs when the kernel acquires a spinlock that is also used in an interrupt handler. If the interrupt occurs while the lock is being held, the interrupt handler preempts the kernel code currently holding the lock and then spins while attempting to acquire the lock, resulting in deadlock. The general strategy for avoiding this situation is to disable interrupts on the current processor before acquiring a spinlock that is also used in an interrupt handler. If `lockdep` detects that interrupts are enabled while kernel code acquires a lock that is also used in an interrupt handler, it will report a possible deadlock scenario.

`lockdep` was developed to be used as a tool in developing or modifying code in the kernel and not to be used on production systems, as it can significantly slow down a system. Its purpose is to test whether software such as a new device driver or kernel module provides a possible source of deadlock. The designers of `lockdep` have reported that within a few years of its development in 2006, the number of deadlocks from system reports had been reduced by an order of magnitude.âŁž Although `lockdep` was originally designed only for use in the kernel, recent revisions of this tool can now be used for detecting deadlocks in user applications using Pthreads mutex locks. Further details on the `lockdep` tool can be found at https://www.kernel.org/doc/Documentation/locking/lockdep-design.txt.

8.6.1 Safe State

A state is *safe* if the system can allocate resources to each thread (up to its maximum) in some order and still avoid a deadlock. More formally, a system is in a safe state only if there exists a **safe sequence**. A sequence of threads $<T_1, T_2, ..., T_n>$ is a safe sequence for the current allocation state if, for each T_i, the resource requests that T_i can still make can be satisfied by the currently available resources plus the resources held by all T_j, with $j < i$. In this situation, if the resources that T_i needs are not immediately available, then T_i can wait until all T_j have finished. When they have finished, T_i can obtain all of its

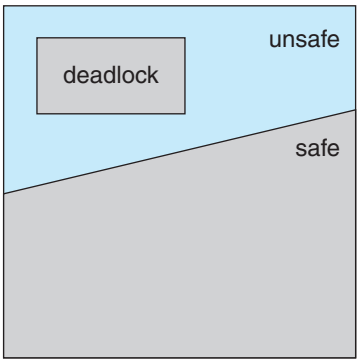

Figure 8.8 Safe, unsafe, and deadlocked state spaces.

needed resources, complete its designated task, return its allocated resources, and terminate. When T_i terminates, T_{i+1} can obtain its needed resources, and so on. If no such sequence exists, then the system state is said to be *unsafe*.

A safe state is not a deadlocked state. Conversely, a deadlocked state is an unsafe state. Not all unsafe states are deadlocks, however (Figure 8.8). An unsafe state ***may*** lead to a deadlock. As long as the state is safe, the operating system can avoid unsafe (and deadlocked) states. In an unsafe state, the operating system cannot prevent threads from requesting resources in such a way that a deadlock occurs. The behavior of the threads controls unsafe states.

To illustrate, consider a system with twelve resources and three threads: T_0, T_1, and T_2. Thread T_0 requires ten resources, thread T_1 may need as many as four, and thread T_2 may need up to nine resources. Suppose that, at time t_0, thread T_0 is holding five resources, thread T_1 is holding two resources, and thread T_2 is holding two resources. (Thus, there are three free resources.)

	Maximum Needs	Current Needs
T_0	10	5
T_1	4	2
T_2	9	2

At time t_0, the system is in a safe state. The sequence $<T_1, T_0, T_2>$ satisfies the safety condition. Thread T_1 can immediately be allocated all its resources and then return them (the system will then have five available resources); then thread T_0 can get all its resources and return them (the system will then have ten available resources); and finally thread T_2 can get all its resources and return them (the system will then have all twelve resources available).

A system can go from a safe state to an unsafe state. Suppose that, at time t_1, thread T_2 requests and is allocated one more resource. The system is no longer in a safe state. At this point, only thread T_1 can be allocated all its resources. When it returns them, the system will have only four available resources. Since thread T_0 is allocated five resources but has a maximum of ten, it may request five more resources. If it does so, it will have to wait, because they are unavailable. Similarly, thread T_2 may request six additional resources and have to wait, resulting in a deadlock. Our mistake was in granting the request from thread T_2 for one more resource. If we had made T_2 wait until either of the other

threads had finished and released its resources, then we could have avoided the deadlock.

Given the concept of a safe state, we can define avoidance algorithms that ensure that the system will never deadlock. The idea is simply to ensure that the system will always remain in a safe state. Initially, the system is in a safe state. Whenever a thread requests a resource that is currently available, the system must decide whether the resource can be allocated immediately or the thread must wait. The request is granted only if the allocation leaves the system in a safe state.

In this scheme, if a thread requests a resource that is currently available, it may still have to wait. Thus, resource utilization may be lower than it would otherwise be.

8.6.2 Resource-Allocation-Graph Algorithm

If we have a resource-allocation system with only one instance of each resource type, we can use a variant of the resource-allocation graph defined in Section 8.3.2 for deadlock avoidance. In addition to the request and assignment edges already described, we introduce a new type of edge, called a **claim edge**. A claim edge $T_i \rightarrow R_j$ indicates that thread T_i may request resource R_j at some time in the future. This edge resembles a request edge in direction but is represented in the graph by a dashed line. When thread T_i requests resource R_j, the claim edge $T_i \rightarrow R_j$ is converted to a request edge. Similarly, when a resource R_j is released by T_i, the assignment edge $R_j \rightarrow T_i$ is reconverted to a claim edge $T_i \rightarrow R_j$.

Note that the resources must be claimed a priori in the system. That is, before thread T_i starts executing, all its claim edges must already appear in the resource-allocation graph. We can relax this condition by allowing a claim edge $T_i \rightarrow R_j$ to be added to the graph only if all the edges associated with thread T_i are claim edges.

Now suppose that thread T_i requests resource R_j. The request can be granted only if converting the request edge $T_i \rightarrow R_j$ to an assignment edge $R_j \rightarrow T_i$ does not result in the formation of a cycle in the resource-allocation graph. We check for safety by using a cycle-detection algorithm. An algorithm for detecting a cycle in this graph requires an order of n^2 operations, where n is the number of threads in the system.

If no cycle exists, then the allocation of the resource will leave the system in a safe state. If a cycle is found, then the allocation will put the system in an unsafe state. In that case, thread T_i will have to wait for its requests to be satisfied.

To illustrate this algorithm, we consider the resource-allocation graph of Figure 8.9. Suppose that T_2 requests R_2. Although R_2 is currently free, we cannot allocate it to T_2, since this action will create a cycle in the graph (Figure 8.10). A cycle, as mentioned, indicates that the system is in an unsafe state. If T_1 requests R_2, and T_2 requests R_1, then a deadlock will occur.

8.6.3 Banker's Algorithm

The resource-allocation-graph algorithm is not applicable to a resource-allocation system with multiple instances of each resource type. The

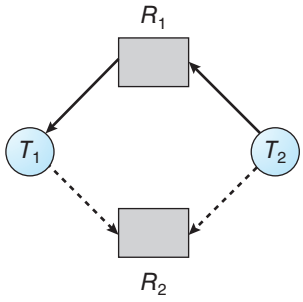

Figure 8.9 Resource-allocation graph for deadlock avoidance.

deadlock-avoidance algorithm that we describe next is applicable to such a system but is less efficient than the resource-allocation graph scheme. This algorithm is commonly known as the **banker's algorithm**. The name was chosen because the algorithm could be used in a banking system to ensure that the bank never allocated its available cash in such a way that it could no longer satisfy the needs of all its customers.

When a new thread enters the system, it must declare the maximum number of instances of each resource type that it may need. This number may not exceed the total number of resources in the system. When a user requests a set of resources, the system must determine whether the allocation of these resources will leave the system in a safe state. If it will, the resources are allocated; otherwise, the thread must wait until some other thread releases enough resources.

Several data structures must be maintained to implement the banker's algorithm. These data structures encode the state of the resource-allocation system. We need the following data structures, where n is the number of threads in the system and m is the number of resource types:

- **Available**. A vector of length m indicates the number of available resources of each type. If ***Available***$[j]$ equals k, then k instances of resource type R_j are available.

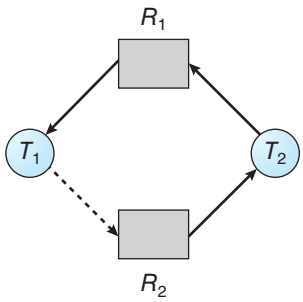

Figure 8.10 An unsafe state in a resource-allocation graph.

- **Max**. An $n \times m$ matrix defines the maximum demand of each thread. If ***Max***$[i][j]$ equals k, then thread T_i may request at most k instances of resource type R_j.
- **Allocation**. An $n \times m$ matrix defines the number of resources of each type currently allocated to each thread. If ***Allocation***$[i][j]$ equals k, then thread T_i is currently allocated k instances of resource type R_j.
- **Need**. An $n \times m$ matrix indicates the remaining resource need of each thread. If ***Need***$[i][j]$ equals k, then thread T_i may need k more instances of resource type R_j to complete its task. Note that ***Need***$[i][j]$ equals ***Max***$[i][j]$ $-$ ***Allocation***$[i][j]$.

These data structures vary over time in both size and value.

To simplify the presentation of the banker's algorithm, we next establish some notation. Let X and Y be vectors of length n. We say that $X \leq Y$ if and only if $X[i] \leq Y[i]$ for all $i = 1, 2, \ldots, n$. For example, if $X = (1,7,3,2)$ and $Y = (0,3,2,1)$, then $Y \leq X$. In addition, $Y < X$ if $Y \leq X$ and $Y \neq X$.

We can treat each row in the matrices ***Allocation*** and ***Need*** as vectors and refer to them as ***Allocation***$_i$ and ***Need***$_i$. The vector ***Allocation***$_i$ specifies the resources currently allocated to thread T_i; the vector ***Need***$_i$ specifies the additional resources that thread T_i may still request to complete its task.

8.6.3.1 Safety Algorithm

We can now present the algorithm for finding out whether or not a system is in a safe state. This algorithm can be described as follows:

1. Let ***Work*** and ***Finish*** be vectors of length m and n, respectively. Initialize ***Work*** = ***Available*** and ***Finish***$[i]$ = ***false*** for $i = 0, 1, \ldots, n - 1$.
2. Find an index i such that both
   a. ***Finish***$[i]$ == ***false***
   b. ***Need***$_i \leq$ ***Work***

   If no such i exists, go to step 4.
3. ***Work*** = ***Work*** + ***Allocation***$_i$
   Finish$[i]$ = ***true***
   Go to step 2.
4. If ***Finish***$[i]$ == ***true*** for all i, then the system is in a safe state.

This algorithm may require an order of $m \times n^2$ operations to determine whether a state is safe.

8.6.3.2 Resource-Request Algorithm

Next, we describe the algorithm for determining whether requests can be safely granted. Let ***Request***$_i$ be the request vector for thread T_i. If ***Request***$_i$ $[j]$ == k, then thread T_i wants k instances of resource type R_j. When a request for resources is made by thread T_i, the following actions are taken:

1. If $\boldsymbol{Request}_i \leq \boldsymbol{Need}_i$, go to step 2. Otherwise, raise an error condition, since the thread has exceeded its maximum claim.
2. If $\boldsymbol{Request}_i \leq \boldsymbol{Available}$, go to step 3. Otherwise, T_i must wait, since the resources are not available.
3. Have the system pretend to have allocated the requested resources to thread T_i by modifying the state as follows:

$$\boldsymbol{Available} = \boldsymbol{Available} - \boldsymbol{Request}_i$$
$$\boldsymbol{Allocation}_i = \boldsymbol{Allocation}_i + \boldsymbol{Request}_i$$
$$\boldsymbol{Need}_i = \boldsymbol{Need}_i - \boldsymbol{Request}_i$$

If the resulting resource-allocation state is safe, the transaction is completed, and thread T_i is allocated its resources. However, if the new state is unsafe, then T_i must wait for $\boldsymbol{Request}_i$, and the old resource-allocation state is restored.

8.6.3.3 An Illustrative Example

To illustrate the use of the banker's algorithm, consider a system with five threads T_0 through T_4 and three resource types A, B, and C. Resource type A has ten instances, resource type B has five instances, and resource type C has seven instances. Suppose that the following snapshot represents the current state of the system:

	Allocation	***Max***	***Available***
	A B C	*A B C*	*A B C*
T_0	0 1 0	7 5 3	3 3 2
T_1	2 0 0	3 2 2	
T_2	3 0 2	9 0 2	
T_3	2 1 1	2 2 2	
T_4	0 0 2	4 3 3	

The content of the matrix ***Need*** is defined to be ***Max*** − ***Allocation*** and is as follows:

	Need
	A B C
T_0	7 4 3
T_1	1 2 2
T_2	6 0 0
T_3	0 1 1
T_4	4 3 1

We claim that the system is currently in a safe state. Indeed, the sequence $<T_1, T_3, T_4, T_2, T_0>$ satisfies the safety criteria. Suppose now that thread T_1 requests one additional instance of resource type A and two instances of resource type C, so $\boldsymbol{Request}_1 = (1,0,2)$. To decide whether this request can be immediately granted, we first check that $\boldsymbol{Request}_1 \leq \boldsymbol{Available}$—that is, that

(1,0,2) ≤ (3,3,2), which is true. We then pretend that this request has been fulfilled, and we arrive at the following new state:

	Allocation	*Need*	*Available*
	A B C	*A B C*	*A B C*
T_0	0 1 0	7 4 3	2 3 0
T_1	3 0 2	0 2 0	
T_2	3 0 2	6 0 0	
T_3	2 1 1	0 1 1	
T_4	0 0 2	4 3 1	

We must determine whether this new system state is safe. To do so, we execute our safety algorithm and find that the sequence $<T_1, T_3, T_4, T_0, T_2>$ satisfies the safety requirement. Hence, we can immediately grant the request of thread T_1.

You should be able to see, however, that when the system is in this state, a request for (3,3,0) by T_4 cannot be granted, since the resources are not available. Furthermore, a request for (0,2,0) by T_0 cannot be granted, even though the resources are available, since the resulting state is unsafe.

We leave it as a programming exercise for students to implement the banker's algorithm.

8.7 Deadlock Detection

If a system does not employ either a deadlock-prevention or a deadlock-avoidance algorithm, then a deadlock situation may occur. In this environment, the system may provide:

- An algorithm that examines the state of the system to determine whether a deadlock has occurred
- An algorithm to recover from the deadlock

Next, we discuss these two requirements as they pertain to systems with only a single instance of each resource type, as well as to systems with several instances of each resource type. At this point, however, we note that a detection-and-recovery scheme requires overhead that includes not only the run-time costs of maintaining the necessary information and executing the detection algorithm but also the potential losses inherent in recovering from a deadlock.

8.7.1 Single Instance of Each Resource Type

If all resources have only a single instance, then we can define a deadlock-detection algorithm that uses a variant of the resource-allocation graph, called a **wait-for** graph. We obtain this graph from the resource-allocation graph by removing the resource nodes and collapsing the appropriate edges.

More precisely, an edge from T_i to T_j in a wait-for graph implies that thread T_i is waiting for thread T_j to release a resource that T_i needs. An edge $T_i \rightarrow T_j$

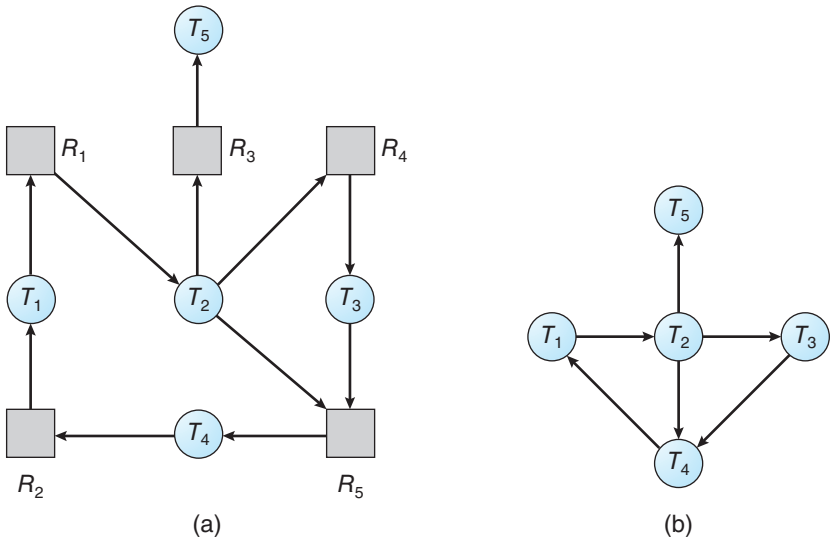

Figure 8.11 (a) Resource-allocation graph. (b) Corresponding wait-for graph.

exists in a wait-for graph if and only if the corresponding resource-allocation graph contains two edges $T_i \rightarrow R_q$ and $R_q \rightarrow T_j$ for some resource R_q. In Figure 8.11, we present a resource-allocation graph and the corresponding wait-for graph.

As before, a deadlock exists in the system if and only if the wait-for graph contains a cycle. To detect deadlocks, the system needs to ***maintain*** the wait-for graph and periodically ***invoke an algorithm*** that searches for a cycle in the graph. An algorithm to detect a cycle in a graph requires $O(n^2)$ operations, where n is the number of vertices in the graph.

The BCC toolkit described in Section 2.10.4 provides a tool that can detect potential deadlocks with Pthreads mutex locks in a user process running on a Linux system. The BCC tool `deadlock_detector` operates by inserting probes which trace calls to the `pthread_mutex_lock()` and `pthread_mutex_unlock()` functions. When the specified process makes a call to either function, `deadlock_detector` constructs a wait-for graph of mutex locks in that process, and reports the possibility of deadlock if it detects a cycle in the graph.

8.7.2 Several Instances of a Resource Type

The wait-for graph scheme is not applicable to a resource-allocation system with multiple instances of each resource type. We turn now to a deadlock-detection algorithm that is applicable to such a system. The algorithm employs several time-varying data structures that are similar to those used in the banker's algorithm (Section 8.6.3):

- **Available**. A vector of length m indicates the number of available resources of each type.

DEADLOCK DETECTION USING JAVA THREAD DUMPS

Although Java does not provide explicit support for deadlock detection, a **thread dump** can be used to analyze a running program to determine if there is a deadlock. A thread dump is a useful debugging tool that displays a snapshot of the states of all threads in a Java application. Java thread dumps also show locking information, including which locks a blocked thread is waiting to acquire. When a thread dump is generated, the JVM searches the wait-for graph to detect cycles, reporting any deadlocks it detects. To generate a thread dump of a running application, from the command line enter:

`Ctrl-L` (UNIX, Linux, or macOS)
`Ctrl-Break` (Windows)

In the source-code download for this text, we provide a Java example of the program shown in Figure 8.1 and describe how to generate a thread dump that reports the deadlocked Java threads.

- **Allocation**. An $n \times m$ matrix defines the number of resources of each type currently allocated to each thread.
- **Request**. An $n \times m$ matrix indicates the current request of each thread. If ***Request***$[i][j]$ equals k, then thread T_i is requesting k more instances of resource type R_j.

The $\leq$ relation between two vectors is defined as in Section 8.6.3. To simplify notation, we again treat the rows in the matrices ***Allocation*** and ***Request*** as vectors; we refer to them as $\boldsymbol{Allocation}_i$ and $\boldsymbol{Request}_i$. The detection algorithm described here simply investigates every possible allocation sequence for the threads that remain to be completed. Compare this algorithm with the banker's algorithm of Section 8.6.3.

1. Let ***Work*** and ***Finish*** be vectors of length m and n, respectively. Initialize ***Work*** = ***Available***. For $i = 0, 1, ..., n-1$, if $\boldsymbol{Allocation}_i \neq 0$, then ***Finish***$[i]$ = ***false***. Otherwise, ***Finish***$[i]$ = ***true***.
2. Find an index i such that both
   a. ***Finish***$[i]$ == ***false***
   b. $\boldsymbol{Request}_i \leq$ ***Work***

   If no such i exists, go to step 4.
3. ***Work*** = ***Work*** + $\boldsymbol{Allocation}_i$
   Finish$[i]$ = ***true***
   Go to step 2.
4. If ***Finish***$[i]$ == ***false*** for some i, $0 \leq i < n$, then the system is in a deadlocked state. Moreover, if ***Finish***$[i]$ == ***false***, then thread T_i is deadlocked.

This algorithm requires an order of $m \times n^2$ operations to detect whether the system is in a deadlocked state.

You may wonder why we reclaim the resources of thread T_i (in step 3) as soon as we determine that ***Request***$_i \leq$ ***Work*** (in step 2b). We know that T_i is currently ***not*** involved in a deadlock (since ***Request***$_i \leq$ ***Work***). Thus, we take an optimistic attitude and assume that T_i will require no more resources to complete its task; it will thus soon return all currently allocated resources to the system. If our assumption is incorrect, a deadlock may occur later. That deadlock will be detected the next time the deadlock-detection algorithm is invoked.

To illustrate this algorithm, we consider a system with five threads T_0 through T_4 and three resource types *A, B,* and *C.* Resource type *A* has seven instances, resource type *B* has two instances, and resource type *C* has six instances. The following snapshot represents the current state of the system:

	Allocation	***Request***	***Available***
	A B C	*A B C*	*A B C*
T_0	0 1 0	0 0 0	0 0 0
T_1	2 0 0	2 0 2	
T_2	3 0 3	0 0 0	
T_3	2 1 1	1 0 0	
T_4	0 0 2	0 0 2	

We claim that the system is not in a deadlocked state. Indeed, if we execute our algorithm, we will find that the sequence $<T_0, T_2, T_3, T_1, T_4>$ results in ***Finish***[*i*] == *true* for all *i.*

Suppose now that thread T_2 makes one additional request for an instance of type *C.* The ***Request*** matrix is modified as follows:

	Request
	A B C
T_0	0 0 0
T_1	2 0 2
T_2	0 0 1
T_3	1 0 0
T_4	0 0 2

We claim that the system is now deadlocked. Although we can reclaim the resources held by thread T_0, the number of available resources is not sufficient to fulfill the requests of the other threads. Thus, a deadlock exists, consisting of threads T_1, T_2, T_3, and T_4.

8.7.3 Detection-Algorithm Usage

When should we invoke the detection algorithm? The answer depends on two factors:

1. How ***often*** is a deadlock likely to occur?
2. How ***many*** threads will be affected by deadlock when it happens?

MANAGING DEADLOCK IN DATABASES

Database systems provide a useful illustration of how both open-source and commercial software manage deadlock. Updates to a database may be performed as ***transactions***, and to ensure data integrity, locks are typically used. A transaction may involve several locks, so it comes as no surprise that deadlocks are possible in a database with multiple concurrent transactions. To manage deadlock, most transactional database systems include a deadlock detection and recovery mechanism. The database server will periodically search for cycles in the wait-for graph to detect deadlock among a set of transactions. When deadlock is detected, a victim is selected and the transaction is aborted and rolled back, releasing the locks held by the victim transaction and freeing the remaining transactions from deadlock. Once the remaining transactions have resumed, the aborted transaction is reissued. Choice of a victim transaction depends on the database system; for instance, MySQL attempts to select transactions that minimize the number of rows being inserted, updated, or deleted.

If deadlocks occur frequently, then the detection algorithm should be invoked frequently. Resources allocated to deadlocked threads will be idle until the deadlock can be broken. In addition, the number of threads involved in the deadlock cycle may grow.

Deadlocks occur only when some thread makes a request that cannot be granted immediately. This request may be the final request that completes a chain of waiting threads. In the extreme, then, we can invoke the deadlock-detection algorithm every time a request for allocation cannot be granted immediately. In this case, we can identify not only the deadlocked set of threads but also the specific thread that "caused" the deadlock. (In reality, each of the deadlocked threads is a link in the cycle in the resource graph, so all of them, jointly, caused the deadlock.) If there are many different resource types, one request may create many cycles in the resource graph, each cycle completed by the most recent request and "caused" by the one identifiable thread.

Of course, invoking the deadlock-detection algorithm for every resource request will incur considerable overhead in computation time. A less expensive alternative is simply to invoke the algorithm at defined intervals—for example, once per hour or whenever CPU utilization drops below 40 percent. (A deadlock eventually cripples system throughput and causes CPU utilization to drop.) If the detection algorithm is invoked at arbitrary points in time, the resource graph may contain many cycles. In this case, we generally cannot tell which of the many deadlocked threads "caused" the deadlock.

8.8 Recovery from Deadlock

When a detection algorithm determines that a deadlock exists, several alternatives are available. One possibility is to inform the operator that a deadlock has occurred and to let the operator deal with the deadlock manually. Another possibility is to let the system **recover** from the deadlock automatically. There

are two options for breaking a deadlock. One is simply to abort one or more threads to break the circular wait. The other is to preempt some resources from one or more of the deadlocked threads.

8.8.1 Process and Thread Termination

To eliminate deadlocks by aborting a process or thread, we use one of two methods. In both methods, the system reclaims all resources allocated to the terminated processes.

- **Abort all deadlocked processes**. This method clearly will break the deadlock cycle, but at great expense. The deadlocked processes may have computed for a long time, and the results of these partial computations must be discarded and probably will have to be recomputed later.
- **Abort one process at a time until the deadlock cycle is eliminated**. This method incurs considerable overhead, since after each process is aborted, a deadlock-detection algorithm must be invoked to determine whether any processes are still deadlocked.

Aborting a process may not be easy. If the process was in the midst of updating a file, terminating it may leave that file in an incorrect state. Similarly, if the process was in the midst of updating shared data while holding a mutex lock, the system must restore the status of the lock as being available, although no guarantees can be made regarding the integrity of the shared data.

If the partial termination method is used, then we must determine which deadlocked process (or processes) should be terminated. This determination is a policy decision, similar to CPU-scheduling decisions. The question is basically an economic one; we should abort those processes whose termination will incur the minimum cost. Unfortunately, the term ***minimum cost*** is not a precise one. Many factors may affect which process is chosen, including:

1. What the priority of the process is
2. How long the process has computed and how much longer the process will compute before completing its designated task
3. How many and what types of resources the process has used (for example, whether the resources are simple to preempt)
4. How many more resources the process needs in order to complete
5. How many processes will need to be terminated

8.8.2 Resource Preemption

To eliminate deadlocks using resource preemption, we successively preempt some resources from processes and give these resources to other processes until the deadlock cycle is broken.

If preemption is required to deal with deadlocks, then three issues need to be addressed:

1. **Selecting a victim**. Which resources and which processes are to be preempted? As in process termination, we must determine the order of preemption to minimize cost. Cost factors may include such parameters as the number of resources a deadlocked process is holding and the amount of time the process has thus far consumed.

2. **Rollback**. If we preempt a resource from a process, what should be done with that process? Clearly, it cannot continue with its normal execution; it is missing some needed resource. We must roll back the process to some safe state and restart it from that state.

   Since, in general, it is difficult to determine what a safe state is, the simplest solution is a total rollback: abort the process and then restart it. Although it is more effective to roll back the process only as far as necessary to break the deadlock, this method requires the system to keep more information about the state of all running processes.

3. **Starvation**. How do we ensure that starvation will not occur? That is, how can we guarantee that resources will not always be preempted from the same process?

   In a system where victim selection is based primarily on cost factors, it may happen that the same process is always picked as a victim. As a result, this process never completes its designated task, a starvation situation any practical system must address. Clearly, we must ensure that a process can be picked as a victim only a (small) finite number of times. The most common solution is to include the number of rollbacks in the cost factor.

8.9 Summary

- Deadlock occurs in a set of processes when every process in the set is waiting for an event that can only be caused by another process in the set.
- There are four necessary conditions for deadlock: (1) mutual exclusion, (2) hold and wait, (3) no preemption, and (4) circular wait. Deadlock is only possible when all four conditions are present.
- Deadlocks can be modeled with resource-allocation graphs, where a cycle indicates deadlock.
- Deadlocks can be prevented by ensuring that one of the four necessary conditions for deadlock cannot occur. Of the four necessary conditions, eliminating the circular wait is the only practical approach.
- Deadlock can be avoided by using the banker's algorithm, which does not grant resources if doing so would lead the system into an unsafe state where deadlock would be possible.
- A deadlock-detection algorithm can evaluate processes and resources on a running system to determine if a set of processes is in a deadlocked state.
- If deadlock does occur, a system can attempt to recover from the deadlock by either aborting one of the processes in the circular wait or preempting resources that have been assigned to a deadlocked process.

Practice Exercises

8.1 List three examples of deadlocks that are not related to a computer-system environment.

8.2 Suppose that a system is in an unsafe state. Show that it is possible for the threads to complete their execution without entering a deadlocked state.

8.3 Consider the following snapshot of a system:

	Allocation	*Max*	*Available*
	A B C D	*A B C D*	*A B C D*
T_0	0 0 1 2	0 0 1 2	1 5 2 0
T_1	1 0 0 0	1 7 5 0	
T_2	1 3 5 4	2 3 5 6	
T_3	0 6 3 2	0 6 5 2	
T_4	0 0 1 4	0 6 5 6	

Answer the following questions using the banker's algorithm:

a. What is the content of the matrix ***Need***?

b. Is the system in a safe state?

c. If a request from thread T_1 arrives for (0,4,2,0), can the request be granted immediately?

8.4 A possible method for preventing deadlocks is to have a single, higher-order resource that must be requested before any other resource. For example, if multiple threads attempt to access the synchronization objects $A \cdots E$, deadlock is possible. (Such synchronization objects may include mutexes, semaphores, condition variables, and the like.) We can prevent deadlock by adding a sixth object F. Whenever a thread wants to acquire the synchronization lock for any object $A \cdots E$, it must first acquire the lock for object F. This solution is known as **containment**: the locks for objects $A \cdots E$ are contained within the lock for object F. Compare this scheme with the circular-wait scheme of Section 8.5.4.

8.5 Prove that the safety algorithm presented in Section 8.6.3 requires an order of $m \times n^2$ operations.

8.6 Consider a computer system that runs 5,000 jobs per month and has no deadlock-prevention or deadlock-avoidance scheme. Deadlocks occur about twice per month, and the operator must terminate and rerun about ten jobs per deadlock. Each job is worth about two dollars (in CPU time), and the jobs terminated tend to be about half done when they are aborted.

A systems programmer has estimated that a deadlock-avoidance algorithm (like the banker's algorithm) could be installed in the system with an increase of about 10 percent in the average execution time per

job. Since the machine currently has 30 percent idle time, all 5,000 jobs per month could still be run, although turnaround time would increase by about 20 percent on average.

a. What are the arguments for installing the deadlock-avoidance algorithm?

b. What are the arguments against installing the deadlock-avoidance algorithm?

8.7 Can a system detect that some of its threads are starving? If you answer "yes," explain how it can. If you answer "no," explain how the system can deal with the starvation problem.

8.8 Consider the following resource-allocation policy. Requests for and releases of resources are allowed at any time. If a request for resources cannot be satisfied because the resources are not available, then we check any threads that are blocked waiting for resources. If a blocked thread has the desired resources, then these resources are taken away from it and are given to the requesting thread. The vector of resources for which the blocked thread is waiting is increased to include the resources that were taken away.

For example, a system has three resource types, and the vector ***Available*** is initialized to (4,2,2). If thread T_0 asks for (2,2,1), it gets them. If T_1 asks for (1,0,1), it gets them. Then, if T_0 asks for (0,0,1), it is blocked (resource not available). If T_2 now asks for (2,0,0), it gets the available one (1,0,0), as well as one that was allocated to T_0 (since T_0 is blocked). T_0's ***Allocation*** vector goes down to (1,2,1), and its ***Need*** vector goes up to (1,0,1).

a. Can deadlock occur? If you answer "yes," give an example. If you answer "no," specify which necessary condition cannot occur.

b. Can indefinite blocking occur? Explain your answer.

8.9 Consider the following snapshot of a system:

	Allocation	***Max***
	A B C D	*A B C D*
T_0	3 0 1 4	5 1 1 7
T_1	2 2 1 0	3 2 1 1
T_2	3 1 2 1	3 3 2 1
T_3	0 5 1 0	4 6 1 2
T_4	4 2 1 2	6 3 2 5

Using the banker's algorithm, determine whether or not each of the following states is unsafe. If the state is safe, illustrate the order in which the threads may complete. Otherwise, illustrate why the state is unsafe.

a. ***Available*** $= (0, 3, 0, 1)$

b. ***Available*** $= (1, 0, 0, 2)$

8.10 Suppose that you have coded the deadlock-avoidance safety algorithm that determines if a system is in a safe state or not, and now have been asked to implement the deadlock-detection algorithm. Can you do so by simply using the safety algorithm code and redefining $\boldsymbol{Max}_i = \boldsymbol{Waiting}_i + \boldsymbol{Allocation}_i$, where $\boldsymbol{Waiting}_i$ is a vector specifying the resources for which thread i is waiting and $\boldsymbol{Allocation}_i$ is as defined in Section 8.6? Explain your answer.

8.11 Is it possible to have a deadlock involving only one single-threaded process? Explain your answer.

Further Reading

Most research involving deadlock was conducted many years ago. [Dijkstra (1965)] was one of the first and most influential contributors in the deadlock area.

Details of how the MySQL database manages deadlock can be found at http://dev.mysql.com/.

Details on the `lockdep` tool can be found at https://www.kernel.org/doc/Documentation/locking/lockdep-design.txt.

Bibliography

[Dijkstra (1965)] E. W. Dijkstra, "Cooperating Sequential Processes", Technical report, Technological University, Eindhoven, the Netherlands (1965).

Chapter 8 Exercises

8.12 Consider the traffic deadlock depicted in Figure 8.12.

a. Show that the four necessary conditions for deadlock hold in this example.

b. State a simple rule for avoiding deadlocks in this system.

8.13 Draw the resource-allocation graph that illustrates deadlock from the program example shown in Figure 8.1 in Section 8.2.

8.14 In Section 6.8.1, we described a potential deadlock scenario involving processes P_0 and P_1 and semaphores `S` and `Q`. Draw the resource-allocation graph that illustrates deadlock under the scenario presented in that section.

8.15 Assume that a multithreaded application uses only reader–writer locks for synchronization. Applying the four necessary conditions for deadlock, is deadlock still possible if multiple reader–writer locks are used?

8.16 The program example shown in Figure 8.1 doesn't always lead to deadlock. Describe what role the CPU scheduler plays and how it can contribute to deadlock in this program.

8.17 In Section 8.5.4, we described a situation in which we prevent deadlock by ensuring that all locks are acquired in a certain order. However, we also point out that deadlock is possible in this situation if two threads simultaneously invoke the `transaction()` function. Fix the `transaction()` function to prevent deadlocks.

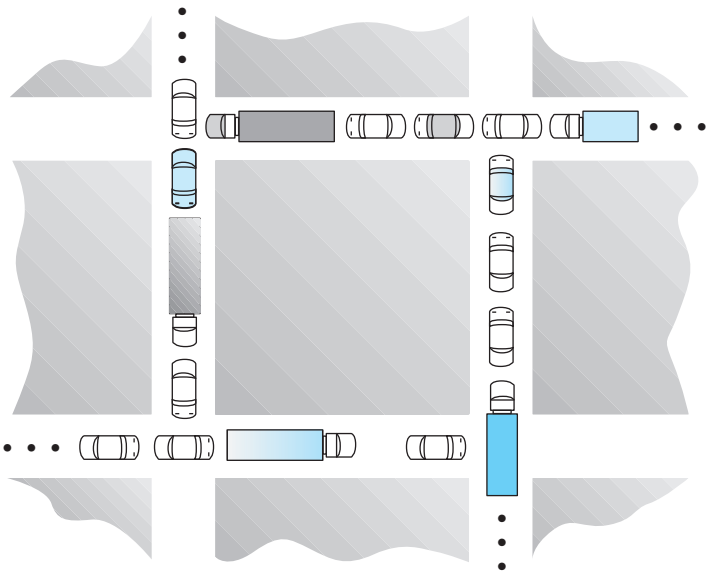

Figure 8.11 Traffic deadlock for Exercise 8.12.

8.18 Which of the six resource-allocation graphs shown in Figure 8.12 illustrate deadlock? For those situations that are deadlocked, provide the cycle of threads and resources. Where there is not a deadlock situation, illustrate the order in which the threads may complete execution.

8.19 Compare the circular-wait scheme with the various deadlock-avoidance schemes (like the banker's algorithm) with respect to the following issues:

a. Runtime overhead

b. System throughput

8.20 In a real computer system, neither the resources available nor the demands of threads for resources are consistent over long periods (months). Resources break or are replaced, new processes and threads come and go, and new resources are bought and added to the system. If deadlock is controlled by the banker's algorithm, which of the

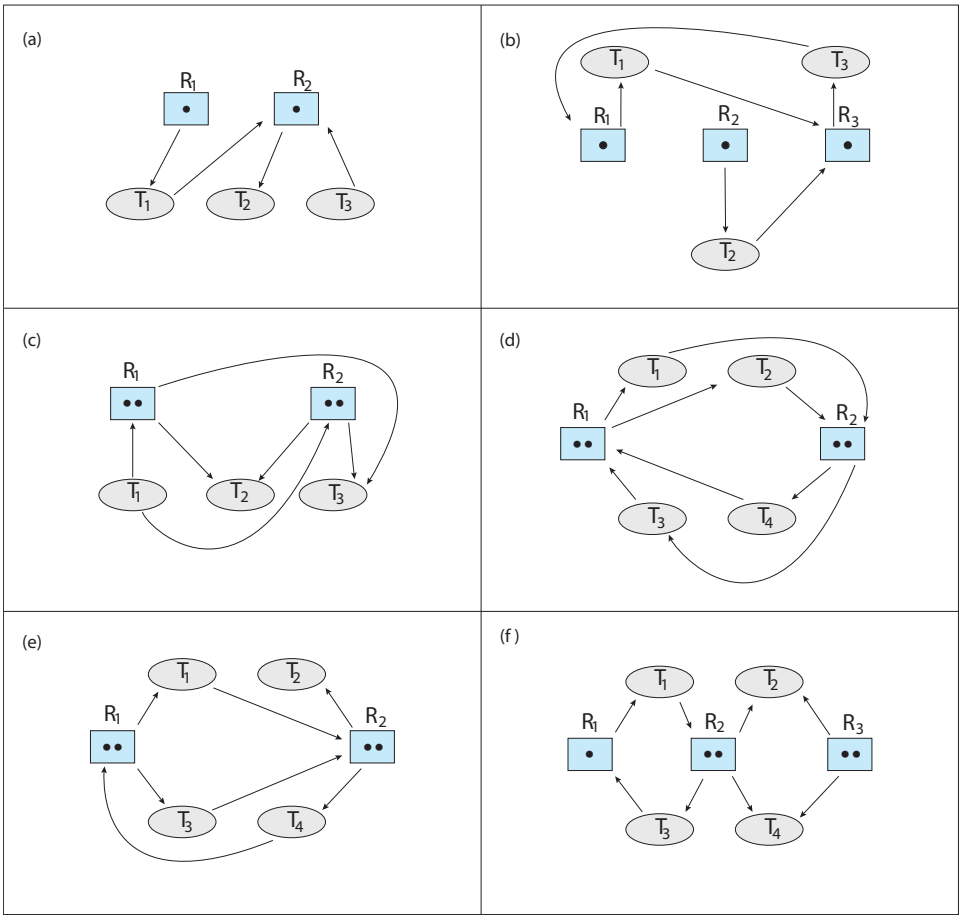

Figure 8.12 Resource-allocation graphs for Exercise 8.18.

following changes can be made safely (without introducing the possibility of deadlock), and under what circumstances?

a. Increase ***Available*** (new resources added).

b. Decrease ***Available*** (resource permanently removed from system).

c. Increase ***Max*** for one thread (the thread needs or wants more resources than allowed).

d. Decrease ***Max*** for one thread (the thread decides it does not need that many resources).

e. Increase the number of threads.

f. Decrease the number of threads.

8.21 Consider the following snapshot of a system:

	Allocation	***Max***
	A B C D	*A B C D*
T_0	2 1 0 6	6 3 2 7
T_1	3 3 1 3	5 4 1 5
T_2	2 3 1 2	6 6 1 4
T_3	1 2 3 4	4 3 4 5
T_4	3 0 3 0	7 2 6 1

What are the contents of the ***Need*** matrix?

8.22 Consider a system consisting of four resources of the same type that are shared by three threads, each of which needs at most two resources. Show that the system is deadlock free.

8.23 Consider a system consisting of m resources of the same type being shared by n threads. A thread can request or release only one resource at a time. Show that the system is deadlock free if the following two conditions hold:

a. The maximum need of each thread is between one resource and m resources.

b. The sum of all maximum needs is less than $m + n$.

8.24 Consider the version of the dining-philosophers problem in which the chopsticks are placed at the center of the table and any two of them can be used by a philosopher. Assume that requests for chopsticks are made one at a time. Describe a simple rule for determining whether a particular request can be satisfied without causing deadlock given the current allocation of chopsticks to philosophers.

8.25 Consider again the setting in the preceding exercise. Assume now that each philosopher requires three chopsticks to eat. Resource requests are still issued one at a time. Describe some simple rules for determining whether a particular request can be satisfied without causing deadlock given the current allocation of chopsticks to philosophers.

8.26 We can obtain the banker's algorithm for a single resource type from the general banker's algorithm simply by reducing the dimensionality of the various arrays by 1.

Show through an example that we cannot implement the multiple-resource-type banker's scheme by applying the single-resource-type scheme to each resource type individually.

8.27 Consider the following snapshot of a system:

	Allocation	*Max*
	A B C D	*A B C D*
T_0	1 2 0 2	4 3 1 6
T_1	0 1 1 2	2 4 2 4
T_2	1 2 4 0	3 6 5 1
T_3	1 2 0 1	2 6 2 3
T_4	1 0 0 1	3 1 1 2

Using the banker's algorithm, determine whether or not each of the following states is unsafe. If the state is safe, illustrate the order in which the threads may complete. Otherwise, illustrate why the state is unsafe.

a. ***Available*** = (2, 2, 2, 3)

b. ***Available*** = (4, 4, 1, 1)

c. ***Available*** = (3, 0, 1, 4)

d. ***Available*** = (1, 5, 2, 2)

8.28 Consider the following snapshot of a system:

	Allocation	*Max*	*Available*
	A B C D	*A B C D*	*A B C D*
T_0	3 1 4 1	6 4 7 3	2 2 2 4
T_1	2 1 0 2	4 2 3 2	
T_2	2 4 1 3	2 5 3 3	
T_3	4 1 1 0	6 3 3 2	
T_4	2 2 2 1	5 6 7 5	

Answer the following questions using the banker's algorithm:

a. Illustrate that the system is in a safe state by demonstrating an order in which the threads may complete.

b. If a request from thread T_4 arrives for (2, 2, 2, 4), can the request be granted immediately?

c. If a request from thread T_2 arrives for (0, 1, 1, 0), can the request be granted immediately?

d. If a request from thread T_3 arrives for (2, 2, 1, 2), can the request be granted immediately?

8.29 What is the optimistic assumption made in the deadlock-detection algorithm? How can this assumption be violated?

8.30 A single-lane bridge connects the two Vermont villages of North Tunbridge and South Tunbridge. Farmers in the two villages use this bridge to deliver their produce to the neighboring town. The bridge can become deadlocked if a northbound and a southbound farmer get on the bridge at the same time. (Vermont farmers are stubborn and are unable to back up.) Using semaphores and/or mutex locks, design an algorithm in pseudocode that prevents deadlock. Initially, do not be concerned about starvation (the situation in which northbound farmers prevent southbound farmers from using the bridge, or vice versa).

8.31 Modify your solution to Exercise 8.30 so that it is starvation-free.

Programming Problems

8.32 Implement your solution to Exercise 8.30 using POSIX synchronization. In particular, represent northbound and southbound farmers as separate threads. Once a farmer is on the bridge, the associated thread will sleep for a random period of time, representing traveling across the bridge. Design your program so that you can create several threads representing the northbound and southbound farmers.

8.33 In Figure 8.7, we illustrate a `transaction()` function that dynamically acquires locks. In the text, we describe how this function presents difficulties for acquiring locks in a way that avoids deadlock. Using the Java implementation of `transaction()` that is provided in the source-code download for this text, modify it using the `System.identityHashCode()` method so that the locks are acquired in order.

Programming Projects

Banker's Algorithm

For this project, you will write a program that implements the banker's algorithm discussed in Section 8.6.3. Customers request and release resources from the bank. The banker will grant a request only if it leaves the system in a safe state. A request that leaves the system in an unsafe state will be denied. Although the code examples that describe this project are illustrated in C, you may also develop a solution using Java.

The Banker

The banker will consider requests from n customers for m resources types, as outlined in Section 8.6.3. The banker will keep track of the resources using the following data structures:

```
#define NUMBER_OF_CUSTOMERS 5
#define NUMBER_OF_RESOURCES 4

/* the available amount of each resource */
int available[NUMBER_OF_RESOURCES];

/*the maximum demand of each customer */
int maximum[NUMBER_OF_CUSTOMERS][NUMBER_OF_RESOURCES];

/* the amount currently allocated to each customer */
int allocation[NUMBER_OF_CUSTOMERS][NUMBER_OF_RESOURCES];

/* the remaining need of each customer */
int need[NUMBER_OF_CUSTOMERS][NUMBER_OF_RESOURCES];
```

The banker will grant a request if it satisfies the safety algorithm outlined in Section 8.6.3.1. If a request does not leave the system in a safe state, the banker will deny it. Function prototypes for requesting and releasing resources are as follows:

```
int request_resources(int customer_num, int request[]);

void release_resources(int customer_num, int release[]);
```

The `request_resources()` function should return 0 if successful and −1 if unsuccessful.

Testing Your Implementation

Design a program that allows the user to interactively enter a request for resources, to release resources, or to output the values of the different data structures (`available`, `maximum`, `allocation`, and `need`) used with the banker's algorithm.

You should invoke your program by passing the number of resources of each type on the command line. For example, if there were four resource types, with ten instances of the first type, five of the second type, seven of the third type, and eight of the fourth type, you would invoke your program as follows:

```
./a.out 10 5 7 8
```

The `available` array would be initialized to these values.

Your program will initially read in a file containing the maximum number of requests for each customer. For example, if there are five customers and four resources, the input file would appear as follows:

```
6,4,7,3
4,2,3,2
2,5,3,3
6,3,3,2
5,6,7,5
```

where each line in the input file represents the maximum request of each resource type for each customer. Your program will initialize the `maximum` array to these values.

Your program will then have the user enter commands responding to a request of resources, a release of resources, or the current values of the different data structures. Use the command '`RQ`' for requesting resources, '`RL`' for releasing resources, and '`*`' to output the values of the different data structures. For example, if customer 0 were to request the resources (3, 1, 2, 1), the following command would be entered:

```
RQ 0 3 1 2 1
```

Your program would then output whether the request would be satisfied or denied using the safety algorithm outlined in Section 8.6.3.1.

Similarly, if customer 4 were to release the resources (1, 2, 3, 1), the user would enter the following command:

```
RL 4 1 2 3 1
```

Finally, if the command '*' is entered, your program would output the values of the `available`, `maximum`, `allocation`, and `need` arrays.