These problems are certainly not insurmountable, but they do show that just introducing threads into an existing system without a fairly substantial system redesign is not going to work at all. The semantics of system calls may have to be redefined and libraries rewritten, at the very least. And all of these things must be done in such a way as to remain backward compatible with existing programs for the limiting case of a process with only one thread. For additional information about threads, see Hauser et al. (1993), Marsh et al. (1991), and Rodrigues et al. (2010).

2.3 INTERPROCESS COMMUNICATION

Processes frequently need to communicate with other processes. For example, in a shell pipeline, the output of the first process must be passed to the second process, and so on down the line. Thus there is a need for communication between processes, preferably in a well-structured way not using interrupts. In the following sections we will look at some of the issues related to this **InterProcess Communication**, or **IPC**.

Very briefly, there are three issues here. The first was alluded to above: how one process can pass information to another. The second has to do with making sure two or more processes do not get in each other's way, for example, two processes in an airline reservation system each trying to grab the last seat on a plane for a different customer. The third concerns proper sequencing when dependencies are present: if process *A* produces data and process *B* prints them, *B* has to wait until *A* has produced some data before starting to print. We will examine all three of these issues starting in the next section.

It is also important to mention that two of these issues apply equally well to threads. The first one—passing information—is easy for threads since they share a common address space (threads in different address spaces that need to communicate fall under the heading of communicating processes). However, the other two—keeping out of each other's hair and proper sequencing—apply equally well to threads. The same problems exist and the same solutions apply. Below we will discuss the problem in the context of processes, but please keep in mind that the same problems and solutions also apply to threads.

2.3.1 Race Conditions

In some operating systems, processes that are working together may share some common storage that each one can read and write. The shared storage may be in main memory (possibly in a kernel data structure) or it may be a shared file; the location of the shared memory does not change the nature of the communication or the problems that arise. To see how interprocess communication works in practice, let us now consider a simple but common example: a print spooler. When a process

wants to print a file, it enters the file name in a special **spooler directory**. Another process, the **printer daemon**, periodically checks to see if there are any files to be printed, and if there are, it prints them and then removes their names from the directory.

Imagine that our spooler directory has a very large number of slots, numbered 0, 1, 2, ..., each one capable of holding a file name. Also imagine that there are two shared variables, *out*, which points to the next file to be printed, and *in*, which points to the next free slot in the directory. These two variables might well be kept in a two-word file available to all processes. At a certain instant, slots 0 to 3 are empty (the files have already been printed) and slots 4 to 6 are full (with the names of files queued for printing). More or less simultaneously, processes *A* and *B* decide they want to queue a file for printing. This situation is shown in Fig. 2-21.

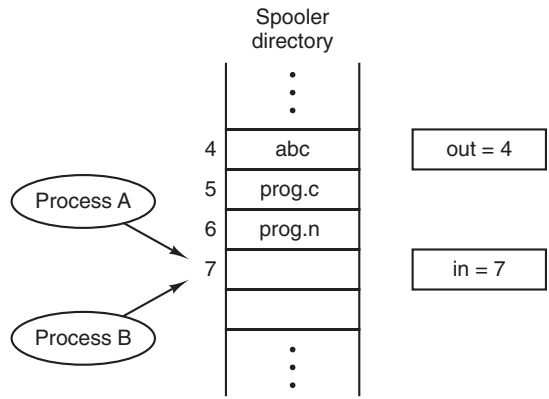

Figure 2-21. Two processes want to access shared memory at the same time.

In jurisdictions where Murphy's law† is applicable, the following could happen. Process *A* reads *in* and stores the value, 7, in a local variable called *next_free_slot*. Just then a clock interrupt occurs and the CPU decides that process *A* has run long enough, so it switches to process *B*. Process *B* also reads *in* and also gets a 7. It, too, stores it in *its* local variable *next_free_slot*. At this instant both processes think that the next available slot is 7.

Process *B* now continues to run. It stores the name of its file in slot 7 and updates *in* to be an 8. Then it goes off and does other things.

Eventually, process *A* runs again, starting from the place it left off. It looks at *next_free_slot*, finds a 7 there, and writes its file name in slot 7, erasing the name that process *B* just put there. Then it computes *next_free_slot* + 1, which is 8, and sets *in* to 8. The spooler directory is now internally consistent, so the printer daemon will not notice anything wrong, but process *B* will never receive any output. User *B* will hang around the printer for years, wistfully hoping for output that

† If something can go wrong, it will.

never comes. Situations like this, where two or more processes are reading or writing some shared data and the final result depends on who runs precisely when, are called **race conditions**. Debugging programs containing race conditions is no fun at all. The results of most test runs are fine, but once in a blue moon something weird and unexplained happens. Unfortunately, with increasing parallelism due to increasing numbers of cores, race condition are becoming more common.

2.3.2 Critical Regions

How do we avoid race conditions? The key to preventing trouble here and in many other situations involving shared memory, shared files, and shared everything else is to find some way to prohibit more than one process from reading and writing the shared data at the same time. Put in other words, what we need is **mutual exclusion**, that is, some way of making sure that if one process is using a shared variable or file, the other processes will be excluded from doing the same thing. The difficulty above occurred because process *B* started using one of the shared variables before process *A* was finished with it. The choice of appropriate primitive operations for achieving mutual exclusion is a major design issue in any operating system, and a subject that we will examine in great detail in the following sections.

The problem of avoiding race conditions can also be formulated in an abstract way. Part of the time, a process is busy doing internal computations and other things that do not lead to race conditions. However, sometimes a process has to access shared memory or files, or do other critical things that can lead to races. That part of the program where the shared memory is accessed is called the **critical region** or **critical section**. If we could arrange matters such that no two processes were ever in their critical regions at the same time, we could avoid races.

Although this requirement avoids race conditions, it is not sufficient for having parallel processes cooperate correctly and efficiently using shared data. We need four conditions to hold to have a good solution:

1. No two processes may be simultaneously inside their critical regions.
2. No assumptions may be made about speeds or the number of CPUs.
3. No process running outside its critical region may block any process.
4. No process should have to wait forever to enter its critical region.

In an abstract sense, the behavior that we want is shown in Fig. 2-22. Here process *A* enters its critical region at time T_1. A little later, at time T_2 process *B* attempts to enter its critical region but fails because another process is already in its critical region and we allow only one at a time. Consequently, *B* is temporarily suspended until time T_3 when *A* leaves its critical region, allowing *B* to enter immediately. Eventually *B* leaves (at T_4) and we are back to the original situation with no processes in their critical regions.

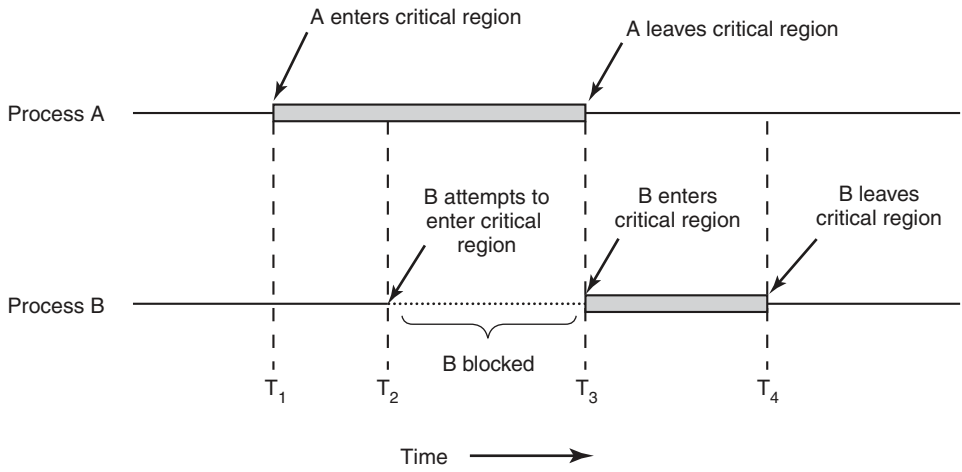

Figure 2-22. Mutual exclusion using critical regions.

2.3.3 Mutual Exclusion with Busy Waiting

In this section we will examine various proposals for achieving mutual exclusion, so that while one process is busy updating shared memory in its critical region, no other process will enter *its* critical region and cause trouble.

Disabling Interrupts

On a single-processor system, the simplest solution is to have each process disable all interrupts just after entering its critical region and re-enable them just before leaving it. With interrupts disabled, no clock interrupts can occur. The CPU is only switched from process to process as a result of clock or other interrupts, after all, and with interrupts turned off the CPU will not be switched to another process. Thus, once a process has disabled interrupts, it can examine and update the shared memory without fear that any other process will intervene.

This approach is generally unattractive because it is unwise to give user processes the power to turn off interrupts. What if one of them did it, and never turned them on again? That could be the end of the system. Furthermore, if the system is a multiprocessor (with two or more CPUs) disabling interrupts affects only the CPU that executed the disable instruction. The other ones will continue running and can access the shared memory.

On the other hand, it is frequently convenient for the kernel itself to disable interrupts for a few instructions while it is updating variables or especially lists. If an interrupt occurrs while the list of ready processes, for example, is in an inconsistent state, race conditions could occur. The conclusion is: disabling interrupts is

often a useful technique within the operating system itself but is not appropriate as a general mutual exclusion mechanism for user processes.

The possibility of achieving mutual exclusion by disabling interrupts—even within the kernel—is becoming less every day due to the increasing number of multicore chips even in low-end PCs. Two cores are already common, four are present in many machines, and eight, 16, or 32 are not far behind. In a multicore (i.e., multiprocessor system) disabling the interrupts of one CPU does not prevent other CPUs from interfering with operations the first CPU is performing. Consequently, more sophisticated schemes are needed.

Lock Variables

As a second attempt, let us look for a software solution. Consider having a single, shared (lock) variable, initially 0. When a process wants to enter its critical region, it first tests the lock. If the lock is 0, the process sets it to 1 and enters the critical region. If the lock is already 1, the process just waits until it becomes 0. Thus, a 0 means that no process is in its critical region, and a 1 means that some process is in its critical region.

Unfortunately, this idea contains exactly the same fatal flaw that we saw in the spooler directory. Suppose that one process reads the lock and sees that it is 0. Before it can set the lock to 1, another process is scheduled, runs, and sets the lock to 1. When the first process runs again, it will also set the lock to 1, and two processes will be in their critical regions at the same time.

Now you might think that we could get around this problem by first reading out the lock value, then checking it again just before storing into it, but that really does not help. The race now occurs if the second process modifies the lock just after the first process has finished its second check.

Strict Alternation

A third approach to the mutual exclusion problem is shown in Fig. 2-23. This program fragment, like nearly all the others in this book, is written in C. C was chosen here because real operating systems are virtually always written in C (or occasionally C++), but hardly ever in languages like Java, Python, or Haskell. C is powerful, efficient, and predictable, characteristics critical for writing operating systems. Java, for example, is not predictable because it might run out of storage at a critical moment and need to invoke the garbage collector to reclaim memory at a most inopportune time. This cannot happen in C because there is no garbage collection in C. A quantitative comparison of C, C++, Java, and four other languages is given by Prechelt (2000).

In Fig. 2-23, the integer variable *turn*, initially 0, keeps track of whose turn it is to enter the critical region and examine or update the shared memory. Initially, process 0 inspects *turn*, finds it to be 0, and enters its critical region. Process 1 also

```
while (TRUE) {
    while (turn != 0)        /* loop */ ;
    critical_region( );
    turn = 1;
    noncritical_region( );
}
```

(a)

```
while (TRUE) {
    while (turn != 1)        /* loop */ ;
    critical_region( );
    turn = 0;
    noncritical_region( );
}
```

(b)

Figure 2-23. A proposed solution to the critical-region problem. (a) Process 0. (b) Process 1. In both cases, be sure to note the semicolons terminating the while statements.

finds it to be 0 and therefore sits in a tight loop continually testing *turn* to see when it becomes 1. Continuously testing a variable until some value appears is called **busy waiting**. It should usually be avoided, since it wastes CPU time. Only when there is a reasonable expectation that the wait will be short is busy waiting used. A lock that uses busy waiting is called a **spin lock**.

When process 0 leaves the critical region, it sets *turn* to 1, to allow process 1 to enter its critical region. Suppose that process 1 finishes its critical region quickly, so that both processes are in their noncritical regions, with *turn* set to 0. Now process 0 executes its whole loop quickly, exiting its critical region and setting *turn* to 1. At this point *turn* is 1 and both processes are executing in their noncritical regions.

Suddenly, process 0 finishes its noncritical region and goes back to the top of its loop. Unfortunately, it is not permitted to enter its critical region now, because *turn* is 1 and process 1 is busy with its noncritical region. It hangs in its while loop until process 1 sets *turn* to 0. Put differently, taking turns is not a good idea when one of the processes is much slower than the other.

This situation violates condition 3 set out above: process 0 is being blocked by a process not in its critical region. Going back to the spooler directory discussed above, if we now associate the critical region with reading and writing the spooler directory, process 0 would not be allowed to print another file because process 1 was doing something else.

In fact, this solution requires that the two processes strictly alternate in entering their critical regions, for example, in spooling files. Neither one would be permitted to spool two in a row. While this algorithm does avoid all races, it is not really a serious candidate as a solution because it violates condition 3.

Peterson's Solution

By combining the idea of taking turns with the idea of lock variables and warning variables, a Dutch mathematician, T. Dekker, was the first one to devise a software solution to the mutual exclusion problem that does not require strict alternation. For a discussion of Dekker's algorithm, see Dijkstra (1965).

In 1981, G. L. Peterson discovered a much simpler way to achieve mutual exclusion, thus rendering Dekker's solution obsolete. Peterson's algorithm is shown in Fig. 2-24. This algorithm consists of two procedures written in ANSI C, which means that function prototypes should be supplied for all the functions defined and used. However, to save space, we will not show prototypes here or later.

```
#define FALSE  0
#define TRUE   1
#define N      2                        /* number of processes */

int turn;                               /* whose turn is it? */
int interested[N];                      /* all values initially 0 (FALSE) */

void enter_region(int process);         /* process is 0 or 1 */
{
     int other;                         /* number of the other process */

     other = 1 – process;               /* the opposite of process */
     interested[process] = TRUE;        /* show that you are interested */
     turn = process;                    /* set flag */
     while (turn == process && interested[other] == TRUE)  /* null statement */ ;
}

void leave_region(int process)          /* process: who is leaving */
{
     interested[process] = FALSE;       /* indicate departure from critical region */
}
```

Figure 2-24. Peterson's solution for achieving mutual exclusion.

Before using the shared variables (i.e., before entering its critical region), each process calls *enter_region* with its own process number, 0 or 1, as parameter. This call will cause it to wait, if need be, until it is safe to enter. After it has finished with the shared variables, the process calls *leave_region* to indicate that it is done and to allow the other process to enter, if it so desires.

Let us see how this solution works. Initially neither process is in its critical region. Now process 0 calls *enter_region*. It indicates its interest by setting its array element and sets *turn* to 0. Since process 1 is not interested, *enter_region* returns immediately. If process 1 now makes a call to *enter_region*, it will hang there until *interested*[0] goes to *FALSE*, an event that happens only when process 0 calls *leave_region* to exit the critical region.

Now consider the case that both processes call *enter_region* almost simultaneously. Both will store their process number in *turn*. Whichever store is done last is the one that counts; the first one is overwritten and lost. Suppose that process 1 stores last, so *turn* is 1. When both processes come to the while statement, process 0 executes it zero times and enters its critical region. Process 1 loops and does not enter its critical region until process 0 exits its critical region.

The TSL Instruction

Now let us look at a proposal that requires a little help from the hardware. Some computers, especially those designed with multiple processors in mind, have an instruction like

```
TSL RX,LOCK
```

(Test and Set Lock) that works as follows. It reads the contents of the memory word *lock* into register RX and then stores a nonzero value at the memory address *lock*. The operations of reading the word and storing into it are guaranteed to be indivisible—no other processor can access the memory word until the instruction is finished. The CPU executing the TSL instruction locks the memory bus to prohibit other CPUs from accessing memory until it is done.

It is important to note that locking the memory bus is very different from disabling interrupts. Disabling interrupts then performing a read on a memory word followed by a write does not prevent a second processor on the bus from accessing the word between the read and the write. In fact, disabling interrupts on processor 1 has no effect at all on processor 2. The only way to keep processor 2 out of the memory until processor 1 is finished is to lock the bus, which requires a special hardware facility (basically, a bus line asserting that the bus is locked and not available to processors other than the one that locked it).

To use the TSL instruction, we will use a shared variable, *lock*, to coordinate access to shared memory. When *lock* is 0, any process may set it to 1 using the TSL instruction and then read or write the shared memory. When it is done, the process sets *lock* back to 0 using an ordinary move instruction.

How can this instruction be used to prevent two processes from simultaneously entering their critical regions? The solution is given in Fig. 2-25. There a four-instruction subroutine in a fictitious (but typical) assembly language is shown. The first instruction copies the old value of *lock* to the register and then sets *lock* to 1. Then the old value is compared with 0. If it is nonzero, the lock was already set, so the program just goes back to the beginning and tests it again. Sooner or later it will become 0 (when the process currently in its critical region is done with its critical region), and the subroutine returns, with the lock set. Clearing the lock is very simple. The program just stores a 0 in *lock*. No special synchronization instructions are needed.

One solution to the critical-region problem is now easy. Before entering its critical region, a process calls *enter_region*, which does busy waiting until the lock is free; then it acquires the lock and returns. After leaving the critical region the process calls *leave_region*, which stores a 0 in *lock*. As with all solutions based on critical regions, the processes must call *enter_region* and *leave_region* at the correct times for the method to work. If one process cheats, the mutual exclusion will fail. In other words, critical regions work only if the processes cooperate.

```
enter_region:
        TSL REGISTER,LOCK       | copy lock to register and set lock to 1
        CMP REGISTER,#0         | was lock zero?
        JNE enter_region        | if it was not zero, lock was set, so loop
        RET                     | return to caller; critical region entered

leave_region:
        MOVE LOCK,#0            | store a 0 in lock
        RET                     | return to caller
```

Figure 2-25. Entering and leaving a critical region using the TSL instruction.

An alternative instruction to TSL is XCHG, which exchanges the contents of two locations atomically, for example, a register and a memory word. The code is shown in Fig. 2-26, and, as can be seen, is essentially the same as the solution with TSL. All Intel x86 CPUs use XCHG instruction for low-level synchronization.

```
enter_region:
        MOVE REGISTER,#1        | put a 1 in the register
        XCHG REGISTER,LOCK      | swap the contents of the register and lock variable
        CMP REGISTER,#0         | was lock zero?
        JNE enter_region        | if it was non zero, lock was set, so loop
        RET                     | return to caller; critical region entered

leave_region:
        MOVE LOCK,#0            | store a 0 in lock
        RET                     | return to caller
```

Figure 2-26. Entering and leaving a critical region using the XCHG instruction.

2.3.4 Sleep and Wakeup

Both Peterson's solution and the solutions using TSL or XCHG are correct, but both have the defect of requiring busy waiting. In essence, what these solutions do is this: when a process wants to enter its critical region, it checks to see if the entry is allowed. If it is not, the process just sits in a tight loop waiting until it is.

Not only does this approach waste CPU time, but it can also have unexpected effects. Consider a computer with two processes, *H*, with high priority, and *L*, with low priority. The scheduling rules are such that *H* is run whenever it is in ready state. At a certain moment, with *L* in its critical region, *H* becomes ready to run (e.g., an I/O operation completes). *H* now begins busy waiting, but since *L* is never

scheduled while *H* is running, *L* never gets the chance to leave its critical region, so *H* loops forever. This situation is sometimes referred to as the **priority inversion problem**.

Now let us look at some interprocess communication primitives that block instead of wasting CPU time when they are not allowed to enter their critical regions. One of the simplest is the pair sleep and wakeup. Sleep is a system call that causes the caller to block, that is, be suspended until another process wakes it up. The wakeup call has one parameter, the process to be awakened. Alternatively, both sleep and wakeup each have one parameter, a memory address used to match up sleeps with wakeups.

The Producer-Consumer Problem

As an example of how these primitives can be used, let us consider the **producer-consumer** problem (also known as the **bounded-buffer** problem). Two processes share a common, fixed-size buffer. One of them, the producer, puts information into the buffer, and the other one, the consumer, takes it out. (It is also possible to generalize the problem to have *m* producers and *n* consumers, but we will consider only the case of one producer and one consumer because this assumption simplifies the solutions.)

Trouble arises when the producer wants to put a new item in the buffer, but it is already full. The solution is for the producer to go to sleep, to be awakened when the consumer has removed one or more items. Similarly, if the consumer wants to remove an item from the buffer and sees that the buffer is empty, it goes to sleep until the producer puts something in the buffer and wakes it up.

This approach sounds simple enough, but it leads to the same kinds of race conditions we saw earlier with the spooler directory. To keep track of the number of items in the buffer, we will need a variable, *count*. If the maximum number of items the buffer can hold is *N*, the producer's code will first test to see if *count* is *N*. If it is, the producer will go to sleep; if it is not, the producer will add an item and increment *count*.

The consumer's code is similar: first test *count* to see if it is 0. If it is, go to sleep; if it is nonzero, remove an item and decrement the counter. Each of the processes also tests to see if the other should be awakened, and if so, wakes it up. The code for both producer and consumer is shown in Fig. 2-27.

To express system calls such as sleep and wakeup in C, we will show them as calls to library routines. They are not part of the standard C library but presumably would be made available on any system that actually had these system calls. The procedures *insert_item* and *remove_item*, which are not shown, handle the bookkeeping of putting items into the buffer and taking items out of the buffer.

Now let us get back to the race condition. It can occur because access to *count* is unconstrained. As a consequence, the following situation could possibly occur. The buffer is empty and the consumer has just read *count* to see if it is 0. At that

```
#define N 100                                   /* number of slots in the buffer */
int count = 0;                                  /* number of items in the buffer */

void producer(void)
{
     int item;

     while (TRUE) {                             /* repeat forever */
          item = produce_item( );               /* generate next item */
          if (count == N) sleep( );             /* if buffer is full, go to sleep */
          insert_item(item);                    /* put item in buffer */
          count = count + 1;                    /* increment count of items in buffer */
          if (count == 1) wakeup(consumer);     /* was buffer empty? */
     }
}


void consumer(void)
{
     int item;

     while (TRUE) {                             /* repeat forever */
          if (count == 0) sleep( );             /* if buffer is empty, got to sleep */
          item = remove_item( );                /* take item out of buffer */
          count = count – 1;                    /* decrement count of items in buffer */
          if (count == N – 1) wakeup(producer); /* was buffer full? */
          consume_item(item);                   /* print item */
     }
}
```

Figure 2-27. The producer-consumer problem with a fatal race condition.

instant, the scheduler decides to stop running the consumer temporarily and start running the producer. The producer inserts an item in the buffer, increments *count*, and notices that it is now 1. Reasoning that *count* was just 0, and thus the consumer must be sleeping, the producer calls *wakeup* to wake the consumer up.

Unfortunately, the consumer is not yet logically asleep, so the wakeup signal is lost. When the consumer next runs, it will test the value of *count* it previously read, find it to be 0, and go to sleep. Sooner or later the producer will fill up the buffer and also go to sleep. Both will sleep forever.

The essence of the problem here is that a wakeup sent to a process that is not (yet) sleeping is lost. If it were not lost, everything would work. A quick fix is to modify the rules to add a **wakeup waiting bit** to the picture. When a wakeup is sent to a process that is still awake, this bit is set. Later, when the process tries to go to sleep, if the wakeup waiting bit is on, it will be turned off, but the process will stay awake. The wakeup waiting bit is a piggy bank for storing wakeup signals. The consumer clears the wakeup waiting bit in every iteration of the loop.

While the wakeup waiting bit saves the day in this simple example, it is easy to construct examples with three or more processes in which one wakeup waiting bit is insufficient. We could make another patch and add a second wakeup waiting bit, or maybe 8 or 32 of them, but in principle the problem is still there.

2.3.5 Semaphores

This was the situation in 1965, when E. W. Dijkstra (1965) suggested using an integer variable to count the number of wakeups saved for future use. In his proposal, a new variable type, which he called a **semaphore**, was introduced. A semaphore could have the value 0, indicating that no wakeups were saved, or some positive value if one or more wakeups were pending.

Dijkstra proposed having two operations on semaphores, now usually called down and up (generalizations of sleep and wakeup, respectively). The down operation on a semaphore checks to see if the value is greater than 0. If so, it decrements the value (i.e., uses up one stored wakeup) and just continues. If the value is 0, the process is put to sleep without completing the down for the moment. Checking the value, changing it, and possibly going to sleep, are all done as a single, indivisible **atomic action**. It is guaranteed that once a semaphore operation has started, no other process can access the semaphore until the operation has completed or blocked. This atomicity is absolutely essential to solving synchronization problems and avoiding race conditions. Atomic actions, in which a group of related operations are either all performed without interruption or not performed at all, are extremely important in many other areas of computer science as well.

The up operation increments the value of the semaphore addressed. If one or more processes were sleeping on that semaphore, unable to complete an earlier down operation, one of them is chosen by the system (e.g., at random) and is allowed to complete its down. Thus, after an up on a semaphore with processes sleeping on it, the semaphore will still be 0, but there will be one fewer process sleeping on it. The operation of incrementing the semaphore and waking up one process is also indivisible. No process ever blocks doing an up, just as no process ever blocks doing a wakeup in the earlier model.

As an aside, in Dijkstra's original paper, he used the names P and V instead of down and up, respectively. Since these have no mnemonic significance to people who do not speak Dutch and only marginal significance to those who do—*Proberen* (try) and *Verhogen* (raise, make higher)—we will use the terms down and up instead. These were first introduced in the Algol 68 programming language.

Solving the Producer-Consumer Problem Using Semaphores

Semaphores solve the lost-wakeup problem, as shown in Fig. 2-28. To make them work correctly, it is essential that they be implemented in an indivisible way. The normal way is to implement up and down as system calls, with the operating

system briefly disabling all interrupts while it is testing the semaphore, updating it, and putting the process to sleep, if necessary. As all of these actions take only a few instructions, no harm is done in disabling interrupts. If multiple CPUs are being used, each semaphore should be protected by a lock variable, with the TSL or XCHG instructions used to make sure that only one CPU at a time examines the semaphore.

Be sure you understand that using TSL or XCHG to prevent several CPUs from accessing the semaphore at the same time is quite different from the producer or consumer busy waiting for the other to empty or fill the buffer. The semaphore operation will take only a few microseconds, whereas the producer or consumer might take arbitrarily long.

```
#define N 100                                   /* number of slots in the buffer */
typedef int semaphore;                          /* semaphores are a special kind of int */
semaphore mutex = 1;                            /* controls access to critical region */
semaphore empty = N;                            /* counts empty buffer slots */
semaphore full = 0;                             /* counts full buffer slots */

void producer(void)
{
     int item;

     while (TRUE) {                             /* TRUE is the constant 1 */
          item = produce_item( );               /* generate something to put in buffer */
          down(&empty);                         /* decrement empty count */
          down(&mutex);                         /* enter critical region */
          insert_item(item);                    /* put new item in buffer */
          up(&mutex);                           /* leave critical region */
          up(&full);                            /* increment count of full slots */
     }
}


void consumer(void)
{
     int item;

     while (TRUE) {                             /* infinite loop */
          down(&full);                          /* decrement full count */
          down(&mutex);                         /* enter critical region */
          item = remove_item( );                /* take item from buffer */
          up(&mutex);                           /* leave critical region */
          up(&empty);                           /* increment count of empty slots */
          consume_item(item);                   /* do something with the item */
     }
}
```

Figure 2-28. The producer-consumer problem using semaphores.

This solution uses three semaphores: one called *full* for counting the number of slots that are full, one called *empty* for counting the number of slots that are empty, and one called *mutex* to make sure the producer and consumer do not access the buffer at the same time. *Full* is initially 0, *empty* is initially equal to the number of slots in the buffer, and *mutex* is initially 1. Semaphores that are initialized to 1 and used by two or more processes to ensure that only one of them can enter its critical region at the same time are called **binary semaphores**. If each process does a down just before entering its critical region and an up just after leaving it, mutual exclusion is guaranteed.

Now that we have a good interprocess communication primitive at our disposal, let us go back and look at the interrupt sequence of Fig. 2-5 again. In a system using semaphores, the natural way to hide interrupts is to have a semaphore, initially set to 0, associated with each I/O device. Just after starting an I/O device, the managing process does a down on the associated semaphore, thus blocking immediately. When the interrupt comes in, the interrupt handler then does an up on the associated semaphore, which makes the relevant process ready to run again. In this model, step 5 in Fig. 2-5 consists of doing an up on the device's semaphore, so that in step 6 the scheduler will be able to run the device manager. Of course, if several processes are now ready, the scheduler may choose to run an even more important process next. We will look at some of the algorithms used for scheduling later on in this chapter.

In the example of Fig. 2-28, we have actually used semaphores in two different ways. This difference is important enough to make explicit. The *mutex* semaphore is used for mutual exclusion. It is designed to guarantee that only one process at a time will be reading or writing the buffer and the associated variables. This mutual exclusion is required to prevent chaos. We will study mutual exclusion and how to achieve it in the next section.

The other use of semaphores is for **synchronization**. The *full* and *empty* semaphores are needed to guarantee that certain event sequences do or do not occur. In this case, they ensure that the producer stops running when the buffer is full, and that the consumer stops running when it is empty. This use is different from mutual exclusion.

2.3.6 Mutexes

When the semaphore's ability to count is not needed, a simplified version of the semaphore, called a mutex, is sometimes used. Mutexes are good only for managing mutual exclusion to some shared resource or piece of code. They are easy and efficient to implement, which makes them especially useful in thread packages that are implemented entirely in user space.

A **mutex** is a shared variable that can be in one of two states: unlocked or locked. Consequently, only 1 bit is required to represent it, but in practice an integer often is used, with 0 meaning unlocked and all other values meaning locked.

Two procedures are used with mutexes. When a thread (or process) needs access to a critical region, it calls *mutex_lock*. If the mutex is currently unlocked (meaning that the critical region is available), the call succeeds and the calling thread is free to enter the critical region.

On the other hand, if the mutex is already locked, the calling thread is blocked until the thread in the critical region is finished and calls *mutex_unlock*. If multiple threads are blocked on the mutex, one of them is chosen at random and allowed to acquire the lock.

Because mutexes are so simple, they can easily be implemented in user space provided that a TSL or XCHG instruction is available. The code for *mutex_lock* and *mutex_unlock* for use with a user-level threads package are shown in Fig. 2-29. The solution with XCHG is essentially the same.

```
mutex_lock:
        TSL REGISTER,MUTEX      | copy mutex to register and set mutex to 1
        CMP REGISTER,#0         | was mutex zero?
        JZE ok                  | if it was zero, mutex was unlocked, so return
        CALL thread_yield       | mutex is busy; schedule another thread
        JMP mutex_lock          | try again
ok:     RET                     | return to caller; critical region entered


mutex_unlock:
        MOVE MUTEX,#0           | store a 0 in mutex
        RET                     | return to caller
```

Figure 2-29. Implementation of *mutex_lock* and *mutex_unlock*.

The code of *mutex_lock* is similar to the code of *enter_region* of Fig. 2-25 but with a crucial difference. When *enter_region* fails to enter the critical region, it keeps testing the lock repeatedly (busy waiting). Eventually, the clock runs out and some other process is scheduled to run. Sooner or later the process holding the lock gets to run and releases it.

With (user) threads, the situation is different because there is no clock that stops threads that have run too long. Consequently, a thread that tries to acquire a lock by busy waiting will loop forever and never acquire the lock because it never allows any other thread to run and release the lock.

That is where the difference between *enter_region* and *mutex_lock* comes in. When the later fails to acquire a lock, it calls *thread_yield* to give up the CPU to another thread. Consequently there is no busy waiting. When the thread runs the next time, it tests the lock again.

Since *thread_yield* is just a call to the thread scheduler in user space, it is very fast. As a consequence, neither *mutex_lock* nor *mutex_unlock* requires any kernel calls. Using them, user-level threads can synchronize entirely in user space using procedures that require only a handful of instructions.

The mutex system that we have described above is a bare-bones set of calls. With all software, there is always a demand for more features, and synchronization primitives are no exception. For example, sometimes a thread package offers a call *mutex_trylock* that either acquires the lock or returns a code for failure, but does not block. This call gives the thread the flexibility to decide what to do next if there are alternatives to just waiting.

There is a subtle issue that up until now we have glossed over but which is worth at least making explicit. With a user-space threads package there is no problem with multiple threads having access to the same mutex, since all the threads operate in a common address space. However, with most of the earlier solutions, such as Peterson's algorithm and semaphores, there is an unspoken assumption that multiple processes have access to at least some shared memory, perhaps only one word, but something. If processes have disjoint address spaces, as we have consistently said, how can they share the *turn* variable in Peterson's algorithm, or semaphores or a common buffer?

There are two answers. First, some of the shared data structures, such as the semaphores, can be stored in the kernel and accessed only by means of system calls. This approach eliminates the problem. Second, most modern operating systems (including UNIX and Windows) offer a way for processes to share some portion of their address space with other processes. In this way, buffers and other data structures can be shared. In the worst case, that nothing else is possible, a shared file can be used.

If two or more processes share most or all of their address spaces, the distinction between processes and threads becomes somewhat blurred but is nevertheless present. Two processes that share a common address space still have different open files, alarm timers, and other per-process properties, whereas the threads within a single process share them. And it is always true that multiple processes sharing a common address space never have the efficiency of user-level threads since the kernel is deeply involved in their management.

Futexes

With increasing parallelism, efficient synchronization and locking is very important for performance. Spin locks are fast if the wait is short, but waste CPU cycles if not. If there is much contention, it is therefore more efficient to block the process and let the kernel unblock it only when the lock is free. Unfortunately, this has the inverse problem: it works well under heavy contention, but continuously switching to the kernel is expensive if there is very little contention to begin with. To make matters worse, it may not be easy to predict the amount of lock contention.

One interesting solution that tries to combine the best of both worlds is known as **futex**, or "fast user space mutex." A futex is a feature of Linux that implements basic locking (much like a mutex) but avoids dropping into the kernel unless it

really has to. Since switching to the kernel and back is quite expensive, doing so improves performance considerably. A futex consists of two parts: a kernel service and a user library. The kernel service provides a "wait queue" that allows multiple processes to wait on a lock. They will not run, unless the kernel explicitly unblocks them. For a process to be put on the wait queue requires an (expensive) system call and should be avoided. In the absence of contention, therefore, the futex works completely in user space. Specifically, the processes share a common lock variable—a fancy name for an aligned 32-bit integer that serves as the lock. Suppose the lock is initially 1—which we assume to mean that the lock is free. A thread grabs the lock by performing an atomic "decrement and test" (atomic functions in Linux consist of inline assembly wrapped in C functions and are defined in header files). Next, the thread inspects the result to see whether or not the lock was free. If it was not in the locked state, all is well and our thread has successfully grabbed the lock. However, if the lock is held by another thread, our thread has to wait. In that case, the futex library does not spin, but uses a system call to put the thread on the wait queue in the kernel. Hopefully, the cost of the switch to the kernel is now justified, because the thread was blocked anyway. When a thread is done with the lock, it releases the lock with an atomic "increment and test" and checks the result to see if any processes are still blocked on the kernel wait queue. If so, it will let the kernel know that it may unblock one or more of these processes. If there is no contention, the kernel is not involved at all.

Mutexes in Pthreads

Pthreads provides a number of functions that can be used to synchronize threads. The basic mechanism uses a mutex variable, which can be locked or unlocked, to guard each critical region. A thread wishing to enter a critical region first tries to lock the associated mutex. If the mutex is unlocked, the thread can enter immediately and the lock is atomically set, preventing other threads from entering. If the mutex is already locked, the calling thread is blocked until it is unlocked. If multiple threads are waiting on the same mutex, when it is unlocked, only one of them is allowed to continue and relock it. These locks are not mandatory. It is up to the programmer to make sure threads use them correctly.

The major calls relating to mutexes are shown in Fig. 2-30. As expected, mutexes can be created and destroyed. The calls for performing these operations are *pthread_mutex_init* and *pthread_mutex_destroy*, respectively. They can also be locked—by *pthread_mutex_lock*—which tries to acquire the lock and blocks if is already locked. There is also an option for trying to lock a mutex and failing with an error code instead of blocking if it is already blocked. This call is *pthread_mutex_trylock*. This call allows a thread to effectively do busy waiting if that is ever needed. Finally, *pthread_mutex_unlock* unlocks a mutex and releases exactly one thread if one or more are waiting on it. Mutexes can also have attributes, but these are used only for specialized purposes.

Thread call	Description
Pthread_mutex_init	Create a mutex
Pthread_mutex_destroy	Destroy an existing mutex
Pthread_mutex_lock	Acquire a lock or block
Pthread_mutex_trylock	Acquire a lock or fail
Pthread_mutex_unlock	Release a lock

Figure 2-30. Some of the Pthreads calls relating to mutexes.

In addition to mutexes, Pthreads offers a second synchronization mechanism: **condition variables**. Mutexes are good for allowing or blocking access to a critical region. Condition variables allow threads to block due to some condition not being met. Almost always the two methods are used together. Let us now look at the interaction of threads, mutexes, and condition variables in a bit more detail.

As a simple example, consider the producer-consumer scenario again: one thread puts things in a buffer and another one takes them out. If the producer discovers that there are no more free slots available in the buffer, it has to block until one becomes available. Mutexes make it possible to do the check atomically without interference from other threads, but having discovered that the buffer is full, the producer needs a way to block and be awakened later. This is what condition variables allow.

The most important calls related to condition variables are shown in Fig. 2-31. As you would probably expect, there are calls to create and destroy condition variables. They can have attributes and there are various calls for managing them (not shown). The primary operations on condition variables are *pthread_cond_wait* and *pthread_cond_signal*. The former blocks the calling thread until some other thread signals it (using the latter call). The reasons for blocking and waiting are not part of the waiting and signaling protocol, of course. The blocking thread often is waiting for the signaling thread to do some work, release some resource, or perform some other activity. Only then can the blocking thread continue. The condition variables allow this waiting and blocking to be done atomically. The *pthread_cond_broadcast* call is used when there are multiple threads potentially all blocked and waiting for the same signal.

Condition variables and mutexes are always used together. The pattern is for one thread to lock a mutex, then wait on a conditional variable when it cannot get what it needs. Eventually another thread will signal it and it can continue. The *pthread_cond_wait* call atomically unlocks the mutex it is holding. For this reason, the mutex is one of the parameters.

It is also worth noting that condition variables (unlike semaphores) have no memory. If a signal is sent to a condition variable on which no thread is waiting, the signal is lost. Programmers have to be careful not to lose signals.

Thread call	Description
Pthread_cond_init	Create a condition variable
Pthread_cond_destroy	Destroy a condition variable
Pthread_cond_wait	Block waiting for a signal
Pthread_cond_signal	Signal another thread and wake it up
Pthread_cond_broadcast	Signal multiple threads and wake all of them

Figure 2-31. Some of the Pthreads calls relating to condition variables.

As an example of how mutexes and condition variables are used, Fig. 2-32 shows a very simple producer-consumer problem with a single buffer. When the producer has filled the buffer, it must wait until the consumer empties it before producing the next item. Similarly, when the consumer has removed an item, it must wait until the producer has produced another one. While very simple, this example illustrates the basic mechanisms. The statement that puts a thread to sleep should always check the condition to make sure it is satisfied before continuing, as the thread might have been awakened due to a UNIX signal or some other reason.

2.3.7 Monitors

With semaphores and mutexes interprocess communication looks easy, right? Forget it. Look closely at the order of the downs before inserting or removing items from the buffer in Fig. 2-28. Suppose that the two downs in the producer's code were reversed in order, so *mutex* was decremented before *empty* instead of after it. If the buffer were completely full, the producer would block, with *mutex* set to 0. Consequently, the next time the consumer tried to access the buffer, it would do a down on *mutex*, now 0, and block too. Both processes would stay blocked forever and no more work would ever be done. This unfortunate situation is called a deadlock. We will study deadlocks in detail in Chap. 6.

This problem is pointed out to show how careful you must be when using semaphores. One subtle error and everything comes to a grinding halt. It is like programming in assembly language, only worse, because the errors are race conditions, deadlocks, and other forms of unpredictable and irreproducible behavior.

To make it easier to write correct programs, Brinch Hansen (1973) and Hoare (1974) proposed a higher-level synchronization primitive called a **monitor**. Their proposals differed slightly, as described below. A monitor is a collection of procedures, variables, and data structures that are all grouped together in a special kind of module or package. Processes may call the procedures in a monitor whenever they want to, but they cannot directly access the monitor's internal data structures from procedures declared outside the monitor. Figure 2-33 illustrates a monitor written in an imaginary language, Pidgin Pascal. C cannot be used here because monitors are a *language* concept and C does not have them.

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

#define MAX 1000000000                          /* how many numbers to produce */
pthread_mutex_t the_mutex;
pthread_cond_t condc, condp;                    /* used for signaling */
int buffer = 0;                                 /* buffer used between producer and consumer */

void *producer(void *ptr)                       /* produce data */
{       int i;

        for (i= 1; i <= MAX; i++) {
                pthread_mutex_lock(&the_mutex);     /* get exclusive access to buffer */
                while (buffer != 0) pthread_cond_wait(&condp, &the_mutex);
                buffer = i;                         /* put item in buffer */
                pthread_cond_signal(&condc);        /* wake up consumer */
                pthread_mutex_unlock(&the_mutex);/* release access to buffer */
        }
        pthread_exit(0);
}

void *consumer(void *ptr)                       /* consume data */
{       int i;

        for (i = 1; i <= MAX; i++) {
                pthread_mutex_lock(&the_mutex);     /* get exclusive access to buffer */
                while (buffer ==0 ) pthread_cond_wait(&condc, &the_mutex);
                buffer = 0;                         /* take item out of buffer */
                pthread_cond_signal(&condp);        /* wake up producer */
                pthread_mutex_unlock(&the_mutex);/* release access to buffer */
        }
        pthread_exit(0);
}

int main(int argc, char **argv)
{
        pthread_t pro, con;
        pthread_mutex_init(&the_mutex, 0);
        pthread_cond_init(&condc, 0);
        pthread_cond_init(&condp, 0);
        pthread_create(&con, 0, consumer, 0);
        pthread_create(&pro, 0, producer, 0);
        pthread_join(pro, 0);
        pthread_join(con, 0);
        pthread_cond_destroy(&condc);
        pthread_cond_destroy(&condp);
        pthread_mutex_destroy(&the_mutex);
}
```

Figure 2-32. Using threads to solve the producer-consumer problem.

Monitors have an important property that makes them useful for achieving mutual exclusion: only one process can be active in a monitor at any instant. Monitors are a programming-language construct, so the compiler knows they are special and can handle calls to monitor procedures differently from other procedure calls. Typically, when a process calls a monitor procedure, the first few instructions of the procedure will check to see if any other process is currently active within the monitor. If so, the calling process will be suspended until the other process has left the monitor. If no other process is using the monitor, the calling process may enter.

It is up to the compiler to implement mutual exclusion on monitor entries, but a common way is to use a mutex or a binary semaphore. Because the compiler, not the programmer, is arranging for the mutual exclusion, it is much less likely that something will go wrong. In any event, the person writing the monitor does not have to be aware of how the compiler arranges for mutual exclusion. It is sufficient to know that by turning all the critical regions into monitor procedures, no two processes will ever execute their critical regions at the same time.

Although monitors provide an easy way to achieve mutual exclusion, as we have seen above, that is not enough. We also need a way for processes to block when they cannot proceed. In the producer-consumer problem, it is easy enough to put all the tests for buffer-full and buffer-empty in monitor procedures, but how should the producer block when it finds the buffer full?

The solution lies in the introduction of **condition variables**, along with two operations on them, wait and signal. When a monitor procedure discovers that it cannot continue (e.g., the producer finds the buffer full), it does a wait on some condition variable, say, *full*. This action causes the calling process to block. It also allows another process that had been previously prohibited from entering the monitor to enter now. We saw condition variables and these operations in the context of Pthreads earlier.

This other process, for example, the consumer, can wake up its sleeping partner by doing a signal on the condition variable that its partner is waiting on. To avoid having two active processes in the monitor at the same time, we need a rule telling what happens after a signal. Hoare proposed letting the newly awakened process run, suspending the other one. Brinch Hansen proposed finessing the problem by requiring that a process doing a signal *must* exit the monitor immediately. In other words, a signal statement may appear only as the final statement in a monitor procedure. We will use Brinch Hansen's proposal because it is conceptually simpler and is also easier to implement. If a signal is done on a condition variable on which several processes are waiting, only one of them, determined by the system scheduler, is revived.

As an aside, there is also a third solution, not proposed by either Hoare or Brinch Hansen. This is to let the signaler continue to run and allow the waiting process to start running only after the signaler has exited the monitor.

Condition variables are not counters. They do not accumulate signals for later use the way semaphores do. Thus, if a condition variable is signaled with no one

```
monitor example
        integer i;
        condition c;

        procedure producer( );
        .
        .
        .
        end;

        procedure consumer( );
        .           .           .
        end;
end monitor;
```

Figure 2-33. A monitor.

waiting on it, the signal is lost forever. In other words, the wait must come before the signal. This rule makes the implementation much simpler. In practice, it is not a problem because it is easy to keep track of the state of each process with variables, if need be. A process that might otherwise do a signal can see that this operation is not necessary by looking at the variables.

A skeleton of the producer-consumer problem with monitors is given in Fig. 2-34 in an imaginary language, Pidgin Pascal. The advantage of using Pidgin Pascal here is that it is pure and simple and follows the Hoare/Brinch Hansen model exactly.

You may be thinking that the operations wait and signal look similar to sleep and wakeup, which we saw earlier had fatal race conditions. Well, they *are* very similar, but with one crucial difference: sleep and wakeup failed because while one process was trying to go to sleep, the other one was trying to wake it up. With monitors, that cannot happen. The automatic mutual exclusion on monitor procedures guarantees that if, say, the producer inside a monitor procedure discovers that the buffer is full, it will be able to complete the wait operation without having to worry about the possibility that the scheduler may switch to the consumer just before the wait completes. The consumer will not even be let into the monitor at all until the wait is finished and the producer has been marked as no longer runnable.

Although Pidgin Pascal is an imaginary language, some real programming languages also support monitors, although not always in the form designed by Hoare and Brinch Hansen. One such language is Java. Java is an object-oriented language that supports user-level threads and also allows methods (procedures) to be grouped together into classes. By adding the keyword synchronized to a method declaration, Java guarantees that once any thread has started executing that method, no other thread will be allowed to start executing any other synchronized method of that object. Without synchronized, there are no guarantees about interleaving.

```
monitor ProducerConsumer
        condition full, empty;
        integer count;

        procedure insert(item: integer);
        begin
                if count = N then wait(full);
                insert_item(item);
                count := count + 1;
                if count = 1 then signal(empty)
        end;

        function remove: integer;
        begin
                if count = 0 then wait(empty);
                remove = remove_item;
                count := count - 1;
                if count = N - 1 then signal(full)
        end;

        count := 0;
end monitor;

procedure producer;
begin
        while true do
        begin
                item = produce_item;
                ProducerConsumer.insert(item)
        end
end;

procedure consumer;
begin
        while true do
        begin
                item = ProducerConsumer.remove;
                consume_item(item)
        end
end;
```

Figure 2-34. An outline of the producer-consumer problem with monitors. Only one monitor procedure at a time is active. The buffer has *N* slots.

A solution to the producer-consumer problem using monitors in Java is given in Fig. 2-35. Our solution has four classes. The outer class, *ProducerConsumer*, creates and starts two threads, *p* and *c*. The second and third classes, *producer* and *consumer*, respectively, contain the code for the producer and consumer. Finally, the class *our_monitor*, is the monitor. It contains two synchronized threads that are used for actually inserting items into the shared buffer and taking them out. Unlike the previous examples, here we have the full code of *insert* and *remove*.

```
public class ProducerConsumer {
        static final int N = 100;       // constant giving the buffer size
        static producer p = new producer( );    // instantiate a new producer thread
        static consumer c = new consumer( ); // instantiate a new consumer thread
        static our_monitor mon = new our_monitor( );       // instantiate a new monitor

        public static void main(String args[ ]) {
            p.start( );       // start the producer thread
            c.start( );       // start the consumer thread
        }

        static class producer extends Thread {
            public void run( )  { // run method contains the thread code
                int item;
                while (true) {      // producer loop
                    item = produce_item( );
                    mon.insert(item);
                }
            }
            private int produce_item( ) { ... }       // actually produce
        }

        static class consumer extends Thread {
            public void run( )  { run method contains the thread code
                int item;
                while (true) {      // consumer loop
                    item = mon.remove( );
                    consume_item (item);
                }
            }
            private void consume_item(int item) { ... } // actually consume
        }

        static class our_monitor {  // this is a monitor
            private int buffer[ ] = new int[N];
            private int count = 0, lo = 0, hi = 0;  // counters and indices

            public synchronized void insert(int val) {
                if (count == N) go_to_sleep( );     // if the buffer is full, go to sleep
                buffer [hi] = val; // insert an item into the buffer
                hi = (hi + 1) % N;        // slot to place next item in
                count = count + 1;      // one more item in the buffer now
                if (count == 1) notify( );        // if consumer was sleeping, wake it up
            }

            public synchronized int remove( ) {
                int val;
                if (count == 0) go_to_sleep( );     // if the buffer is empty, go to sleep
                val = buffer [lo]; // fetch an item from the buffer
                lo = (lo + 1) % N;        // slot to fetch next item from
                count = count – 1;      // one few items in the buffer
                if (count == N – 1) notify( ); // if producer was sleeping, wake it up
                return val;
            }
            private void go_to_sleep( ) { try{wait( );} catch(InterruptedException exc) {};}
        }
}
```

Figure 2-35. A solution to the producer-consumer problem in Java.

The producer and consumer threads are functionally identical to their counterparts in all our previous examples. The producer has an infinite loop generating data and putting it into the common buffer. The consumer has an equally infinite loop taking data out of the common buffer and doing some fun thing with it.

The interesting part of this program is the class *our_monitor*, which holds the buffer, the administration variables, and two synchronized methods. When the producer is active inside *insert*, it knows for sure that the consumer cannot be active inside *remove*, making it safe to update the variables and the buffer without fear of race conditions. The variable *count* keeps track of how many items are in the buffer. It can take on any value from 0 through and including $N - 1$. The variable *lo* is the index of the buffer slot where the next item is to be fetched. Similarly, *hi* is the index of the buffer slot where the next item is to be placed. It is permitted that $lo = hi$, which means that either 0 items or N items are in the buffer. The value of *count* tells which case holds.

Synchronized methods in Java differ from classical monitors in an essential way: Java does not have condition variables built in. Instead, it offers two procedures, *wait* and *notify*, which are the equivalent of *sleep* and *wakeup* except that when they are used inside synchronized methods, they are not subject to race conditions. In theory, the method *wait* can be interrupted, which is what the code surrounding it is all about. Java requires that the exception handling be made explicit. For our purposes, just imagine that *go_to_sleep* is the way to go to sleep.

By making the mutual exclusion of critical regions automatic, monitors make parallel programming much less error prone than using semaphores. Nevertheless, they too have some drawbacks. It is not for nothing that our two examples of monitors were in Pidgin Pascal instead of C, as are the other examples in this book. As we said earlier, monitors are a programming-language concept. The compiler must recognize them and arrange for the mutual exclusion somehow or other. C, Pascal, and most other languages do not have monitors, so it is unreasonable to expect their compilers to enforce any mutual exclusion rules. In fact, how could the compiler even know which procedures were in monitors and which were not?

These same languages do not have semaphores either, but adding semaphores is easy: all you need to do is add two short assembly-code routines to the library to issue the up and down system calls. The compilers do not even have to know that they exist. Of course, the operating systems have to know about the semaphores, but at least if you have a semaphore-based operating system, you can still write the user programs for it in C or C++ (or even assembly language if you are masochistic enough). With monitors, you need a language that has them built in.

Another problem with monitors, and also with semaphores, is that they were designed for solving the mutual exclusion problem on one or more CPUs that all have access to a common memory. By putting the semaphores in the shared memory and protecting them with TSL or XCHG instructions, we can avoid races. When we move to a distributed system consisting of multiple CPUs, each with its own private memory and connected by a local area network, these primitives become

inapplicable. The conclusion is that semaphores are too low level and monitors are not usable except in a few programming languages. Also, none of the primitives allow information exchange between machines. Something else is needed.

2.3.8 Message Passing

That something else is **message passing**. This method of interprocess communication uses two primitives, send and receive, which, like semaphores and unlike monitors, are system calls rather than language constructs. As such, they can easily be put into library procedures, such as

```
send(destination, &message);
```

and

```
receive(source, &message);
```

The former call sends a message to a given destination and the latter one receives a message from a given source (or from *ANY*, if the receiver does not care). If no message is available, the receiver can block until one arrives. Alternatively, it can return immediately with an error code.

Design Issues for Message-Passing Systems

Message-passing systems have many problems and design issues that do not arise with semaphores or with monitors, especially if the communicating processes are on different machines connected by a network. For example, messages can be lost by the network. To guard against lost messages, the sender and receiver can agree that as soon as a message has been received, the receiver will send back a special **acknowledgement** message. If the sender has not received the acknowledgement within a certain time interval, it retransmits the message.

Now consider what happens if the message is received correctly, but the acknowledgement back to the sender is lost. The sender will retransmit the message, so the receiver will get it twice. It is essential that the receiver be able to distinguish a new message from the retransmission of an old one. Usually, this problem is solved by putting consecutive sequence numbers in each original message. If the receiver gets a message bearing the same sequence number as the previous message, it knows that the message is a duplicate that can be ignored. Successfully communicating in the face of unreliable message passing is a major part of the study of computer networks. For more information, see Tanenbaum and Wetherall (2010).

Message systems also have to deal with the question of how processes are named, so that the process specified in a send or receive call is unambiguous. **Authentication** is also an issue in message systems: how can the client tell that it is communicating with the real file server, and not with an imposter?

At the other end of the spectrum, there are also design issues that are important when the sender and receiver are on the same machine. One of these is performance. Copying messages from one process to another is always slower than doing a semaphore operation or entering a monitor. Much work has gone into making message passing efficient.

The Producer-Consumer Problem with Message Passing

Now let us see how the producer-consumer problem can be solved with message passing and no shared memory. A solution is given in Fig. 2-36. We assume that all messages are the same size and that messages sent but not yet received are buffered automatically by the operating system. In this solution, a total of *N* messages is used, analogous to the *N* slots in a shared-memory buffer. The consumer starts out by sending *N* empty messages to the producer. Whenever the producer has an item to give to the consumer, it takes an empty message and sends back a full one. In this way, the total number of messages in the system remains constant in time, so they can be stored in a given amount of memory known in advance.

If the producer works faster than the consumer, all the messages will end up full, waiting for the consumer; the producer will be blocked, waiting for an empty to come back. If the consumer works faster, then the reverse happens: all the messages will be empties waiting for the producer to fill them up; the consumer will be blocked, waiting for a full message.

Many variants are possible with message passing. For starters, let us look at how messages are addressed. One way is to assign each process a unique address and have messages be addressed to processes. A different way is to invent a new data structure, called a **mailbox**. A mailbox is a place to buffer a certain number of messages, typically specified when the mailbox is created. When mailboxes are used, the address parameters in the send and receive calls are mailboxes, not processes. When a process tries to send to a mailbox that is full, it is suspended until a message is removed from that mailbox, making room for a new one.

For the producer-consumer problem, both the producer and consumer would create mailboxes large enough to hold *N* messages. The producer would send messages containing actual data to the consumer's mailbox, and the consumer would send empty messages to the producer's mailbox. When mailboxes are used, the buffering mechanism is clear: the destination mailbox holds messages that have been sent to the destination process but have not yet been accepted.

The other extreme from having mailboxes is to eliminate all buffering. When this approach is taken, if the send is done before the receive, the sending process is blocked until the receive happens, at which time the message can be copied directly from the sender to the receiver, with no buffering. Similarly, if the receive is done first, the receiver is blocked until a send happens. This strategy is often known as a **rendezvous**. It is easier to implement than a buffered message scheme but is less flexible since the sender and receiver are forced to run in lockstep.

```
#define N 100                                   /* number of slots in the buffer */

void producer(void)
{
     int item;
     message m;                                 /* message buffer */

     while (TRUE) {
          item = produce_item( );               /* generate something to put in buffer */
          receive(consumer, &m);                /* wait for an empty to arrive */
          build_message(&m, item);              /* construct a message to send */
          send(consumer, &m);                   /* send item to consumer */
     }
}

void consumer(void)
{
     int item, i;
     message m;

     for (i = 0; i < N; i++) send(producer, &m);  /* send N empties */
     while (TRUE) {
          receive(producer, &m);                /* get message containing item */
          item = extract_item(&m);              /* extract item from message */
          send(producer, &m);                   /* send back empty reply */
          consume_item(item);                   /* do something with the item */
     }
}
```

Figure 2-36. The producer-consumer problem with *N* messages.

Message passing is commonly used in parallel programming systems. One well-known message-passing system, for example, is **MPI** (**Message-Passing Interface**). It is widely used for scientific computing. For more information about it, see for example Gropp et al. (1994), and Snir et al. (1996).

2.3.9 Barriers

Our last synchronization mechanism is intended for groups of processes rather than two-process producer-consumer type situations. Some applications are divided into phases and have the rule that no process may proceed into the next phase until all processes are ready to proceed to the next phase. This behavior may be achieved by placing a **barrier** at the end of each phase. When a process reaches the barrier, it is blocked until all processes have reached the barrier. This allows groups of processes to synchronize. Barrier operation is illustrated in Fig. 2-37.

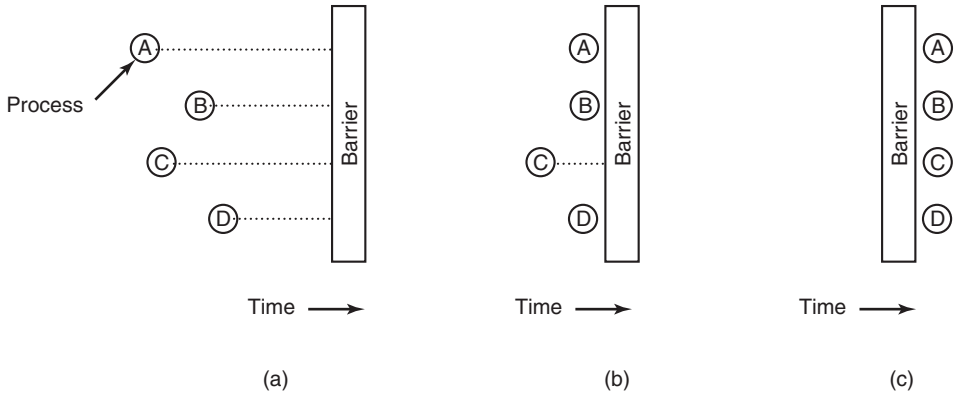

Figure 2-37. Use of a barrier. (a) Processes approaching a barrier. (b) All processes but one blocked at the barrier. (c) When the last process arrives at the barrier, all of them are let through.

In Fig. 2-37(a) we see four processes approaching a barrier. What this means is that they are just computing and have not reached the end of the current phase yet. After a while, the first process finishes all the computing required of it during the first phase. It then executes the barrier primitive, generally by calling a library procedure. The process is then suspended. A little later, a second and then a third process finish the first phase and also execute the barrier primitive. This situation is illustrated in Fig. 2-37(b). Finally, when the last process, *C*, hits the barrier, all the processes are released, as shown in Fig. 2-37(c).

As an example of a problem requiring barriers, consider a common relaxation problem in physics or engineering. There is typically a matrix that contains some initial values. The values might represent temperatures at various points on a sheet of metal. The idea might be to calculate how long it takes for the effect of a flame placed at one corner to propagate throughout the sheet.

Starting with the current values, a transformation is applied to the matrix to get the second version of the matrix, for example, by applying the laws of thermodynamics to see what all the temperatures are ΔT later. Then the process is repeated over and over, giving the temperatures at the sample points as a function of time as the sheet heats up. The algorithm produces a sequence of matrices over time, each one for a given point in time.

Now imagine that the matrix is very large (for example, 1 million by 1 million), so that parallel processes are needed (possibly on a multiprocessor) to speed up the calculation. Different processes work on different parts of the matrix, calculating the new matrix elements from the old ones according to the laws of physics. However, no process may start on iteration $n + 1$ until iteration n is complete, that is, until all processes have finished their current work. The way to achieve this goal

is to program each process to execute a barrier operation after it has finished its part of the current iteration. When all of them are done, the new matrix (the input to the next iteration) will be finished, and all processes will be simultaneously released to start the next iteration.

2.3.10 Avoiding Locks: Read-Copy-Update

The fastest locks are no locks at all. The question is whether we can allow for concurrent read and write accesses to shared data structures without locking. In the general case, the answer is clearly no. Imagine process A sorting an array of numbers, while process B is calculating the average. Because A moves the values back and forth across the array, B may encounter some values multiple times and others not at all. The result could be anything, but it would almost certainly be wrong.

In some cases, however, we can allow a writer to update a data structure even though other processes are still using it. The trick is to ensure that each reader either reads the old version of the data, or the new one, but not some weird combination of old and new. As an illustration, consider the tree shown in Fig. 2-38. Readers traverse the tree from the root to its leaves. In the top half of the figure, a new node X is added. To do so, we make the node "just right" before making it visible in the tree: we initialize all values in node X, including its child pointers. Then, with one atomic write, we make X a child of A. No reader will ever read an inconsistent version. In the bottom half of the figure, we subsequently remove B and D. First, we make A's left child pointer point to C. All readers that were in A will continue with node C and never see B or D. In other words, they will see only the new version. Likewise, all readers currently in B or D will continue following the original data structure pointers and see the old version. All is well, and we never need to lock anything. The main reason that the removal of B and D works without locking the data structure, is that **RCU** (**Read-Copy-Update**), decouples the *removal* and *reclamation* phases of the update.

Of course, there is a problem. As long as we are not sure that there are no more readers of B or D, we cannot really free them. But how long should we wait? One minute? Ten? We have to wait until the last reader has left these nodes. RCU carefully determines the maximum time a reader may hold a reference to the data structure. After that period, it can safely reclaim the memory. Specifically, readers access the data structure in what is known as a **read-side critical section** which may contain any code, as long as it does not block or sleep. In that case, we know the maximum time we need to wait. Specifically, we define a **grace period** as any time period in which we know that each thread to be outside the read-side critical section at least once. All will be well if we wait for a duration that is at least equal to the grace period before reclaiming. As the code in a read-side critical section is not allowed to block or sleep, a simple criterion is to wait until all the threads have executed a context switch.

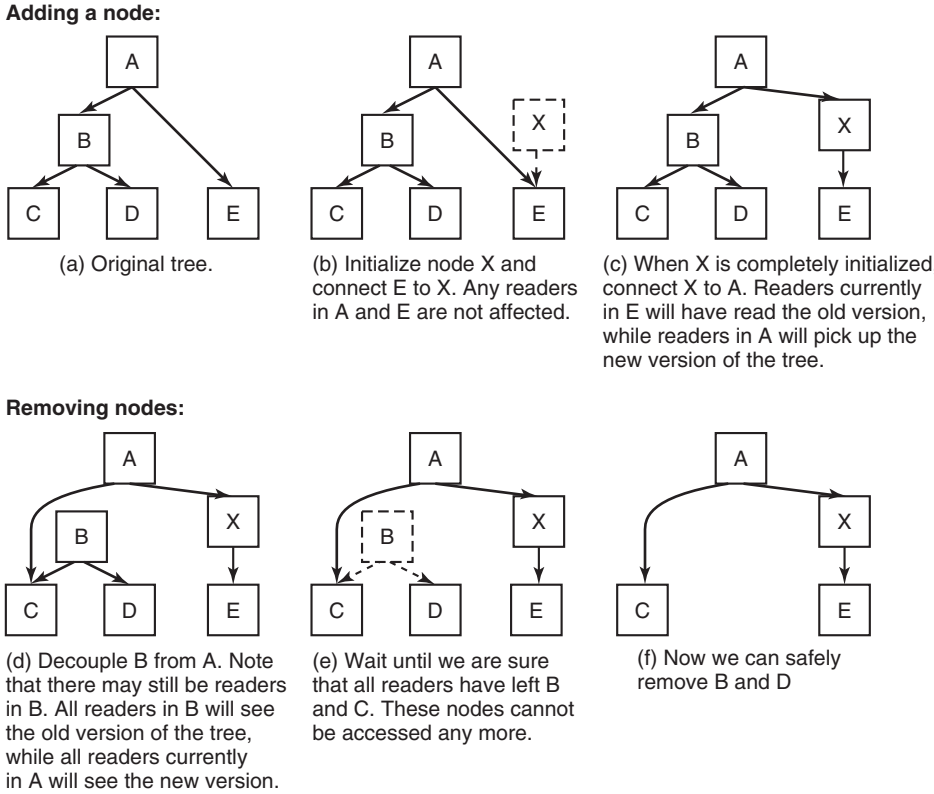

Figure 2-38. Read-Copy-Update: inserting a node in the tree and then removing a branch—all without locks.

2.4 SCHEDULING

When a computer is multiprogrammed, it frequently has multiple processes or threads competing for the CPU at the same time. This situation occurs whenever two or more of them are simultaneously in the ready state. If only one CPU is available, a choice has to be made which process to run next. The part of the operating system that makes the choice is called the **scheduler**, and the algorithm it uses is called the **scheduling algorithm**. These topics form the subject matter of the following sections.

Many of the same issues that apply to process scheduling also apply to thread scheduling, although some are different. When the kernel manages threads, scheduling is usually done per thread, with little or no regard to which process the thread belongs. Initially we will focus on scheduling issues that apply to both processes and threads. Later on we will explicitly look at thread scheduling and some of the unique issues it raises. We will deal with multicore chips in Chap. 8.