

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 **spin-lock** 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

```
 $S_1;$ 
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);
```