2.4.6 Thread Scheduling

When several processes each have multiple threads, we have two levels of parallelism present: processes and threads. Scheduling in such systems differs substantially depending on whether user-level threads or kernel-level threads (or both) are supported.

Let us consider user-level threads first. Since the kernel is not aware of the existence of threads, it operates as it always does, picking a process, say, *A*, and giving *A* control for its quantum. The thread scheduler inside *A* decides which thread to run, say *A1*. Since there are no clock interrupts to multiprogram threads, this thread may continue running as long as it wants to. If it uses up the process' entire quantum, the kernel will select another process to run.

When the process *A* finally runs again, thread *A1* will resume running. It will continue to consume all of *A*'s time until it is finished. However, its antisocial behavior will not affect other processes. They will get whatever the scheduler considers their appropriate share, no matter what is going on inside process *A*.

Now consider the case that *A*'s threads have relatively little work to do per CPU burst, for example, 5 msec of work within a 50-msec quantum. Consequently, each one runs for a little while, then yields the CPU back to the thread scheduler. This might lead to the sequence *A1*, *A2*, *A3*, *A1*, *A2*, *A3*, *A1*, *A2*, *A3*, *A1*, before the kernel switches to process *B*. This situation is illustrated in Fig. 2-44(a).

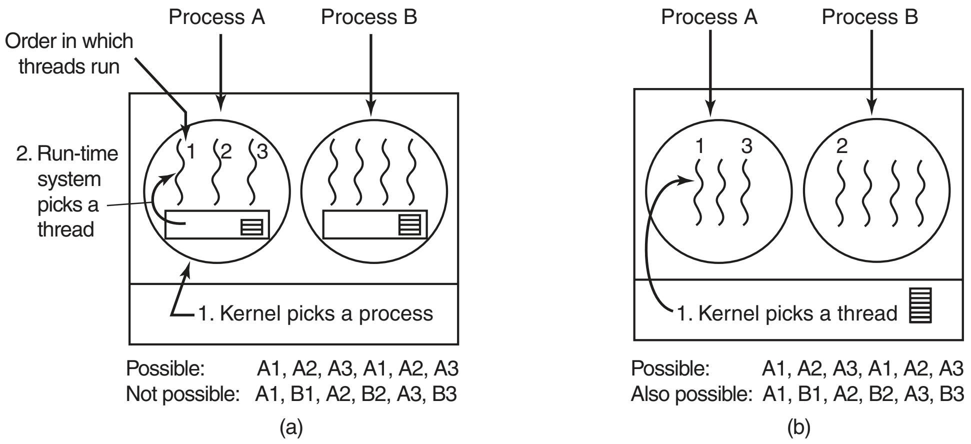
Process A
Process B
Order in which threads run
1
2
3
2. Run-time system picks a thread
1. Kernel picks a process
Possible: A1, A2, A3, A1, A2, A3
Not possible: A1, B1, A2, B2, A3, B3
(a)
Process A
Process B
1
3
2
1. Kernel picks a thread
Possible: A1, A2, A3, A1, A2, A3
Also possible: A1, B1, A2, B2, A3, B3
(b)

Figure 2-44. (a) Possible scheduling of user-level threads with a 50-msec process quantum and threads that run 5 msec per CPU burst. (b) Possible scheduling of kernel-level threads with the same characteristics as (a).

The scheduling algorithm used by the run-time system can be any of the ones described above. In practice, round-robin scheduling and priority scheduling are most common. The only constraint is the absence of a clock to interrupt a thread that has run too long. Since threads cooperate, this is usually not an issue.

Now consider the situation with kernel-level threads. Here the kernel picks a particular thread to run. It does not have to take into account which process the thread belongs to, but it can if it wants to. The thread is given a quantum and is forcibly suspended if it exceeds the quantum. With a 50-msec quantum but threads that block after 5 msec, the thread order for some period of 30 msec might be *A1*, *B1*, *A2*, *B2*, *A3*, *B3*, something not possible with these parameters and user-level threads. This situation is partially depicted in Fig. 2-44(b).

A major difference between user-level threads and kernel-level threads is the performance. Doing a thread switch with user-level threads takes a handful of machine instructions. With kernel-level threads it requires a full context switch, changing the memory map and invalidating the cache, which is several orders of magnitude slower. On the other hand, with kernel-level threads, having a thread block on I/O does not suspend the entire process as it does with user-level threads.

Since the kernel knows that switching from a thread in process *A* to a thread in process *B* is more expensive than running a second thread in process *A* (due to having to change the memory map and having the memory cache spoiled), it can take this information into account when making a decision. For example, given two threads that are otherwise equally important, with one of them belonging to the same process as a thread that just blocked and one belonging to a different process, preference could be given to the former.

Another important factor is that user-level threads can employ an application-specific thread scheduler. Consider, for example, the Web server of Fig. 2-8. Suppose that a worker thread has just blocked and the dispatcher thread and two worker threads are ready. Who should run next? The run-time system, knowing what all the threads do, can easily pick the dispatcher to run next, so that it can start another worker running. This strategy maximizes the amount of parallelism in an environment where workers frequently block on disk I/O. With kernel-level threads, the kernel would never know what each thread did (although they could be assigned different priorities). In general, however, application-specific thread schedulers can tune an application better than the kernel can.

2.5 CLASSICAL IPC PROBLEMS

The operating systems literature is full of interesting problems that have been widely discussed and analyzed using a variety of synchronization methods. In the following sections we will examine three of the better-known problems.

2.5.1 The Dining Philosophers Problem

In 1965, Dijkstra posed and then solved a synchronization problem he called the **dining philosophers problem**. Since that time, everyone inventing yet another synchronization primitive has felt obligated to demonstrate how wonderful the new primitive is by showing how elegantly it solves the dining philosophers problem. The problem can be stated quite simply as follows. Five philosophers are seated around a circular table. Each philosopher has a plate of spaghetti. The spaghetti is so slippery that a philosopher needs two forks to eat it. Between each pair of plates is one fork. The layout of the table is illustrated in Fig. 2-45.

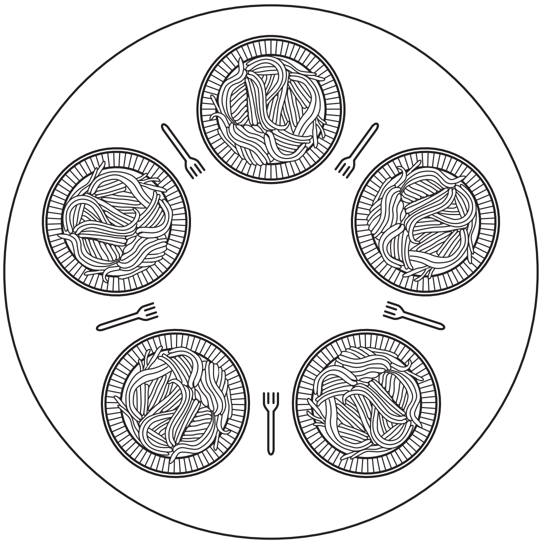

Figure 2-45. Lunch time in the Philosophy Department.

The life of a philosopher consists of alternating periods of eating and thinking. (This is something of an abstraction, even for philosophers, but the other activities are irrelevant here.) When a philosopher gets sufficiently hungry, she tries to acquire her left and right forks, one at a time, in either order. If successful in acquiring two forks, she eats for a while, then puts down the forks, and continues to think. The key question is: Can you write a program for each philosopher that does what it is supposed to do and never gets stuck? (It has been pointed out that the two-fork requirement is somewhat artificial; perhaps we should switch from Italian food to Chinese food, substituting rice for spaghetti and chopsticks for forks.)

Figure 2-46 shows the obvious solution. The procedure *take_fork* waits until the specified fork is available and then seizes it. Unfortunately, the obvious solution is wrong. Suppose that all five philosophers take their left forks simultaneously. None will be able to take their right forks, and there will be a deadlock.

We could easily modify the program so that after taking the left fork, the program checks to see if the right fork is available. If it is not, the philosopher puts down the left one, waits for some time, and then repeats the whole process. This proposal too, fails, although for a different reason. With a little bit of bad luck, all the philosophers could start the algorithm simultaneously, picking up their left forks, seeing that their right forks were not available, putting down their left forks,

```
#define N 5                              /* number of philosophers */

void philosopher(int i)                  /* i: philosopher number, from 0 to 4 */
{
     while (TRUE) {
          think( );                      /* philosopher is thinking */
          take_fork(i);                  /* take left fork */
          take_fork((i+1) % N);          /* take right fork; % is modulo operator */
          eat( );                        /* yum-yum, spaghetti */
          put_fork(i);                   /* put left fork back on the table */
          put_fork((i+1) % N);           /* put right fork back on the table */
     }
}
```

Figure 2-46. A nonsolution to the dining philosophers problem.

waiting, picking up their left forks again simultaneously, and so on, forever. A situation like this, in which all the programs continue to run indefinitely but fail to make any progress, is called **starvation**. (It is called starvation even when the problem does not occur in an Italian or a Chinese restaurant.)

Now you might think that if the philosophers would just wait a random time instead of the same time after failing to acquire the right-hand fork, the chance that everything would continue in lockstep for even an hour is very small. This observation is true, and in nearly all applications trying again later is not a problem. For example, in the popular Ethernet local area network, if two computers send a packet at the same time, each one waits a random time and tries again; in practice this solution works fine. However, in a few applications one would prefer a solution that always works and cannot fail due to an unlikely series of random numbers. Think about safety control in a nuclear power plant.

One improvement to Fig. 2-46 that has no deadlock and no starvation is to protect the five statements following the call to *think* by a binary semaphore. Before starting to acquire forks, a philosopher would do a down on *mutex*. After replacing the forks, she would do an up on *mutex*. From a theoretical viewpoint, this solution is adequate. From a practical one, it has a performance bug: only one philosopher can be eating at any instant. With five forks available, we should be able to allow two philosophers to eat at the same time.

The solution presented in Fig. 2-47 is deadlock-free and allows the maximum parallelism for an arbitrary number of philosophers. It uses an array, *state*, to keep track of whether a philosopher is eating, thinking, or hungry (trying to acquire forks). A philosopher may move into eating state only if neither neighbor is eating. Philosopher *i*'s neighbors are defined by the macros *LEFT* and *RIGHT*. In other words, if *i* is 2, *LEFT* is 1 and *RIGHT* is 3.

The program uses an array of semaphores, one per philosopher, so hungry philosophers can block if the needed forks are busy. Note that each process runs the procedure *philosopher* as its main code, but the other procedures, *take_forks*, *put_forks*, and *test*, are ordinary procedures and not separate processes.

```
#define N             5               /* number of philosophers */
#define LEFT          (i+N−1)%N       /* number of i's left neighbor */
#define RIGHT         (i+1)%N         /* number of i's right neighbor */
#define THINKING      0               /* philosopher is thinking */
#define HUNGRY        1               /* philosopher is trying to get forks */
#define EATING        2               /* philosopher is eating */

typedef int semaphore;                /* semaphores are a special kind of int */
int state[N];                         /* array to keep track of everyone's state */
semaphore mutex = 1;                  /* mutual exclusion for critical regions */
semaphore s[N];                       /* one semaphore per philosopher */


void philosopher(int i)               /* i: philosopher number, from 0 to N−1 */
{
      while (TRUE) {                  /* repeat forever */
            think( );                 /* philosopher is thinking */
            take_forks(i);            /* acquire two forks or block */
            eat( );                   /* yum-yum, spaghetti */
            put_forks(i);             /* put both forks back on table */
      }
}

void take_forks(int i)                /* i: philosopher number, from 0 to N−1 */
{
      down(&mutex);                   /* enter critical region */
      state[i] = HUNGRY;              /* record fact that philosopher i is hungry */
      test(i);                        /* try to acquire 2 forks */
      up(&mutex);                     /* exit critical region */
      down(&s[i]);                    /* block if forks were not acquired */
}

void put_forks(i)                     /* i: philosopher number, from 0 to N−1 */
{
      down(&mutex);                   /* enter critical region */
      state[i] = THINKING;            /* philosopher has finished eating */
      test(LEFT);                     /* see if left neighbor can now eat */
      test(RIGHT);                    /* see if right neighbor can now eat */
      up(&mutex);                     /* exit critical region */
}

void test(i) /* i: philosopher number, from 0 to N−1 */
{
      if (state[i] == HUNGRY && state[LEFT] != EATING && state[RIGHT] != EATING) {
            state[i] = EATING;
            up(&s[i]);
      }
}
```

Figure 2-47. A solution to the dining philosophers problem.

2.5.2 The Readers and Writers Problem

The dining philosophers problem is useful for modeling processes that are competing for exclusive access to a limited number of resources, such as I/O devices. Another famous problem is the readers and writers problem (Courtois et al., 1971), which models access to a database. Imagine, for example, an airline reservation system, with many competing processes wishing to read and write it. It is acceptable to have multiple processes reading the database at the same time, but if one process is updating (writing) the database, no other processes may have access to the database, not even readers. The question is how do you program the readers and the writers? One solution is shown in Fig. 2-48.

```
typedef int semaphore;                  /* use your imagination */
semaphore mutex = 1;                    /* controls access to rc */
semaphore db = 1;                       /* controls access to the database */
int rc = 0;                             /* # of processes reading or wanting to */

void reader(void)
{
      while (TRUE) {                    /* repeat forever */
            down(&mutex);               /* get exclusive access to rc */
            rc = rc + 1;                /* one reader more now */
            if (rc == 1) down(&db);     /* if this is the first reader ... */
            up(&mutex);                 /* release exclusive access to rc */
            read_data_base( );          /* access the data */
            down(&mutex);               /* get exclusive access to rc */
            rc = rc − 1;                /* one reader fewer now */
            if (rc == 0) up(&db);       /* if this is the last reader ... */
            up(&mutex);                 /* release exclusive access to rc */
            use_data_read( );           /* noncritical region */
      }
}


void writer(void)
{
      while (TRUE) {                    /* repeat forever */
            think_up_data( );           /* noncritical region */
            down(&db);                  /* get exclusive access */
            write_data_base( );         /* update the data */
            up(&db);                    /* release exclusive access */
      }
}
```

Figure 2-48. A solution to the readers and writers problem.

In this solution, the first reader to get access to the database does a down on the semaphore *db*. Subsequent readers merely increment a counter, *rc*. As readers leave, they decrement the counter, and the last to leave does an up on the semaphore, allowing a blocked writer, if there is one, to get in.

The solution presented here implicitly contains a subtle decision worth noting. Suppose that while a reader is using the database, another reader comes along. Since having two readers at the same time is not a problem, the second reader is admitted. Additional readers can also be admitted if they come along.

Now suppose a writer shows up. The writer may not be admitted to the database, since writers must have exclusive access, so the writer is suspended. Later, additional readers show up. As long as at least one reader is still active, subsequent readers are admitted. As a consequence of this strategy, as long as there is a steady supply of readers, they will all get in as soon as they arrive. The writer will be kept suspended until no reader is present. If a new reader arrives, say, every 2 sec, and each reader takes 5 sec to do its work, the writer will never get in.

To avoid this situation, the program could be written slightly differently: when a reader arrives and a writer is waiting, the reader is suspended behind the writer instead of being admitted immediately. In this way, a writer has to wait for readers that were active when it arrived to finish but does not have to wait for readers that came along after it. The disadvantage of this solution is that it achieves less concurrency and thus lower performance. Courtois et al. present a solution that gives priority to writers. For details, we refer you to the paper.

2.6 RESEARCH ON PROCESSES AND THREADS

In Chap. 1, we looked at some of the current research in operating system structure. In this and subsequent chapters we will look at more narrowly focused research, starting with processes. As will become clear in time, some subjects are much more settled than others. Most of the research tends to be on the new topics, rather than ones that have been around for decades.

The concept of a process is an example of something that is fairly well settled. Almost every system has some notion of a process as a container for grouping together related resources such as an address space, threads, open files, protection permissions, and so on. Different systems do the grouping slightly differently, but these are just engineering differences. The basic idea is not very controversial any more, and there is little new research on the subject of processes.

Threads are a newer idea than processes, but they, too, have been chewed over quite a bit. Still, the occasional paper about threads appears from time to time, for example, about thread clustering on multiprocessors (Tam et al., 2007), or on how well modern operating systems like Linux scale with many threads and many cores (Boyd-Wickizer, 2010).

One particularly active research area deals with recording and replaying a process' execution (Viennot et al., 2013). Replaying helps developers track down hard-to-find bugs and security experts to investigate incidents.

Similarly, much research in the operating systems community these days focuses on security issues. Numerous incidents have demonstrated that users need better protection from attackers (and, occasionally, from themselves). One approach is to track and restrict carefully the information flows in an operating system (Giffin et al., 2012).

Scheduling (both uniprocessor and multiprocessor) is still a topic near and dear to the heart of some researchers. Some topics being researched include energy-efficient scheduling on mobile devices (Yuan and Nahrstedt, 2006), hyperthreading-aware scheduling (Bulpin and Pratt, 2005), and bias-aware scheduling (Koufaty, 2010). With increasing computation on underpowered, battery-constrained smartphones, some researchers propose to migrate the process to a more powerful server in the cloud, as and when useful (Gordon et al., 2012). However, few actual system designers are walking around all day wringing their hands for lack of a decent thread-scheduling algorithm, so it appears that this type of research is more researcher-push than demand-pull. All in all, processes, threads, and scheduling are not hot topics for research as they once were. The research has moved on to topics like power management, virtualization, clouds, and security.

2.7 SUMMARY

To hide the effects of interrupts, operating systems provide a conceptual model consisting of sequential processes running in parallel. Processes can be created and terminated dynamically. Each process has its own address space.

For some applications it is useful to have multiple threads of control within a single process. These threads are scheduled independently and each one has its own stack, but all the threads in a process share a common address space. Threads can be implemented in user space or in the kernel.

Processes can communicate with one another using interprocess communication primitives, for example, semaphores, monitors, or messages. These primitives are used to ensure that no two processes are ever in their critical regions at the same time, a situation that leads to chaos. A process can be running, runnable, or blocked and can change state when it or another process executes one of the interprocess communication primitives. Interthread communication is similar.

Interprocess communication primitives can be used to solve such problems as the producer-consumer, dining philosophers, and reader-writer. Even with these primitives, care has to be taken to avoid errors and deadlocks.

A great many scheduling algorithms have been studied. Some of these are primarily used for batch systems, such as shortest-job-first scheduling. Others are common in both batch systems and interactive systems. These algorithms include round robin, priority scheduling, multilevel queues, guaranteed scheduling, lottery scheduling, and fair-share scheduling. Some systems make a clean separation between the scheduling mechanism and the scheduling policy, which allows users to have control of the scheduling algorithm.