Part I

Virtualization

3

A Dialogue on Virtualization

Professor: *And thus we reach the first of our three pieces on operating systems:* ***virtualization****.*

Student: *But what is virtualization, oh noble professor?*

Professor: *Imagine we have a peach.*

Student: *A peach? (incredulous)*

Professor: *Yes, a peach. Let us call that the* ***physical*** *peach. But we have many eaters who would like to eat this peach. What we would like to present to each eater is their own peach, so that they can be happy. We call the peach we give eaters* ***virtual*** *peaches; we somehow create many of these virtual peaches out of the one physical peach. And the important thing: in this illusion, it looks to each eater like they have a physical peach, but in reality they don't.*

Student: *So you are sharing the peach, but you don't even know it?*

Professor: *Right! Exactly.*

Student: *But there's only one peach.*

Professor: *Yes. And...?*

Student: *Well, if I was sharing a peach with somebody else, I think I would notice.*

Professor: *Ah yes! Good point. But that is the thing with many eaters; most of the time they are napping or doing something else, and thus, you can snatch that peach away and give it to someone else for a while. And thus we create the illusion of many virtual peaches, one peach for each person!*

Student: *Sounds like a bad campaign slogan. You are talking about computers, right Professor?*

Professor: *Ah, young grasshopper, you wish to have a more concrete example. Good idea! Let us take the most basic of resources, the CPU. Assume there is one physical CPU in a system (though now there are often two or four or more). What virtualization does is take that single CPU and make it look like many virtual CPUs to the applications running on the system. Thus, while each application*

thinks it has its own CPU to use, there is really only one. And thus the OS has created a beautiful illusion: it has virtualized the CPU.

Student: *Wow! That sounds like magic. Tell me more! How does that work?*

Professor: *In time, young student, in good time. Sounds like you are ready to begin.*

Student: *I am! Well, sort of. I must admit, I'm a little worried you are going to start talking about peaches again.*

Professor: *Don't worry too much; I don't even like peaches. And thus we begin...*

4

The Abstraction: The Process

In this chapter, we discuss one of the most fundamental abstractions that the OS provides to users: the **process**. The definition of a process, informally, is quite simple: it is a **running program** [V+65,BH70]. The program itself is a lifeless thing: it just sits there on the disk, a bunch of instructions (and maybe some static data), waiting to spring into action. It is the operating system that takes these bytes and gets them running, transforming the program into something useful.

It turns out that one often wants to run more than one program at once; for example, consider your desktop or laptop where you might like to run a web browser, mail program, a game, a music player, and so forth. In fact, a typical system may be seemingly running tens or even hundreds of processes at the same time. Doing so makes the system easy to use, as one never need be concerned with whether a CPU is available; one simply runs programs. Hence our challenge:

THE CRUX OF THE PROBLEM:
HOW TO PROVIDE THE ILLUSION OF MANY CPUS?
Although there are only a few physical CPUs available, how can the OS provide the illusion of a nearly-endless supply of said CPUs?

The OS creates this illusion by **virtualizing** the CPU. By running one process, then stopping it and running another, and so forth, the OS can promote the illusion that many virtual CPUs exist when in fact there is only one physical CPU (or a few). This basic technique, known as **time sharing** of the CPU, allows users to run as many concurrent processes as they would like; the potential cost is performance, as each will run more slowly if the CPU(s) must be shared.

To implement virtualization of the CPU, and to implement it well, the OS will need both some low-level machinery as well as some high-level intelligence. We call the low-level machinery **mechanisms**; mechanisms are low-level methods or protocols that implement a needed piece

TIP: USE TIME SHARING (AND SPACE SHARING)
Time sharing is one of the most basic techniques used by an OS to share a resource. By allowing the resource to be used for a little while by one entity, and then a little while by another, and so forth, the resource in question (e.g., the CPU, or a network link) can be shared by many. The natural counterpart of time sharing is **space sharing**, where a resource is divided (in space) among those who wish to use it. For example, disk space is naturally a space-shared resource, as once a block is assigned to a file, it is not likely to be assigned to another file until the user deletes it.

of functionality. For example, we'll learn later how to implement a **context switch**, which gives the OS the ability to stop running one program and start running another on a given CPU; this **time-sharing** mechanism is employed by all modern OSes.

On top of these mechanisms resides some of the intelligence in the OS, in the form of **policies**. Policies are algorithms for making some kind of decision within the OS. For example, given a number of possible programs to run on a CPU, which program should the OS run? A **scheduling policy** in the OS will make this decision, likely using historical information (e.g., which program has run more over the last minute?), workload knowledge (e.g., what types of programs are run), and performance metrics (e.g., is the system optimizing for interactive performance, or throughput?) to make its decision.

4.1 The Abstraction: A Process

The abstraction provided by the OS of a running program is something we will call a **process**. As we said above, a process is simply a running program; at any instant in time, we can summarize a process by taking an inventory of the different pieces of the system it accesses or affects during the course of its execution.

To understand what constitutes a process, we thus have to understand its **machine state**: what a program can read or update when it is running. At any given time, what parts of the machine are important to the execution of this program?

One obvious component of machine state that comprises a process is its *memory*. Instructions lie in memory; the data that the running program reads and writes sits in memory as well. Thus the memory that the process can address (called its **address space**) is part of the process.

Also part of the process's machine state are *registers*; many instructions explicitly read or update registers and thus clearly they are important to the execution of the process.

Note that there are some particularly special registers that form part of this machine state. For example, the **program counter** (**PC**) (sometimes called the **instruction pointer** or **IP**) tells us which instruction of the pro-

TIP: SEPARATE POLICY AND MECHANISM
In many operating systems, a common design paradigm is to separate high-level policies from their low-level mechanisms [L+75]. You can think of the mechanism as providing the answer to a *how* question about a system; for example, *how* does an operating system perform a context switch? The policy provides the answer to a *which* question; for example, *which* process should the operating system run right now? Separating the two allows one easily to change policies without having to rethink the mechanism and is thus a form of **modularity**, a general software design principle.

gram is currently being executed; similarly a **stack pointer** and associated **frame pointer** are used to manage the stack for function parameters, local variables, and return addresses.

Finally, programs often access persistent storage devices too. Such *I/O information* might include a list of the files the process currently has open.

4.2 Process API

Though we defer discussion of a real process API until a subsequent chapter, here we first give some idea of what must be included in any interface of an operating system. These APIs, in some form, are available on any modern operating system.

- **Create:** An operating system must include some method to create new processes. When you type a command into the shell, or double-click on an application icon, the OS is invoked to create a new process to run the program you have indicated.
- **Destroy:** As there is an interface for process creation, systems also provide an interface to destroy processes forcefully. Of course, many processes will run and just exit by themselves when complete; when they don't, however, the user may wish to kill them, and thus an interface to halt a runaway process is quite useful.
- **Wait:** Sometimes it is useful to wait for a process to stop running; thus some kind of waiting interface is often provided.
- **Miscellaneous Control:** Other than killing or waiting for a process, there are sometimes other controls that are possible. For example, most operating systems provide some kind of method to suspend a process (stop it from running for a while) and then resume it (continue it running).
- **Status:** There are usually interfaces to get some status information about a process as well, such as how long it has run for, or what state it is in.

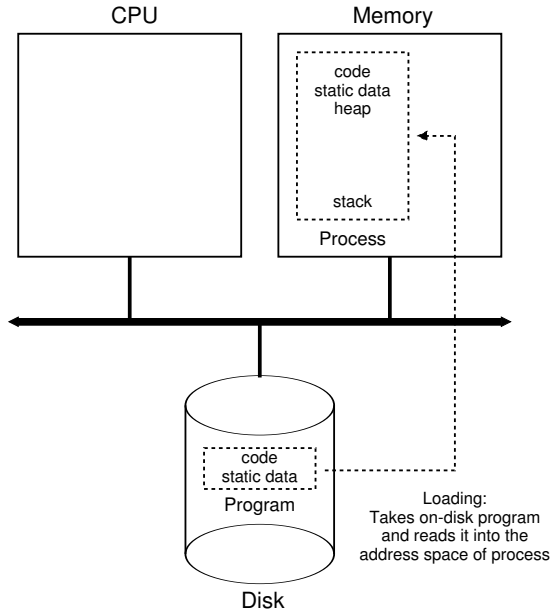


Figure 4.1: **Loading: From Program To Process**

4.3 Process Creation: A Little More Detail

One mystery that we should unmask a bit is how programs are transformed into processes. Specifically, how does the OS get a program up and running? How does process creation actually work?

The first thing that the OS must do to run a program is to **load** its code and any static data (e.g., initialized variables) into memory, into the address space of the process. Programs initially reside on **disk** (or, in some modern systems, **flash-based SSDs**) in some kind of **executable format**; thus, the process of loading a program and static data into memory requires the OS to read those bytes from disk and place them in memory somewhere (as shown in Figure 4.1).

In early (or simple) operating systems, the loading process is done **eagerly**, i.e., all at once before running the program; modern OSes perform the process **lazily**, i.e., by loading pieces of code or data only as they are needed during program execution. To truly understand how lazy loading of pieces of code and data works, you'll have to understand more about the machinery of **paging** and **swapping**, topics we'll cover in the future when we discuss the virtualization of memory. For now, just remember that before running anything, the OS clearly must do some work to get the important program bits from disk into memory.

Once the code and static data are loaded into memory, there are a few other things the OS needs to do before running the process. Some memory must be allocated for the program's **run-time stack** (or just **stack**). As you should likely already know, C programs use the stack for local variables, function parameters, and return addresses; the OS allocates this memory and gives it to the process. The OS will also likely initialize the stack with arguments; specifically, it will fill in the parameters to the `main()` function, i.e., `argc` and the `argv` array.

The OS may also allocate some memory for the program's **heap**. In C programs, the heap is used for explicitly requested dynamically-allocated data; programs request such space by calling `malloc()` and free it explicitly by calling `free()`. The heap is needed for data structures such as linked lists, hash tables, trees, and other interesting data structures. The heap will be small at first; as the program runs, and requests more memory via the `malloc()` library API, the OS may get involved and allocate more memory to the process to help satisfy such calls.

The OS will also do some other initialization tasks, particularly as related to input/output (I/O). For example, in UNIX systems, each process by default has three open **file descriptors**, for standard input, output, and error; these descriptors let programs easily read input from the terminal as well as print output to the screen. We'll learn more about I/O, file descriptors, and the like in the third part of the book on **persistence**.

By loading the code and static data into memory, by creating and initializing a stack, and by doing other work as related to I/O setup, the OS has now (finally) set the stage for program execution. It thus has one last task: to start the program running at the entry point, namely `main()`. By jumping to the `main()` routine (through a specialized mechanism that we will discuss next chapter), the OS transfers control of the CPU to the newly-created process, and thus the program begins its execution.

4.4 Process States

Now that we have some idea of what a process is (though we will continue to refine this notion), and (roughly) how it is created, let us talk about the different **states** a process can be in at a given time. The notion that a process can be in one of these states arose in early computer systems [DV66,V+65]. In a simplified view, a process can be in one of three states:

- **Running**: In the running state, a process is running on a processor. This means it is executing instructions.
- **Ready**: In the ready state, a process is ready to run but for some reason the OS has chosen not to run it at this given moment.
- **Blocked**: In the blocked state, a process has performed some kind of operation that makes it not ready to run until some other event takes place. A common example: when a process initiates an I/O request to a disk, it becomes blocked and thus some other process can use the processor.

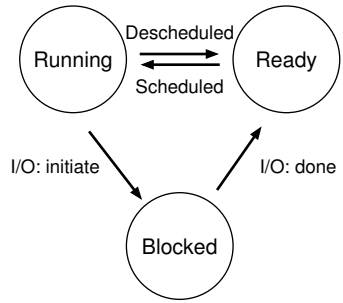


Figure 4.2: **Process: State Transitions**

If we were to map these states to a graph, we would arrive at the diagram in Figure 4.2. As you can see in the diagram, a process can be moved between the ready and running states at the discretion of the OS. Being moved from ready to running means the process has been **scheduled**; being moved from running to ready means the process has been **descheduled**. Once a process has become blocked (e.g., by initiating an I/O operation), the OS will keep it as such until some event occurs (e.g., I/O completion); at that point, the process moves to the ready state again (and potentially immediately to running again, if the OS so decides).

Let's look at an example of how two processes might transition through some of these states. First, imagine two processes running, each of which only use the CPU (they do no I/O). In this case, a trace of the state of each process might look like this (Figure 4.3).

Time	Process_0	Process_1	Notes
1	Running	Ready	
2	Running	Ready	
3	Running	Ready	
4	Running	Ready	Process_0 now done
5	–	Running	
6	–	Running	
7	–	Running	
8	–	Running	Process_1 now done

Figure 4.3: **Tracing Process State: CPU Only**

In this next example, the first process issues an I/O after running for some time. At that point, the process is blocked, giving the other process a chance to run. Figure 4.4 shows a trace of this scenario.

More specifically, Process_0 initiates an I/O and becomes blocked waiting for it to complete; processes become blocked, for example, when read-

Time	Process_0	Process_1	Notes
1	Running	Ready	
2	Running	Ready	
3	Running	Ready	Process_0 initiates I/O
4	Blocked	Running	Process_0 is blocked,
5	Blocked	Running	so Process_1 runs
6	Blocked	Running	
7	Ready	Running	I/O done
8	Ready	Running	Process_1 now done
9	Running	–	
10	Running	–	Process_0 now done

Figure 4.4: **Tracing Process State: CPU and I/O**

ing from a disk or waiting for a packet from a network. The OS recognizes Process_0 is not using the CPU and starts running Process_1. While Process_1 is running, the I/O completes, moving Process_0 back to ready. Finally, Process_1 finishes, and Process_0 runs and then is done.

Note that there are many decisions the OS must make, even in this simple example. First, the system had to decide to run Process_1 while Process_0 issued an I/O; doing so improves resource utilization by keeping the CPU busy. Second, the system decided not to switch back to Process_0 when its I/O completed; it is not clear if this is a good decision or not. What do you think? These types of decisions are made by the OS **scheduler**, a topic we will discuss a few chapters in the future.

4.5 Data Structures

The OS is a program, and like any program, it has some key data structures that track various relevant pieces of information. To track the state of each process, for example, the OS likely will keep some kind of **process list** for all processes that are ready, as well as some additional information to track which process is currently running. The OS must also track, in some way, blocked processes; when an I/O event completes, the OS should make sure to wake the correct process and ready it to run again.

Figure 4.5 shows what type of information an OS needs to track about each process in the xv6 kernel [CK+08]. Similar process structures exist in "real" operating systems such as Linux, Mac OS X, or Windows; look them up and see how much more complex they are.

From the figure, you can see a couple of important pieces of information the OS tracks about a process. The **register context** will hold, for a stopped process, the contents of its registers. When a process is stopped, its registers will be saved to this memory location; by restoring these registers (i.e., placing their values back into the actual physical registers), the OS can resume running the process. We'll learn more about this technique known as a **context switch** in future chapters.

```
// the registers xv6 will save and restore
// to stop and subsequently restart a process
struct context {
  int eip;
  int esp;
  int ebx;
  int ecx;
  int edx;
  int esi;
  int edi;
  int ebp;
};

// the different states a process can be in
enum proc_state { UNUSED, EMBRYO, SLEEPING,
                  RUNNABLE, RUNNING, ZOMBIE };

// the information xv6 tracks about each process
// including its register context and state
struct proc {
  char *mem;                  // Start of process memory
  uint sz;                    // Size of process memory
  char *kstack;               // Bottom of kernel stack
                              // for this process
  enum proc_state state;      // Process state
  int pid;                    // Process ID
  struct proc *parent;        // Parent process
  void *chan;                 // If non-zero, sleeping on chan
  int killed;                 // If non-zero, have been killed
  struct file *ofile[NOFILE]; // Open files
  struct inode *cwd;          // Current directory
  struct context context;     // Switch here to run process
  struct trapframe *tf;       // Trap frame for the
                              // current interrupt
};
```

Figure 4.5: **The xv6 Proc Structure**

You can also see from the figure that there are some other states a process can be in, beyond running, ready, and blocked. Sometimes a system will have an **initial** state that the process is in when it is being created. Also, a process could be placed in a **final** state where it has exited but has not yet been cleaned up (in UNIX-based systems, this is called the **zombie** state[1]). This final state can be useful as it allows other processes (usually the **parent** that created the process) to examine the return code of the process and see if the just-finished process executed successfully (usually, programs return zero in UNIX-based systems when they have accomplished a task successfully, and non-zero otherwise). When finished, the parent will make one final call (e.g., `wait()`) to wait for the completion of the child, and to also indicate to the OS that it can clean up any relevant data structures that referred to the now-extinct process.

[1] Yes, the zombie state. Just like real zombies, these zombies are relatively easy to kill. However, different techniques are usually recommended.

ASIDE: **DATA STRUCTURE — THE PROCESS LIST**
Operating systems are replete with various important **data structures** that we will discuss in these notes. The **process list** is the first such structure. It is one of the simpler ones, but certainly any OS that has the ability to run multiple programs at once will have something akin to this structure in order to keep track of all the running programs in the system. Sometimes people refer to the individual structure that stores information about a process as a **Process Control Block** (**PCB**), a fancy way of talking about a C structure that contains information about each process.

4.6 Summary

We have introduced the most basic abstraction of the OS: the process. It is quite simply viewed as a running program. With this conceptual view in mind, we will now move on to the nitty-gritty: the low-level mechanisms needed to implement processes, and the higher-level policies required to schedule them in an intelligent way. By combining mechanisms and policies, we will build up our understanding of how an operating system virtualizes the CPU.

References

[BH70] "The Nucleus of a Multiprogramming System"
Per Brinch Hansen
Communications of the ACM, Volume 13, Number 4, April 1970
*This paper introduces one of the first **microkernels** in operating systems history, called Nucleus. The idea of smaller, more minimal systems is a theme that rears its head repeatedly in OS history; it all began with Brinch Hansen's work described herein.*

[CK+08] "The xv6 Operating System"
Russ Cox, Frans Kaashoek, Robert Morris, Nickolai Zeldovich
From: http://pdos.csail.mit.edu/6.828/2008/index.html
The coolest real and little OS in the world. Download and play with it to learn more about the details of how operating systems actually work.

[DV66] "Programming Semantics for Multiprogrammed Computations"
Jack B. Dennis and Earl C. Van Horn
Communications of the ACM, Volume 9, Number 3, March 1966
This paper defined many of the early terms and concepts around building multiprogrammed systems.

[L+75] "Policy/mechanism separation in Hydra"
R. Levin, E. Cohen, W. Corwin, F. Pollack, W. Wulf
SOSP 1975
An early paper about how to structure operating systems in a research OS known as Hydra. While Hydra never became a mainstream OS, some of its ideas influenced OS designers.

[V+65] "Structure of the Multics Supervisor"
V.A. Vyssotsky, F. J. Corbato, R. M. Graham
Fall Joint Computer Conference, 1965
An early paper on Multics, which described many of the basic ideas and terms that we find in modern systems. Some of the vision behind computing as a utility are finally being realized in modern cloud systems.

Homework

ASIDE: **SIMULATION HOMEWORKS**

Simulation homeworks come in the form of simulators you run to make sure you understand some piece of the material. The simulators are generally python programs that enable you both to *generate* different problems (using different random seeds) as well as to have the program solve the problem for you (with the `-c` flag) so that you can check your answers. Running any simulator with a `-h` or `--help` flag will provide with more information as to all the options the simulator gives you.

The README provided with each simulator gives more detail as to how to run it. Each flag is described in some detail therein.

This program, `process-run.py`, allows you to see how process states change as programs run and either use the CPU (e.g., perform an add instruction) or do I/O (e.g., send a request to a disk and wait for it to complete). See the README for details.

Questions

1. Run the program with the following flags: `./process-run.py -l 5:100,5:100`. What should the CPU utilization be (e.g., the percent of time the CPU is in use?) Why do you know this? Use the `-c` and `-p` flags to see if you were right.
2. Now run with these flags: `./process-run.py -l 4:100,1:0`. These flags specify one process with 4 instructions (all to use the CPU), and one that simply issues an I/O and waits for it to be done. How long does it take to complete both processes? Use `-c` and `-p` to find out if you were right.
3. Now switch the order of the processes: `./process-run.py -l 1:0,4:100`. What happens now? Does switching the order matter? Why? (As always, use `-c` and `-p` to see if you were right)
4. We'll now explore some of the other flags. One important flag is `-S`, which determines how the system reacts when a process issues an I/O. With the flag set to SWITCH_ON_END, the system will NOT switch to another process while one is doing I/O, instead waiting until the process is completely finished. What happens when you run the following two processes, one doing I/O and the other doing CPU work? (`-l 1:0,4:100 -c -S SWITCH_ON_END`)
5. Now, run the same processes, but with the switching behavior set to switch to another process whenever one is WAITING for I/O (`-l 1:0,4:100 -c -S SWITCH_ON_IO`). What happens now? Use `-c` and `-p` to confirm that you are right.
6. One other important behavior is what to do when an I/O completes. With `-I IO_RUN_LATER`, when an I/O completes, the pro-

cess that issued it is not necessarily run right away; rather, whatever was running at the time keeps running. What happens when you run this combination of processes? (`./process-run.py -l 3:0,5:100,5:100,5:100 -S SWITCH_ON_IO -I IO_RUN_LATER -c -p`) Are system resources being effectively utilized?

7. Now run the same processes, but with `-I IO_RUN_IMMEDIATE` set, which immediately runs the process that issued the I/O. How does this behavior differ? Why might running a process that just completed an I/O again be a good idea?
8. Now run with some randomly generated processes, e.g., `-s 1 -l 3:50,3:50, -s 2 -l 3:50,3:50, -s 3 -l 3:50,3:50`. See if you can predict how the trace will turn out. What happens when you use `-I IO_RUN_IMMEDIATE` vs. `-I IO_RUN_LATER`? What happens when you use `-S SWITCH_ON_IO` vs. `-S SWITCH_ON_END`?

5

Interlude: Process API

ASIDE: **INTERLUDES**
Interludes will cover more practical aspects of systems, including a particular focus on operating system APIs and how to use them. If you don't like practical things, you could skip these interludes. But you should like practical things, because, well, they are generally useful in real life; companies, for example, don't usually hire you for your non-practical skills.

In this interlude, we discuss process creation in UNIX systems. UNIX presents one of the most intriguing ways to create a new process with a pair of system calls: `fork()` and `exec()`. A third routine, `wait()`, can be used by a process wishing to wait for a process it has created to complete. We now present these interfaces in more detail, with a few simple examples to motivate us. And thus, our problem:

CRUX: HOW TO CREATE AND CONTROL PROCESSES
What interfaces should the OS present for process creation and control? How should these interfaces be designed to enable ease of use as well as utility?

5.1 The `fork()` System Call

The `fork()` system call is used to create a new process [C63]. However, be forewarned: it is certainly the strangest routine you will ever call[1]. More specifically, you have a running program whose code looks like what you see in Figure 5.1; examine the code, or better yet, type it in and run it yourself!

[1] Well, OK, we admit that we don't know that for sure; who knows what routines you call when no one is looking? But `fork()` is pretty odd, no matter how unusual your routine-calling patterns are.

```
1  #include <stdio.h>
2  #include <stdlib.h>
3  #include <unistd.h>
4
5  int
6  main(int argc, char *argv[])
7  {
8      printf("hello world (pid:%d)\n", (int) getpid());
9      int rc = fork();
10     if (rc < 0) {          // fork failed; exit
11         fprintf(stderr, "fork failed\n");
12         exit(1);
13     } else if (rc == 0) { // child (new process)
14         printf("hello, I am child (pid:%d)\n", (int) getpid());
15     } else {               // parent goes down this path (main)
16         printf("hello, I am parent of %d (pid:%d)\n",
17                rc, (int) getpid());
18     }
19     return 0;
20 }
```

Figure 5.1: **Calling `fork()` (`p1.c`)**

When you run this program (called `p1.c`), you'll see the following:

```
prompt> ./p1
hello world (pid:29146)
hello, I am parent of 29147 (pid:29146)
hello, I am child (pid:29147)
prompt>
```

Let us understand what happened in more detail in `p1.c`. When it first started running, the process prints out a hello world message; included in that message is its **process identifier**, also known as a **PID**. The process has a PID of 29146; in UNIX systems, the PID is used to name the process if one wants to do something with the process, such as (for example) stop it from running. So far, so good.

Now the interesting part begins. The process calls the `fork()` system call, which the OS provides as a way to create a new process. The odd part: the process that is created is an (almost) *exact copy of the calling process*. That means that to the OS, it now looks like there are two copies of the program `p1` running, and both are about to return from the `fork()` system call. The newly-created process (called the **child**, in contrast to the creating **parent**) doesn't start running at `main()`, like you might expect (note, the "hello, world" message only got printed out once); rather, it just comes into life as if it had called `fork()` itself.

You might have noticed: the child isn't an *exact* copy. Specifically, although it now has its own copy of the address space (i.e., its own private memory), its own registers, its own PC, and so forth, the value it returns to the caller of **fork()** is different. Specifically, while the parent receives the PID of the newly-created child, the child is simply returned a 0. This differentiation is useful, because it is simple then to write the code that handles the two different cases (as above).

```
1  #include <stdio.h>
2  #include <stdlib.h>
3  #include <unistd.h>
4  #include <sys/wait.h>
5
6  int
7  main(int argc, char *argv[])
8  {
9      printf("hello world (pid:%d)\n", (int) getpid());
10     int rc = fork();
11     if (rc < 0) {          // fork failed; exit
12         fprintf(stderr, "fork failed\n");
13         exit(1);
14     } else if (rc == 0) { // child (new process)
15         printf("hello, I am child (pid:%d)\n", (int) getpid());
16     } else {               // parent goes down this path (main)
17         int wc = wait(NULL);
18         printf("hello, I am parent of %d (wc:%d) (pid:%d)\n",
19                rc, wc, (int) getpid());
20     }
21     return 0;
22 }
```

Figure 5.2: **Calling `fork()` And `wait()` (`p2.c`)**

You might also have noticed: the output (of `p1.c`) is not **deterministic**. When the child process is created, there are now two active processes in the system that we care about: the parent and the child. Assuming we are running on a system with a single CPU (for simplicity), then either the child or the parent might run at that point. In our example (above), the parent did and thus printed out its message first. In other cases, the opposite might happen, as we show in this output trace:

```
prompt> ./p1
hello world (pid:29146)
hello, I am child (pid:29147)
hello, I am parent of 29147 (pid:29146)
prompt>
```

The CPU **scheduler**, a topic we'll discuss in great detail soon, determines which process runs at a given moment in time; because the scheduler is complex, we cannot usually make strong assumptions about what it will choose to do, and hence which process will run first. This **nondeterminism**, as it turns out, leads to some interesting problems, particularly in **multi-threaded programs**; hence, we'll see a lot more nondeterminism when we study **concurrency** in the second part of the book.

5.2 The `wait()` System Call

So far, we haven't done much: just created a child that prints out a message and exits. Sometimes, as it turns out, it is quite useful for a parent to wait for a child process to finish what it has been doing. This task is accomplished with the `wait()` system call (or its more complete sibling `waitpid()`); see Figure 5.2 for details.

In this example (`p2.c`), the parent process calls `wait()` to delay its execution until the child finishes executing. When the child is done, `wait()` returns to the parent.

Adding a `wait()` call to the code above makes the output deterministic. Can you see why? Go ahead, think about it.

(waiting for you to think .... and done)

Now that you have thought a bit, here is the output:

```
prompt> ./p2
hello world (pid:29266)
hello, I am child (pid:29267)
hello, I am parent of 29267 (wc:29267) (pid:29266)
prompt>
```

With this code, we now know that the child will always print first. Why do we know that? Well, it might simply run first, as before, and thus print before the parent. However, if the parent does happen to run first, it will immediately call `wait()`; this system call won't return until the child has run and exited[2]. Thus, even when the parent runs first, it politely waits for the child to finish running, then `wait()` returns, and then the parent prints its message.

5.3 Finally, The `exec()` System Call

A final and important piece of the process creation API is the `exec()` system call[3]. This system call is useful when you want to run a program that is different from the calling program. For example, calling `fork()` in `p2.c` is only useful if you want to keep running copies of the same program. However, often you want to run a *different* program; `exec()` does just that (Figure 5.3, page 5).

In this example, the child process calls `execvp()` in order to run the program `wc`, which is the word counting program. In fact, it runs `wc` on the source file `p3.c`, thus telling us how many lines, words, and bytes are found in the file:

```
prompt> ./p3
hello world (pid:29383)
hello, I am child (pid:29384)
      29     107    1030 p3.c
hello, I am parent of 29384 (wc:29384) (pid:29383)
prompt>
```

[2] There are a few cases where `wait()` returns before the child exits; read the man page for more details, as always. And beware of any absolute and unqualified statements this book makes, such as "the child will always print first" or "UNIX is the best thing in the world, even better than ice cream."

[3] Actually, there are six variants of `exec()`: `execl()`, `execle()`, `execlp()`, `execv()`, and `execvp()`. Read the man pages to learn more.

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <string.h>
#include <sys/wait.h>

int
main(int argc, char *argv[])
{
    printf("hello world (pid:%d)\n", (int) getpid());
    int rc = fork();
    if (rc < 0) {         // fork failed; exit
        fprintf(stderr, "fork failed\n");
        exit(1);
    } else if (rc == 0) { // child (new process)
        printf("hello, I am child (pid:%d)\n", (int) getpid());
        char *myargs[3];
        myargs[0] = strdup("wc");   // program: "wc" (word count)
        myargs[1] = strdup("p3.c"); // argument: file to count
        myargs[2] = NULL;           // marks end of array
        execvp(myargs[0], myargs);  // runs word count
        printf("this shouldn't print out");
    } else {              // parent goes down this path (main)
        int wc = wait(NULL);
        printf("hello, I am parent of %d (wc:%d) (pid:%d)\n",
               rc, wc, (int) getpid());
    }
    return 0;
}
```

Figure 5.3: **Calling `fork()`, `wait()`, And `exec()` (`p3.c`)**

The `fork()` system call is strange; its partner in crime, `exec()`, is not so normal either. What it does: given the name of an executable (e.g., `wc`), and some arguments (e.g., `p3.c`), it **loads** code (and static data) from that executable and overwrites its current code segment (and current static data) with it; the heap and stack and other parts of the memory space of the program are re-initialized. Then the OS simply runs that program, passing in any arguments as the `argv` of that process. Thus, it does *not* create a new process; rather, it transforms the currently running program (formerly `p3`) into a different running program (`wc`). After the `exec()` in the child, it is almost as if `p3.c` never ran; a successful call to `exec()` never returns.

5.4 Why? Motivating The API

Of course, one big question you might have: why would we build such an odd interface to what should be the simple act of creating a new process? Well, as it turns out, the separation of `fork()` and `exec()` is essential in building a UNIX shell, because it lets the shell run code *after* the call to `fork()` but *before* the call to `exec()`; this code can alter the environment of the about-to-be-run program, and thus enables a variety of interesting features to be readily built.

TIP: GETTING IT RIGHT (LAMPSON'S LAW)

As Lampson states in his well-regarded "Hints for Computer Systems Design" [L83], "**Get it right**. Neither abstraction nor simplicity is a substitute for getting it right." Sometimes, you just have to do the right thing, and when you do, it is way better than the alternatives. There are lots of ways to design APIs for process creation; however, the combination of `fork()` and `exec()` are simple and immensely powerful. Here, the UNIX designers simply got it right. And because Lampson so often "got it right", we name the law in his honor.

The shell is just a user program[4]. It shows you a **prompt** and then waits for you to type something into it. You then type a command (i.e., the name of an executable program, plus any arguments) into it; in most cases, the shell then figures out where in the file system the executable resides, calls `fork()` to create a new child process to run the command, calls some variant of `exec()` to run the command, and then waits for the command to complete by calling `wait()`. When the child completes, the shell returns from `wait()` and prints out a prompt again, ready for your next command.

The separation of `fork()` and `exec()` allows the shell to do a whole bunch of useful things rather easily. For example:

```
prompt> wc p3.c > newfile.txt
```

In the example above, the output of the program `wc` is **redirected** into the output file `newfile.txt` (the greater-than sign is how said redirection is indicated). The way the shell accomplishes this task is quite simple: when the child is created, before calling `exec()`, the shell closes **standard output** and opens the file `newfile.txt`. By doing so, any output from the soon-to-be-running program `wc` are sent to the file instead of the screen.

Figure 5.4 shows a program that does exactly this. The reason this redirection works is due to an assumption about how the operating system manages file descriptors. Specifically, UNIX systems start looking for free file descriptors at zero. In this case, STDOUT_FILENO will be the first available one and thus get assigned when `open()` is called. Subsequent writes by the child process to the standard output file descriptor, for example by routines such as `printf()`, will then be routed transparently to the newly-opened file instead of the screen.

Here is the output of running the `p4.c` program:

```
prompt> ./p4
prompt> cat p4.output
      32     109     846 p4.c
prompt>
```

[4] And there are lots of shells; `tcsh`, `bash`, and `zsh` to name a few. You should pick one, read its man pages, and learn more about it; all UNIX experts do.

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <string.h>
#include <fcntl.h>
#include <sys/wait.h>

int
main(int argc, char *argv[])
{
    int rc = fork();
    if (rc < 0) {          // fork failed; exit
        fprintf(stderr, "fork failed\n");
        exit(1);
    } else if (rc == 0) { // child: redirect standard output to a file
        close(STDOUT_FILENO);
        open("./p4.output", O_CREAT|O_WRONLY|O_TRUNC, S_IRWXU);

        // now exec "wc"...
        char *myargs[3];
        myargs[0] = strdup("wc");   // program: "wc" (word count)
        myargs[1] = strdup("p4.c"); // argument: file to count
        myargs[2] = NULL;           // marks end of array
        execvp(myargs[0], myargs);  // runs word count
    } else {                // parent goes down this path (main)
        int wc = wait(NULL);
    }
    return 0;
}
```

Figure 5.4: **All Of The Above With Redirection (`p4.c`)**

You'll notice (at least) two interesting tidbits about this output. First, when `p4` is run, it looks as if nothing has happened; the shell just prints the command prompt and is immediately ready for your next command. However, that is not the case; the program `p4` did indeed call `fork()` to create a new child, and then run the `wc` program via a call to `execvp()`. You don't see any output printed to the screen because it has been redirected to the file `p4.output`. Second, you can see that when we `cat` the output file, all the expected output from running `wc` is found. Cool, right?

UNIX pipes are implemented in a similar way, but with the `pipe()` system call. In this case, the output of one process is connected to an in-kernel **pipe** (i.e., queue), and the input of another process is connected to that same pipe; thus, the output of one process seamlessly is used as input to the next, and long and useful chains of commands can be strung together. As a simple example, consider looking for a word in a file, and then counting how many times said word occurs; with pipes and the utilities `grep` and `wc`, it is easy — just type `grep -o foo file | wc -l` into the command prompt and marvel at the result.

Finally, while we just have sketched out the process API at a high level, there is a lot more detail about these calls out there to be learned and digested; we'll learn more, for example, about file descriptors when we talk about file systems in the third part of the book. For now, suffice it to say that the `fork()/exec()` combination is a powerful way to create and manipulate processes.

ASIDE: **RTFM — READ THE MAN PAGES**

Many times in this book, when referring to a particular system call or library call, we'll tell you to read the **manual pages**, or **man pages** for short. Man pages are the original form of documentation that exist on UNIX systems; realize that they were created before the thing called **the web** existed.

Spending some time reading man pages is a key step in the growth of a systems programmer; there are tons of useful tidbits hidden in those pages. Some particularly useful pages to read are the man pages for whichever shell you are using (e.g., **tcsh**, or **bash**), and certainly for any system calls your program makes (in order to see what return values and error conditions exist).

Finally, reading the man pages can save you some embarrassment. When you ask colleagues about some intricacy of `fork()`, they may simply reply: "RTFM." This is your colleagues' way of gently urging you to Read The Man pages. The F in RTFM just adds a little color to the phrase...

5.5 Other Parts Of The API

Beyond `fork()`, `exec()`, and `wait()`, there are a lot of other interfaces for interacting with processes in UNIX systems. For example, the `kill()` system call is used to send **signals** to a process, including directives to go to sleep, die, and other useful imperatives. In fact, the entire signals subsystem provides a rich infrastructure to deliver external events to processes, including ways to receive and process those signals.

There are many command-line tools that are useful as well. For example, using the `ps` command allows you to see which processes are running; read the **man pages** for some useful flags to pass to `ps`. The tool `top` is also quite helpful, as it displays the processes of the system and how much CPU and other resources they are eating up. Humorously, many times when you run it, `top` claims it is the top resource hog; perhaps it is a bit of an egomaniac. Finally, there are many different kinds of CPU meters you can use to get a quick glance understanding of the load on your system; for example, we always keep **MenuMeters** (from Raging Menace software) running on our Macintosh toolbars, so we can see how much CPU is being utilized at any moment in time. In general, the more information about what is going on, the better.

5.6 Summary

We have introduced some of the APIs dealing with UNIX process creation: `fork()`, `exec()`, and `wait()`. However, we have just skimmed the surface. For more detail, read Stevens and Rago [SR05], of course, particularly the chapters on Process Control, Process Relationships, and Signals. There is much to extract from the wisdom therein.

References

[C63] "A Multiprocessor System Design"
Melvin E. Conway
AFIPS '63 Fall Joint Computer Conference
New York, USA 1963
An early paper on how to design multiprocessing systems; may be the first place the term `fork()` was used in the discussion of spawning new processes.

[DV66] "Programming Semantics for Multiprogrammed Computations"
Jack B. Dennis and Earl C. Van Horn
Communications of the ACM, Volume 9, Number 3, March 1966
A classic paper that outlines the basics of multiprogrammed computer systems. Undoubtedly had great influence on Project MAC, Multics, and eventually UNIX.

[L83] "Hints for Computer Systems Design"
Butler Lampson
ACM Operating Systems Review, 15:5, October 1983
Lampson's famous hints on how to design computer systems. You should read it at some point in your life, and probably at many points in your life.

[SR05] "Advanced Programming in the UNIX Environment"
W. Richard Stevens and Stephen A. Rago
Addison-Wesley, 2005
All nuances and subtleties of using UNIX *APIs are found herein. Buy this book! Read it! And most importantly,* ***live it.***

ASIDE: **CODING HOMEWORKS**

Coding homeworks are small exercises where you write code to run on a real machine to get some experience with some of the basic APIs that modern operating systems have to offer. After all, you are (probably) a computer scientist, and therefore should like to code, right? Of course, to truly become an expert, you have to spend more than a little time hacking away at the machine; indeed, find every excuse you can to write some code and see how it works. Spend the time, and become the wise master you know you can be.

Homework (Code)

In this homework, you are to gain some familiarity with the process management APIs about which you just read. Don't worry – it's even more fun than it sounds! You'll in general be much better off if you find as much time as you can to write some code[5], so why not start now?

Questions

1. Write a program that calls `fork()`. Before calling `fork()`, have the main process access a variable (e.g., `x`) and set its value to something (e.g., `100`). What value is the variable in the child process? What happens to the variable when both the child and parent change the value of `x`?
2. Write a program that opens a file (with the `open()` system call) and then calls `fork()` to create a new process. Can both the child and parent access the file descriptor returned by `open()`? What happens when they are writing to the file concurrently, i.e., at the same time?
3. Write another program using `fork()`. The child process should print "hello"; the parent process should print "goodbye". You should try to ensure that the child process always prints first; can you do this *without* calling **wait()** in the parent?
4. Write a program that calls `fork()` and then calls some form of `exec()` to run the program `/bin/ls`. See if you can try all of the variants of `exec()`, including `execl()`, `execle()`, `execlp()`, `execv()`, `execvp()`, and `execvP()`. Why do you think there are so many variants of the same basic call?
5. Now write a program that uses `wait()` to wait for the child process to finish in the parent. What does `wait()` return? What happens if you use `wait()` in the child?

[5] If you don't like to code, but want to become a computer scientist, this means you need to either (a) become really good at the theory of computer science, or (b) perhaps rethink this whole "computer science" thing you've been telling everyone about.

6. Write a slight modification of the previous program, this time using `waitpid()` instead of `wait()`. When would `waitpid()` be useful?
7. Write a program that creates a child process, and then in the child closes standard output (`STDOUT_FILENO`). What happens if the child calls `printf()` to print some output after closing the descriptor?
8. Write a program that creates two children, and connects the standard output of one to the standard input of the other, using the `pipe()` system call.

6

Mechanism: Limited Direct Execution

In order to virtualize the CPU, the operating system needs to somehow share the physical CPU among many jobs running seemingly at the same time. The basic idea is simple: run one process for a little while, then run another one, and so forth. By **time sharing** the CPU in this manner, virtualization is achieved.

There are a few challenges, however, in building such virtualization machinery. The first is *performance*: how can we implement virtualization without adding excessive overhead to the system? The second is *control*: how can we run processes efficiently while retaining control over the CPU? Control is particularly important to the OS, as it is in charge of resources; without control, a process could simply run forever and take over the machine, or access information that it should not be allowed to access. Obtaining high performance while maintaining control is thus one of the central challenges in building an operating system.

THE CRUX:
HOW TO EFFICIENTLY VIRTUALIZE THE CPU WITH CONTROL

The OS must virtualize the CPU in an efficient manner while retaining control over the system. To do so, both hardware and operating-system support will be required. The OS will often use a judicious bit of hardware support in order to accomplish its work effectively.

6.1 Basic Technique: Limited Direct Execution

To make a program run as fast as one might expect, not surprisingly OS developers came up with a technique, which we call **limited direct execution**. The "direct execution" part of the idea is simple: just run the program directly on the CPU. Thus, when the OS wishes to start a program running, it creates a process entry for it in a process list, allocates some memory for it, loads the program code into memory (from disk), locates its entry point (i.e., the `main()` routine or something similar), jumps

OS	Program
Create entry for process list	
Allocate memory for program	
Load program into memory	
Set up stack with argc/argv	
Clear registers	
Execute **call** main()	
	Run main()
	Execute **return** from main
Free memory of process	
Remove from process list	

Figure 6.1: **Direct Execution Protocol (Without Limits)**

to it, and starts running the user's code. Figure 6.1 shows this basic direct execution protocol (without any limits, yet), using a normal call and return to jump to the program's `main()` and later to get back into the kernel.

Sounds simple, no? But this approach gives rise to a few problems in our quest to virtualize the CPU. The first is simple: if we just run a program, how can the OS make sure the program doesn't do anything that we don't want it to do, while still running it efficiently? The second: when we are running a process, how does the operating system stop it from running and switch to another process, thus implementing the **time sharing** we require to virtualize the CPU?

In answering these questions below, we'll get a much better sense of what is needed to virtualize the CPU. In developing these techniques, we'll also see where the "limited" part of the name arises from; without limits on running programs, the OS wouldn't be in control of anything and thus would be "just a library" — a very sad state of affairs for an aspiring operating system!

6.2 Problem #1: Restricted Operations

Direct execution has the obvious advantage of being fast; the program runs natively on the hardware CPU and thus executes as quickly as one would expect. But running on the CPU introduces a problem: what if the process wishes to perform some kind of restricted operation, such as issuing an I/O request to a disk, or gaining access to more system resources such as CPU or memory?

THE CRUX: HOW TO PERFORM RESTRICTED OPERATIONS

A process must be able to perform I/O and some other restricted operations, but without giving the process complete control over the system. How can the OS and hardware work together to do so?

TIP: USE PROTECTED CONTROL TRANSFER
The hardware assists the OS by providing different modes of execution. In **user mode**, applications do not have full access to hardware resources. In **kernel mode**, the OS has access to the full resources of the machine. Special instructions to **trap** into the kernel and **return-from-trap** back to user-mode programs are also provided, as well instructions that allow the OS to tell the hardware where the **trap table** resides in memory.

One approach would simply be to let any process do whatever it wants in terms of I/O and other related operations. However, doing so would prevent the construction of many kinds of systems that are desirable. For example, if we wish to build a file system that checks permissions before granting access to a file, we can't simply let any user process issue I/Os to the disk; if we did, a process could simply read or write the entire disk and thus all protections would be lost.

Thus, the approach we take is to introduce a new processor mode, known as **user mode**; code that runs in user mode is restricted in what it can do. For example, when running in user mode, a process can't issue I/O requests; doing so would result in the processor raising an exception; the OS would then likely kill the process.

In contrast to user mode is **kernel mode**, which the operating system (or kernel) runs in. In this mode, code that runs can do what it likes, including privileged operations such as issuing I/O requests and executing all types of restricted instructions.

We are still left with a challenge, however: what should a user process do when it wishes to perform some kind of privileged operation, such as reading from disk? To enable this, virtually all modern hardware provides the ability for user programs to perform a **system call**. Pioneered on ancient machines such as the Atlas [K+61,L78], system calls allow the kernel to carefully expose certain key pieces of functionality to user programs, such as accessing the file system, creating and destroying processes, communicating with other processes, and allocating more memory. Most operating systems provide a few hundred calls (see the POSIX standard for details [P10]); early Unix systems exposed a more concise subset of around twenty calls.

To execute a system call, a program must execute a special **trap** instruction. This instruction simultaneously jumps into the kernel and raises the privilege level to kernel mode; once in the kernel, the system can now perform whatever privileged operations are needed (if allowed), and thus do the required work for the calling process. When finished, the OS calls a special **return-from-trap** instruction, which, as you might expect, returns into the calling user program while simultaneously reducing the privilege level back to user mode.

The hardware needs to be a bit careful when executing a trap, in that it must make sure to save enough of the caller's registers in order to be able

ASIDE: **WHY SYSTEM CALLS LOOK LIKE PROCEDURE CALLS**

You may wonder why a call to a system call, such as `open()` or `read()`, looks exactly like a typical procedure call in C; that is, if it looks just like a procedure call, how does the system know it's a system call, and do all the right stuff? The simple reason: it *is* a procedure call, but hidden inside that procedure call is the famous trap instruction. More specifically, when you call `open()` (for example), you are executing a procedure call into the C library. Therein, whether for `open()` or any of the other system calls provided, the library uses an agreed-upon calling convention with the kernel to put the arguments to open in well-known locations (e.g., on the stack, or in specific registers), puts the system-call number into a well-known location as well (again, onto the stack or a register), and then executes the aforementioned trap instruction. The code in the library after the trap unpacks return values and returns control to the program that issued the system call. Thus, the parts of the C library that make system calls are hand-coded in assembly, as they need to carefully follow convention in order to process arguments and return values correctly, as well as execute the hardware-specific trap instruction. And now you know why you personally don't have to write assembly code to trap into an OS; somebody has already written that assembly for you.

to return correctly when the OS issues the return-from-trap instruction. On x86, for example, the processor will push the program counter, flags, and a few other registers onto a per-process **kernel stack**; the return-from-trap will pop these values off the stack and resume execution of the user-mode program (see the Intel systems manuals [I11] for details). Other hardware systems use different conventions, but the basic concepts are similar across platforms.

There is one important detail left out of this discussion: how does the trap know which code to run inside the OS? Clearly, the calling process can't specify an address to jump to (as you would when making a procedure call); doing so would allow programs to jump anywhere into the kernel which clearly is a bad idea (imagine jumping into code to access a file, but just after a permission check; in fact, it is likely such an ability would enable a wily programmer to get the kernel to run arbitrary code sequences [S07]). Thus the kernel must carefully control what code executes upon a trap.

The kernel does so by setting up a **trap table** at boot time. When the machine boots up, it does so in privileged (kernel) mode, and thus is free to configure machine hardware as need be. One of the first things the OS thus does is to tell the hardware what code to run when certain exceptional events occur. For example, what code should run when a hard-disk interrupt takes place, when a keyboard interrupt occurs, or when a program makes a system call? The OS informs the hardware of the locations of these **trap handlers**, usually with some kind of special in-

OS @ boot (kernel mode)	**Hardware**	
initialize trap table		
	remember address of... syscall handler	

OS @ run (kernel mode)	**Hardware**	**Program (user mode)**
Create entry for process list		
Allocate memory for program		
Load program into memory		
Setup user stack with argv		
Fill kernel stack with reg/PC		
return-from-trap		
	restore regs from kernel stack	
	move to user mode	
	jump to main	
		Run main()
		...
		Call system call **trap** into OS
	save regs to kernel stack	
	move to kernel mode	
	jump to trap handler	
Handle trap		
Do work of syscall		
return-from-trap		
	restore regs from kernel stack	
	move to user mode	
	jump to PC after trap	
		...
		return from main **trap** (via `exit()`)
Free memory of process		
Remove from process list		

Figure 6.2: **Limited Direct Execution Protocol**

struction. Once the hardware is informed, it remembers the location of these handlers until the machine is next rebooted, and thus the hardware knows what to do (i.e., what code to jump to) when system calls and other exceptional events take place.

One last aside: being able to execute the instruction to tell the hardware where the trap tables are is a very powerful capability. Thus, as you might have guessed, it is also a **privileged** operation. If you try to execute this instruction in user mode, the hardware won't let you, and you can probably guess what will happen (hint: adios, offending program). Point to ponder: what horrible things could you do to a system if you could install your own trap table? Could you take over the machine?

The timeline (with time increasing downward, in Figure 6.2) summarizes the protocol. We assume each process has a kernel stack where registers (including general purpose registers and the program counter) are saved to and restored from (by the hardware) when transitioning into and out of the kernel.

There are two phases in the LDE protocol. In the first (at boot time), the kernel initializes the trap table, and the CPU remembers its location for subsequent use. The kernel does so via a privileged instruction (all privileged instructions are highlighted in bold).

In the second (when running a process), the kernel sets up a few things (e.g., allocating a node on the process list, allocating memory) before using a return-from-trap instruction to start the execution of the process; this switches the CPU to user mode and begins running the process. When the process wishes to issue a system call, it traps back into the OS, which handles it and once again returns control via a return-from-trap to the process. The process then completes its work, and returns from `main()`; this usually will return into some stub code which will properly exit the program (say, by calling the `exit()` system call, which traps into the OS). At this point, the OS cleans up and we are done.

6.3 Problem #2: Switching Between Processes

The next problem with direct execution is achieving a switch between processes. Switching between processes should be simple, right? The OS should just decide to stop one process and start another. What's the big deal? But it actually is a little bit tricky: specifically, if a process is running on the CPU, this by definition means the OS is *not* running. If the OS is not running, how can it do anything at all? (hint: it can't) While this sounds almost philosophical, it is a real problem: there is clearly no way for the OS to take an action if it is not running on the CPU. Thus we arrive at the crux of the problem.

THE CRUX: HOW TO REGAIN CONTROL OF THE CPU
How can the operating system **regain control** of the CPU so that it can switch between processes?

A Cooperative Approach: Wait For System Calls

One approach that some systems have taken in the past (for example, early versions of the Macintosh operating system [M11], or the old Xerox Alto system [A79]) is known as the **cooperative** approach. In this style, the OS *trusts* the processes of the system to behave reasonably. Processes that run for too long are assumed to periodically give up the CPU so that the OS can decide to run some other task.

Thus, you might ask, how does a friendly process give up the CPU in this utopian world? Most processes, as it turns out, transfer control of the CPU to the OS quite frequently by making **system calls**, for example, to open a file and subsequently read it, or to send a message to another machine, or to create a new process. Systems like this often include an

TIP: DEALING WITH APPLICATION MISBEHAVIOR
Operating systems often have to deal with misbehaving processes, those that either through design (maliciousness) or accident (bugs) attempt to do something that they shouldn't. In modern systems, the way the OS tries to handle such malfeasance is to simply terminate the offender. One strike and you're out! Perhaps brutal, but what else should the OS do when you try to access memory illegally or execute an illegal instruction?

explicit **yield** system call, which does nothing except to transfer control to the OS so it can run other processes.

Applications also transfer control to the OS when they do something illegal. For example, if an application divides by zero, or tries to access memory that it shouldn't be able to access, it will generate a **trap** to the OS. The OS will then have control of the CPU again (and likely terminate the offending process).

Thus, in a cooperative scheduling system, the OS regains control of the CPU by waiting for a system call or an illegal operation of some kind to take place. You might also be thinking: isn't this passive approach less than ideal? What happens, for example, if a process (whether malicious, or just full of bugs) ends up in an infinite loop, and never makes a system call? What can the OS do then?

A Non-Cooperative Approach: The OS Takes Control

Without some additional help from the hardware, it turns out the OS can't do much at all when a process refuses to make system calls (or mistakes) and thus return control to the OS. In fact, in the cooperative approach, your only recourse when a process gets stuck in an infinite loop is to resort to the age-old solution to all problems in computer systems: **reboot the machine**. Thus, we again arrive at a subproblem of our general quest to gain control of the CPU.

THE CRUX: HOW TO GAIN CONTROL WITHOUT COOPERATION
How can the OS gain control of the CPU even if processes are not being cooperative? What can the OS do to ensure a rogue process does not take over the machine?

The answer turns out to be simple and was discovered by a number of people building computer systems many years ago: a **timer interrupt** [M+63]. A timer device can be programmed to raise an interrupt every so many milliseconds; when the interrupt is raised, the currently running process is halted, and a pre-configured **interrupt handler** in the OS runs. At this point, the OS has regained control of the CPU, and thus can do what it pleases: stop the current process, and start a different one.

TIP: USE THE TIMER INTERRUPT TO REGAIN CONTROL
The addition of a **timer interrupt** gives the OS the ability to run again on a CPU even if processes act in a non-cooperative fashion. Thus, this hardware feature is essential in helping the OS maintain control of the machine.

As we discussed before with system calls, the OS must inform the hardware of which code to run when the timer interrupt occurs; thus, at boot time, the OS does exactly that. Second, also during the boot sequence, the OS must start the timer, which is of course a privileged operation. Once the timer has begun, the OS can thus feel safe in that control will eventually be returned to it, and thus the OS is free to run user programs. The timer can also be turned off (also a privileged operation), something we will discuss later when we understand concurrency in more detail.

Note that the hardware has some responsibility when an interrupt occurs, in particular to save enough of the state of the program that was running when the interrupt occurred such that a subsequent return-from-trap instruction will be able to resume the running program correctly. This set of actions is quite similar to the behavior of the hardware during an explicit system-call trap into the kernel, with various registers thus getting saved (e.g., onto a kernel stack) and thus easily restored by the return-from-trap instruction.

Saving and Restoring Context

Now that the OS has regained control, whether cooperatively via a system call, or more forcefully via a timer interrupt, a decision has to be made: whether to continue running the currently-running process, or switch to a different one. This decision is made by a part of the operating system known as the **scheduler**; we will discuss scheduling policies in great detail in the next few chapters.

If the decision is made to switch, the OS then executes a low-level piece of code which we refer to as a **context switch**. A context switch is conceptually simple: all the OS has to do is save a few register values for the currently-executing process (onto its kernel stack, for example) and restore a few for the soon-to-be-executing process (from its kernel stack). By doing so, the OS thus ensures that when the return-from-trap instruction is finally executed, instead of returning to the process that was running, the system resumes execution of another process.

To save the context of the currently-running process, the OS will execute some low-level assembly code to save the general purpose registers, PC, as well as the kernel stack pointer of the currently-running process, and then restore said registers, PC, and switch to the kernel stack for the soon-to-be-executing process. By switching stacks, the kernel enters the

OS @ boot (kernel mode)	Hardware	
initialize trap table		
	remember addresses of...	
	syscall handler	
	timer handler	
start interrupt timer		
	start timer	
	interrupt CPU in X ms	

OS @ run (kernel mode)	Hardware	Program (user mode)
		Process A
		...
	timer interrupt	
	save regs(A) to k-stack(A)	
	move to kernel mode	
	jump to trap handler	
Handle the trap		
Call `switch()` routine		
save regs(A) to proc-struct(A)		
restore regs(B) from proc-struct(B)		
switch to k-stack(B)		
return-from-trap (into B)		
	restore regs(B) from k-stack(B)	
	move to user mode	
	jump to B's PC	
		Process B
		...

Figure 6.3: **Limited Direct Execution Protocol (Timer Interrupt)**

call to the switch code in the context of one process (the one that was interrupted) and returns in the context of another (the soon-to-be-executing one). When the OS then finally executes a return-from-trap instruction, the soon-to-be-executing process becomes the currently-running process. And thus the context switch is complete.

A timeline of the entire process is shown in Figure 6.3. In this example, Process A is running and then is interrupted by the timer interrupt. The hardware saves its registers (onto its kernel stack) and enters the kernel (switching to kernel mode). In the timer interrupt handler, the OS decides to switch from running Process A to Process B. At that point, it calls the `switch()` routine, which carefully saves current register values (into the process structure of A), restores the registers of Process B (from its process structure entry), and then **switches contexts**, specifically by changing the stack pointer to use B's kernel stack (and not A's). Finally, the OS returns-from-trap, which restores B's registers and starts running it.

Note that there are two types of register saves/restores that happen during this protocol. The first is when the timer interrupt occurs; in this case, the *user registers* of the running process are implicitly saved by the *hardware*, using the kernel stack of that process. The second is when the OS decides to switch from A to B; in this case, the *kernel registers* are ex-

```
1  # void swtch(struct context **old, struct context *new);
2  #
3  # Save current register context in old
4  # and then load register context from new.
5  .globl swtch
6  swtch:
7    # Save old registers
8    movl 4(%esp), %eax  # put old ptr into eax
9    popl 0(%eax)        # save the old IP
10   movl %esp, 4(%eax)  # and stack
11   movl %ebx, 8(%eax)  # and other registers
12   movl %ecx, 12(%eax)
13   movl %edx, 16(%eax)
14   movl %esi, 20(%eax)
15   movl %edi, 24(%eax)
16   movl %ebp, 28(%eax)
17
18   # Load new registers
19   movl 4(%esp), %eax  # put new ptr into eax
20   movl 28(%eax), %ebp # restore other registers
21   movl 24(%eax), %edi
22   movl 20(%eax), %esi
23   movl 16(%eax), %edx
24   movl 12(%eax), %ecx
25   movl 8(%eax), %ebx
26   movl 4(%eax), %esp  # stack is switched here
27   pushl 0(%eax)       # return addr put in place
28   ret                 # finally return into new ctxt
```

Figure 6.4: **The xv6 Context Switch Code**

plicitly saved by the *software* (i.e., the OS), but this time into memory in the process structure of the process. The latter action moves the system from running as if it just trapped into the kernel from A to as if it just trapped into the kernel from B.

To give you a better sense of how such a switch is enacted, Figure 6.4 shows the context switch code for xv6. See if you can make sense of it (you'll have to know a bit of x86, as well as some xv6, to do so). The `context` structures `old` and `new` are found in the old and new process's process structures, respectively.

6.4 Worried About Concurrency?

Some of you, as attentive and thoughtful readers, may be now thinking: "Hmm... what happens when, during a system call, a timer interrupt occurs?" or "What happens when you're handling one interrupt and another one happens? Doesn't that get hard to handle in the kernel?" Good questions — we really have some hope for you yet!

The answer is yes, the OS does indeed need to be concerned as to what happens if, during interrupt or trap handling, another interrupt occurs. This, in fact, is the exact topic of the entire second piece of this book, on **concurrency**; we'll defer a detailed discussion until then.

ASIDE: **HOW LONG CONTEXT SWITCHES TAKE**

A natural question you might have is: how long does something like a context switch take? Or even a system call? For those of you that are curious, there is a tool called **lmbench** [MS96] that measures exactly those things, as well as a few other performance measures that might be relevant.

Results have improved quite a bit over time, roughly tracking processor performance. For example, in 1996 running Linux 1.3.37 on a 200-MHz P6 CPU, system calls took roughly 4 microseconds, and a context switch roughly 6 microseconds [MS96]. Modern systems perform almost an order of magnitude better, with sub-microsecond results on systems with 2- or 3-GHz processors.

It should be noted that not all operating-system actions track CPU performance. As Ousterhout observed, many OS operations are memory intensive, and memory bandwidth has not improved as dramatically as processor speed over time [O90]. Thus, depending on your workload, buying the latest and greatest processor may not speed up your OS as much as you might hope.

To whet your appetite, we'll just sketch some basics of how the OS handles these tricky situations. One simple thing an OS might do is **disable interrupts** during interrupt processing; doing so ensures that when one interrupt is being handled, no other one will be delivered to the CPU. Of course, the OS has to be careful in doing so; disabling interrupts for too long could lead to lost interrupts, which is (in technical terms) bad.

Operating systems also have developed a number of sophisticated **locking** schemes to protect concurrent access to internal data structures. This enables multiple activities to be on-going within the kernel at the same time, particularly useful on multiprocessors. As we'll see in the next piece of this book on concurrency, though, such locking can be complicated and lead to a variety of interesting and hard-to-find bugs.

6.5 Summary

We have described some key low-level mechanisms to implement CPU virtualization, a set of techniques which we collectively refer to as **limited direct execution**. The basic idea is straightforward: just run the program you want to run on the CPU, but first make sure to set up the hardware so as to limit what the process can do without OS assistance.

This general approach is taken in real life as well. For example, those of you who have children, or, at least, have heard of children, may be familiar with the concept of **baby proofing** a room: locking cabinets containing dangerous stuff and covering electrical sockets. When the room is thus readied, you can let your baby roam freely, secure in the knowledge that the most dangerous aspects of the room have been restricted.

TIP: REBOOT IS USEFUL

Earlier on, we noted that the only solution to infinite loops (and similar behaviors) under cooperative preemption is to **reboot** the machine. While you may scoff at this hack, researchers have shown that reboot (or in general, starting over some piece of software) can be a hugely useful tool in building robust systems [C+04].

Specifically, reboot is useful because it moves software back to a known and likely more tested state. Reboots also reclaim stale or leaked resources (e.g., memory) which may otherwise be hard to handle. Finally, reboots are easy to automate. For all of these reasons, it is not uncommon in large-scale cluster Internet services for system management software to periodically reboot sets of machines in order to reset them and thus obtain the advantages listed above.

Thus, next time you reboot, you are not just enacting some ugly hack. Rather, you are using a time-tested approach to improving the behavior of a computer system. Well done!

In an analogous manner, the OS "baby proofs" the CPU, by first (during boot time) setting up the trap handlers and starting an interrupt timer, and then by only running processes in a restricted mode. By doing so, the OS can feel quite assured that processes can run efficiently, only requiring OS intervention to perform privileged operations or when they have monopolized the CPU for too long and thus need to be switched out.

We thus have the basic mechanisms for virtualizing the CPU in place. But a major question is left unanswered: which process should we run at a given time? It is this question that the scheduler must answer, and thus the next topic of our study.

References

[A79] "Alto User's Handbook"
Xerox Palo Alto Research Center, September 1979
Available: http://history-computer.com/Library/AltoUsersHandbook.pdf
An amazing system, way ahead of its time. Became famous because Steve Jobs visited, took notes, and built Lisa and eventually Mac.

[C+04] "Microreboot — A Technique for Cheap Recovery"
George Candea, Shinichi Kawamoto, Yuichi Fujiki, Greg Friedman, Armando Fox
OSDI '04, San Francisco, CA, December 2004
An excellent paper pointing out how far one can go with reboot in building more robust systems.

[I11] "Intel 64 and IA-32 Architectures Software Developer's Manual"
Volume 3A and 3B: System Programming Guide
Intel Corporation, January 2011

[K+61] "One-Level Storage System"
T. Kilburn, D.B.G. Edwards, M.J. Lanigan, F.H. Sumner
IRE Transactions on Electronic Computers, April 1962
The Atlas pioneered much of what you see in modern systems. However, this paper is not the best one to read. If you were to only read one, you might try the historical perspective below [L78].

[L78] "The Manchester Mark I and Atlas: A Historical Perspective"
S. H. Lavington
Communications of the ACM, 21:1, January 1978
A history of the early development of computers and the pioneering efforts of Atlas.

[M+63] "A Time-Sharing Debugging System for a Small Computer"
J. McCarthy, S. Boilen, E. Fredkin, J. C. R. Licklider
AFIPS '63 (Spring), May, 1963, New York, USA
An early paper about time-sharing that refers to using a timer interrupt; the quote that discusses it: "The basic task of the channel 17 clock routine is to decide whether to remove the current user from core and if so to decide which user program to swap in as he goes out."

[MS96] "lmbench: Portable tools for performance analysis"
Larry McVoy and Carl Staelin
USENIX Annual Technical Conference, January 1996
A fun paper about how to measure a number of different things about your OS and its performance. Download lmbench and give it a try.

[M11] "Mac OS 9"
January 2011
Available: http://en.wikipedia.org/wiki/Mac_OS_9

[O90] "Why Aren't Operating Systems Getting Faster as Fast as Hardware?"
J. Ousterhout
USENIX Summer Conference, June 1990
A classic paper on the nature of operating system performance.

[P10] "The Single UNIX Specification, Version 3"
The Open Group, May 2010
Available: http://www.unix.org/version3/
This is hard and painful to read, so probably avoid it if you can.

[S07] "The Geometry of Innocent Flesh on the Bone:
Return-into-libc without Function Calls (on the x86)"
Hovav Shacham
CCS '07, October 2007
One of those awesome, mind-blowing ideas that you'll see in research from time to time. The author shows that if you can jump into code arbitrarily, you can essentially stitch together any code sequence you like (given a large code base); read the paper for the details. The technique makes it even harder to defend against malicious attacks, alas.

Homework (Measurement)

ASIDE: **MEASUREMENT HOMEWORKS**
Measurement homeworks are small exercises where you write code to run on a real machine, in order to measure some aspect of OS or hardware performance. The idea behind such homeworks is to give you a little bit of hands-on experience with a real operating system.

In this homework, you'll measure the costs of a system call and context switch. Measuring the cost of a system call is relatively easy. For example, you could repeatedly call a simple system call (e.g., performing a 0-byte read), and time how long it takes; dividing the time by the number of iterations gives you an estimate of the cost of a system call.

One thing you'll have to take into account is the precision and accuracy of your timer. A typical timer that you can use is `gettimeofday()`; read the man page for details. What you'll see there is that `gettimeofday()` returns the time in microseconds since 1970; however, this does not mean that the timer is precise to the microsecond. Measure back-to-back calls to `gettimeofday()` to learn something about how precise the timer really is; this will tell you how many iterations of your null system-call test you'll have to run in order to get a good measurement result. If `gettimeofday()` is not precise enough for you, you might look into using the `rdtsc` instruction available on x86 machines.

Measuring the cost of a context switch is a little trickier. The lmbench benchmark does so by running two processes on a single CPU, and setting up two UNIX pipes between them; a pipe is just one of many ways processes in a UNIX system can communicate with one another. The first process then issues a write to the first pipe, and waits for a read on the second; upon seeing the first process waiting for something to read from the second pipe, the OS puts the first process in the blocked state, and switches to the other process, which reads from the first pipe and then writes to the second. When the second process tries to read from the first pipe again, it blocks, and thus the back-and-forth cycle of communication continues. By measuring the cost of communicating like this repeatedly, lmbench can make a good estimate of the cost of a context switch. You can try to re-create something similar here, using pipes, or perhaps some other communication mechanism such as UNIX sockets.

One difficulty in measuring context-switch cost arises in systems with more than one CPU; what you need to do on such a system is ensure that your context-switching processes are located on the same processor. Fortunately, most operating systems have calls to bind a process to a particular processor; on Linux, for example, the `sched_setaffinity()` call is what you're looking for. By ensuring both processes are on the same processor, you are making sure to measure the cost of the OS stopping one process and restoring another on the same CPU.

7

Scheduling: Introduction

By now low-level **mechanisms** of running processes (e.g., context switching) should be clear; if they are not, go back a chapter or two, and read the description of how that stuff works again. However, we have yet to understand the high-level **policies** that an OS scheduler employs. We will now do just that, presenting a series of **scheduling policies** (sometimes called **disciplines**) that various smart and hard-working people have developed over the years.

The origins of scheduling, in fact, predate computer systems; early approaches were taken from the field of operations management and applied to computers. This reality should be no surprise: assembly lines and many other human endeavors also require scheduling, and many of the same concerns exist therein, including a laser-like desire for efficiency. And thus, our problem:

THE CRUX: HOW TO DEVELOP SCHEDULING POLICY

How should we develop a basic framework for thinking about scheduling policies? What are the key assumptions? What metrics are important? What basic approaches have been used in the earliest of computer systems?

7.1 Workload Assumptions

Before getting into the range of possible policies, let us first make a number of simplifying assumptions about the processes running in the system, sometimes collectively called the **workload**. Determining the workload is a critical part of building policies, and the more you know about workload, the more fine-tuned your policy can be.

The workload assumptions we make here are mostly unrealistic, but that is alright (for now), because we will relax them as we go, and eventually develop what we will refer to as ... *(dramatic pause) ...*

a **fully-operational scheduling discipline**[1].

We will make the following assumptions about the processes, sometimes called **jobs**, that are running in the system:

1. Each job runs for the same amount of time.
2. All jobs arrive at the same time.
3. Once started, each job runs to completion.
4. All jobs only use the CPU (i.e., they perform no I/O)
5. The run-time of each job is known.

We said many of these assumptions were unrealistic, but just as some animals are more equal than others in Orwell's *Animal Farm* [O45], some assumptions are more unrealistic than others in this chapter. In particular, it might bother you that the run-time of each job is known: this would make the scheduler omniscient, which, although it would be great (probably), is not likely to happen anytime soon.

7.2 Scheduling Metrics

Beyond making workload assumptions, we also need one more thing to enable us to compare different scheduling policies: a **scheduling metric**. A metric is just something that we use to *measure* something, and there are a number of different metrics that make sense in scheduling.

For now, however, let us also simplify our life by simply having a single metric: **turnaround time**. The turnaround time of a job is defined as the time at which the job completes minus the time at which the job arrived in the system. More formally, the turnaround time $T_{turnaround}$ is:

$$T_{turnaround} = T_{completion} - T_{arrival} \tag{7.1}$$

Because we have assumed that all jobs arrive at the same time, for now $T_{arrival} = 0$ and hence $T_{turnaround} = T_{completion}$. This fact will change as we relax the aforementioned assumptions.

You should note that turnaround time is a **performance** metric, which will be our primary focus this chapter. Another metric of interest is **fairness**, as measured (for example) by **Jain's Fairness Index** [J91]. Performance and fairness are often at odds in scheduling; a scheduler, for example, may optimize performance but at the cost of preventing a few jobs from running, thus decreasing fairness. This conundrum shows us that life isn't always perfect.

7.3 First In, First Out (FIFO)

The most basic algorithm we can implement is known as **First In, First Out** (**FIFO**) scheduling or sometimes **First Come, First Served** (**FCFS**).

[1] Said in the same way you would say "A fully-operational Death Star."

FIFO has a number of positive properties: it is clearly simple and thus easy to implement. And, given our assumptions, it works pretty well.

Let's do a quick example together. Imagine three jobs arrive in the system, A, B, and C, at roughly the same time ($T_{arrival} = 0$). Because FIFO has to put some job first, let's assume that while they all arrived simultaneously, A arrived just a hair before B which arrived just a hair before C. Assume also that each job runs for 10 seconds. What will the **average turnaround time** be for these jobs?

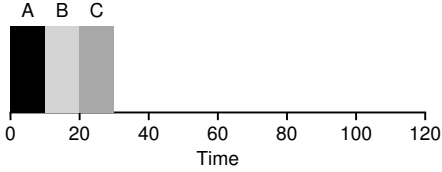


Figure 7.1: **FIFO Simple Example**

From Figure 7.1, you can see that A finished at 10, B at 20, and C at 30. Thus, the average turnaround time for the three jobs is simply $\frac{10+20+30}{3} = 20$. Computing turnaround time is as easy as that.

Now let's relax one of our assumptions. In particular, let's relax assumption 1, and thus no longer assume that each job runs for the same amount of time. How does FIFO perform now? What kind of workload could you construct to make FIFO perform poorly?

(think about this before reading on ... keep thinking ... got it?!)

Presumably you've figured this out by now, but just in case, let's do an example to show how jobs of different lengths can lead to trouble for FIFO scheduling. In particular, let's again assume three jobs (A, B, and C), but this time A runs for 100 seconds while B and C run for 10 each.

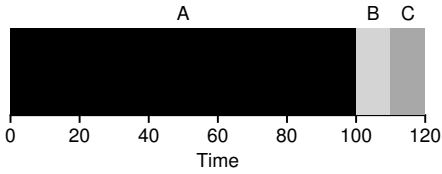


Figure 7.2: **Why FIFO Is Not That Great**

As you can see in Figure 7.2, Job A runs first for the full 100 seconds before B or C even get a chance to run. Thus, the average turnaround time for the system is high: a painful 110 seconds ($\frac{100+110+120}{3} = 110$).

This problem is generally referred to as the **convoy effect** [B+79], where a number of relatively-short potential consumers of a resource get queued behind a heavyweight resource consumer. This scheduling scenario might remind you of a single line at a grocery store and what you feel like when

TIP: THE PRINCIPLE OF SJF
Shortest Job First represents a general scheduling principle that can be applied to any system where the perceived turnaround time per customer (or, in our case, a job) matters. Think of any line you have waited in: if the establishment in question cares about customer satisfaction, it is likely they have taken SJF into account. For example, grocery stores commonly have a "ten-items-or-less" line to ensure that shoppers with only a few things to purchase don't get stuck behind the family preparing for some upcoming nuclear winter.

you see the person in front of you with three carts full of provisions and a checkbook out; it's going to be a while[2].

So what should we do? How can we develop a better algorithm to deal with our new reality of jobs that run for different amounts of time? Think about it first; then read on.

7.4 Shortest Job First (SJF)

It turns out that a very simple approach solves this problem; in fact it is an idea stolen from operations research [C54,PV56] and applied to scheduling of jobs in computer systems. This new scheduling discipline is known as **Shortest Job First (SJF)**, and the name should be easy to remember because it describes the policy quite completely: it runs the shortest job first, then the next shortest, and so on.

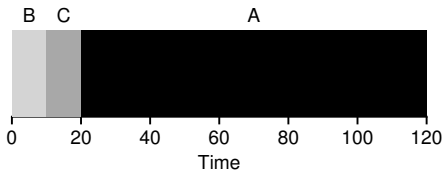


Figure 7.3: **SJF Simple Example**

Let's take our example above but with SJF as our scheduling policy. Figure 7.3 shows the results of running A, B, and C. Hopefully the diagram makes it clear why SJF performs much better with regards to average turnaround time. Simply by running B and C before A, SJF reduces average turnaround from 110 seconds to 50 ($\frac{10+20+120}{3} = 50$), more than a factor of two improvement.

In fact, given our assumptions about jobs all arriving at the same time, we could prove that SJF is indeed an **optimal** scheduling algorithm. How-

[2]Recommended action in this case: either quickly switch to a different line, or take a long, deep, and relaxing breath. That's right, breathe in, breathe out. It will be OK, don't worry.

ASIDE: **PREEMPTIVE SCHEDULERS**
In the old days of batch computing, a number of **non-preemptive** schedulers were developed; such systems would run each job to completion before considering whether to run a new job. Virtually all modern schedulers are **preemptive**, and quite willing to stop one process from running in order to run another. This implies that the scheduler employs the mechanisms we learned about previously; in particular, the scheduler can perform a **context switch**, stopping one running process temporarily and resuming (or starting) another.

ever, you are in a systems class, not theory or operations research; no proofs are allowed.

Thus we arrive upon a good approach to scheduling with SJF, but our assumptions are still fairly unrealistic. Let's relax another. In particular, we can target assumption 2, and now assume that jobs can arrive at any time instead of all at once. What problems does this lead to?

(Another pause to think ... are you thinking? Come on, you can do it)

Here we can illustrate the problem again with an example. This time, assume A arrives at $t = 0$ and needs to run for 100 seconds, whereas B and C arrive at $t = 10$ and each need to run for 10 seconds. With pure SJF, we'd get the schedule seen in Figure 7.4.

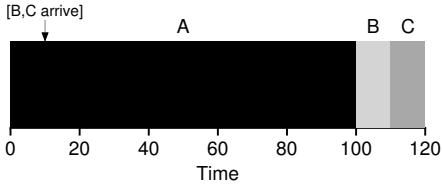


Figure 7.4: **SJF With Late Arrivals From B and C**

As you can see from the figure, even though B and C arrived shortly after A, they still are forced to wait until A has completed, and thus suffer the same convoy problem. Average turnaround time for these three jobs is 103.33 seconds ($\frac{100+(110-10)+(120-10)}{3}$). What can a scheduler do?

7.5 Shortest Time-to-Completion First (STCF)

To address this concern, we need to relax assumption 3 (that jobs must run to completion), so let's do that. We also need some machinery within the scheduler itself. As you might have guessed, given our previous discussion about timer interrupts and context switching, the scheduler can certainly do something else when B and C arrive: it can **preempt** job A and decide to run another job, perhaps continuing A later. SJF by our definition is a **non-preemptive** scheduler, and thus suffers from the problems described above.

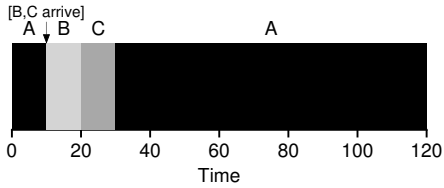


Figure 7.5: **STCF Simple Example**

Fortunately, there is a scheduler which does exactly that: add preemption to SJF, known as the **Shortest Time-to-Completion First** (**STCF**) or **Preemptive Shortest Job First** (**PSJF**) scheduler [CK68]. Any time a new job enters the system, the STCF scheduler determines which of the remaining jobs (including the new job) has the least time left, and schedules that one. Thus, in our example, STCF would preempt A and run B and C to completion; only when they are finished would A's remaining time be scheduled. Figure 7.5 shows an example.

The result is a much-improved average turnaround time: 50 seconds ($\frac{(120-0)+(20-10)+(30-10)}{3}$). And as before, given our new assumptions, STCF is provably optimal; given that SJF is optimal if all jobs arrive at the same time, you should probably be able to see the intuition behind the optimality of STCF.

7.6 A New Metric: Response Time

Thus, if we knew job lengths, and that jobs only used the CPU, and our only metric was turnaround time, STCF would be a great policy. In fact, for a number of early batch computing systems, these types of scheduling algorithms made some sense. However, the introduction of time-shared machines changed all that. Now users would sit at a terminal and demand interactive performance from the system as well. And thus, a new metric was born: **response time**.

Response time is defined as the time from when the job arrives in a system to the first time it is scheduled. More formally:

$$T_{response} = T_{firstrun} - T_{arrival} \tag{7.2}$$

For example, if we had the schedule above (with A arriving at time 0, and B and C at time 10), the response time of each job is as follows: 0 for job A, 0 for B, and 10 for C (average: 3.33).

As you might be thinking, STCF and related disciplines are not particularly good for response time. If three jobs arrive at the same time, for example, the third job has to wait for the previous two jobs to run *in their entirety* before being scheduled just once. While great for turnaround time, this approach is quite bad for response time and interactivity. Indeed, imagine sitting at a terminal, typing, and having to wait 10 seconds

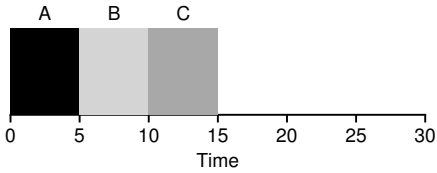


Figure 7.6: **SJF Again (Bad for Response Time)**

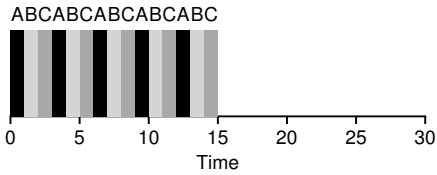


Figure 7.7: **Round Robin (Good for Response Time)**

to see a response from the system just because some other job got scheduled in front of yours: not too pleasant.

Thus, we are left with another problem: how can we build a scheduler that is sensitive to response time?

7.7 Round Robin

To solve this problem, we will introduce a new scheduling algorithm, classically referred to as **Round-Robin (RR)** scheduling [K64]. The basic idea is simple: instead of running jobs to completion, RR runs a job for a **time slice** (sometimes called a **scheduling quantum**) and then switches to the next job in the run queue. It repeatedly does so until the jobs are finished. For this reason, RR is sometimes called **time-slicing**. Note that the length of a time slice must be a multiple of the timer-interrupt period; thus if the timer interrupts every 10 milliseconds, the time slice could be 10, 20, or any other multiple of 10 ms.

To understand RR in more detail, let's look at an example. Assume three jobs A, B, and C arrive at the same time in the system, and that they each wish to run for 5 seconds. An SJF scheduler runs each job to completion before running another (Figure 7.6). In contrast, RR with a time-slice of 1 second would cycle through the jobs quickly (Figure 7.7).

The average response time of RR is: $\frac{0+1+2}{3} = 1$; for SJF, average response time is: $\frac{0+5+10}{3} = 5$.

As you can see, the length of the time slice is critical for RR. The shorter it is, the better the performance of RR under the response-time metric. However, making the time slice too short is problematic: suddenly the cost of context switching will dominate overall performance. Thus, deciding on the length of the time slice presents a trade-off to a system designer, making it long enough to **amortize** the cost of switching without making it so long that the system is no longer responsive.

TIP: AMORTIZATION CAN REDUCE COSTS
The general technique of **amortization** is commonly used in systems when there is a fixed cost to some operation. By incurring that cost less often (i.e., by performing the operation fewer times), the total cost to the system is reduced. For example, if the time slice is set to 10 ms, and the context-switch cost is 1 ms, roughly 10% of time is spent context switching and is thus wasted. If we want to *amortize* this cost, we can increase the time slice, e.g., to 100 ms. In this case, less than 1% of time is spent context switching, and thus the cost of time-slicing has been amortized.

Note that the cost of context switching does not arise solely from the OS actions of saving and restoring a few registers. When programs run, they build up a great deal of state in CPU caches, TLBs, branch predictors, and other on-chip hardware. Switching to another job causes this state to be flushed and new state relevant to the currently-running job to be brought in, which may exact a noticeable performance cost [MB91].

RR, with a reasonable time slice, is thus an excellent scheduler if response time is our only metric. But what about our old friend turnaround time? Let's look at our example above again. A, B, and C, each with running times of 5 seconds, arrive at the same time, and RR is the scheduler with a (long) 1-second time slice. We can see from the picture above that A finishes at 13, B at 14, and C at 15, for an average of 14. Pretty awful!

It is not surprising, then, that RR is indeed one of the *worst* policies if turnaround time is our metric. Intuitively, this should make sense: what RR is doing is stretching out each job as long as it can, by only running each job for a short bit before moving to the next. Because turnaround time only cares about when jobs finish, RR is nearly pessimal, even worse than simple FIFO in many cases.

More generally, any policy (such as RR) that is **fair**, i.e., that evenly divides the CPU among active processes on a small time scale, will perform poorly on metrics such as turnaround time. Indeed, this is an inherent trade-off: if you are willing to be unfair, you can run shorter jobs to completion, but at the cost of response time; if you instead value fairness, response time is lowered, but at the cost of turnaround time. This type of **trade-off** is common in systems; you can't have your cake and eat it too[3].

We have developed two types of schedulers. The first type (SJF, STCF) optimizes turnaround time, but is bad for response time. The second type (RR) optimizes response time but is bad for turnaround. And we still have two assumptions which need to be relaxed: assumption 4 (that jobs do no I/O), and assumption 5 (that the run-time of each job is known). Let's tackle those assumptions next.

[3] A saying that confuses people, because it should be "You can't *keep* your cake and eat it too" (which is kind of obvious, no?). Amazingly, there is a wikipedia page about this saying; even more amazingly, it is kind of fun to read [W15]. As they say in Italian, you can't *Avere la botte piena e la moglie ubriaca.*

TIP: OVERLAP ENABLES HIGHER UTILIZATION
When possible, **overlap** operations to maximize the utilization of systems. Overlap is useful in many different domains, including when performing disk I/O or sending messages to remote machines; in either case, starting the operation and then switching to other work is a good idea, and improves the overall utilization and efficiency of the system.

7.8 Incorporating I/O

First we will relax assumption 4 — of course all programs perform I/O. Imagine a program that didn't take any input: it would produce the same output each time. Imagine one without output: it is the proverbial tree falling in the forest, with no one to see it; it doesn't matter that it ran.

A scheduler clearly has a decision to make when a job initiates an I/O request, because the currently-running job won't be using the CPU during the I/O; it is **blocked** waiting for I/O completion. If the I/O is sent to a hard disk drive, the process might be blocked for a few milliseconds or longer, depending on the current I/O load of the drive. Thus, the scheduler should probably schedule another job on the CPU at that time.

The scheduler also has to make a decision when the I/O completes. When that occurs, an interrupt is raised, and the OS runs and moves the process that issued the I/O from blocked back to the ready state. Of course, it could even decide to run the job at that point. How should the OS treat each job?

To understand this issue better, let us assume we have two jobs, A and B, which each need 50 ms of CPU time. However, there is one obvious difference: A runs for 10 ms and then issues an I/O request (assume here that I/Os each take 10 ms), whereas B simply uses the CPU for 50 ms and performs no I/O. The scheduler runs A first, then B after (Figure 7.8).

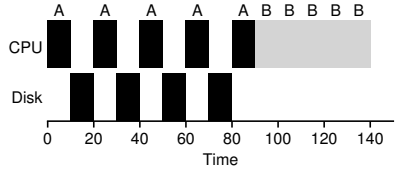


Figure 7.8: **Poor Use of Resources**

Assume we are trying to build a STCF scheduler. How should such a scheduler account for the fact that A is broken up into 5 10-ms sub-jobs, whereas B is just a single 50-ms CPU demand? Clearly, just running one job and then the other without considering how to take I/O into account makes little sense.

A common approach is to treat each 10-ms sub-job of A as an independent job. Thus, when the system starts, its choice is whether to schedule

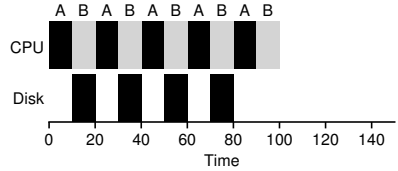


Figure 7.9: **Overlap Allows Better Use of Resources**

a 10-ms A or a 50-ms B. With STCF, the choice is clear: choose the shorter one, in this case A. Then, when the first sub-job of A has completed, only B is left, and it begins running. Then a new sub-job of A is submitted, and it preempts B and runs for 10 ms. Doing so allows for **overlap**, with the CPU being used by one process while waiting for the I/O of another process to complete; the system is thus better utilized (see Figure 7.9).

And thus we see how a scheduler might incorporate I/O. By treating each CPU burst as a job, the scheduler makes sure processes that are "interactive" get run frequently. While those interactive jobs are performing I/O, other CPU-intensive jobs run, thus better utilizing the processor.

7.9 No More Oracle

With a basic approach to I/O in place, we come to our final assumption: that the scheduler knows the length of each job. As we said before, this is likely the worst assumption we could make. In fact, in a general-purpose OS (like the ones we care about), the OS usually knows very little about the length of each job. Thus, how can we build an approach that behaves like SJF/STCF without such *a priori* knowledge? Further, how can we incorporate some of the ideas we have seen with the RR scheduler so that response time is also quite good?

7.10 Summary

We have introduced the basic ideas behind scheduling and developed two families of approaches. The first runs the shortest job remaining and thus optimizes turnaround time; the second alternates between all jobs and thus optimizes response time. Both are bad where the other is good, alas, an inherent trade-off common in systems. We have also seen how we might incorporate I/O into the picture, but have still not solved the problem of the fundamental inability of the OS to see into the future. Shortly, we will see how to overcome this problem, by building a scheduler that uses the recent past to predict the future. This scheduler is known as the **multi-level feedback queue**, and it is the topic of the next chapter.

References

[B+79] "The Convoy Phenomenon"
M. Blasgen, J. Gray, M. Mitoma, T. Price
ACM Operating Systems Review, 13:2, April 1979
Perhaps the first reference to convoys, which occurs in databases as well as the OS.

[C54] "Priority Assignment in Waiting Line Problems"
A. Cobham
Journal of Operations Research, 2:70, pages 70–76, 1954
The pioneering paper on using an SJF approach in scheduling the repair of machines.

[K64] "Analysis of a Time-Shared Processor"
Leonard Kleinrock
Naval Research Logistics Quarterly, 11:1, pages 59–73, March 1964
May be the first reference to the round-robin scheduling algorithm; certainly one of the first analyses of said approach to scheduling a time-shared system.

[CK68] "Computer Scheduling Methods and their Countermeasures"
Edward G. Coffman and Leonard Kleinrock
AFIPS '68 (Spring), April 1968
An excellent early introduction to and analysis of a number of basic scheduling disciplines.

[J91] "The Art of Computer Systems Performance Analysis:
Techniques for Experimental Design, Measurement, Simulation, and Modeling"
R. Jain
Interscience, New York, April 1991
The standard text on computer systems measurement. A great reference for your library, for sure.

[O45] "Animal Farm"
George Orwell
Secker and Warburg (London), 1945
A great but depressing allegorical book about power and its corruptions. Some say it is a critique of Stalin and the pre-WWII Stalin era in the U.S.S.R; we say it's a critique of pigs.

[PV56] "Machine Repair as a Priority Waiting-Line Problem"
Thomas E. Phipps Jr. and W. R. Van Voorhis
Operations Research, 4:1, pages 76–86, February 1956
Follow-on work that generalizes the SJF approach to machine repair from Cobham's original work; also postulates the utility of an STCF approach in such an environment. Specifically, "There are certain types of repair work, ... involving much dismantling and covering the floor with nuts and bolts, which certainly should not be interrupted once undertaken; in other cases it would be inadvisable to continue work on a long job if one or more short ones became available (p.81)."

[MB91] "The effect of context switches on cache performance"
Jeffrey C. Mogul and Anita Borg
ASPLOS, 1991
A nice study on how cache performance can be affected by context switching; less of an issue in today's systems where processors issue billions of instructions per second but context-switches still happen in the millisecond time range.

[W15] "You can't have your cake and eat it"
`http://en.wikipedia.org/wiki/You_can't_have_your_cake_and_eat_it`
Wikipedia, as of December 2015
The best part of this page is reading all the similar idioms from other languages. In Tamil, you can't "have both the moustache and drink the soup."

Homework

This program, `scheduler.py`, allows you to see how different schedulers perform under scheduling metrics such as response time, turnaround time, and total wait time. See the README for details.

Questions

1. Compute the response time and turnaround time when running three jobs of length 200 with the SJF and FIFO schedulers.
2. Now do the same but with jobs of different lengths: 100, 200, and 300.
3. Now do the same, but also with the RR scheduler and a time-slice of 1.
4. For what types of workloads does SJF deliver the same turnaround times as FIFO?
5. For what types of workloads and quantum lengths does SJF deliver the same response times as RR?
6. What happens to response time with SJF as job lengths increase? Can you use the simulator to demonstrate the trend?
7. What happens to response time with RR as quantum lengths increase? Can you write an equation that gives the worst-case response time, given N jobs?

8

Scheduling: The Multi-Level Feedback Queue

In this chapter, we'll tackle the problem of developing one of the most well-known approaches to scheduling, known as the **Multi-level Feedback Queue (MLFQ)**. The Multi-level Feedback Queue (MLFQ) scheduler was first described by Corbato et al. in 1962 [C+62] in a system known as the Compatible Time-Sharing System (CTSS), and this work, along with later work on Multics, led the ACM to award Corbato its highest honor, the **Turing Award**. The scheduler has subsequently been refined throughout the years to the implementations you will encounter in some modern systems.

The fundamental problem MLFQ tries to address is two-fold. First, it would like to optimize *turnaround time*, which, as we saw in the previous note, is done by running shorter jobs first; unfortunately, the OS doesn't generally know how long a job will run for, exactly the knowledge that algorithms like SJF (or STCF) require. Second, MLFQ would like to make a system feel responsive to interactive users (i.e., users sitting and staring at the screen, waiting for a process to finish), and thus minimize *response time*; unfortunately, algorithms like Round Robin reduce response time but are terrible for turnaround time. Thus, our problem: given that we in general do not know anything about a process, how can we build a scheduler to achieve these goals? How can the scheduler learn, as the system runs, the characteristics of the jobs it is running, and thus make better scheduling decisions?

THE CRUX:
HOW TO SCHEDULE WITHOUT PERFECT KNOWLEDGE?
How can we design a scheduler that both minimizes response time for interactive jobs while also minimizing turnaround time without *a priori* knowledge of job length?

TIP: LEARN FROM HISTORY
The multi-level feedback queue is an excellent example of a system that learns from the past to predict the future. Such approaches are common in operating systems (and many other places in Computer Science, including hardware branch predictors and caching algorithms). Such approaches work when jobs have phases of behavior and are thus predictable; of course, one must be careful with such techniques, as they can easily be wrong and drive a system to make worse decisions than they would have with no knowledge at all.

8.1 MLFQ: Basic Rules

To build such a scheduler, in this chapter we will describe the basic algorithms behind a multi-level feedback queue; although the specifics of many implemented MLFQs differ [E95], most approaches are similar.

In our treatment, the MLFQ has a number of distinct **queues**, each assigned a different **priority level**. At any given time, a job that is ready to run is on a single queue. MLFQ uses priorities to decide which job should run at a given time: a job with higher priority (i.e., a job on a higher queue) is chosen to run.

Of course, more than one job may be on a given queue, and thus have the *same* priority. In this case, we will just use round-robin scheduling among those jobs.

Thus, the key to MLFQ scheduling lies in how the scheduler sets priorities. Rather than giving a fixed priority to each job, MLFQ *varies* the priority of a job based on its *observed behavior*. If, for example, a job repeatedly relinquishes the CPU while waiting for input from the keyboard, MLFQ will keep its priority high, as this is how an interactive process might behave. If, instead, a job uses the CPU intensively for long periods of time, MLFQ will reduce its priority. In this way, MLFQ will try to *learn* about processes as they run, and thus use the *history* of the job to predict its *future* behavior.

Thus, we arrive at the first two basic rules for MLFQ:

- **Rule 1:** If Priority(A) $>$ Priority(B), A runs (B doesn't).
- **Rule 2:** If Priority(A) $=$ Priority(B), A & B run in RR.

If we were to put forth a picture of what the queues might look like at a given instant, we might see something like the following (Figure 8.1). In the figure, two jobs (A and B) are at the highest priority level, while job C is in the middle and Job D is at the lowest priority. Given our current knowledge of how MLFQ works, the scheduler would just alternate time slices between A and B because they are the highest priority jobs in the system; poor jobs C and D would never even get to run — an outrage!

Of course, just showing a static snapshot of some queues does not really give you an idea of how MLFQ works. What we need is to under-

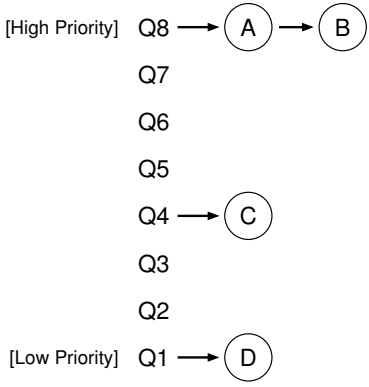


Figure 8.1: **MLFQ Example**

stand how job priority *changes* over time. And that, in a surprise only to those who are reading a chapter from this book for the first time, is exactly what we will do next.

8.2 Attempt #1: How To Change Priority

We now must decide how MLFQ is going to change the priority level of a job (and thus which queue it is on) over the lifetime of a job. To do this, we must keep in mind our workload: a mix of interactive jobs that are short-running (and may frequently relinquish the CPU), and some longer-running "CPU-bound" jobs that need a lot of CPU time but where response time isn't important. Here is our first attempt at a priority-adjustment algorithm:

- **Rule 3:** When a job enters the system, it is placed at the highest priority (the topmost queue).
- **Rule 4a:** If a job uses up an entire time slice while running, its priority is *reduced* (i.e., it moves down one queue).
- **Rule 4b:** If a job gives up the CPU before the time slice is up, it stays at the *same* priority level.

Example 1: A Single Long-Running Job

Let's look at some examples. First, we'll look at what happens when there has been a long running job in the system. Figure 8.2 shows what happens to this job over time in a three-queue scheduler.

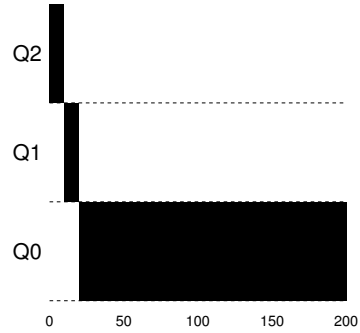


Figure 8.2: **Long-running Job Over Time**

As you can see in the example, the job enters at the highest priority (Q2). After a single time-slice of 10 ms, the scheduler reduces the job's priority by one, and thus the job is on Q1. After running at Q1 for a time slice, the job is finally lowered to the lowest priority in the system (Q0), where it remains. Pretty simple, no?

Example 2: Along Came A Short Job

Now let's look at a more complicated example, and hopefully see how MLFQ tries to approximate SJF. In this example, there are two jobs: A, which is a long-running CPU-intensive job, and B, which is a short-running interactive job. Assume A has been running for some time, and then B arrives. What will happen? Will MLFQ approximate SJF for B?

Figure 8.3 plots the results of this scenario. A (shown in black) is running along in the lowest-priority queue (as would any long-running CPU-intensive jobs); B (shown in gray) arrives at time $T = 100$, and thus is

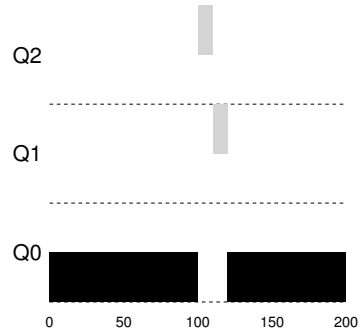


Figure 8.3: **Along Came An Interactive Job**

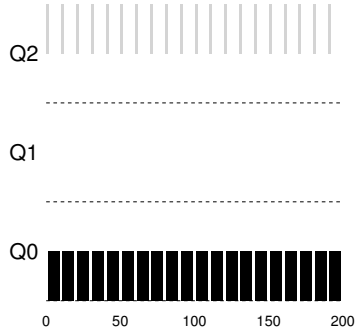


Figure 8.4: **A Mixed I/O-intensive and CPU-intensive Workload**

inserted into the highest queue; as its run-time is short (only 20 ms), B completes before reaching the bottom queue, in two time slices; then A resumes running (at low priority).

From this example, you can hopefully understand one of the major goals of the algorithm: because it doesn't *know* whether a job will be a short job or a long-running job, it first *assumes* it might be a short job, thus giving the job high priority. If it actually is a short job, it will run quickly and complete; if it is not a short job, it will slowly move down the queues, and thus soon prove itself to be a long-running more batch-like process. In this manner, MLFQ approximates SJF.

Example 3: What About I/O?

Let's now look at an example with some I/O. As Rule 4b states above, if a process gives up the processor before using up its time slice, we keep it at the same priority level. The intent of this rule is simple: if an interactive job, for example, is doing a lot of I/O (say by waiting for user input from the keyboard or mouse), it will relinquish the CPU before its time slice is complete; in such case, we don't wish to penalize the job and thus simply keep it at the same level.

Figure 8.4 shows an example of how this works, with an interactive job B (shown in gray) that needs the CPU only for 1 ms before performing an I/O competing for the CPU with a long-running batch job A (shown in black). The MLFQ approach keeps B at the highest priority because B keeps releasing the CPU; if B is an interactive job, MLFQ further achieves its goal of running interactive jobs quickly.

Problems With Our Current MLFQ

We thus have a basic MLFQ. It seems to do a fairly good job, sharing the CPU fairly between long-running jobs, and letting short or I/O-intensive interactive jobs run quickly. Unfortunately, the approach we have developed thus far contains serious flaws. Can you think of any?

(This is where you pause and think as deviously as you can)

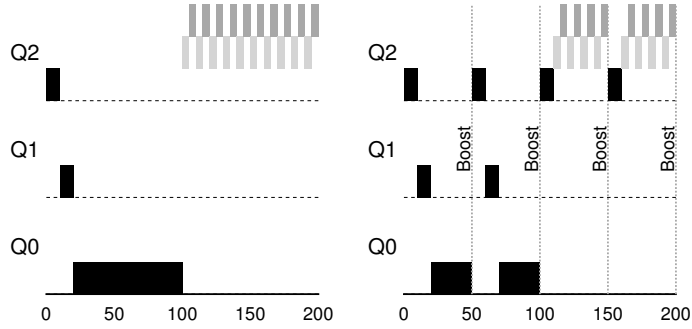


Figure 8.5: **Without (Left) and With (Right) Priority Boost**

First, there is the problem of **starvation**: if there are "too many" interactive jobs in the system, they will combine to consume *all* CPU time, and thus long-running jobs will *never* receive any CPU time (they **starve**). We'd like to make some progress on these jobs even in this scenario.

Second, a smart user could rewrite their program to **game the scheduler**. Gaming the scheduler generally refers to the idea of doing something sneaky to trick the scheduler into giving you more than your fair share of the resource. The algorithm we have described is susceptible to the following attack: before the time slice is over, issue an I/O operation (to some file you don't care about) and thus relinquish the CPU; doing so allows you to remain in the same queue, and thus gain a higher percentage of CPU time. When done right (e.g., by running for 99% of a time slice before relinquishing the CPU), a job could nearly monopolize the CPU.

Finally, a program may *change its behavior* over time; what was CPU-bound may transition to a phase of interactivity. With our current approach, such a job would be out of luck and not be treated like the other interactive jobs in the system.

8.3 Attempt #2: The Priority Boost

Let's try to change the rules and see if we can avoid the problem of starvation. What could we do in order to guarantee that CPU-bound jobs will make some progress (even if it is not much?).

The simple idea here is to periodically **boost** the priority of all the jobs in system. There are many ways to achieve this, but let's just do something simple: throw them all in the topmost queue; hence, a new rule:

- **Rule 5:** After some time period S, move all the jobs in the system to the topmost queue.

Our new rule solves two problems at once. First, processes are guaranteed not to starve: by sitting in the top queue, a job will share the CPU

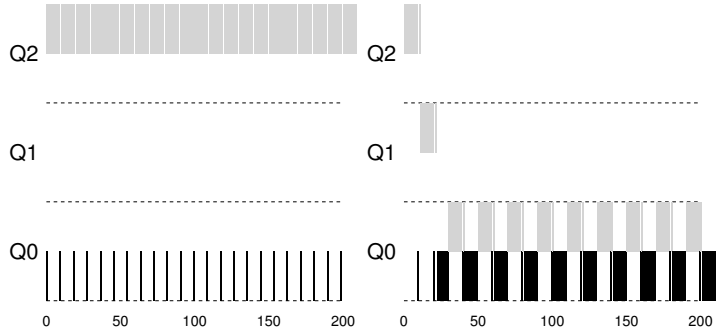


Figure 8.6: **Without (Left) and With (Right) Gaming Tolerance**

with other high-priority jobs in a round-robin fashion, and thus eventually receive service. Second, if a CPU-bound job has become interactive, the scheduler treats it properly once it has received the priority boost.

Let's see an example. In this scenario, we just show the behavior of a long-running job when competing for the CPU with two short-running interactive jobs. Two graphs are shown in Figure 8.5 (page 6). On the left, there is no priority boost, and thus the long-running job gets starved once the two short jobs arrive; on the right, there is a priority boost every 50 ms (which is likely too small of a value, but used here for the example), and thus we at least guarantee that the long-running job will make some progress, getting boosted to the highest priority every 50 ms and thus getting to run periodically.

Of course, the addition of the time period S leads to the obvious question: what should S be set to? John Ousterhout, a well-regarded systems researcher [O11], used to call such values in systems **voo-doo constants**, because they seemed to require some form of black magic to set them correctly. Unfortunately, S has that flavor. If it is set too high, long-running jobs could starve; too low, and interactive jobs may not get a proper share of the CPU.

8.4 Attempt #3: Better Accounting

We now have one more problem to solve: how to prevent gaming of our scheduler? The real culprit here, as you might have guessed, are Rules 4a and 4b, which let a job retain its priority by relinquishing the CPU before the time slice expires. So what should we do?

The solution here is to perform better **accounting** of CPU time at each level of the MLFQ. Instead of forgetting how much of a time slice a process used at a given level, the scheduler should keep track; once a process has used its allotment, it is demoted to the next priority queue. Whether

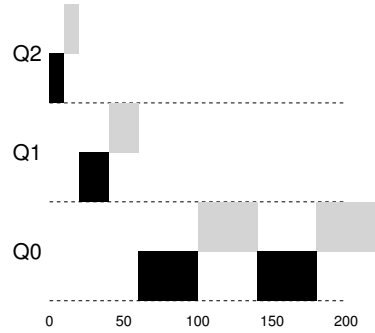


Figure 8.7: **Lower Priority, Longer Quanta**

it uses the time slice in one long burst or many small ones does not matter. We thus rewrite Rules 4a and 4b to the following single rule:

- **Rule 4:** Once a job uses up its time allotment at a given level (regardless of how many times it has given up the CPU), its priority is reduced (i.e., it moves down one queue).

Let's look at an example. Figure 8.6 (page 7) shows what happens when a workload tries to game the scheduler with the old Rules 4a and 4b (on the left) as well the new anti-gaming Rule 4. Without any protection from gaming, a process can issue an I/O just before a time slice ends and thus dominate CPU time. With such protections in place, regardless of the I/O behavior of the process, it slowly moves down the queues, and thus cannot gain an unfair share of the CPU.

8.5 Tuning MLFQ And Other Issues

A few other issues arise with MLFQ scheduling. One big question is how to **parameterize** such a scheduler. For example, how many queues should there be? How big should the time slice be per queue? How often should priority be boosted in order to avoid starvation and account for changes in behavior? There are no easy answers to these questions, and thus only some experience with workloads and subsequent tuning of the scheduler will lead to a satisfactory balance.

For example, most MLFQ variants allow for varying time-slice length across different queues. The high-priority queues are usually given short time slices; they are comprised of interactive jobs, after all, and thus quickly alternating between them makes sense (e.g., 10 or fewer milliseconds). The low-priority queues, in contrast, contain long-running jobs that are CPU-bound; hence, longer time slices work well (e.g., 100s of ms). Figure 8.7 shows an example in which two long-running jobs run for 10 ms at the highest queue, 20 in the middle, and 40 at the lowest.

TIP: AVOID VOO-DOO CONSTANTS (OUSTERHOUT'S LAW)
Avoiding voo-doo constants is a good idea whenever possible. Unfortunately, as in the example above, it is often difficult. One could try to make the system learn a good value, but that too is not straightforward. The frequent result: a configuration file filled with default parameter values that a seasoned administrator can tweak when something isn't quite working correctly. As you can imagine, these are often left unmodified, and thus we are left to hope that the defaults work well in the field. This tip brought to you by our old OS professor, John Ousterhout, and hence we call it **Ousterhout's Law**.

The Solaris MLFQ implementation — the Time-Sharing scheduling class, or TS — is particularly easy to configure; it provides a set of tables that determine exactly how the priority of a process is altered throughout its lifetime, how long each time slice is, and how often to boost the priority of a job [AD00]; an administrator can muck with this table in order to make the scheduler behave in different ways. Default values for the table are 60 queues, with slowly increasing time-slice lengths from 20 milliseconds (highest priority) to a few hundred milliseconds (lowest), and priorities boosted around every 1 second or so.

Other MLFQ schedulers don't use a table or the exact rules described in this chapter; rather they adjust priorities using mathematical formulae. For example, the FreeBSD scheduler (version 4.3) uses a formula to calculate the current priority level of a job, basing it on how much CPU the process has used [LM+89]; in addition, usage is decayed over time, providing the desired priority boost in a different manner than described herein. See Epema's paper for an excellent overview of such **decay-usage** algorithms and their properties [E95].

Finally, many schedulers have a few other features that you might encounter. For example, some schedulers reserve the highest priority levels for operating system work; thus typical user jobs can never obtain the highest levels of priority in the system. Some systems also allow some user **advice** to help set priorities; for example, by using the command-line utility `nice` you can increase or decrease the priority of a job (somewhat) and thus increase or decrease its chances of running at any given time. See the man page for more.

8.6 MLFQ: Summary

We have described a scheduling approach known as the Multi-Level Feedback Queue (MLFQ). Hopefully you can now see why it is called that: it has *multiple levels* of queues, and uses *feedback* to determine the priority of a given job. History is its guide: pay attention to how jobs behave over time and treat them accordingly.

TIP: USE ADVICE WHERE POSSIBLE

As the operating system rarely knows what is best for each and every process of the system, it is often useful to provide interfaces to allow users or administrators to provide some **hints** to the OS. We often call such hints **advice**, as the OS need not necessarily pay attention to it, but rather might take the advice into account in order to make a better decision. Such hints are useful in many parts of the OS, including the scheduler (e.g., with `nice`), memory manager (e.g., `madvise`), and file system (e.g., informed prefetching and caching [P+95]).

The refined set of MLFQ rules, spread throughout the chapter, are reproduced here for your viewing pleasure:

- **Rule 1:** If Priority(A) $>$ Priority(B), A runs (B doesn't).
- **Rule 2:** If Priority(A) $=$ Priority(B), A & B run in RR.
- **Rule 3:** When a job enters the system, it is placed at the highest priority (the topmost queue).
- **Rule 4:** Once a job uses up its time allotment at a given level (regardless of how many times it has given up the CPU), its priority is reduced (i.e., it moves down one queue).
- **Rule 5:** After some time period S, move all the jobs in the system to the topmost queue.

MLFQ is interesting for the following reason: instead of demanding *a priori* knowledge of the nature of a job, it observes the execution of a job and prioritizes it accordingly. In this way, it manages to achieve the best of both worlds: it can deliver excellent overall performance (similar to SJF/STCF) for short-running interactive jobs, and is fair and makes progress for long-running CPU-intensive workloads. For this reason, many systems, including BSD UNIX derivatives [LM+89, B86], Solaris [M06], and Windows NT and subsequent Windows operating systems [CS97] use a form of MLFQ as their base scheduler.

References

[AD00] "Multilevel Feedback Queue Scheduling in Solaris"
Andrea Arpaci-Dusseau
Available: http://www.cs.wisc.edu/~remzi/solaris-notes.pdf
A great short set of notes by one of the authors on the details of the Solaris scheduler. OK, we are probably biased in this description, but the notes are pretty darn good.

[B86] "The Design of the UNIX Operating System"
M.J. Bach
Prentice-Hall, 1986
One of the classic old books on how a real UNIX operating system is built; a definite must-read for kernel hackers.

[C+62] "An Experimental Time-Sharing System"
F. J. Corbato, M. M. Daggett, R. C. Daley
IFIPS 1962
A bit hard to read, but the source of many of the first ideas in multi-level feedback scheduling. Much of this later went into Multics, which one could argue was the most influential operating system of all time.

[CS97] "Inside Windows NT"
Helen Custer and David A. Solomon
Microsoft Press, 1997
The NT book, if you want to learn about something other than UNIX. Of course, why would you? OK, we're kidding; you might actually work for Microsoft some day you know.

[E95] "An Analysis of Decay-Usage Scheduling in Multiprocessors"
D.H.J. Epema
SIGMETRICS '95
A nice paper on the state of the art of scheduling back in the mid 1990s, including a good overview of the basic approach behind decay-usage schedulers.

[LM+89] "The Design and Implementation of the 4.3BSD UNIX Operating System"
S.J. Leffler, M.K. McKusick, M.J. Karels, J.S. Quarterman
Addison-Wesley, 1989
Another OS classic, written by four of the main people behind BSD. The later versions of this book, while more up to date, don't quite match the beauty of this one.

[M06] "Solaris Internals: Solaris 10 and OpenSolaris Kernel Architecture"
Richard McDougall
Prentice-Hall, 2006
A good book about Solaris and how it works.

[O11] "John Ousterhout's Home Page"
John Ousterhout
Available: http://www.stanford.edu/~ouster/
The home page of the famous Professor Ousterhout. The two co-authors of this book had the pleasure of taking graduate operating systems from Ousterhout while in graduate school; indeed, this is where the two co-authors got to know each other, eventually leading to marriage, kids, and even this book. Thus, you really can blame Ousterhout for this entire mess you're in.

[P+95] "Informed Prefetching and Caching"
R.H. Patterson, G.A. Gibson, E. Ginting, D. Stodolsky, J. Zelenka
SOSP '95
A fun paper about some very cool ideas in file systems, including how applications can give the OS advice about what files it is accessing and how it plans to access them.

Homework

This program, `mlfq.py`, allows you to see how the MLFQ scheduler presented in this chapter behaves. See the README for details.

Questions

1. Run a few randomly-generated problems with just two jobs and two queues; compute the MLFQ execution trace for each. Make your life easier by limiting the length of each job and turning off I/Os.
2. How would you run the scheduler to reproduce each of the examples in the chapter?
3. How would you configure the scheduler parameters to behave just like a round-robin scheduler?
4. Craft a workload with two jobs and scheduler parameters so that one job takes advantage of the older Rules 4a and 4b (turned on with the `-S` flag) to game the scheduler and obtain 99% of the CPU over a particular time interval.
5. Given a system with a quantum length of 10 ms in its highest queue, how often would you have to boost jobs back to the highest priority level (with the `-B` flag) in order to guarantee that a single long-running (and potentially-starving) job gets at least 5% of the CPU?
6. One question that arises in scheduling is which end of a queue to add a job that just finished I/O; the `-I` flag changes this behavior for this scheduling simulator. Play around with some workloads and see if you can see the effect of this flag.

9

Scheduling: Proportional Share

In this chapter, we'll examine a different type of scheduler known as a **proportional-share** scheduler, also sometimes referred to as a **fair-share** scheduler. Proportional-share is based around a simple concept: instead of optimizing for turnaround or response time, a scheduler might instead try to guarantee that each job obtain a certain percentage of CPU time.

An excellent modern example of proportional-share scheduling is found in research by Waldspurger and Weihl [WW94], and is known as **lottery scheduling**; however, the idea is certainly much older [KL88]. The basic idea is quite simple: every so often, hold a lottery to determine which process should get to run next; processes that should run more often should be given more chances to win the lottery. Easy, no? Now, onto the details! But not before our crux:

CRUX: HOW TO SHARE THE CPU PROPORTIONALLY

How can we design a scheduler to share the CPU in a proportional manner? What are the key mechanisms for doing so? How effective are they?

9.1 Basic Concept: Tickets Represent Your Share

Underlying lottery scheduling is one very basic concept: **tickets**, which are used to represent the share of a resource that a process (or user or whatever) should receive. The percent of tickets that a process has represents its share of the system resource in question.

Let's look at an example. Imagine two processes, A and B, and further that A has 75 tickets while B has only 25. Thus, what we would like is for A to receive 75% of the CPU and B the remaining 25%.

Lottery scheduling achieves this probabilistically (but not deterministically) by holding a lottery every so often (say, every time slice). Holding a lottery is straightforward: the scheduler must know how many total tickets there are (in our example, there are 100). The scheduler then picks

TIP: USE RANDOMNESS

One of the most beautiful aspects of lottery scheduling is its use of **randomness**. When you have to make a decision, using such a randomized approach is often a robust and simple way of doing so.

Random approaches has at least three advantages over more traditional decisions. First, random often avoids strange corner-case behaviors that a more traditional algorithm may have trouble handling. For example, consider the LRU replacement policy (studied in more detail in a future chapter on virtual memory); while often a good replacement algorithm, LRU performs pessimally for some cyclic-sequential workloads. Random, on the other hand, has no such worst case.

Second, random also is lightweight, requiring little state to track alternatives. In a traditional fair-share scheduling algorithm, tracking how much CPU each process has received requires per-process accounting, which must be updated after running each process. Doing so randomly necessitates only the most minimal of per-process state (e.g., the number of tickets each has).

Finally, random can be quite fast. As long as generating a random number is quick, making the decision is also, and thus random can be used in a number of places where speed is required. Of course, the faster the need, the more random tends towards pseudo-random.

a winning ticket, which is a number from 0 to 99[1]. Assuming A holds tickets 0 through 74 and B 75 through 99, the winning ticket simply determines whether A or B runs. The scheduler then loads the state of that winning process and runs it.

Here is an example output of a lottery scheduler's winning tickets:

```
63 85 70 39 76 17 29 41 36 39 10 99 68 83 63 62 43  0 49 49
```

Here is the resulting schedule:

```
A     A  A     A  A  A  A  A  A     A     A  A  A  A  A  A
   B        B                    B     B
```

As you can see from the example, the use of randomness in lottery scheduling leads to a probabilistic correctness in meeting the desired proportion, but no guarantee. In our example above, B only gets to run 4 out of 20 time slices (20%), instead of the desired 25% allocation. However, the longer these two jobs compete, the more likely they are to achieve the desired percentages.

[1] Computer Scientists always start counting at 0. It is so odd to non-computer-types that famous people have felt obliged to write about why we do it this way [D82].

TIP: USE TICKETS TO REPRESENT SHARES

One of the most powerful (and basic) mechanisms in the design of lottery (and stride) scheduling is that of the **ticket**. The ticket is used to represent a process's share of the CPU in these examples, but can be applied much more broadly. For example, in more recent work on virtual memory management for hypervisors, Waldspurger shows how tickets can be used to represent a guest operating system's share of memory [W02]. Thus, if you are ever in need of a mechanism to represent a proportion of ownership, this concept just might be ... (wait for it) ... the ticket.

9.2 Ticket Mechanisms

Lottery scheduling also provides a number of mechanisms to manipulate tickets in different and sometimes useful ways. One way is with the concept of **ticket currency**. Currency allows a user with a set of tickets to allocate tickets among their own jobs in whatever currency they would like; the system then automatically converts said currency into the correct global value.

For example, assume users A and B have each been given 100 tickets. User A is running two jobs, A1 and A2, and gives them each 500 tickets (out of 1000 total) in User A's own currency. User B is running only 1 job and gives it 10 tickets (out of 10 total). The system will convert A1's and A2's allocation from 500 each in A's currency to 50 each in the global currency; similarly, B1's 10 tickets will be converted to 100 tickets. The lottery will then be held over the global ticket currency (200 total) to determine which job runs.

```
User A -> 500 (A's currency) to A1 ->  50 (global currency)
       -> 500 (A's currency) to A2 ->  50 (global currency)
User B ->  10 (B's currency) to B1 -> 100 (global currency)
```

Another useful mechanism is **ticket transfer**. With transfers, a process can temporarily hand off its tickets to another process. This ability is especially useful in a client/server setting, where a client process sends a message to a server asking it to do some work on the client's behalf. To speed up the work, the client can pass the tickets to the server and thus try to maximize the performance of the server while the server is handling the client's request. When finished, the server then transfers the tickets back to the client and all is as before.

Finally, **ticket inflation** can sometimes be a useful technique. With inflation, a process can temporarily raise or lower the number of tickets it owns. Of course, in a competitive scenario with processes that do not trust one another, this makes little sense; one greedy process could give itself a vast number of tickets and take over the machine. Rather, inflation can be applied in an environment where a group of processes trust one another; in such a case, if any one process knows it needs more CPU time, it can boost its ticket value as a way to reflect that need to the system, all without communicating with any other processes.

```
1  // counter: used to track if we've found the winner yet
2  int counter = 0;
3
4  // winner: use some call to a random number generator to
5  //         get a value, between 0 and the total # of tickets
6  int winner = getrandom(0, totaltickets);
7
8  // current: use this to walk through the list of jobs
9  node_t *current = head;
10
11 // loop until the sum of ticket values is > the winner
12 while (current) {
13     counter = counter + current->tickets;
14     if (counter > winner)
15         break; // found the winner
16     current = current->next;
17 }
18 // 'current' is the winner: schedule it...
```

Figure 9.1: **Lottery Scheduling Decision Code**

9.3 Implementation

Probably the most amazing thing about lottery scheduling is the simplicity of its implementation. All you need is a good random number generator to pick the winning ticket, a data structure to track the processes of the system (e.g., a list), and the total number of tickets.

Let's assume we keep the processes in a list. Here is an example comprised of three processes, A, B, and C, each with some number of tickets.

To make a scheduling decision, we first have to pick a random number (the winner) from the total number of tickets (400)[2] Let's say we pick the number 300. Then, we simply traverse the list, with a simple counter used to help us find the winner (Figure 9.1).

The code walks the list of processes, adding each ticket value to `counter` until the value exceeds `winner`. Once that is the case, the current list element is the winner. With our example of the winning ticket being 300, the following takes place. First, `counter` is incremented to 100 to account for A's tickets; because 100 is less than 300, the loop continues. Then `counter` would be updated to 150 (B's tickets), still less than 300 and thus again we continue. Finally, `counter` is updated to 400 (clearly greater than 300), and thus we break out of the loop with `current` pointing at C (the winner).

To make this process most efficient, it might generally be best to organize the list in sorted order, from the highest number of tickets to the

[2]Surprisingly, as pointed out by Björn Lindberg, this can be challenging to do correctly; for more details, see `http://stackoverflow.com/questions/2509679/how-to-generate-a-random-number-from-within-a-range`.

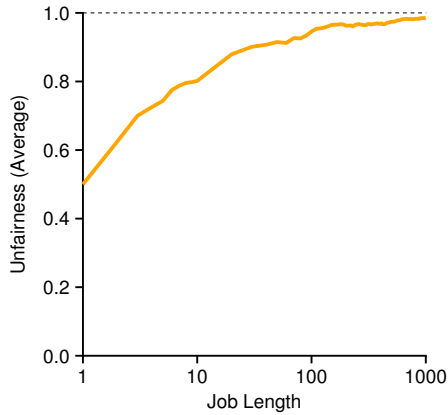


Figure 9.2: **Lottery Fairness Study**

lowest. The ordering does not affect the correctness of the algorithm; however, it does ensure in general that the fewest number of list iterations are taken, especially if there are a few processes that possess most of the tickets.

9.4 An Example

To make the dynamics of lottery scheduling more understandable, we now perform a brief study of the completion time of two jobs competing against one another, each with the same number of tickets (100) and same run time (R, which we will vary).

In this scenario, we'd like for each job to finish at roughly the same time, but due to the randomness of lottery scheduling, sometimes one job finishes before the other. To quantify this difference, we define a simple **unfairness metric**, U which is simply the time the first job completes divided by the time that the second job completes. For example, if $R = 10$, and the first job finishes at time 10 (and the second job at 20), $U = \frac{10}{20} = 0.5$. When both jobs finish at nearly the same time, U will be quite close to 1. In this scenario, that is our goal: a perfectly fair scheduler would achieve $U = 1$.

Figure 9.2 plots the average unfairness as the length of the two jobs (R) is varied from 1 to 1000 over thirty trials (results are generated via the simulator provided at the end of the chapter). As you can see from the graph, when the job length is not very long, average unfairness can be quite severe. Only as the jobs run for a significant number of time slices does the lottery scheduler approach the desired outcome.

9.5 How To Assign Tickets?

One problem we have not addressed with lottery scheduling is: how to assign tickets to jobs? This problem is a tough one, because of course how the system behaves is strongly dependent on how tickets are allocated. One approach is to assume that the users know best; in such a case, each user is handed some number of tickets, and a user can allocate tickets to any jobs they run as desired. However, this solution is a non-solution: it really doesn't tell you what to do. Thus, given a set of jobs, the "ticket-assignment problem" remains open.

9.6 Why Not Deterministic?

You might also be wondering: why use randomness at all? As we saw above, while randomness gets us a simple (and approximately correct) scheduler, it occasionally will not deliver the exact right proportions, especially over short time scales. For this reason, Waldspurger invented **stride scheduling**, a deterministic fair-share scheduler [W95].

Stride scheduling is also straightforward. Each job in the system has a stride, which is inverse in proportion to the number of tickets it has. In our example above, with jobs A, B, and C, with 100, 50, and 250 tickets, respectively, we can compute the stride of each by dividing some large number by the number of tickets each process has been assigned. For example, if we divide 10,000 by each of those ticket values, we obtain the following stride values for A, B, and C: 100, 200, and 40. We call this value the **stride** of each process; every time a process runs, we will increment a counter for it (called its **pass** value) by its stride to track its global progress.

The scheduler then uses the stride and pass to determine which process should run next. The basic idea is simple: at any given time, pick the process to run that has the lowest pass value so far; when you run a process, increment its pass counter by its stride. A pseudocode implementation is provided by Waldspurger [W95]:

```
current = remove_min(queue);       // pick client with minimum pass
schedule(current);                 // use resource for quantum
current->pass += current->stride; // compute next pass using stride
insert(queue, current);            // put back into the queue
```

In our example, we start with three processes (A, B, and C), with stride values of 100, 200, and 40, and all with pass values initially at 0. Thus, at first, any of the processes might run, as their pass values are equally low. Assume we pick A (arbitrarily; any of the processes with equal low pass values can be chosen). A runs; when finished with the time slice, we update its pass value to 100. Then we run B, whose pass value is then set to 200. Finally, we run C, whose pass value is incremented to 40. At this point, the algorithm will pick the lowest pass value, which is C's, and run it, updating its pass to 80 (C's stride is 40, as you recall). Then C will

Pass(A) (stride=100)	Pass(B) (stride=200)	Pass(C) (stride=40)	Who Runs?
0	0	0	A
100	0	0	B
100	200	0	C
100	200	40	C
100	200	80	C
100	200	120	A
200	200	120	C
200	200	160	C
200	200	200	...

Figure 9.3: **Stride Scheduling: A Trace**

run again (still the lowest pass value), raising its pass to 120. A will run now, updating its pass to 200 (now equal to B's). Then C will run twice more, updating its pass to 160 then 200. At this point, all pass values are equal again, and the process will repeat, ad infinitum. Figure 9.3 traces the behavior of the scheduler over time.

As we can see from the figure, C ran five times, A twice, and B just once, exactly in proportion to their ticket values of 250, 100, and 50. Lottery scheduling achieves the proportions probabilistically over time; stride scheduling gets them exactly right at the end of each scheduling cycle.

So you might be wondering: given the precision of stride scheduling, why use lottery scheduling at all? Well, lottery scheduling has one nice property that stride scheduling does not: no global state. Imagine a new job enters in the middle of our stride scheduling example above; what should its pass value be? Should it be set to 0? If so, it will monopolize the CPU. With lottery scheduling, there is no global state per process; we simply add a new process with whatever tickets it has, update the single global variable to track how many total tickets we have, and go from there. In this way, lottery makes it much easier to incorporate new processes in a sensible manner.

9.7 Summary

We have introduced the concept of proportional-share scheduling and briefly discussed two implementations: lottery and stride scheduling. Lottery uses randomness in a clever way to achieve proportional share; stride does so deterministically. Although both are conceptually interesting, they have not achieved wide-spread adoption as CPU schedulers for a variety of reasons. One is that such approaches do not particularly mesh well with I/O [AC97]; another is that they leave open the hard problem of ticket assignment, i.e., how do you know how many tickets your browser should be allocated? General-purpose schedulers (such as the MLFQ we discussed previously, and other similar Linux schedulers) do so more gracefully and thus are more widely deployed.

As a result, proportional-share schedulers are more useful in domains where some of these problems (such as assignment of shares) are relatively easy to solve. For example, in a **virtualized** data center, where you might like to assign one-quarter of your CPU cycles to the Windows VM and the rest to your base Linux installation, proportional sharing can be simple and effective. See Waldspurger [W02] for further details on how such a scheme is used to proportionally share memory in VMWare's ESX Server.

References

[AC97] "Extending Proportional-Share Scheduling to a Network of Workstations"
Andrea C. Arpaci-Dusseau and David E. Culler
PDPTA'97, June 1997
A paper by one of the authors on how to extend proportional-share scheduling to work better in a clustered environment.

[D82] "Why Numbering Should Start At Zero"
Edsger Dijkstra, August 1982
http://www.cs.utexas.edu/users/EWD/ewd08xx/EWD831.PDF
A short note from E. Dijkstra, one of the pioneers of computer science. We'll be hearing much more on this guy in the section on Concurrency. In the meanwhile, enjoy this note, which includes this motivating quote: "One of my colleagues — not a computing scientist — accused a number of younger computing scientists of 'pedantry' because they started numbering at zero." The note explains why doing so is logical.

[KL88] "A Fair Share Scheduler"
J. Kay and P. Lauder
CACM, Volume 31 Issue 1, January 1988
An early reference to a fair-share scheduler.

[WW94] "Lottery Scheduling: Flexible Proportional-Share Resource Management"
Carl A. Waldspurger and William E. Weihl
OSDI '94, November 1994
The landmark paper on lottery scheduling that got the systems community re-energized about scheduling, fair sharing, and the power of simple randomized algorithms.

[W95] "Lottery and Stride Scheduling: Flexible
Proportional-Share Resource Management"
Carl A. Waldspurger
Ph.D. Thesis, MIT, 1995
The award-winning thesis of Waldspurger's that outlines lottery and stride scheduling. If you're thinking of writing a Ph.D. dissertation at some point, you should always have a good example around, to give you something to strive for: this is such a good one.

[W02] "Memory Resource Management in VMware ESX Server"
Carl A. Waldspurger
OSDI '02, Boston, Massachusetts
The paper to read about memory management in VMMs (a.k.a., hypervisors). In addition to being relatively easy to read, the paper contains numerous cool ideas about this new type of VMM-level memory management.

Homework

This program, `lottery.py`, allows you to see how a lottery scheduler works. See the README for details.

Questions

1. Compute the solutions for simulations with 3 jobs and random seeds of 1, 2, and 3.
2. Now run with two specific jobs: each of length 10, but one (job 0) with just 1 ticket and the other (job 1) with 100 (e.g., `-l 10:1,10:100`). What happens when the number of tickets is so imbalanced? Will job 0 ever run before job 1 completes? How often? In general, what does such a ticket imbalance do to the behavior of lottery scheduling?
3. When running with two jobs of length 100 and equal ticket allocations of 100 (`-l 100:100,100:100`), how unfair is the scheduler? Run with some different random seeds to determine the (probabilistic) answer; let unfairness be determined by how much earlier one job finishes than the other.
4. How does your answer to the previous question change as the quantum size (`-q`) gets larger?
5. Can you make a version of the graph that is found in the chapter? What else would be worth exploring? How would the graph look with a stride scheduler?

10

Multiprocessor Scheduling (Advanced)

This chapter will introduce the basics of **multiprocessor scheduling**. As this topic is relatively advanced, it may be best to cover it *after* you have studied the topic of concurrency in some detail (i.e., the second major "easy piece" of the book).

After years of existence only in the high-end of the computing spectrum, **multiprocessor** systems are increasingly commonplace, and have found their way into desktop machines, laptops, and even mobile devices. The rise of the **multicore** processor, in which multiple CPU cores are packed onto a single chip, is the source of this proliferation; these chips have become popular as computer architects have had a difficult time making a single CPU much faster without using (way) too much power. And thus we all now have a few CPUs available to us, which is a good thing, right?

Of course, there are many difficulties that arise with the arrival of more than a single CPU. A primary one is that a typical application (i.e., some C program you wrote) only uses a single CPU; adding more CPUs does not make that single application run faster. To remedy this problem, you'll have to rewrite your application to run in **parallel**, perhaps using **threads** (as discussed in great detail in the second piece of this book). Multi-threaded applications can spread work across multiple CPUs and thus run faster when given more CPU resources.

ASIDE: **ADVANCED CHAPTERS**

Advanced chapters require material from a broad swath of the book to truly understand, while logically fitting into a section that is earlier than said set of prerequisite materials. For example, this chapter on multiprocessor scheduling makes much more sense if you've first read the middle piece on concurrency; however, it logically fits into the part of the book on virtualization (generally) and CPU scheduling (specifically). Thus, it is recommended such chapters be covered out of order; in this case, after the second piece of the book.

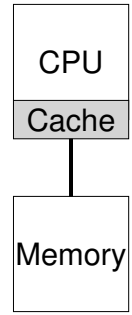


Figure 10.1: **Single CPU With Cache**

Beyond applications, a new problem that arises for the operating system is (not surprisingly!) that of **multiprocessor scheduling**. Thus far we've discussed a number of principles behind single-processor scheduling; how can we extend those ideas to work on multiple CPUs? What new problems must we overcome? And thus, our problem:

CRUX: HOW TO SCHEDULE JOBS ON MULTIPLE CPUS
How should the OS schedule jobs on multiple CPUs? What new problems arise? Do the same old techniques work, or are new ideas required?

10.1 Background: Multiprocessor Architecture

To understand the new issues surrounding multiprocessor scheduling, we have to understand a new and fundamental difference between single-CPU hardware and multi-CPU hardware. This difference centers around the use of hardware **caches** (e.g., Figure 10.1), and exactly how data is shared across multiple processors. We now discuss this issue further, at a high level. Details are available elsewhere [CSG99], in particular in an upper-level or perhaps graduate computer architecture course.

In a system with a single CPU, there are a hierarchy of **hardware caches** that in general help the processor run programs faster. Caches are small, fast memories that (in general) hold copies of *popular* data that is found in the main memory of the system. Main memory, in contrast, holds *all* of the data, but access to this larger memory is slower. By keeping frequently accessed data in a cache, the system can make the large, slow memory appear to be a fast one.

As an example, consider a program that issues an explicit load instruction to fetch a value from memory, and a simple system with only a single CPU; the CPU has a small cache (say 64 KB) and a large main memory.

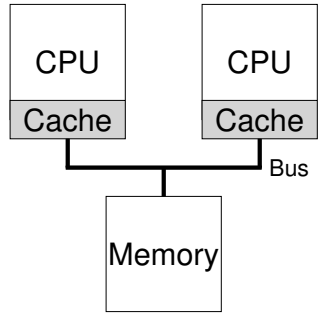


Figure 10.2: **Two CPUs With Caches Sharing Memory**

The first time a program issues this load, the data resides in main memory, and thus takes a long time to fetch (perhaps in the tens of nanoseconds, or even hundreds). The processor, anticipating that the data may be reused, puts a copy of the loaded data into the CPU cache. If the program later fetches this same data item again, the CPU first checks for it in the cache; if it finds it there, the data is fetched much more quickly (say, just a few nanoseconds), and thus the program runs faster.

Caches are thus based on the notion of **locality**, of which there are two kinds: **temporal locality** and **spatial locality**. The idea behind temporal locality is that when a piece of data is accessed, it is likely to be accessed again in the near future; imagine variables or even instructions themselves being accessed over and over again in a loop. The idea behind spatial locality is that if a program accesses a data item at address x, it is likely to access data items near x as well; here, think of a program streaming through an array, or instructions being executed one after the other. Because locality of these types exist in many programs, hardware systems can make good guesses about which data to put in a cache and thus work well.

Now for the tricky part: what happens when you have multiple processors in a single system, with a single shared main memory, as we see in Figure 10.2?

As it turns out, caching with multiple CPUs is much more complicated. Imagine, for example, that a program running on CPU 1 reads a data item (with value D) at address A; because the data is not in the cache on CPU 1, the system fetches it from main memory, and gets the value D. The program then modifies the value at address A, just updating its cache with the new value D'; writing the data through all the way to main memory is slow, so the system will (usually) do that later. Then assume the OS decides to stop running the program and move it to CPU 2. The program then re-reads the value at address A; there is no such data

CPU 2's cache, and thus the system fetches the value from main memory, and gets the old value D instead of the correct value D'. Oops!

This general problem is called the problem of **cache coherence**, and there is a vast research literature that describes many different subtleties involved with solving the problem [SHW11]. Here, we will skip all of the nuance and make some major points; take a computer architecture class (or three) to learn more.

The basic solution is provided by the hardware: by monitoring memory accesses, hardware can ensure that basically the "right thing" happens and that the view of a single shared memory is preserved. One way to do this on a bus-based system (as described above) is to use an old technique known as **bus snooping** [G83]; each cache pays attention to memory updates by observing the bus that connects them to main memory. When a CPU then sees an update for a data item it holds in its cache, it will notice the change and either **invalidate** its copy (i.e., remove it from its own cache) or **update** it (i.e., put the new value into its cache too). Write-back caches, as hinted at above, make this more complicated (because the write to main memory isn't visible until later), but you can imagine how the basic scheme might work.

10.2 Don't Forget Synchronization

Given that the caches do all of this work to provide coherence, do programs (or the OS itself) have to worry about anything when they access shared data? The answer, unfortunately, is yes, and is documented in great detail in the second piece of this book on the topic of concurrency. While we won't get into the details here, we'll sketch/review some of the basic ideas here (assuming you're familiar with concurrency).

When accessing (and in particular, updating) shared data items or structures across CPUs, mutual exclusion primitives (such as locks) should likely be used to guarantee correctness (other approaches, such as building **lock-free** data structures, are complex and only used on occasion; see the chapter on deadlock in the piece on concurrency for details). For example, assume we have a shared queue being accessed on multiple CPUs concurrently. Without locks, adding or removing elements from the queue concurrently will not work as expected, even with the underlying coherence protocols; one needs locks to atomically update the data structure to its new state.

To make this more concrete, imagine this code sequence, which is used to remove an element from a shared linked list, as we see in Figure 10.3. Imagine if threads on two CPUs enter this routine at the same time. If Thread 1 executes the first line, it will have the current value of `head` stored in its `tmp` variable; if Thread 2 then executes the first line as well, it also will have the same value of `head` stored in its own private `tmp` variable (`tmp` is allocated on the stack, and thus each thread will have its own private storage for it). Thus, instead of each thread removing an element from the head of the list, each thread will try to remove the

```
1  typedef struct __Node_t {
2      int              value;
3      struct __Node_t *next;
4  } Node_t;
5
6  int List_Pop() {
7      Node_t *tmp = head;         // remember old head ...
8      int value   = head->value;  // ... and its value
9      head        = head->next;   // advance head to next pointer
10     free(tmp);                  // free old head
11     return value;               // return value at head
12 }
```

Figure 10.3: **Simple List Delete Code**

same head element, leading to all sorts of problems (such as an attempted double free of the head element at line 4, as well as potentially returning the same data value twice).

The solution, of course, is to make such routines correct via **locking**. In this case, allocating a simple mutex (e.g., `pthread_mutex_t m;`) and then adding a `lock(&m)` at the beginning of the routine and an `unlock(&m)` at the end will solve the problem, ensuring that the code will execute as desired. Unfortunately, as we will see, such an approach is not without problems, in particular with regards to performance. Specifically, as the number of CPUs grows, access to a synchronized shared data structure becomes quite slow.

10.3 One Final Issue: Cache Affinity

One final issue arises in building a multiprocessor cache scheduler, known as **cache affinity**. This notion is simple: a process, when run on a particular CPU, builds up a fair bit of state in the caches (and TLBs) of the CPU. The next time the process runs, it is often advantageous to run it on the same CPU, as it will run faster if some of its state is already present in the caches on that CPU. If, instead, one runs a process on a different CPU each time, the performance of the process will be worse, as it will have to reload the state each time it runs (note it will run correctly on a different CPU thanks to the cache coherence protocols of the hardware). Thus, a multiprocessor scheduler should consider cache affinity when making its scheduling decisions, perhaps preferring to keep a process on the same CPU if at all possible.

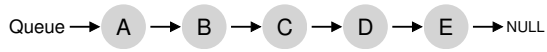
10.4 Single-Queue Scheduling

With this background in place, we now discuss how to build a scheduler for a multiprocessor system. The most basic approach is to simply reuse the basic framework for single processor scheduling, by putting all jobs that need to be scheduled into a single queue; we call this **single-queue multiprocessor scheduling** or **SQMS** for short. This approach has the advantage of simplicity; it does not require much work to take an existing policy that picks the best job to run next and adapt it to work on more than one CPU (where it might pick the best two jobs to run, if there are two CPUs, for example).

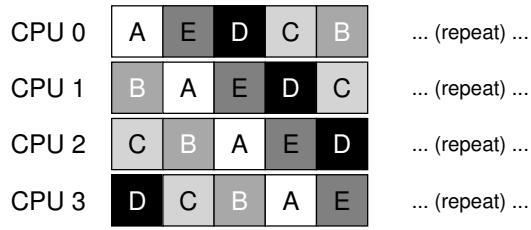
However, SQMS has obvious shortcomings. The first problem is a lack of **scalability**. To ensure the scheduler works correctly on multiple CPUs, the developers will have inserted some form of **locking** into the code, as described above. Locks ensure that when SQMS code accesses the single queue (say, to find the next job to run), the proper outcome arises.

Locks, unfortunately, can greatly reduce performance, particularly as the number of CPUs in the systems grows [A91]. As contention for such a single lock increases, the system spends more and more time in lock overhead and less time doing the work the system should be doing (note: it would be great to include a real measurement of this in here someday).

The second main problem with SQMS is cache affinity. For example, let us assume we have five jobs to run (A, B, C, D, E) and four processors. Our scheduling queue thus looks like this:

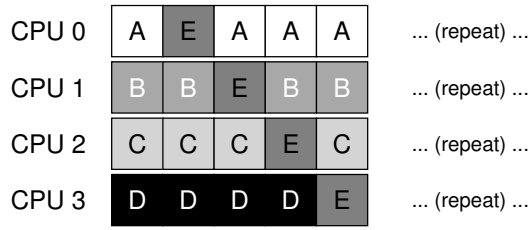


Over time, assuming each job runs for a time slice and then another job is chosen, here is a possible job schedule across CPUs:



Because each CPU simply picks the next job to run from the globally-shared queue, each job ends up bouncing around from CPU to CPU, thus doing exactly the opposite of what would make sense from the standpoint of cache affinity.

To handle this problem, most SQMS schedulers include some kind of affinity mechanism to try to make it more likely that process will continue to run on the same CPU if possible. Specifically, one might provide affinity for some jobs, but move others around to balance load. For example, imagine the same five jobs scheduled as follows:



In this arrangement, jobs A through D are not moved across processors, with only job E **migrating** from CPU to CPU, thus preserving affinity for most. You could then decide to migrate a different job the next time through, thus achieving some kind of affinity fairness as well. Implementing such a scheme, however, can be complex.

Thus, we can see the SQMS approach has its strengths and weaknesses. It is straightforward to implement given an existing single-CPU scheduler, which by definition has only a single queue. However, it does not scale well (due to synchronization overheads), and it does not readily preserve cache affinity.

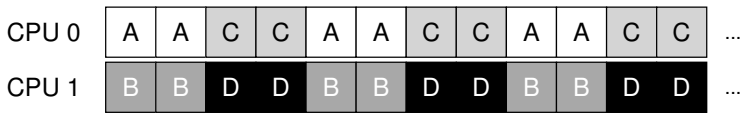
10.5 Multi-Queue Scheduling

Because of the problems caused in single-queue schedulers, some systems opt for multiple queues, e.g., one per CPU. We call this approach **multi-queue multiprocessor scheduling** (or **MQMS**).

In MQMS, our basic scheduling framework consists of multiple scheduling queues. Each queue will likely follow a particular scheduling discipline, such as round robin, though of course any algorithm can be used. When a job enters the system, it is placed on exactly one scheduling queue, according to some heuristic (e.g., random, or picking one with fewer jobs than others). Then it is scheduled essentially independently, thus avoiding the problems of information sharing and synchronization found in the single-queue approach.

For example, assume we have a system where there are just two CPUs (labeled CPU 0 and CPU 1), and some number of jobs enter the system: A, B, C, and D for example. Given that each CPU has a scheduling queue now, the OS has to decide into which queue to place each job. It might do something like this:

Depending on the queue scheduling policy, each CPU now has two jobs to choose from when deciding what should run. For example, with **round robin**, the system might produce a schedule that looks like this:

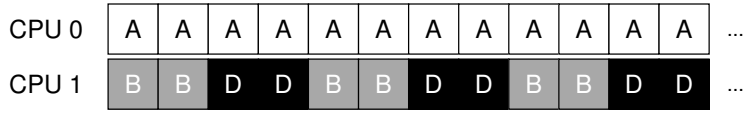


MQMS has a distinct advantage of SQMS in that it should be inherently more scalable. As the number of CPUs grows, so too does the number of queues, and thus lock and cache contention should not become a central problem. In addition, MQMS intrinsically provides cache affinity;

jobs stay on the same CPU and thus reap the advantage of reusing cached contents therein.

But, if you've been paying attention, you might see that we have a new problem, which is fundamental in the multi-queue based approach: **load imbalance**. Let's assume we have the same set up as above (four jobs, two CPUs), but then one of the jobs (say C) finishes. We now have the following scheduling queues:

If we then run our round-robin policy on each queue of the system, we will see this resulting schedule:



As you can see from this diagram, A gets twice as much CPU as B and D, which is not the desired outcome. Even worse, let's imagine that both A and C finish, leaving just jobs B and D in the system. The scheduling queues will look like this:

As a result, CPU 0 will be left idle! *(insert dramatic and sinister music here)* And hence our CPU usage timeline looks sad:

So what should a poor multi-queue multiprocessor scheduler do? How can we overcome the insidious problem of load imbalance and defeat the evil forces of ... the Decepticons[1]? How do we stop asking questions that are hardly relevant to this otherwise wonderful book?

[1]Little known fact is that the home planet of Cybertron was destroyed by bad CPU scheduling decisions. And now let that be the first and last reference to Transformers in this book, for which we sincerely apologize.

CRUX: HOW TO DEAL WITH LOAD IMBALANCE
How should a multi-queue multiprocessor scheduler handle load imbalance, so as to better achieve its desired scheduling goals?

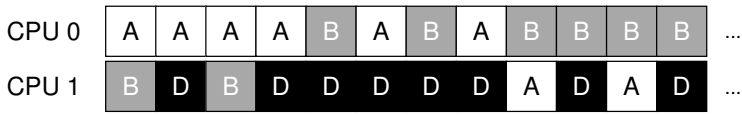
The obvious answer to this query is to move jobs around, a technique which we (once again) refer to as **migration**. By migrating a job from one CPU to another, true load balance can be achieved.

Let's look at a couple of examples to add some clarity. Once again, we have a situation where one CPU is idle and the other has some jobs.

In this case, the desired migration is easy to understand: the OS should simply move one of B or D to CPU 0. The result of this single job migration is evenly balanced load and everyone is happy.

A more tricky case arises in our earlier example, where A was left alone on CPU 0 and B and D were alternating on CPU 1:

In this case, a single migration does not solve the problem. What would you do in this case? The answer, alas, is continuous migration of one or more jobs. One possible solution is to keep switching jobs, as we see in the following timeline. In the figure, first A is alone on CPU 0, and B and D alternate on CPU 1. After a few time slices, B is moved to compete with A on CPU 0, while D enjoys a few time slices alone on CPU 1. And thus load is balanced:



Of course, many other possible migration patterns exist. But now for the tricky part: how should the system decide to enact such a migration?

One basic approach is to use a technique known as **work stealing** [FLR98]. With a work-stealing approach, a (source) queue that is low on jobs will occasionally peek at another (target) queue, to see how full it is. If the target queue is (notably) more full than the source queue, the source will "steal" one or more jobs from the target to help balance load.

Of course, there is a natural tension in such an approach. If you look around at other queues too often, you will suffer from high overhead and have trouble scaling, which was the entire purpose of implementing

the multiple queue scheduling in the first place! If, on the other hand, you don't look at other queues very often, you are in danger of suffering from severe load imbalances. Finding the right threshold remains, as is common in system policy design, a black art.

10.6 Linux Multiprocessor Schedulers

Interestingly, in the Linux community, no common solution has approached to building a multiprocessor scheduler. Over time, three different schedulers arose: the O(1) scheduler, the Completely Fair Scheduler (CFS), and the BF Scheduler (BFS)[2]. See Meehean's dissertation for an excellent overview of the strengths and weaknesses of said schedulers [M11]; here we just summarize a few of the basics.

Both O(1) and CFS use multiple queues, whereas BFS uses a single queue, showing that both approaches can be successful. Of course, there are many other details which separate these schedulers. For example, the O(1) scheduler is a priority-based scheduler (similar to the MLFQ discussed before), changing a process's priority over time and then scheduling those with highest priority in order to meet various scheduling objectives; interactivity is a particular focus. CFS, in contrast, is a deterministic proportional-share approach (more like Stride scheduling, as discussed earlier). BFS, the only single-queue approach among the three, is also proportional-share, but based on a more complicated scheme known as Earliest Eligible Virtual Deadline First (EEVDF) [SA96]. Read more about these modern algorithms on your own; you should be able to understand how they work now!

10.7 Summary

We have seen various approaches to multiprocessor scheduling. The single-queue approach (SQMS) is rather straightforward to build and balances load well but inherently has difficulty with scaling to many processors and cache affinity. The multiple-queue approach (MQMS) scales better and handles cache affinity well, but has trouble with load imbalance and is more complicated. Whichever approach you take, there is no simple answer: building a general purpose scheduler remains a daunting task, as small code changes can lead to large behavioral differences. Only undertake such an exercise if you know exactly what you are doing, or, at least, are getting paid a large amount of money to do so.

[2] Look up what BF stands for on your own; be forewarned, it is not for the faint of heart.

References

[A90] "The Performance of Spin Lock Alternatives for Shared-Memory Multiprocessors"
Thomas E. Anderson
IEEE TPDS Volume 1:1, January 1990
A classic paper on how different locking alternatives do and don't scale. By Tom Anderson, very well known researcher in both systems and networking. And author of a very fine OS textbook, we must say.

[B+10] "An Analysis of Linux Scalability to Many Cores Abstract"
Silas Boyd-Wickizer, Austin T. Clements, Yandong Mao, Aleksey Pesterev, M. Frans Kaashoek, Robert Morris, Nickolai Zeldovich
OSDI '10, Vancouver, Canada, October 2010
A terrific modern paper on the difficulties of scaling Linux to many cores.

[CSG99] "Parallel Computer Architecture: A Hardware/Software Approach"
David E. Culler, Jaswinder Pal Singh, and Anoop Gupta
Morgan Kaufmann, 1999
A treasure filled with details about parallel machines and algorithms. As Mark Hill humorously observes on the jacket, the book contains more information than most research papers.

[FLR98] "The Implementation of the Cilk-5 Multithreaded Language"
Matteo Frigo, Charles E. Leiserson, Keith Randall
PLDI '98, Montreal, Canada, June 1998
Cilk is a lightweight language and runtime for writing parallel programs, and an excellent example of the work-stealing paradigm.

[G83] "Using Cache Memory To Reduce Processor-Memory Traffic"
James R. Goodman
ISCA '83, Stockholm, Sweden, June 1983
The pioneering paper on how to use bus snooping, i.e., paying attention to requests you see on the bus, to build a cache coherence protocol. Goodman's research over many years at Wisconsin is full of cleverness, this being but one example.

[M11] "Towards Transparent CPU Scheduling"
Joseph T. Meehean
Doctoral Dissertation at University of Wisconsin—Madison, 2011
A dissertation that covers a lot of the details of how modern Linux multiprocessor scheduling works. Pretty awesome! But, as co-advisors of Joe's, we may be a bit biased here.

[SHW11] "A Primer on Memory Consistency and Cache Coherence"
Daniel J. Sorin, Mark D. Hill, and David A. Wood
Synthesis Lectures in Computer Architecture
Morgan and Claypool Publishers, May 2011
A definitive overview of memory consistency and multiprocessor caching. Required reading for anyone who likes to know way too much about a given topic.

[SA96] "Earliest Eligible Virtual Deadline First: A Flexible and Accurate Mechanism for Proportional Share Resource Allocation"
Ion Stoica and Hussein Abdel-Wahab
Technical Report TR-95-22, Old Dominion University, 1996
A tech report on this cool scheduling idea, from Ion Stoica, now a professor at U.C. Berkeley and world expert in networking, distributed systems, and many other things.

11

Summary Dialogue on CPU Virtualization

Professor: *So, Student, did you learn anything?*

Student: *Well, Professor, that seems like a loaded question. I think you only want me to say "yes."*

Professor: *That's true. But it's also still an honest question. Come on, give a professor a break, will you?*

Student: *OK, OK. I think I did learn a few things. First, I learned a little about how the OS virtualizes the CPU. There are a bunch of important* ***mechanisms*** *that I had to understand to make sense of this: traps and trap handlers, timer interrupts, and how the OS and the hardware have to carefully save and restore state when switching between processes.*

Professor: *Good, good!*

Student: *All those interactions do seem a little complicated though; how can I learn more?*

Professor: *Well, that's a good question. I think there is no substitute for doing; just reading about these things doesn't quite give you the proper sense. Do the class projects and I bet by the end it will all kind of make sense.*

Student: *Sounds good. What else can I tell you?*

Professor: *Well, did you get some sense of the philosophy of the OS in your quest to understand its basic machinery?*

Student: *Hmm... I think so. It seems like the OS is fairly paranoid. It wants to make sure it stays in charge of the machine. While it wants a program to run as efficiently as possible (and hence the whole reasoning behind* ***limited direct execution****), the OS also wants to be able to say "Ah! Not so fast my friend" in case of an errant or malicious process. Paranoia rules the day, and certainly keeps the OS in charge of the machine. Perhaps that is why we think of the OS as a resource manager.*

Professor: *Yes indeed — sounds like you are starting to put it together! Nice.*

Student: *Thanks.*

Professor: *And what about the policies on top of those mechanisms — any interesting lessons there?*

Student: *Some lessons to be learned there for sure. Perhaps a little obvious, but obvious can be good. Like the notion of bumping short jobs to the front of the queue — I knew that was a good idea ever since the one time I was buying some gum at the store, and the guy in front of me had a credit card that wouldn't work. He was no short job, let me tell you.*

Professor: *That sounds oddly rude to that poor fellow. What else?*

Student: *Well, that you can build a smart scheduler that tries to be like SJF and RR all at once — that MLFQ was pretty neat. Building up a real scheduler seems difficult.*

Professor: *Indeed it is. That's why there is still controversy to this day over which scheduler to use; see the Linux battles between CFS, BFS, and the O(1) scheduler, for example. And no, I will not spell out the full name of BFS.*

Student: *And I won't ask you to! These policy battles seem like they could rage forever; is there really a right answer?*

Professor: *Probably not. After all, even our own metrics are at odds: if your scheduler is good at turnaround time, it's bad at response time, and vice versa. As Lampson said, perhaps the goal isn't to find the best solution, but rather to avoid disaster.*

Student: *That's a little depressing.*

Professor: *Good engineering can be that way. And it can also be uplifting! It's just your perspective on it, really. I personally think being pragmatic is a good thing, and pragmatists realize that not all problems have clean and easy solutions. Anything else that caught your fancy?*

Student: *I really liked the notion of gaming the scheduler; it seems like that might be something to look into when I'm next running a job on Amazon's EC2 service. Maybe I can steal some cycles from some other unsuspecting (and more importantly, OS-ignorant) customer!*

Professor: *It looks like I might have created a monster! Professor Frankenstein is not what I'd like to be called, you know.*

Student: *But isn't that the idea? To get us excited about something, so much so that we look into it on our own? Lighting fires and all that?*

Professor: *I guess so. But I didn't think it would work!*