Operating Systems and Middleware: Supporting Controlled Interaction

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Chapter 3

Scheduling

3.1 Introduction

In Chapter 2 you saw that operating systems support the concurrent execution of multiple threads by repeatedly switching each processor's attention from one thread to another. This switching implies that some mechanism, known as a *scheduler*, is needed to choose which thread to run at each time. Other system resources may need scheduling as well; for example, if several threads read from the same disk drive, a disk scheduler may place them in order. For simplicity, I will consider only processor scheduling. Normally, when people speak of *scheduling*, they mean processor scheduling; similarly, the *scheduler* is understood to mean the processor scheduler.

A scheduler should make decisions in a way that keeps the computer system's users happy. For example, picking the same thread all the time and completely ignoring the others would generally not be a good scheduling policy. Unfortunately, there is no one policy that will make all users happy all the time. Sometimes the reason is as simple as different users having conflicting desires: for example, user A wants task A completed quickly, while user B wants task B completed quickly. Other times, though, the relative merits of different scheduling policies will depend not on whom you ask, but rather on the context in which you ask. As a simple example, a student enrolled in several courses is unlikely to decide which assignment to work on without considering when the assignments are due.

Because scheduling policies need to respond to context, operating systems provide scheduling mechanisms that leave the user in charge of more subtle policy choices. For example, an operating system may provide a mechanism for running whichever thread has the highest numerical priority, while leaving the user the job of assigning priorities to the threads. Even so, no one mechanism (or general family of policies) will suit all goals. Therefore, I spend much of this chapter describing the different goals that users have for schedulers and the mechanisms that can be used to achieve those goals, at least approximately. Particularly since users may wish to achieve several conflicting goals, they will generally have to be satisfied with "good enough."

Before I get into the heavily values-laden scheduling issues, though, I will present one goal everyone can agree upon: A thread that can make productive use of a processor should always be preferred over one that is waiting for something, such as the completion of a time delay or the arrival of input. In Section 3.2, you will see how schedulers arrange for this by keeping track of each thread's state and scheduling only those that can run usefully.

Following the section on thread states, I devote Section 3.3 entirely to the question of users' goals, independent of how they are realized. Then I spend one section apiece on three broad families of schedulers, examining for each not only how it works but also how it can serve users' goals. These three families of schedulers are those based on fixed thread priorities (Section 3.4), those based on dynamically adjusted thread priorities (Section 3.5), and those based less on priorities than on controlling each thread's proportional share of processing time (Section 3.6). This three-way division is not the only possible taxonomy of schedulers, but it will serve to help me introduce several operating systems' schedulers and explain the principles behind them while keeping in mind the context of users' goals. After presenting the three families of schedulers, I will briefly remark in Section 3.7 on the role scheduling plays in system security. The chapter concludes with exercises, programming and exploration projects, and notes.

3.2 Thread States

A typical thread will have times when it is waiting for some event, unable to execute any useful instructions until the event occurs. Consider a web server that reads a client's request from the network, reads the requested web page from disk, and then sends the page over the network to the client. Initially the server thread is waiting for the network interface to have some data available. If the server thread were scheduled on a processor while it was waiting, the best it could do would be to execute a loop that checked over and over whether any data has arrived—hardly a productive use of the processor's time. Once data is available from the network, the server thread can execute some useful instructions to read the bytes in and check whether the request is complete. If not, the server needs to go back to waiting for more data to arrive. Once the request is complete, the server will know what page to load from disk and can issue the appropriate request to the disk drive. At that point, the thread once again needs to wait until such time as the disk has completed the requisite physical movements to locate the page. To take a different example, a video display program may display one frame of video and then wait some fraction of a second before displaying the next so that the movie doesn't play too fast. All the thread could do between frames would be to keep checking the computer's real-time clock to see whether enough time had elapsed—again, not a productive use of the processor.

In a single-thread system, it is plausible to wait by executing a loop that continually checks for the event in question. This approach is known as *busy waiting*. However, a modern general-purpose operating system will have multiple threads competing for the processor. In this case, busy waiting is a bad idea because any time that the scheduler allocates to the busy-waiting thread is lost to the other threads without achieving any added value for the thread that is waiting.

Therefore, operating systems provide an alternative way for threads to wait. The operating system keeps track of which threads can usefully run and which are waiting. The system does this by storing runnable threads in a data structure called the *run queue* and waiting threads in *wait queues*, one per reason for waiting. Although these structures are conventionally called queues, they may not be used in the first-in, first-out style of true queues. For example, there may be a list of threads waiting for time to elapse, kept in order of the desired time. Another example of a wait queue would be a set of threads waiting for the availability of data on a particular network communication channel.

Rather than executing a busy-waiting loop, a thread that wants to wait for some event notifies the operating system of this intention. The operating system removes the thread from the run queue and inserts the thread into the appropriate wait queue, as shown in Figure 3.1. Because the scheduler considers only threads in the run queue for execution, it will never select the waiting thread to run. The scheduler will be choosing only from those threads that can make progress if given a processor on which to run.

In Chapter 2, I mentioned that the arrival of a hardware interrupt can cause the processor to temporarily stop executing instructions from the current thread and to start executing instructions from the operating system's

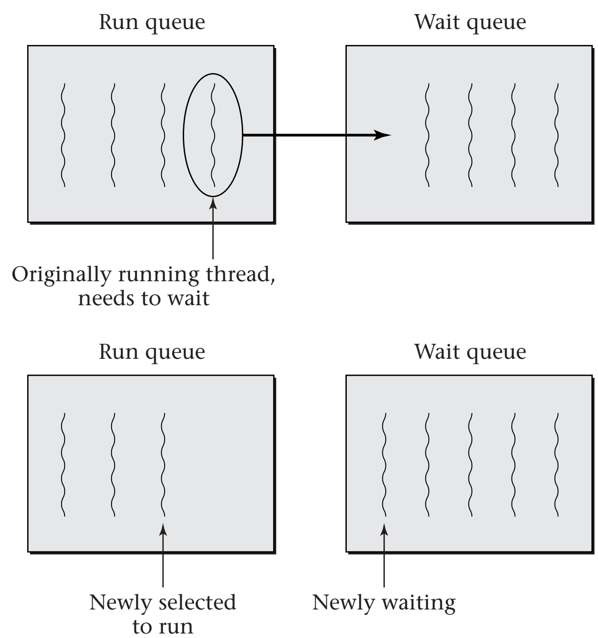


Figure 3.1: When a thread needs to wait, the operating system moves it from the run queue to a wait queue. The scheduler selects one of the threads remaining in the run queue to dispatch, so it starts running.

interrupt handler. One of the services this interrupt handler can perform is determining that a waiting thread doesn't need to wait any longer. For example, the computer's real-time clock may be configured to interrupt the processor every one hundredth of a second. The interrupt handler could check the first thread in the wait queue of threads that are waiting for specific times to elapse. If the time this thread was waiting for has not yet arrived, no further threads need to be checked because the threads are kept in time order. If, on the other hand, the thread has slept as long as it requested, then the operating system can move it out of the list of sleeping threads and into the run queue, where the thread is available for scheduling. In this case, the operating system should check the next thread similarly, as illustrated in Figure 3.2.

Putting together the preceding information, there are at least three distinct states a thread can be in:

- *Runnable* (but not running), awaiting dispatch by the scheduler
- *Running* on a processor
- *Waiting* for some event

Some operating systems may add a few more states in order to make finer distinctions (waiting for one kind of event versus waiting for another kind) or to handle special circumstances (for example, a thread that has finished running, but needs to be kept around until another thread is notified). For simplicity, I will stick to the three basic states in the foregoing list. At critical moments in the thread's lifetime, the operating system will change the thread's state. These thread state changes are indicated in Figure 3.3. Again, a real operating system may add a few additional transitions; for example, it may be possible to forcibly terminate a thread, even while it is in a waiting state, rather than having it terminate only of its own accord while running.

3.3 Scheduling Goals

Users expect a scheduler to maximize the computer system's performance and to allow them to exert control. Each of these goals can be refined into several more precise goals, which I explain in the following subsections. High performance may mean high throughput (Section 3.3.1) or fast response time (Section 3.3.2), and user control may be expressed in terms of urgency, importance, or resource allocation (Section 3.3.3).

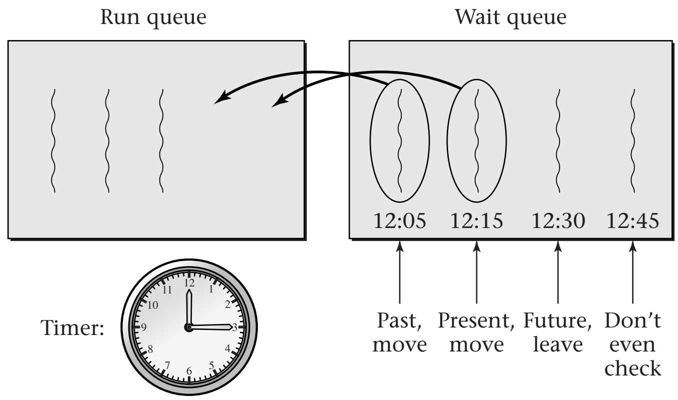


Figure 3.2: When the operating system handles a timer interrupt, all threads waiting for times that have now past are moved to the run queue. Because the wait queue is kept in time order, the scheduler need only check threads until it finds one waiting for a time still in the future. In this figure, times are shown on a human scale for ease of understanding.

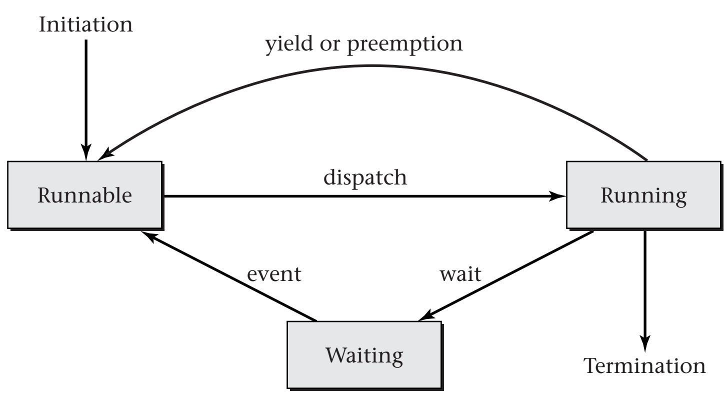


Figure 3.3: Threads change states as shown here. When a thread is initially created, it is runnable, but not actually running on a processor until dispatched by the scheduler. A running thread can voluntarily yield the processor or can be preempted by the scheduler in order to run another thread. In either case, the formerly running thread returns to the runnable state. Alternatively, a running thread may wait for an external event before becoming runnable again. A running thread may also terminate.

3.3.1 Throughput

Many personal computers have far more processing capability available than work to do, and they largely sit idle, patiently waiting for the next keystroke from a user. However, if you look behind the scenes at a large Internet service, such as Google, you'll see a very different situation. Large rooms filled with rack after rack of computers are necessary in order to keep up with the pace of incoming requests; any one computer can cope only with a small fraction of the traffic. For economic reasons, the service provider wants to keep the cluster of servers as small as possible. Therefore, the throughput of each server must be as high as possible. The *throughput* is the rate at which useful work, such as search transactions, is accomplished. An example measure of throughput would be the number of search transactions completed per second.

Maximizing throughput certainly implies that the scheduler should give each processor a runnable thread on which to work, if at all possible. However, there are some other, slightly less obvious, implications as well. Remember that a computer system has more components than just processors. It also has I/O devices (such as disk drives and network interfaces) and a memory hierarchy, including cache memories. Only by using all these resources efficiently can a scheduler maximize throughput.

I already mentioned I/O devices in Chapter 2, with the example of a computationally intensive graphics rendering program running concurrently with a disk-intensive virus scanner. I will return to this example later in the current chapter to see one way in which the two threads can be efficiently interleaved. In a nutshell, the goal is to keep both the processor and the disk drive busy all the time. If you have ever had an assistant for a project, you may have some appreciation for what this entails: whenever your assistant was in danger of falling idle, you had to set your own work aside long enough to explain the next assignment. Similarly, the processor must switch threads when necessary to give the disk more work to do.

Cache memories impact throughput-oriented scheduling in two ways, though one arises only in multiprocessor systems. In any system, switching between different threads more often than necessary will reduce throughput because processor time will be wasted on the overhead of context switching, rather than be available for useful work. The main source of this context-switching overhead is not the direct cost of the switch itself, which entails saving a few registers out and loading them with the other thread's values. Instead, the big cost is in reduced cache memory performance, for reasons I will explain in a moment. On multiprocessor systems a second issue arises:

a thread is likely to run faster when scheduled on the same processor as it last ran on. Again, this results from cache memory effects. To maximize throughput, schedulers therefore try to maintain a specific *processor affinity* for each thread, that is, to consistently schedule the thread on the same processor unless there are other countervailing considerations.

You probably learned in a computer organization course that *cache memories* provide fast storage for those addresses that have been recently accessed or that are near to recently accessed locations. Because programs frequently access the same locations again (that is, exhibit *temporal locality*) or access nearby locations (that is, exhibit *spatial locality*), the processor will often be able to get its data from the cache rather than from the slower main memory. Now suppose the processor switches threads. The new thread will have its own favorite memory locations, which are likely to be quite different. The cache memory will initially suffer many misses, slowing the processor to the speed of the main memory, as shown in Figure 3.4. Over time, however, the new thread's data will displace the data from the old thread, and the performance will improve. Suppose that just at the point where the cache has adapted to the second thread, the scheduler were to decide to switch back. Clearly this is not a recipe for high-throughput computing.

On a multiprocessor system, processor affinity improves throughput in a similar manner by reducing the number of cycles the processor stalls waiting for data from slower parts of the memory hierarchy. Each processor has its own local cache memory. If a thread resumes running on the same processor on which it previously ran, there is some hope it will find its data still in the cache. At worst, the thread will incur cache misses and need to fetch the data from main memory. The phrase "at worst" may seem odd in the context of needing to go all the way to main memory, but in a multiprocessor system, fetching from main memory is not the highest cost situation.

Memory accesses are even more expensive if they refer to data held in another processor's cache. That situation can easily arise if the thread is dispatched on a different processor than it previously ran on, as shown in Figure 3.5 In this circumstance, the multiprocessor system's *cache coherence* protocol comes into play. Typically, this means first transferring the data from the old cache to the main memory and then transferring it from the main memory to the new cache. This excess coherence traffic (beyond what is needed for blocks shared by multiple threads) reduces throughput if the scheduler has not arranged for processor affinity.

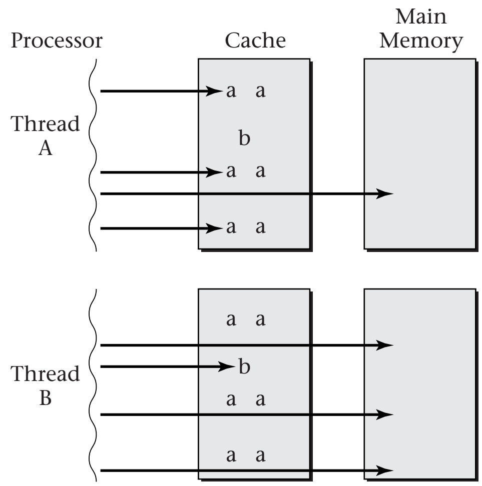


Figure 3.4: When a processor has been executing thread A for a while, the cache will mostly hold thread A's values, and the cache hit rate may be high. If the processor then switches to thread B, most memory accesses will miss in the cache and go to the slower main memory.

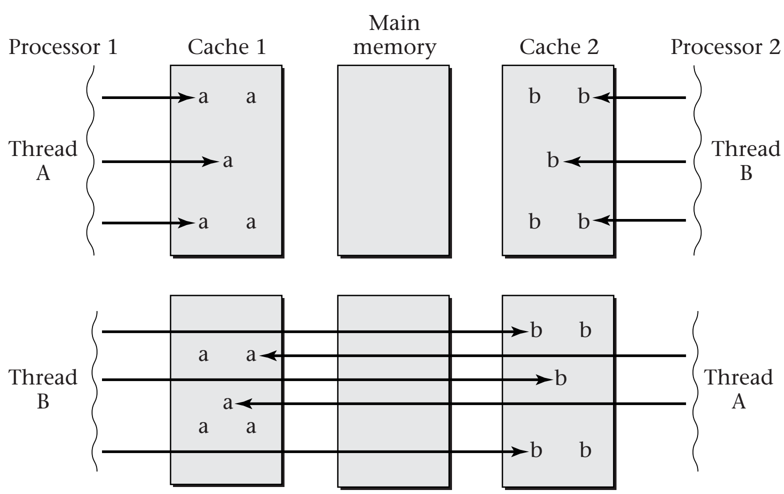


Figure 3.5: If processor 1 executes thread A and processor 2 executes thread B, after a while each cache will hold the corresponding thread's values. If the scheduler later schedules each thread on the opposite processor, most memory accesses will miss in the local cache and need to use the cache coherence protocol to retrieve data from the other cache.

3.3.2 Response Time

Other than throughput, the principle measure of a computer system's performance is *response time*: the elapsed time from a triggering event (such as a keystroke or a network packet's arrival) to the completed response (such as an updated display or the transmission of a reply packet). Notice that a high-performance system in one sense may be low-performance in the other. For example, frequent context switches, which are bad for throughput, may be necessary to optimize response time. Systems intended for direct interaction with a single user tend to be optimized for response time, even at the expense of throughput, whereas centralized servers are usually designed for high throughput as long as the response time is kept tolerable.

If an operating system is trying to schedule more than one runnable thread per processor and if each thread is necessary in order to respond to some event, then response time inevitably involves tradeoffs. Responding more quickly to one event by running the corresponding thread means responding more slowly to some other event by leaving its thread in the runnable state, awaiting later dispatch. One way to resolve this trade-off is by using user-specified information on the relative urgency or importance of the threads, as I describe in Section 3.3.3. However, even without that information, the operating system may be able to do better than just shrug its virtual shoulders.

Consider a real world situation. You get an email from a long-lost friend, reporting what has transpired in her life and asking for a corresponding update on what you have been doing for the last several years. You have barely started writing what will inevitably be a long reply when a second email message arives, from a close friend, asking whether you want to go out tonight. You have two choices. One is to finish writing the long letter and then reply "sure" to the second email. The other choice is to temporarily put your long letter aside, send off the one-word reply regarding tonight, and then go back to telling the story of your life. Either choice extends your response time for one email in order to keep your response time for the other email as short as possible. However, that symmetry doesn't mean there is no logical basis for choice. Prioritizing the one-word reply provides much more benefit to its response time than it inflicts harm on the other, more time-consuming task.

If an operating system knows how much processor time each thread will need in order to respond, it can use the same logic as in the email example to guide its choices. The policy of *Shortest Job First* (*SJF*) scheduling minimizes the average response time, as you can demonstrate in Exercise 3.5.

This policy dates back to *batch processing* systems, which processed a single large *job* of work at a time, such as a company's payroll or accounts payable. System operators could minimize the average *turnaround time* from when a job was submitted until it was completed by processing the shortest one first. The operators usually had a pretty good idea how long each job would take, because the same jobs were run on a regular basis. However, the reason why you should be interested in SJF is not for scheduling batch jobs (which you are unlikely to encounter), but as background for understanding how a modern operating system can improve the responsiveness of threads.

Normally an operating system won't know how much processor time each thread will need in order to respond. One solution is to guess, based on past behavior. The system can prioritize those threads that have not consumed large bursts of processor time in the past, where a *burst* is the amount of processing done between waits for external events. Another solution is for the operating system to hedge its bets, so that that even if it doesn't know which thread needs to run only briefly, it won't sink too much time into the wrong thread. By switching frequently between the runnable threads, if any one of them needs only a little processing time, it will get that time relatively soon even if the other threads involve long computations.

The succesfulness of this hedge depends not only on the duration of the *time slices* given to the threads, but also on the number of runnable threads competing for the processor. On a lightly loaded system, frequent switches may suffice to ensure responsiveness. By contrast, consider a system that is heavily loaded with many long-running computations, but that also occasionally has an interactive thread that needs just a little processor time. The operating system can ensure responsiveness only by identifying and prioritizing the interactive thread, so that it doesn't have to wait in line behind all the other threads' time slices. However brief each of those time slices is, if there are many of them, they will add up to a substantial delay.

3.3.3 Urgency, Importance, and Resource Allocation

The goals of high throughput and quick response time do not inherently involve user control over the scheduler; a sufficiently smart scheduler might make all the right decisions on its own. On the other hand, there are user goals that revolve precisely around the desire to be able to say the following: "*This* thread is a high priority; work on it." I will explain three different notions that often get confusingly lumped under the heading of priority. To disentangle the confusion, I will use different names for each of them: *urgency*, *importance*, and *resource allocation*. I will reserve the word *priority* for my later descriptions of specific scheduling mechanisms, where it may be used to help achieve any of the goals: throughput, responsiveness, or the control of urgency, importance, or resource allocation.

A task is urgent if it needs to be done soon. For example, if you have a small homework assignment due tomorrow and a massive term paper to write within the next two days, the homework is more urgent. That doesn't necessarily mean it would be smart for you to prioritize the homework; you might make a decision to take a zero on the homework in order to free up more time for the term paper. If so, you are basing your decision not only on the two tasks' urgency, but also on their importance; the term paper is more important. In other words, importance indicates how much is at stake in accomplishing a task in a timely fashion.

Importance alone is not enough to make good scheduling decisions either. Suppose the term paper wasn't due until a week from now. In that case, you might decide to work on the homework today, knowing that you would have time to write the paper starting tomorrow. Or, to take a third example, suppose the term paper (which you have yet to even start researching) was due in an hour, with absolutely no late papers accepted. In that case, you might realize it was hopeless to even start the term paper, and so decide to put your time into the homework instead.

Although urgency and importance are quite different matters, the precision with which a user specifies urgency will determine how that user can control scheduling to reflect importance. If tasks have hard deadlines, then importance can be dealt with as in the homework example—through a process of ruthless triage. Here, importance measures the cost of dropping a task entirely. On the other hand, the deadlines may be "soft," with the importance measuring how bad it is for each task to be late. At the other extreme, the user might provide no information at all about urgency, instead demanding all results "as soon as possible." In this case, a high importance task might be one to work on whenever possible, and a low importance task might be one to fill in the idle moments, when there is nothing more important to do.

Other than urgency and importance, another way in which users may wish to express the relationship between different threads is by controlling what fraction of the available processing resources they are allocated. Sometimes, this is a matter of fairness. For example, if two users are sharing a computer, it might be fair to devote half of the processing time to one user's threads and the other half of the processing time to the other user's threads. In other situations, a specific degree of inequity may be desired. For example, a web hosting company may sell shares of a large server to small companies for their web sites. A company that wants to provide good service to a growing customer base might choose to buy two shares of the web server, expecting to get twice as much of the server's processing time in return for a larger monthly fee.

When it was common for thousands of users, such as university students, to share a single computer, considerable attention was devoted to so-called *fair-share scheduling*, in which users' consumption of the shared processor's time was balanced out over relatively long time periods, such as a week. That is, a user who did a lot of computing early in the week might find his threads allocated only a very small portion of the processor's time later in the week, so that the other users would have a chance to catch up. A fair share didn't have to mean an equal share; the system administrator could grant differing allocations to different users. For example, students taking an advanced course might receive more computing time than introductory students.

With the advent of personal computers, fair-share scheduling has fallen out of favor, but another resource-allocation approach, *proportional-share scheduling*, is still very much alive. (For example, you will see that the Linux scheduler is largely based on the proportional-share scheduling idea.) The main reason why I mention fair-share scheduling is to distinguish it from proportional-share scheduling, because the two concepts have names that are so confusingly close.

Proportional-share scheduling balances the processing time given to threads over a much shorter time scale, such as a second. The idea is to focus only on those threads that are runnable and to allocate processor time to them in proportion with the shares the user has specified. For example, suppose that I have a big server on which three companies have purchased time. Company A pays more per month than companies B and C, so I have given two shares to company A and only one share each to companies B and C. Suppose, for simplicity, that each company runs just one thread, which I will call thread A, B, or C, correspondingly. If thread A waits an hour for some input to arrive over the network while threads B and C are runnable, I will give half the processing time to each of B and C, because they each have one share. When thread A's input finally arrives and the thread becomes runnable, it won't be given an hour-long block of processing time to "catch up" with the other two threads. Instead, it will get half the processor's time, and threads B and C will each get one quarter, reflecting the 2:1:1 ratio of their shares.

The simplest sort of proportional-share scheduling allows shares to be specified only for individual threads, such as threads A, B, and C in the preceding example. A more sophisticated version allows shares to be specified collectively for all the threads run by a particular user or otherwise belonging to a logical group. For example, each user might get an equal share of the processor's time, independent of how many runnable threads the user has. Users who run multiple threads simply subdivide their shares of the processing time. Similarly, in the example where a big server is contracted out to multiple companies, I would probably want to allow each company to run multiple threads while still controlling the overall resource allocation among the companies, not just among the individual threads.

Linux's scheduler provides a flexible group scheduling facility. Threads can be treated individually or they can be placed into groups either by user or in any other way that the system administrator chooses. Up through version 2.6.37, the default was for threads to receive processor shares individually. However, this default changed in version 2.6.38. The new default is to automatically establish a group for each terminal window. That way, no matter how many CPU-intensive threads are run from within a particular terminal window, they won't greatly degrade the system's overall performance. (To be completely precise, the automatically created groups correspond not to terminal windows, but to groupings of processes known as sessions. Normally each terminal window corresponds to a session, but there are also other ways sessions can come into existence. Sessions are not explained further in this book.)

Having learned about urgency, importance, and resource allocation, one important lesson is that without further clarification, you cannot understand what a user means by a sentence such as "thread A is higher priority than thread B." The user may want you to devote twice as much processing time to A as to B, because A is higher priority in the sense of meriting a larger proportion of resources. Then again, the user may want you to devote almost all processing time to A, running B only in the spare moments when A goes into a waiting state, because A is higher priority in the sense of greater importance, greater urgency, or both.

Unfortunately, many operating systems have traditionally not given the user a rich enough vocabulary to directly express more than one of these goals. For example, the UNIX family of operating systems (including Mac OS X and Linux) provides a way for the user to specify the *niceness* of a thread. The word *nice* should be understood in the sense that a very nice thread is one that is prone to saying, "Oh no, that's all right, you go ahead of me, I can wait." In other words, a high niceness is akin to a low priority. However, different members of this operating system family interpret this single parameter, niceness, differently.

The original tradition, to which Mac OS X still adheres, is that niceness is an expression of importance; a very nice thread should normally only run when there is spare processor time. Some newer UNIX-family schedulers, such as in Linux, instead interpret the same niceness number as an expression of resource allocation proportion, with nicer threads getting proportionately less processor time. It is pointless arguing which of these interpretations of niceness is the right one; the problem is that users have two different things they may want to tell the scheduler, and they will never be able to do so with only one control knob.

Luckily, some operating systems have provided somewhat more expressive vocabularies for user control. For example, Mac OS X allows the user to either express the urgency of a thread (through a deadline and related information) or its importance (though a niceness). These different classes of threads are placed in a hierarchicial relationship; the assumption is that all threads with explicit urgency information are more important than any of the others. Similarly, some proportional-share schedulers, including Linux's, use niceness for proportion control, but also allow threads to be explicitly flagged as low-importance threads that will receive almost no processing unless a processor is otherwise idle.

As a summary of this section, Figure 3.6 shows a taxonomy of the scheduling goals I have described. Figure 3.7 previews the scheduling mechanisms I describe in the next three sections, and Figure 3.8 shows which goals each of them is designed to satisfy.

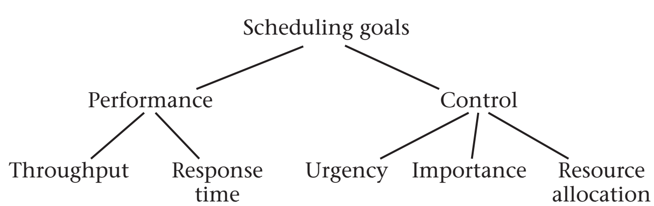


Figure 3.6: A user may want the scheduler to improve system performance or to allow user control. Two different performance goals are high throughput and fast response time. Three different ways in which a user may exert control are by specifying threads' urgency, importance, or resource share.

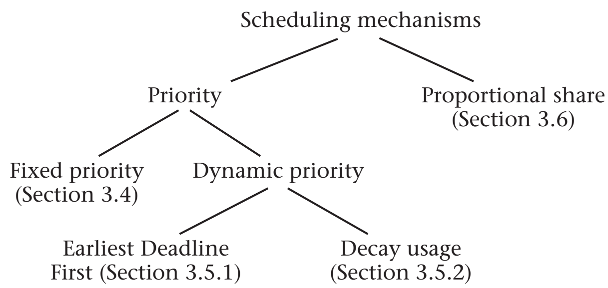


Figure 3.7: A scheduling mechanism may be based on always running the highest priority thread, or on pacing the threads to each receive a proportional share of processor time. Priorities may be fixed, or they may be adjusted to reflect either the deadline by which a thread must finish or the thread's amount of processor usage.

Mechanism	**Goals**
fixed priority	urgency, importance
Earliest Deadline First	urgency
decay usage	importance, throughput, response time
proportional share	resource allocation

Figure 3.8: For each scheduling mechanism I present, I explain how it can satisfy one or more of the scheduling goals.

3.4 Fixed-Priority Scheduling

Many schedulers use a numerical *priority* for each thread; this controls which threads are selected for execution. The threads with higher priority are selected in preference to those with lower priority. No thread will ever be running if another thread with higher priority is not running, but is in the runnable state. The simplest way the priorities can be assigned is for the user to manually specify the priority of each thread, generally with some default value if none is explicitly specified. Although there may be some way for the user to manually change a thread's priority, one speaks of *fixed-priority scheduling* as long as the operating system never automatically adjusts a thread's priority.

Fixed-priority scheduling suffices to achieve user goals only under limited circumstances. However, it is simple, so many real systems offer it, at least as one option. For example, both Linux and Microsoft Windows allow fixed-priority scheduling to be selected for specific threads. Those threads take precedence over any others, which are scheduled using other means I discuss in Sections 3.5.2 and 3.6. In fact, fixed-priority scheduling is included as a part of the international standard known as POSIX, which many operating systems attempt to follow.

As an aside about priorities, whether fixed or otherwise, it is important to note that some real systems use smaller priority numbers to indicate more prefered threads and larger priority numbers to indicate those that are less prefered. Thus, a "higher priority" thread may actually be indicated by a lower priority number. In this book, I will consistenty use "higher priority" and "lower priority" to mean more and less prefered, independent of how those are encoded as numbers by a particular system.

In a fixed-priority scheduler, the run queue can be kept in a data structure ordered by priority. If you have studied algorithms and data structures, you know that in theory this could be efficiently done using a clever representation of a priority queue, such as a binary heap. However, in practice, most operating systems use a much simpler structure, because they use only a small range of integers for the priorities. Thus, it suffices to keep an array with one entry per possible priority. The first entry contains a list of threads with the highest priority, the second entry contains a list of threads with the next highest priority, and so forth.

Whenever a processor becomes idle because a thread has terminated or entered a waiting state, the scheduler dispatches a runnable thread of highest available priority. The scheduler also compares priorities when a thread becomes runnable because it is newly initiated or because it is done waiting. If the newly runnable thread has higher priority than a running thread, the scheduler preempts the running thread of lower priority; that is, the lower-priority thread ceases to run and returns to the run queue. In its place, the scheduler dispatches the newly runnable thread of higher priority.

Two possible strategies exist for dealing with ties, in which two or more runnable threads have equally high priority. (Assume there is only one processor on which to run them, and that no thread has higher priority than they do.) One possibility is to run the thread that became runnable first until it waits for some event or chooses to voluntarily yield the processor. Only then is the second, equally high-priority thread dispatched. The other possibility is to share the processor's attention between those threads that are tied for highest priority by alternating among them in a *round-robin* fashion. That is, each thread runs for some small interval of time (typically tens or hundreds of milliseconds), and then it is preempted from the clock interrupt handler and the next thread of equal priority is dispatched, cycling eventually back to the first of the threads. The POSIX standard provides for both of these options; the user can select either a first in, first out (FIFO) policy or a round robin (RR) policy.

Fixed-priority scheduling is not viable in an open, general-purpose environment where a user might accidentally or otherwise create a high-priority thread that runs for a long time. However, in an environment where all the threads are part of a carefully quality-controlled system design, fixed-priority scheduling may be a reasonable choice. In particular, it is frequently used for so-called *hard-real-time systems*, such as those that control the flaps on an airplane's wings.

Threads in these hard-real-time systems normally perform periodic tasks. For example, one thread may wake up every second to make a particular adjustment in the flaps and then go back to sleep for the remainder of the second. Each of these tasks has a deadline by which it must complete; if the deadline is missed, the program has failed to meet its specification. (That is what is meant by "hard real time.") In the simplest case, the deadline is the same as the period; for example, each second's adjustment must be done before the second is up. The designers of a system like this know all the threads that will be running and carefully analyze the ensemble to make sure no deadlines will ever be missed. In order to do this, the designers need to have a worst-case estimate of how long each thread will run, per period.

I can illustrate the analysis of a fixed-priority schedule for a hard-real-time system with some simple examples, which assume that the threads are all periodic, with deadlines equal to their periods, and with no interactions among them other than the competition for a single processor. To see how the same general ideas can be extended to cases where these assumptions don't hold, you could read a book devoted specifically to real-time systems.

Two key theorems, proved by Liu and Layland in a 1973 article, make it easy to analyze such a periodic hard-real-time system under fixed-priority scheduling:

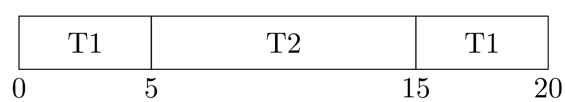
- If the threads will meet their deadlines under any fixed priority assignment, then they will do so under an assignment that prioritizes threads with shorter periods over those with longer periods. This policy is known as *rate-monotonic scheduling*.

- To check that deadlines are met, it suffices to consider the worst-case situation, which is that all the threads' periods start at the same moment.

Therefore, to test whether any fixed-priority schedule is feasible, assign priorities in the rate-monotic fashion. Assume all the threads are newly runnable at time 0 and plot out what happens after that, seeing whether any deadline is missed.

To test the feasibility of a real-time schedule, it is conventional to use a *Gantt chart*. This can be used to see whether a rate-monotonic fixed-priority schedule will work for a given set of threads. If not, some scheduling approach other than fixed priorities may work, or it may be necessary to redesign using less demanding threads or hardware with more processing power.

A Gantt chart is a bar, representing the passage of time, divided into regions labeled to show what thread is running during the corresponding time interval. For example, the Gantt chart



shows thread T1 as running from time 0 to time 5 and again from time 15 to time 20; thread T2 runs from time 5 to time 15.

Consider an example with two periodically executing threads. One, T1, has a period and deadline of four seconds and a worst-case execution time per period of two seconds. The other, T2, has a period and deadline of six seconds and a worst-case execution time per period of three seconds. On the surface, this looks like it might just barely be feasible on a single processor: T1 has an average demand of half a processor (two seconds per four) and T2 also has an average demand of half a processor (three seconds per six), totalling to one fully utilized, but not oversubscribed, processor. Assume that all overheads, such as the time to do context switching between the threads, have been accounted for by including them in the threads' worst-case execution times.

However, to see whether this will really work without any missed deadlines, I need to draw a Gantt chart to determine whether the threads can get the processor when they need it. Because T1 has the shorter period, I assign it the higher priority. By Liu and Layland's other theorem, I assume both T1 and T2 are ready to start a period at time 0. The first six seconds of the resulting Gantt chart looks like this:

T1	T2	T1
0	2	4	6

Note that T1 runs initially, when both threads are runnable, because it has the higher priority. Thus, it has no difficulty making its deadline. When T1 goes into a waiting state at time 2, T2 is able to start running. Unfortunately, it can get only two seconds of running done by the time T1 becomes runnable again, at the start of its second period, which is time 4. At that moment, T2 is preempted by the higher-priority thread T1, which occupies the processor until time 6. Thus, T2 misses its deadline: by time 6, it has run for only two seconds, rather than three.

If you accept Liu and Layland's theorem, you will know that switching to the other fixed-priority assignment (with T2 higher priority than T1) won't solve this problem. However, rather than taking this theorem at face value, you can draw the Gantt chart for this alternative priority assignment in Exercise 3.3 and see that again one of the threads misses its deadline.

In Section 3.5, I will present a scheduling mechanism that can handle the preceding scenario successfully. First, though, I will show one more example—this time one for which fixed-priority scheduling suffices. Suppose T2's worst-case execution time were only two seconds per six second period, with all other details the same as before. In this case, a Gantt chart for the first twelve seconds would look as follows:

T1	T2	T1	T2	T1	idle
0	2	4	6	8	10	12

Notice that T1 has managed to execute for two seconds during each of its three periods (0–4, 4–8, and 8–12), and that T2 has managed to execute for two seconds during each of its two periods (0–6 and 6–12). Thus, neither missed any deadlines. Also, you should be able to convince yourself that you don't need to look any further down the timeline, because the pattern of the first 12 seconds will repeat itself during each subsequent 12 seconds.

3.5 Dynamic-Priority Scheduling

Priority-based scheduling can be made more flexible by allowing the operating system to automatically adjust threads' priorities to reflect changing circumstances. The relevant circumstances, and the appropriate adjustments to make, depend what user goals the system is trying to achieve. In this section, I will present a couple different variations on the theme of dynamically adjusted priorities. First, for continuity with Section 3.4, Section 3.5.1 shows how priorities can be dynamically adjusted for periodic hard-real-time threads using a technique known as Earliest Deadline First scheduling. Then Section 3.5.2 explains decay usage scheduling, a dynamic adjustment policy commonly used in general-purpose computing environments.

3.5.1 Earliest Deadline First Scheduling

You saw in Section 3.4 that rate-monotonic scheduling is the optimal fixed-priority scheduling method, but that even it couldn't schedule two threads, one of which needed two seconds every four and the other of which needed three seconds every six. That goal is achievable with an optimal method for dynamically assigning priorities to threads. This method is known as *Earliest Deadline First* (*EDF*). In EDF scheduling, each time a thread becomes runnable you re-assign priorities according to the following rule: the sooner a thread's next deadline, the higher its priority. The optimality of EDF is another of Liu and Layland's theorems.

Consider again the example with T1 needing two seconds per four and T2 needing three seconds per six. Using EDF scheduling, the Gantt chart for the first twelve seconds of execution would be as follows:

T1	T2	T1	T2	T1

0 2 5 7 10 12

There is no need to continue the Gantt chart any further because it will start repeating. Notice that neither thread misses any deadlines: T1 receives two seconds of processor time in each period (0–4, 4–8, and 8–12), while T2 receives three seconds of processing in each of its periods (0–6 and 6–12). This works better than rate-monotonic scheduling because the threads are prioritized differently at different times. At time 0, T1 is prioritized over T2 because its deadline is sooner (time 4 versus 6). However, when T1 becomes runnable a second time, at time 4, it gets lower priority than T2 because now it has a later deadline (time 8 versus 6). Thus, the processor finishes work on the first period of T2's work, rather than starting in on the second period of T1's work.

In this example, there is a tie in priorities at time 8, when T1 becomes runnable for the third time. Its deadline of 12 is the same as T2's. If you break the priority tie in favor of the already-running thread, T2, you obtain the preceding Gantt chart. In practice, this is the correct way to break the tie, because it will result in fewer context switches. However, in a theoretical sense, any tie-breaking strategy will work equally well. In Exercise 3.4, you can redraw the Gantt chart on the assumption that T2 is preempted in order to run T1.

3.5.2 Decay Usage Scheduling

Although we all benefit from real-time control systems, such as those keeping airplanes in which we ride from crashing, they aren't the most prominent computers in our lives. Instead, we mostly notice the workstation computers that we use for daily chores, like typing this book. These computers may execute a few real-time threads for tasks such as keeping an MP3 file of music decoding and playing at its natural rate. However, typically, most of the computer user's goals are not expressed in terms of deadlines, but rather in terms of a desire for quick response to interaction and efficient (high throughput) processing of major, long-running computations. Dynamic priority adjustment can help with these goals too, in operating systems such as Mac OS X or Microsoft Windows.

Occasionally, users of general-purpose workstation computers want to express an opinion about the priority of certain threads in order to achieve goals related to urgency, importance, or resource allocation. This works especially well for importance; for example, a search for signs of extra-terrestrial intelligence might be rated a low priority based on its small chance of success. These user-specified priorities can serve as *base priorities*, which the operating system will use as a starting point for its automatic adjustments. Most of the time, users will accept the default base priority for all their threads, and so the only reason threads will differ in priority is because of the automatic adjustments. For simplicity, in the subsequent discussion, I will assume that all threads have the same base priority.

In this kind of system, threads that tie for top priority after incorporating the automatic adjustments are processed in a round-robin fashion, as discussed earlier. That is, each gets to run for one *time slice*, and then the scheduler switches to the next of the threads. The length of time each thread is allowed to run before switching may also be called a *quantum*, rather than a time slice. The thread need not run for its full time slice; it could, for example, make an I/O request and go into a waiting state long before the time slice is up. In this case, the scheduler would immediately switch to the next thread.

One reason for the operating system to adjust priorities is to maximize throughput in a situation in which one thread is processor-bound and another is disk-bound. For example, in Chapter 2, I introduced a scenario where the user is running a processor-intensive graphics rendering program in one window, while running a disk-intensive virus scanning program in another window. As I indicated there, the operating system can keep both the processor and the disk busy, resulting in improved throughput relative to using only one part of the computer system at a time. While the disk is working on a read request from the virus scanner, the processor can be doing some of the graphics rendering. As soon as the disk transaction is complete, the scheduler should switch the processor's attention to the virus scanner. That way, the virus scanner can quickly look at the data that was read in and issue its next read request, so that the disk drive can get back to work without much delay. The graphics program will have time enough to run again once the virus scanning thread is back to waiting for the disk. In order to achieve this high-throughput interleaving of threads, the operating system needs to assign the disk-intensive thread a higher priority than the processor-intensive one.

Another reason for the operating system to adjust priorities is to minimize response time in a situation where an interactive thread is competing with a long-running computationally intensive thread. For example, suppose that you are running a program in one window that is trying to set a new world record for computing digits of π, while in another window you are typing a term paper. During the long pauses while you rummage through your notes and try to think of what to write next, you don't mind the processor giving its attention to computing π. But the moment you have an inspiration and start typing, you want the word processing program to take precedence, so that it can respond quickly to your keystrokes. Therefore, the operating system must have given this word processing thread a higher priority.

Notice that in both these situations, a computationally intensive thread is competing with a thread that has been unable to use the processor for a while, either because it was waiting for a disk transaction to complete or because it was waiting for the user to press another key. Therefore, the operating system should adjust upward the priority of threads that are in the waiting state and adjust downward the priority of threads that are in the running state. In a nutshell, that is what *decay usage schedulers*, such as the one in Mac OS X, do. The scheduler in Microsoft Windows also fits the same general pattern, although it is not strictly a decay usage scheduler. I will discuss both these schedulers in more detail in the remainder of this section.

A decay usage scheduler, such as in Mac OS X, adjusts each thread's priority downward from the base priority by an amount that reflects recent processor usage by that thread. (However, there is some cap on this adjustment; no matter how much the thread has run, its priority will not sink below some minimum value.) If the thread has recently been running a lot, it will have a priority substantially lower than its base priority. If the thread has not run for a long time (because it has been waiting for the user, for example), then its priority will equal the base priority. That way, a thread that wakes up after a long waiting period will take priority over a thread that has been able to run.

The thread's recent processor usage increases when the thread runs and *decays* when the thread waits, as shown in Figure 3.9. When the thread has been running, its usage increases by adding in the amount of time that it ran. When the thread has been waiting, its usage decreases by being multiplied by some constant every so often; for example, Mac OS X multiplies the usage by 5/8, eight times per second. Rather than continuously updating the usage of every thread, the system can calculate most of the updates to a particular thread's usage just when its state changes, as I describe in the next two paragraphs.

The currently running thread has its usage updated whenever it voluntarily yields the processor, has its time slice end, or faces potential preemption because another thread comes out of the waiting state. At these points, the amount of time the thread has been running is added to its usage, and its priority is correspondingly lowered. In Mac OS X, the time spent in the running state is scaled by the current overall load on the system before it is added to the thread's usage. That way, a thread that runs during a time of high load will have its priority drop more quickly to give the numerous other contending threads their chances to run.

When a thread is done spending time in the waiting state, its usage is adjusted downward to reflect the number of decay periods that have elapsed. For example, in Mac OS X, the usage is multiplied by $(5/8)^n$, where n is

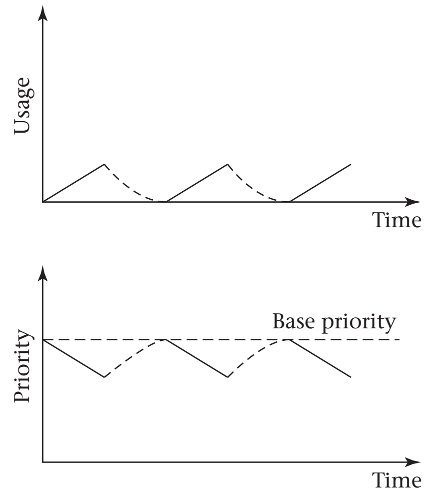


Figure 3.9: In a decay usage scheduler, such as Mac OS X uses, a thread's usage increases while it runs and decays exponentially while it waits. This causes the priority to decrease while running and increase while waiting.

the number of eighths of a second that have elapsed. Because this is an exponential decay, even a fraction of a second of waiting is enough to bring the priority much of the way back to the base, and after a few seconds of waiting, even a thread that previously ran a great deal will be back to base priority. In fact, Mac OS X approximates $(5/8)^n$ as 0 for $n \geq 30$, so any thread that has been waiting for at least 3.75 seconds will be exactly at base priority.

Microsoft Windows uses a variation on this theme. Recall that a decay usage scheduler adjusts the priority downward from the base to reflect recent running and restores the priority back up toward the base when the thead waits. Windows does the reverse: when a thread comes out of a wait state, it is given an elevated priority, which then sinks back down toward the base priority as the thread runs. The net effect is the same: a thread that has been waiting gets a higher priority than one that has been running. The other difference is in how the specific numerical size of the change is calculated. When the thread runs, Windows decreases its priority down to the base in a linear fashion, as with decay usage scheduling. However, Windows does not use exponential decay to boost waiting threads. Instead, a thread that has been waiting is given a priority boost that depends on what it was waiting for: a small boost after waiting for a disk drive, a larger boost after waiting for input from the keyboard, and so forth. Because the larger boosts are associated with the kinds of waiting that usually take longer, the net effect is broadly similar to what exponential decay of a usage estimate achieves.

As described in Section 3.4, a scheduler can store the run queue as an array of thread lists, one per priority level. In this case, it can implement priority adjustments by moving threads from one level to another. Therefore, the Mac OS X and Microsoft Windows schedulers are both considered examples of the broader class of *multilevel feedback queue schedulers*. The original multilevel scheduler placed threads into levels primarily based on the amount of main memory they used. It also used longer time slices for the lower priority levels. Today, the most important multilevel feedback queue schedulers are those approximating decay-usage scheduling.

One advantage to decreasing the priority of running processes below the base, as in Mac OS X, rather than only down to the base, as in Microsoft Windows, is that doing so will normally prevent any runnable thread from being permanently ignored, even if a long-running thread has a higher base priority. Of course, a Windows partisan could reply that if base priorities indicate importance, the less important thread arguably should be ignored. However, in practice, totally shutting out any thread is a bad idea; one reason is the phenomenon of *priority inversion*, which I will explain in Chapter 4. Therefore, Windows has a small escape hatch: every few seconds, it temporarily boosts the priority of any thread that is otherwise unable to get dispatched.

One thing you may notice from the foregoing examples is the tendancy of magic numbers to crop up in these schedulers. Why is the usage decayed by a factor of 5/8, eight times a second, rather than a factor of 1/2, four times a second? Why is the time quantum for round-robin execution 10 milliseconds under one system and 30 milliseconds under another? Why does Microsoft Windows boost a thread's priority by six after waiting for keyboard input, rather than by five or seven?

The answer to all these questions is that system designers have tuned the numerical parameters in each system's scheduler by trial and error. They have done experiments using workloads similar to those they expect their system to encounter in real use. Keeping the workload fixed, the experimenter varies the scheduler parameters and measures such performance indicators as response time and throughput. No one set of parameters will optimize all measures of performance for all workloads. However, by careful, systematic experimentation, parameters can be found that are likely to keep most users happy most of the time. Sometimes system administrators can adjust one or more of the parameters to suit the particular needs of their own installations, as well.

Before leaving decay usage schedulers, it is worth pointing out one kind of user goal that these schedulers are not very good at achieving. Suppose you have two processing-intensive threads and have decided you would like to devote two-thirds of your processor's attention to one and one-third to the other. If other threads start running, they can get some of the processor's time, but you still want your first thread to get twice as much processing as any of the other threads. In principle, you might be able to achieve this resource allocation goal under a decay usage scheduler by appropriately fiddling with the base priorities of the threads. However, in practice it is very difficult to come up with appropriate base priorities to achieve desired processor proportions. Therefore, if this kind of goal is important to a system's users, a different form of scheduler should be used, such as I discuss in Section 3.6.

3.6 Proportional-Share Scheduling

When resource allocation is a primary user goal, the scheduler needs to take a somewhat longer-term perspective than the approaches I have discussed thus far. Rather than focusing just on which thread is most important to run at the moment, the scheduler needs to be pacing the threads, doling out processor time to them at controlled rates.

Researchers have proposed three basic mechanisms for controlling the rate at which threads are granted processor time:

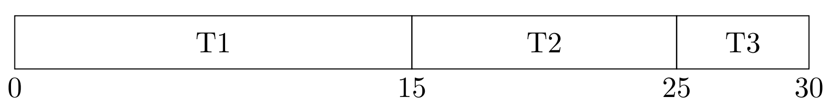
- Each thread can be granted the use of the processor equally often, just as in a simple round-robin. However, those that have larger allocations are granted a longer time slice each time around than those with smaller allocations. This mechanism is known as *weighted round-robin scheduling* (*WRR*).

- A uniform time slice can be used for all threads. However, those that have larger allocations can run more often, because the threads with smaller allocations "sit out" some of the rotations through the list of runnable threads. Several names are used for this mechanism, depending on the context and minor variations: *weighted fair queuing* (*WFQ*), *stride scheduling*, and *virtual time round-robin scheduling* (*VTRR*).

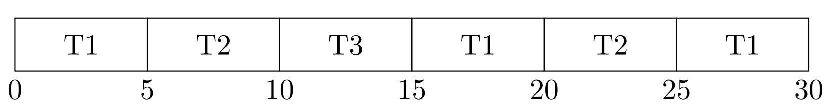
- A uniform time slice can be used for all threads. However, those with larger allocations are chosen to run more often (on the average), because the threads are selected by a lottery with weighted odds, rather than in any sort of rotation. This mechanism is called *lottery scheduling*.

Lottery scheduling is not terribly practical, because although each thread will get its appropriate share of processing time over the long run, there may be significant deviations over the short run. Consider, for example, a system with two threads, each of which should get half the processing time. If the time-slice duration is one twentieth of a second, each thread should run ten times per second. Yet one thread might get shut out for a whole second, risking a major loss of responsiveness, just by having a string of bad luck. A coin flipped twenty times per second all day long may well come up heads twenty times in a row at some point. In Programming Project 3.2, you will calculate the probability and discover that over the course of a day the chance of one thread or the other going a whole second without running is actually quite high. Despite this shortcoming, lottery scheduling has received considerable attention in the research literature.

Turning to the two non-lottery approaches, I can illustrate the difference between them with an example. Suppose three threads (T1, T2, and T3) are to be allocated resources in the proportions 3:2:1. Thus, T1 should get half the processor's time, T2 one-third, and T3 one-sixth. With weighted round-robin scheduling, I might get the following Gantt chart with times in milliseconds:



Taking the other approach, I could use a fixed time slice of 5 milliseconds, but with T2 sitting out one round in every three, and T3 sitting out two rounds out of three. The Gantt chart for the first three scheduling rounds would look as follows (thereafter, the pattern would repeat):



Weighted round-robin scheduling has the advantage of fewer thread switches. Weighted fair queueing, on the other hand, can keep the threads accumulated runtimes more consistently close to the desired proportions. Exercise 3.7 allows you to explore the difference.

In Linux, the user-specified *niceness* of a thread controls the proportion of processor time that the thread will receive. The core of the scheduling algorithm is a weighted round-robin, as in the first Gantt chart. (A separate scheduling policy is used for fixed-priority scheduling of real-time threads. The discussion here concerns the scheduler used for ordinary threads.) This proportional-share scheduler is called the *Completely Fair Scheduler* (*CFS*). On a multiprocessor system, CFS schedules the threads running on each processor; a largely independent mechanism balances the overall computational load between processors. The end-of-chapter notes revisit the question of how proportional-share scheduling fits into the multiprocessor context.

Rather than directly assign each niceness level a time slice, CFS assigns each niceness level a *weight* and then calculates the time slices based on the weights of the runnable threads. Each thread is given a time slice proportional to its weight divided by the total weight of the runnable threads. CFS starts with a target time for how long it should take to make one complete round-robin through the runnable threads. Suppose, for example, that the target is 6 milliseconds. Then with two runnable threads of equal niceness, and hence equal weight, each thread will run for 3 milliseconds, independent of whether they both have niceness 0 or both have niceness 19. With four equal-niceness threads, each would run 1.5 milliseconds.

Notice that the thread-switching rate is dependent on the overall system load, unlike with a fixed time slice. This means that as a system using CFS becomes more loaded, it will tend to sacrifice some throughput in order to retain a desired level of responsiveness. The level of responsiveness is controlled by the target time that a thread may wait between successive opportunities to run, which is settable by the system administrator. The value of 6 milliseconds used in the examples is the default for uniprocessor systems.

However, if system load becomes extremely high, CFS does not continue sacrificing throughput to response time. This is because there is a lower bound on how little time each thread can receive. After that point is reached, adding additional threads will increase the total time to cycle through the threads, rather than continuing to reduce the per-thread time. The minimum time per thread is also a parameter the system administrator can configure; the default value causes the time per thread to stop shrinking once the number of runnable threads reaches 8.

Now consider a case where two threads share the CPU, one with niceness 0 and the other with niceness 5. CFS assigns these niceness levels the weights of 1024 and 335 respectively. The time that the threads get is therefore proportional to $1024/(1024 + 335)$ and $335/(1024 + 335)$. Because 1024 is roughly 3 times as large as 335, we can estimate that the thread with niceness 0 will receive approximately 4.5 milliseconds out of each 6 milliseconds and the thread with niceness 5 will receive approximately 1.5 milliseconds out of each 6 milliseconds. The same result would be achieved if the threads had niceness 5 and 10 rather than 0 and 5, because the weights would then be 335 and 110, which are still in approximately a 3-to-1 ratio. More generally, the CPU proportion is determined only by the relative difference in nicenesses, rather than the absolute niceness levels, because the weights are arranged in a geometric progression. (This is analogous to well-tempered musical scales, where a particular interval, such as a major fifth, has the same harmonic quality no matter where on the scale it is positioned, because the ratio of frequencies is the same.)

Having seen this overview of how nicenesses control the allocation of processor time in CFS, we can now move into a discussion of the actual mechanism used to meter out the processor time. The CFS scheduling mechanism is based around one big idea, with lots of smaller details that I will largely ignore.

The big idea is keeping track for each thread of how much total running it has done, measured in units that are scaled in accordance with the thread's weight. That is, a niceness 0 thread is credited with 1 nanosecond of running for each nanosecond of time that elapses with the thread running, but a niceness 5 thread would be credited with approximately 3 nanoseconds of running for each nanosecond it actually runs. (More precisely, it would be credited with 1024/335 nanoseconds of running for each actual nanosecond.)

Given this funny accounting of how much running the threads are doing (which is called *virtual runtime*), the goal of keeping the threads running in their proper proportion simply amounts to running whichever is the furthest behind. However, if CFS always devoted the CPU to the thread that was furthest behind, it would be constantly switching back and forth between the threads. Instead, the scheduler sticks with the current thread until its time slice runs out or it is preempted by a waking thread. Once the scheduler does choose a new thread, it picks the thread with minimum virtual runtime. Thus, over the long haul, the virtual runtimes are kept approximately in balance, which means the actual runtimes are kept in the proportion specified by the threads' weights, which reflect the threads' nicenesses.

This concept of keeping virtual runtimes in balance is important enough to consider a couple concrete examples. First, consider a case where two threads have equal niceness, so the scheduler tries to make sure that the two threads have run for equal amounts of time. After x nanoseconds have elapsed, each of the two threads should have run for $x/2$ nanoseconds. To make this always exactly true, the scheduler would need to keep switching back and for between the threads, which is inefficient. Instead, the scheduler is willing to stick with one thread for a length of time, the time slice. As a result, you might see that after 9 milliseconds, instead of each of the two threads having run for 4.5 milliseconds, maybe Thread A has run for 6 milliseconds and Thread B has run for 3 milliseconds, as shown in Figure 3.10. When the scheduler decides which thread to run next, it will pick the one that has only run for 3 milliseconds, that is, Thread B, so that it has a chance to catch up with Thread A. That way, if you check again later, you won't see Thread A continuing to get further and further advantaged over Thread B. Instead, you will see the two threads taking turns for which one has run more, but with the difference between the two of them never being very large, perhaps 3 milliseconds at most, as this example suggests.

Now consider what happens when the two threads have different niceness. For example, suppose Thread A has niceness 0 and Thread B has niceness 5. To make the arithmetic easier, let us pretend that 1024/335 is exactly 3, so that Thread A should run exactly 3 times more than Thread B. Now, even if the scheduler did not have to worry about the efficiency problems of switching between the threads, the ideal situation after 9 milliseconds would no longer be that each thread has run for 4.5 milliseconds. Instead, the ideal would be for Thread A to have run for 6.75 milliseconds and Thread B for only 2.25 milliseconds. But again, if the scheduler is only switching threads when discrete time slices expire, this ideal situation will not actually happen. Instead, you may see that Thread A has run for 6 milliseconds and Thread B has run for 3 milliseconds, as shown in Figure 3.11. Which one should run next? We can no longer say that Thread B is further behind and should be allowed to catch up. In fact, Thread B has run for longer than it ought to have. (Remember, it really ought to have only run for 2.25 milliseconds.) The way the scheduler figures this out is that it multiplies each thread's time by a scaling factor. For Thread A, that scaling factor is 1, whereas for Thread B, it is 3. Thus, although their actual runtimes are 6 milliseconds and 3 milliseconds, their virtual runtimes are 6 milliseconds and 9 milliseconds. Now, looking at these virtual runtimes, it is clear that Thread A is further behind (it has only 6 virtual milliseconds) and Thread B is ahead (it has 9 virtual milliseconds). Thus, the scheduler knows to choose Thread A to run next.

Notice that if Thread A and Thread B in this example were in their ideal situation of having received 6.75 real milliseconds and 2.25 real milliseconds, then their virtual runtimes would be exactly tied. Both threads would have run for 6.75 virtual milliseconds, once the scaling factors are taken into account.

This description of accumulating virtual runtime would suffice if all

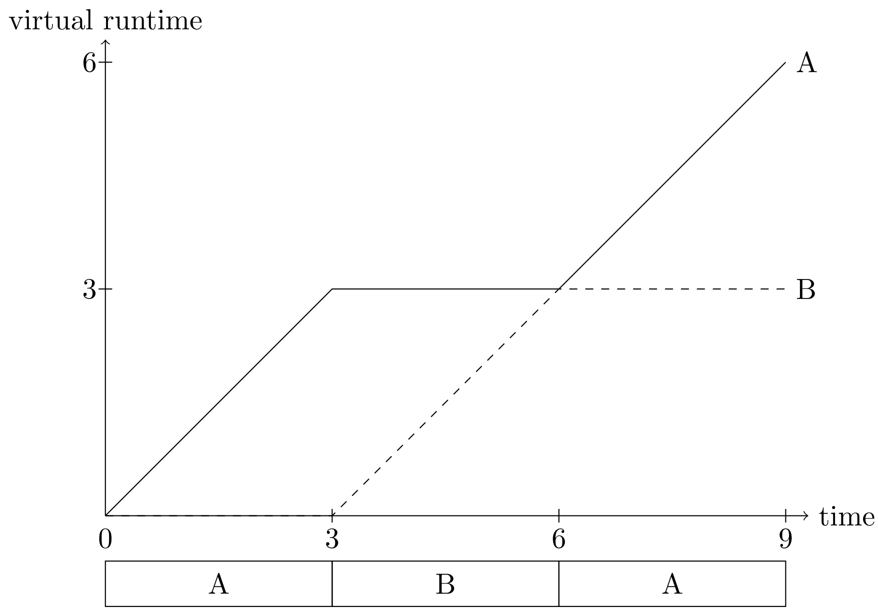


Figure 3.10: Because Thread A and Thread B both have niceness 0, each accumulates 1 millisecond of virtual runtime for each elapsed millisecond during which it runs. The bottom of this figure shows a Gantt chart indicating which thread is running at each point. The top of the figure plots virtual runtime versus time for Thread A (solid) and Thread B (dashed). At the 9 millisecond point, the scheduler would choose Thread B to run next, because it has the lower virtual runtime.

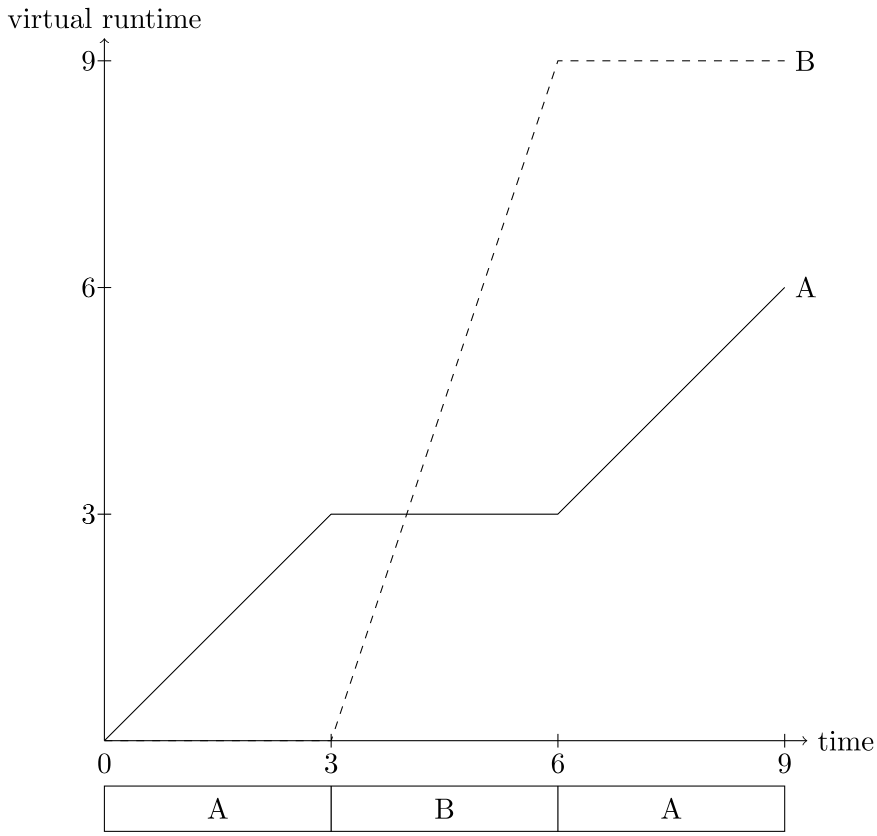


Figure 3.11: Thread A still accumulates 1 millisecond of virtual runtime for each elapsed millisecond during which it runs, but Thread B accumulates virtual runtime at approximately 3 times as fast a rate, because it has niceness 5. The bottom of this figure shows a Gantt chart indicating which thread is running at each point. The top of the figure plots virtual runtime versus time for Thread A (solid) and Thread B (dashed). At the 9 millisecond point, the scheduler would choose Thread A to run next, because it has the lower virtual runtime, corresponding to the fact that it has only run twice as much as Thread B, rather than three times as much. (Assuming both threads remained runnable the whole time, the actual Linux CFS scheduler would not have given them equal time slices as shown here. However, the accounting for virtual runtime works the same in any case.)

threads started when the system was first booted and stayed continuously runnable. However, it needs a bit of enhancement to deal with threads being created or waking up from timed sleeps and I/O waits. If the scheduler didn't do anything special with them, they would get to run until they caught up with the pre-existing threads, which could be a ridiculous amount of runtime for a newly created thread or one that has been asleep a long time. Giving that much runtime to one thread would deprive all the other threads of their normal opportunity to run.

For a thread that has only been briefly out of the run queue, the CFS actually does allow it to catch up on runtime. But once a thread has been non-runnable for more than a threshold amount of time, when it wakes up, its virtual runtime is set forward so as to be only slightly less than the minimum virtual runtime of any of the previously runnable threads. That way, it will get to run soon but not for much longer than usual. This is similar to the effect achieved through dynamic priority adjustments in decay usage schedulers and Microsoft Windows. As with those adjustments, the goal is not proportional sharing, but responsiveness and throughput.

Any newly created thread is given a virtual runtime slightly greater than the minimum virtual runtime of the previously runnable threads, essentially as though it had just run and were now waiting for its next turn to run.

The run queue is kept sorted in order of the runnable threads' virtual runtimes. The data structure used for this purpose is a red-black tree, which is a variant of a binary search tree with the efficiency-enhancing property that no leaf can ever be more than twice as deep as any other leaf. When the CFS scheduler decides to switch threads, it switches to the leftmost thread in the red-black tree, that is, the one with the earliest virtual runtime.

The scheduler performs these thread switches under two circumstances. One is the expiration of a time slice. The other is when a new thread enters the run queue, provided that the currently running thread hasn't just recently started running. (There is a configurable lower limit on how quickly a thread can be preempted.)

One of the advantages of positioning runnable threads on a timeline of virtual runtimes (represented as the red-black tree) is that it naturally prevents waking threads from starving other threads that have remained runnable, as was possible with earlier Linux schedulers. As time marches on, threads that wake up get inserted into the timeline at later and later virtual runtimes. A runnable thread that has been patiently waiting for the CPU, on the other hand, retains a fixed virtual runtime. As such, it will eventually have the lowest virtual runtime, and hence will be chosen to run (once a thread switch occurs).

3.7 Security and Scheduling

The kind of attack most relevant to scheduling is the *denial of service* (*DoS*) attack, that is, an attack with the goal of preventing legitimate users of a system from being able to use it. Denial of service attacks are frequently nuisances motivated by little more than the immaturity of the perpetrators. However, they can be part of a more sophisticated scheme. For example, consider the consequences if a system used for coordinating a military force were vulnerable to a denial of service attack.

The most straightforward way an attacker could misuse a scheduler in order to mount a denial of service attack would be to usurp the mechanisms provided for administrative control. Recall that schedulers typically provide some control parameter for each thread, such as a deadline, a priority, a base priority, or a resource share. An authorized system administrator needs to be able to say "This thread is a really low priority" or the analogous statement about one of the other parameters. If an attacker could exercise that same control, a denial of service attack could be as simple as giving a low priority to a critical thread.

Therefore, real operating systems guard the thread-control interfaces. Typically, only a user who has been authenticated as the "owner" of a particular thread or as a bona fide system administrator can control that thread's scheduling parameters. Naturally, this relies upon other aspects of the system's security that I will consider in later chapters: the system must be protected from tampering, must be able to authenticate the identity of its users, and must be programmed in a sufficiently error-free fashion that its checks cannot be evaded.

Because real systems guard against an unauthorized user de-prioritizing a thread, attackers use a slightly more sophisticated strategy. Rather than de-prioritizing the targeted thread, they compete with it. That is, the attackers create other threads that attempt to siphon off enough of a scarce resource, such as processor time, so that little or none will be left for the targeted thread.

One response of system designers has been to arrange that any denial of service attack will be sufficiently cumbersome that it can be easily distinguished from normal behavior and hence interdicted. For example, recall that a single thread at a high fixed priority could completely starve all the normal threads. Therefore, most systems prohibit normal users from running such threads, reserving that privilege to authorized system administrators. In fact, typical systems place off-limits all fixed priorities and all higher-than-normal priorities, even if subject to decay-usage adjustment.

The result is that an attacker must run many concurrent threads in order to drain off a significant fraction of the processor's time. Because legitimate users generally won't have any reason to do that, denial of service attacks can be distinguished from ordinary behavior. A limit on the number of threads per user will constrain denial of service attacks without causing most users much hardship. However, there will inevitably be a trade-off between the degree to which denial of service attacks are mitigated and the degree to which normal users retain flexibility to create threads.

Alternatively, a scheduling policy can be used that is intrinsically more resistant to denial of service attacks. In particular, proportional-share schedulers have considerable promise in this regard. The version that Linux includes can assign resource shares to users or other larger groups, with those shares subject to hierarchical subdivision. This was originally proposed by Waldspurger as part of lottery scheduling, which I observed is disfavored because of its susceptibility to short-term unfairness in the distribution of processing time. Waldspurger later showed how the same hierarchical approach could be used with *stride scheduling*, a deterministic proportional-share scheduler, and it has subsequently been used with a variety of other proportional-share schedulers.

Long-running server threads, which over their lifetimes may process requests originating from many different users, present an additional complication. If resources are allocated per user, which user should be funding the server thread's resource consumption? The simplest approach is to have a special user just for the purpose with a large enough resource allocation to provide for all the work the server thread does on behalf of all the users. Unfortunately, that is too coarse-grained to prevent denial of service attacks. If a user submits many requests to the server thread, he or she may use up its entire processor time allocation. This would deny service to other users' requests made to the same server thread. Admittedly, threads not using the service will be isolated from the problem, but that may be small solace if the server thread in question is a critical one.

To address this issue, recent research has suggested that threads should be able to switch from one user's resource allocation to another, as the threads handle different requests. The idea is to allocate resources not directly to threads, but to independent *resource containers* instead. At any one time, each thread draws resources from one resource container. However, it can switch to drawing from a different resource container. This solves the problem of fairly accounting for server threads' usage. Because multiple threads can be made to draw out of a single resource container, the same proposal also can prevent users from receiving more processor time by running more threads.

Finally, keep in mind that no approach to processor scheduling taken alone will prevent denial of service attacks. An attacker will simply overwhelm some other resource than processor time. For example, in the 1990s, attackers frequently targeted systems' limited ability to establish new network connections. Nonetheless, a comprehensive approach to security needs to include processor scheduling, as well as networking and other components.

Exercises

3.1 Gantt charts, which I introduced in the context of hard-real-time scheduling, can also be used to illustrate other scheduling concepts, such as those concerning response time. Suppose thread T1 is triggered by an event at time 0 and needs to run for 1.5 seconds before it can respond. Suppose thread T2 is triggered by an event occurring 0.3 seconds later than T1's trigger, and that T2 needs to run 0.2 seconds before it can respond. Draw a Gantt chart for each of the following three cases, and for each indicate the response time of T1, the response time of T2, and the average response time:

   (a) T1 is allowed to run to completion before T2 is run.

   (b) T1 is preempted when T2 is triggered; only after T2 has completed does T1 resume.

   (c) T1 is preempted when T2 is triggered; the two threads are then executed in a round-robin fashion (starting with T2), until one of them completes. The time slice (or quantum) is .05 seconds.

3.2 Suppose a Linux system is running three threads, each of which runs an infinite loop with nothing in the body, so that it just chews up as much processor time as it is given. One thread is run by one user, whereas the other two threads are run by a second user (perhaps logged in over the network or in a second virtual console). Does the scheduler give each user a fair share (one-half) of the the processor's time, or does it give each thread a fair share (one-third)? You can answer this question from the text of this chapter, but see also Exploration Project 3.1. Also, which behavior would you prefer? Explain why.

3.3 Draw a Gantt chart for two threads, T1 and T2, scheduled in accordance to fixed priorities with T2 higher priority than T1. Both threads run periodically. One, T1, has a period and deadline of four seconds and an execution time per period of two seconds. The other, T2, has a period and deadline of six seconds and an execution time per period of three seconds. Assume both threads start a period at time 0. Draw the Gantt chart far enough to show one of the threads missing a deadline.

3.4 Draw a Gantt chart for two threads, T1 and T2, scheduled in accordance with the Earliest Deadline First policy. If the threads are tied for earliest deadline, preempt the already-running thread in favor of the newly runnable thread. Both threads run periodically. One, T1, has a period and deadline of four seconds and an execution time per period of two seconds. The other, T2, has a period and deadline of six seconds and an execution time per period of three seconds. Assume both threads start a period at time 0. Draw the Gantt chart to the point where it would start to repeat. Are the deadlines met?

3.5 Suppose a system has three threads (T1, T2, and T3) that are all available to run at time 0 and need one, two, and three seconds of processing respectively. Suppose that each thread is run to completion before starting another. Draw six different Gantt charts, one for each possible order the threads can be run in. For each chart, compute the turnaround time of each thread; that is, the time elapsed from when it was ready (time 0) until it is complete. Also, compute the average turnaround time for each order. Which order has the shortest average turnaround time? What is the name for the scheduling policy that produces this order?

3.6 The following analysis is relevant to lottery scheduling and is used in Programming Project 3.2. Consider a coin that is weighted so that it comes up heads with probability p and tails with probability $1-p$, for some value of p between 0 and 1. Let $f(n,k,p)$ be the probability that in a sequence of n tosses of this coin there is a run of at least k consecutive heads.

(a) Prove that $f(n,k,p)$ can be defined by the following recurrence. If $n<k$, $f(n,k,p)=0$. If $n=k$, $f(n,k,p)=p^k$. If $n>k$,

$$f(n,k,p) = f(n-1,k,p) + p^k(1-p)(1-f(n-k-1,k,p)).$$

(b) Consider the probability that in n tosses of a fair coin, there are at least k consecutive heads or at least k consecutive tails. Show that this is equal to $f(n-1,k-1,1/2)$.

3.7 Section 3.6 shows two Gantt charts for an example with three threads that are to share a processor in the proportion 3:2:1. The first Gantt chart shows the three threads scheduled using WRR and the second using WFQ. For each of the two Gantt charts, draw a corresponding graph with one line for each the three threads, showing that thread's accumulated virtual runtime (on the vertical axis) versus real time (on the horizontal axis). Thread T1 should accumulate 2 milliseconds of virtual runtime for each millisecond that it actually runs. Similarly, Thread T2 should accumulate 3 milliseconds of virtual runtime for each millisecond it runs and Thread T3 should accumulate 6 milliseconds for each millisecond it runs. In both graphs, the three lines should all start at $(0, 0)$ and end at $(30, 30)$. Look at how far the lines deviate from the diagonal connecting these two points. Which scheduling approach keeps the lines closer to the diagonal? This reflects how close each approach is coming to continuously metering out computation to the three threads at their respective rates.

3.8 Draw a variant of Figure 3.11 on page 77 based on the assumption that the scheduler devotes 4.5 milliseconds to Thread A, then 1.5 milliseconds to Thread B, and then another 3 milliseconds to Thread A. If the scheduler is again called upon to choose a thread at the 9 millisecond point, which will it choose? Why?

Programming Projects

3.1 On a system where you can install modified Linux kernels, test the effect of eliminating dynamic priority adjustments. (You will find the relevant code in the file `kernel/sched.c`.) You should be able to demonstrate that there is no change in how compute-bound processes share the processor in accordance with their niceness. You should also be able to demonstrate that the responsiveness of interactive processes is degraded when there are lots of compute-bound processes running as well. Rather than testing response time with a process that reads input from the user, you can more easily get quantitative results with a process that repeatedly sleeps and measures how much longer each sleeping period actually is than was requested. Write a report in which you explain what you did, and the hardware and software system context in which you did it, carefully enough that someone could replicate your results.

3.2 Consider a coin that is weighted so that it comes up heads with probability p and tails with probability $1-p$, for some value of p between 0 and 1. Let $f(n,k,p)$ be the probability that in a sequence of n tosses of this coin there is a run of at least k consecutive heads.

(a) Write a program to calculate $f(n,k,p)$ using the recurrence given in Exercise 3.6(a). To make your program reasonably efficient, you will need to use the algorithm design technique known as dynamic programming. That is, you should create an $n+1$ element array, and then for i from 0 to n, fill in element i of the array with $f(i,k,p)$. Whenever the calculation of one of these values of f requires another value of f, retrieve the required value from the array, rather than using a recursive call. At the end, return element n of the array.

(b) If threads A and B each are selected with probability 1/2 and the time slice is 1/20 of a second, the probability that sometime during a day thread A will go a full second without running is $f(20\cdot 60\cdot 60\cdot 24, 20, 1/2)$. Calculate this value using your program.

(c) The system's performance is no better if thread B goes a long time without running than if thread A does. Use the result from Exercise 3.6(b) to calculate the probability that at least one of threads A and B goes a second without processor time in the course of a day.

Exploration Projects

3.1 Experimentally verify your answer to Exercise 3.2 with the help of another user. The `top` command will show you what fraction of the processor each thread gets.

3.2 Experimentally measure the impact of *niceness* on the amount of processor time given to compute-bound threads under as many UNIX-like uniprocessor systems as you have access to. This will be most interesting if you can compare a system with a proportional-share scheduler (such as Linux) with a system that uses a decay usage scheduler (such as Mac OS X or most older versions of UNIX). Be sure to experiment on a system that is otherwise idle. Write a simple test program that just loops. Run one copy normally (niceness 0) and another using the `nice` command at elevated niceness. Use the `top` command to observe what fraction of the processor each thread gets. Repeat the test using different degrees of elevated niceness, from 1 to 19. Also, repeat the test in situations other than one thread of each niceness; for example, what if there are four normal niceness threads and only one elevated niceness thread? Write a report in which you explain what you did, and the hardware and software system context in which you did it, carefully enough that someone could replicate your results. Try to draw some conclusions about the suitability of niceness as a resource allocation tool on the systems you studied.

3.3 The instructions for this project assume that you are using a Linux system; an analogous exploration may be possible on other systems, but the specific commands will differ. Some portions of the project assume you have permission to run fixed-priority threads, which ordinarily requires you to have full system administration privileges. Those portions of the project can be omitted if you don't have the requisite permission. Some portions of the project assume you have at least two processors, which can be two "cores" within a single processor chip; in fact, even a single core will do if it has "hyper-threading" support (the ability to run two threads). Only quite old computers fail to meet this assumption; if you have such an old computer, you can omit those portions of the project.

The C++ program shown in Figures 3.12 and 3.13 runs a number of threads that is specified on the command line. (The main thread is one; it creates a child thread for each of the others.) Each thread gets the time of day when it starts running and then continues running until the time of day is at least 5 seconds later. If you save the source code of this program in `threads.cpp`, you can compile it using the following command:

```
g++ -o threads -lpthread threads.cpp
```

(a) Suppose you run this program on a single processor using the normal CFS scheduler. As you increase the number of threads from 1 to 2, 3, and 4, what would you expect to happen to the total elapsed time that the program needs to run? Would it stay nearly constant at approximately 5 seconds or grow linearly upward to 10, 15, and 20 seconds? Why? To test your prediction, run the following commands and look at the elapsed time that each one reports. The `schedtool` program is used in these commands in order to limit the threads to a single processor (processor number 0):

```
#include <sys/time.h>
#include <stdio.h>
#include <string.h>
#include <stdlib.h>
#include <pthread.h>
#include <iostream>
#include <sstream>
#include <unistd.h>

void killTime(int secs){
  struct timeval start, now;
  if(gettimeofday(&start, 0) < 0){
    perror("gettimeofday");
    exit(1);
  }
  while(1){
    if(gettimeofday(&now, 0) < 0){
      perror("gettimeofday");
      exit(1);
    }
    if(now.tv_sec - start.tv_sec > secs ||
       now.tv_sec - start.tv_sec == secs && now.tv_usec >= start.tv_usec){
      return;
    }
  }
}

void *run(void *arg){
  killTime(5);
  return 0;
}
```

Figure 3.12: This is the first portion of `threads.cpp`, a C++ program that runs a number of threads specified on the command line. Each thread runs until at least 5 seconds of time has elapsed since the thread started. The program is continued in the next figure.

```
int main(int argc, char *argv[]){
  int nThreads;
  std::istringstream arg1(argv[1]);
  arg1 >> nThreads;
  pthread_t thread[nThreads-1];
  int code;

  for(int i = 0; i < nThreads-1; i++){
    code = pthread_create(&thread[i], 0, run, 0);
    if(code){
      std::cerr << "pthread_create failed: " << strerror(code) << std::endl;
      exit(1);
    }
  }
  run(0);
  for(int i = 0; i < nThreads-1; i++){
    code = pthread_join(thread[i], 0);
    if(code){
      std::cerr << "pthread_join failed: " << strerror(code) << std::endl;
      exit(1);
    }
  }
  return 0;
}
```

Figure 3.13: This is the second portion of `threads.cpp`, a C++ program that runs a number of threads specified on the command line. Each thread runs until at least 5 seconds of time has elapsed since the thread started. The program is continued from the previous figure.

```
schedtool -a 0 -e time ./threads 1
schedtool -a 0 -e time ./threads 2
schedtool -a 0 -e time ./threads 3
schedtool -a 0 -e time ./threads 4
```

(b) Suppose you run the program on a single processor but using the fixed-priority scheduler. All the threads are at the same priority level and are scheduled using the FIFO rule. As you increase the number of threads from 1 to 2, 3, and 4, what would you expect to happen to the total elapsed time that the program needs to run? Would it stay nearly constant at approximately 5 seconds or grow linearly upward to 10, 15, and 20 seconds? Why? To test your prediction, run the following commands and look at the elapsed time that each one reports. The `schedtool` program is used in these commands not only to limit the threads to a single processor, but also to specify FIFO scheduling with priority level 50. The `sudo` program is used in these commands to run with system administration privileges (assuming you have this permission); this allows the FIFO fixed-priority scheduling to be selected:

```
sudo schedtool -a 0 -F -p 50 -e time ./threads 1
sudo schedtool -a 0 -F -p 50 -e time ./threads 2
sudo schedtool -a 0 -F -p 50 -e time ./threads 3
sudo schedtool -a 0 -F -p 50 -e time ./threads 4
```

(c) The time output lines that were generated by the prior experiments included not only elapsed time, but also user and system processor times. If you add together the user and system processor times to get total processor times, you should find that the total is in each case quite similar to the elapsed time, because the `threads` program kept the one processor busy essentially the full time. Now suppose you switch to using two processors. With normal CFS scheduling, what do you expect to happen to the total processor time as the number of threads goes from 1 to 2, 3, and 4? Why? To test your prediction, run the following commands:

```
schedtool -a 0,1 -e time ./threads 1
schedtool -a 0,1 -e time ./threads 2
schedtool -a 0,1 -e time ./threads 3
schedtool -a 0,1 -e time ./threads 4
```

(d) Suppose you use two processors with fixed-priority FIFO scheduling. What do you expect to happen to the total processor time as the number of threads goes from 1 to 2, 3, and 4? Why? How about the elapsed time; what do you expect will happen to it as the number of threads goes from 1 to 2, 3, and 4? Why? To test your predictions, run the following commands:

```
sudo schedtool -a 0,1 -F -p 50 -e time ./threads 1
sudo schedtool -a 0,1 -F -p 50 -e time ./threads 2
sudo schedtool -a 0,1 -F -p 50 -e time ./threads 3
sudo schedtool -a 0,1 -F -p 50 -e time ./threads 4
```

Notes

I motivated the notion of thread states by explaining the inefficiency of busy waiting and indicated that the alternative is for a thread that wants to wait to notify the operating system. This issue was recognized early in the history of operating systems. For example, the same 1959 paper [34] by Codd et al. that I quoted in Chapter 2 remarks, "For the sake of efficient use of the machine, one further demand is made of the programmer or compiler. When a point is reached in a problem program beyond which activity on the central processing unit cannot proceed until one or more input-output operations are completed, the control must be passed to the supervisory program so that other problem programs may be serviced." (The "supervisory program" is what today is called an operating system.)

I remarked that the main cost of thread switching is lost cache performance. This observation has been quantified in various measurement studies, such as one by Regehr [115].

I use the terms *quantum* and *time slice* interchangeably, in keeping with contemporary usage. Early operating systems used these words differently: *quanta* were finer subdivisions of coarser time slices. A subset of the runnable threads would get brief quanta in a round-robin. When a thread had received enough quanta to use up its whole time slice, it would be moved out of the round-robin for a while, and another thread would move in to take its place.

I mentioned fair-share, multilevel feedback queue, lottery, and stride scheduling only in passing. Early references for them are numbers [85], [38], [148], and [149], respectively.

Liu and Layland wrote a seminal 1973 article on hard-real-time scheduling [100]. For a survey of how rate-monotonic scheduling has been generalized to more realistic circumstances, see the article by Sha, Rajkumar, and Sathaye [130].

I drew examples from three real systems' schedulers: Mac OS X, Microsoft Windows, and Linux. For two of these (Max OS X and Linux), the only reliable way to find the information is by reading the kernel source code, as I did (versions Darwin 6.6 and Linux 2.6.38). For Microsoft Windows, the source code is not publicly available, but conversely, one doesn't need to dig through it to find a more detailed description than mine: there is a very careful one in Russinovich and Solomon's book [123].

My segue from decay usage scheduling to proportional-share scheduling was the remark that one could, in principle, achieve proportional shares by suitably setting the base priorities of a decay usage scheduler, but that in practice, it was difficult to map proportions to base priorities. The mathematical modeling study by Hellerstein [73] provides evidence for both aspects of this claim. Hellerstein explicitly shows that one can, in principle, achieve what he terms "service rate objectives." However, less explicitly, he also shows this is not practical; reading his graphs carefully, one can see that there are two choices. Either the service rates are so insensitive to the base priorities as to render most proportions out of reach, or there is a region of such extreme sensitivity that one jumps over many potential proportions in stepping from one base priority difference to the next.

I remarked that although Linux's CFS acts as a proportional-share scheduler on each processor, a relatively independent load-balancing mechanism is used to apportion a system's threads to its processors. In considering whether the proportional-share concept could be more directly applied to the multiprocessor context, the first question is what that would mean. Suppose two threads are runnable and that they have weights 2 and 1. On a single processor, it is clear that the first should get two-thirds of the processing capacity and the other should get one-third. But what if you have two processors? Then the most that one thread can receive is half of the system's total processing capacity. The other thread *could* receive half as much, but only by leaving one of the processors idle half the time; a more practical approach would be to give each thread the full use of one processor. Generalizing from this to a suitable definition of how weights should behave on a multiprocessor system requires some care; Chandra and his coworkers explained this in their work on "Surplus Fair Scheduling" [29]. Once this definitional question is resolved, the next question is how the scheduler can efficiently run on multiple processors without the bottleneck of synchronized access to a single run queue. Although this is still an active research topic, the Distributed Weighted Round Robin scheduler of Li, Baumberger, and

Hahn [97] looks promising.

An alternative to proportional-share scheduling is to augment the scheduler with a higher-level resource manager that adjusts thread priorities when the system is heavily utilized so as to achieve the desired resource allocation. An example of this approach is the Windows System Resource Manager that Microsoft includes in Windows Server 2008 R2. This resource manager can support policies that divide CPU time equally per process, per user, per remote desktop session, or per web application pool, as well as allowing some users or groups to be given larger shares than others. The details do not appear to be publicly documented, though some information is available through Microsoft's online TechNet library.

Resource containers are described by Banga, Druschel, and Mogul [10].