

Introduction to Operating Systems

If you are taking an undergraduate operating systems course, you should already have some idea of what a computer program does when it runs. If not, this book (and the corresponding course) is going to be difficult — so you should probably stop reading this book, or run to the nearest bookstore and quickly consume the necessary background material before continuing (both Patt & Patel [PP03] and Bryant & O'Hallaron [BOH10] are pretty great books).

So what happens when a program runs?

Well, a running program does one very simple thing: it executes instructions. Many millions (and these days, even billions) of times every second, the processor **fetches** an instruction from memory, **decodes** it (i.e., figures out which instruction this is), and **executes** it (i.e., it does the thing that it is supposed to do, like add two numbers together, access memory, check a condition, jump to a function, and so forth). After it is done with this instruction, the processor moves on to the next instruction, and so on, and so on, until the program finally completes¹.

Thus, we have just described the basics of the **Von Neumann** model of computing². Sounds simple, right? But in this class, we will be learning that while a program runs, a lot of other wild things are going on with the primary goal of making the system **easy to use**.

There is a body of software, in fact, that is responsible for making it easy to run programs (even allowing you to seemingly run many at the same time), allowing programs to share memory, enabling programs to interact with devices, and other fun stuff like that. That body of software

¹Of course, modern processors do many bizarre and frightening things underneath the hood to make programs run faster, e.g., executing multiple instructions at once, and even issuing and completing them out of order! But that is not our concern here; we are just concerned with the simple model most programs assume: that instructions seemingly execute one at a time, in an orderly and sequential fashion.

²Von Neumann was one of the early pioneers of computing systems. He also did pioneering work on game theory and atomic bombs, and played in the NBA for six years. OK, one of those things isn't true.

THE CRUX OF THE PROBLEM:
HOW TO VIRTUALIZE RESOURCES

One central question we will answer in this book is quite simple: how does the operating system virtualize resources? This is the crux of our problem. *Why* the OS does this is not the main question, as the answer should be obvious: it makes the system easier to use. Thus, we focus on the *how*: what mechanisms and policies are implemented by the OS to attain virtualization? How does the OS do so efficiently? What hardware support is needed?

We will use the “crux of the problem”, in shaded boxes such as this one, as a way to call out specific problems we are trying to solve in building an operating system. Thus, within a note on a particular topic, you may find one or more *crucies* (yes, this is the proper plural) which highlight the problem. The details within the chapter, of course, present the solution, or at least the basic parameters of a solution.

is called the **operating system (OS)**³, as it is in charge of making sure the system operates correctly and efficiently in an easy-to-use manner.

The primary way the OS does this is through a general technique that we call **virtualization**. That is, the OS takes a **physical** resource (such as the processor, or memory, or a disk) and transforms it into a more general, powerful, and easy-to-use **virtual** form of itself. Thus, we sometimes refer to the operating system as a **virtual machine**.

Of course, in order to allow users to tell the OS what to do and thus make use of the features of the virtual machine (such as running a program, or allocating memory, or accessing a file), the OS also provides some interfaces (APIs) that you can call. A typical OS, in fact, exports a few hundred **system calls** that are available to applications. Because the OS provides these calls to run programs, access memory and devices, and other related actions, we also sometimes say that the OS provides a **standard library** to applications.

Finally, because virtualization allows many programs to run (thus sharing the CPU), and many programs to concurrently access their own instructions and data (thus sharing memory), and many programs to access devices (thus sharing disks and so forth), the OS is sometimes known as a **resource manager**. Each of the CPU, memory, and disk is a **resource** of the system; it is thus the operating system’s role to **manage** those resources, doing so efficiently or fairly or indeed with many other possible goals in mind. To understand the role of the OS a little bit better, let’s take a look at some examples.

³ Another early name for the OS was the **supervisor** or even the **master control program**. Apparently, the latter sounded a little overzealous (see the movie *Tron* for details) and thus, thankfully, “operating system” caught on instead.

```
1  #include <stdio.h>
2  #include <stdlib.h>
3  #include <sys/time.h>
4  #include <assert.h>
5  #include "common.h"
6
7  int
8  main(int argc, char *argv[])
9  {
10     if (argc != 2) {
11         fprintf(stderr, "usage: cpu <string>\n");
12         exit(1);
13     }
14     char *str = argv[1];
15     while (1) {
16         Spin(1);
17         printf("%s\n", str);
18     }
19     return 0;
20 }
```

Figure 2.1: **Simple Example: Code That Loops And Prints (cpu.c)**

2.1 Virtualizing The CPU

Figure 2.1 depicts our first program. It doesn't do much. In fact, all it does is call `Spin()`, a function that repeatedly checks the time and returns once it has run for a second. Then, it prints out the string that the user passed in on the command line, and repeats, forever.

Let's say we save this file as `cpu.c` and decide to compile and run it on a system with a single processor (or **CPU** as we will sometimes call it). Here is what we will see:

```
prompt> gcc -o cpu cpu.c -Wall
prompt> ./cpu "A"
A
A
A
A
^C
prompt>
```

Not too interesting of a run — the system begins running the program, which repeatedly checks the time until a second has elapsed. Once a second has passed, the code prints the input string passed in by the user (in this example, the letter "A"), and continues. Note the program will run forever; by pressing "Control-c" (which on UNIX-based systems will terminate the program running in the foreground) we can halt the program.

```
prompt> ./cpu A & ./cpu B & ./cpu C & ./cpu D &  
[1] 7353  
[2] 7354  
[3] 7355  
[4] 7356  
A  
B  
D  
C  
A  
B  
D  
C  
A  
...
```

Figure 2.2: Running Many Programs At Once

Now, let's do the same thing, but this time, let's run many different instances of this same program. Figure 2.2 shows the results of this slightly more complicated example.

Well, now things are getting a little more interesting. Even though we have only one processor, somehow all four of these programs seem to be running at the same time! How does this magic happen?⁴

It turns out that the operating system, with some help from the hardware, is in charge of this **illusion**, i.e., the illusion that the system has a very large number of virtual CPUs. Turning a single CPU (or a small set of them) into a seemingly infinite number of CPUs and thus allowing many programs to seemingly run at once is what we call **virtualizing the CPU**, the focus of the first major part of this book.

Of course, to run programs, and stop them, and otherwise tell the OS which programs to run, there need to be some interfaces (APIs) that you can use to communicate your desires to the OS. We'll talk about these APIs throughout this book; indeed, they are the major way in which most users interact with operating systems.

You might also notice that the ability to run multiple programs at once raises all sorts of new questions. For example, if two programs want to run at a particular time, which *should* run? This question is answered by a **policy** of the OS; policies are used in many different places within an OS to answer these types of questions, and thus we will study them as we learn about the basic **mechanisms** that operating systems implement (such as the ability to run multiple programs at once). Hence the role of the OS as a **resource manager**.

⁴Note how we ran four processes at the same time, by using the `&` symbol. Doing so runs a job in the background in the `zsh` shell, which means that the user is able to immediately issue their next command, which in this case is another program to run. If you're using a different shell (e.g., `tcsh`), it works slightly differently; read documentation online for details.

```

1  #include <unistd.h>
2  #include <stdio.h>
3  #include <stdlib.h>
4  #include "common.h"
5
6  int
7  main(int argc, char *argv[])
8  {
9      int *p = malloc(sizeof(int));           // a1
10     assert(p != NULL);
11     printf("(%) address pointed to by p: %p\n",
12            getpid(), p);
13     *p = 0;                                   // a2
14     while (1) {
15         Spin(1);
16         *p = *p + 1;
17         printf("(%) p: %d\n", getpid(), *p);   // a4
18     }
19     return 0;
20 }

```

Figure 2.3: A Program That Accesses Memory (`mem.c`)

2.2 Virtualizing Memory

Now let's consider memory. The model of **physical memory** presented by modern machines is very simple. Memory is just an array of bytes; to **read** memory, one must specify an **address** to be able to access the data stored there; to **write** (or **update**) memory, one must also specify the data to be written to the given address.

Memory is accessed all the time when a program is running. A program keeps all of its data structures in memory, and accesses them through various instructions, like loads and stores or other explicit instructions that access memory in doing their work. Don't forget that each instruction of the program is in memory too; thus memory is accessed on each instruction fetch.

Let's take a look at a program (in Figure 2.3) that allocates some memory by calling `malloc()`. The output of this program can be found here:

```

prompt> ./mem
(2134) address pointed to by p: 0x200000
(2134) p: 1
(2134) p: 2
(2134) p: 3
(2134) p: 4
(2134) p: 5
^C

```

```

prompt> ./mem &; ./mem &
[1] 24113
[2] 24114
(24113) address pointed to by p: 0x200000
(24114) address pointed to by p: 0x200000
(24113) p: 1
(24114) p: 1
(24114) p: 2
(24113) p: 2
(24113) p: 3
(24114) p: 3
(24113) p: 4
(24114) p: 4
...

```

Figure 2.4: Running The Memory Program Multiple Times

The program does a couple of things. First, it allocates some memory (line a1). Then, it prints out the address of the memory (a2), and then puts the number zero into the first slot of the newly allocated memory (a3). Finally, it loops, delaying for a second and incrementing the value stored at the address held in `p`. With every print statement, it also prints out what is called the process identifier (the PID) of the running program. This PID is unique per running process.

Again, this first result is not too interesting. The newly allocated memory is at address `0x200000`. As the program runs, it slowly updates the value and prints out the result.

Now, we again run multiple instances of this same program to see what happens (Figure 2.4). We see from the example that each running program has allocated memory at the same address (`0x200000`), and yet each seems to be updating the value at `0x200000` independently! It is as if each running program has its own private memory, instead of sharing the same physical memory with other running programs⁵.

Indeed, that is exactly what is happening here as the OS is **virtualizing memory**. Each process accesses its own private **virtual address space** (sometimes just called its **address space**), which the OS somehow maps onto the physical memory of the machine. A memory reference within one running program does not affect the address space of other processes (or the OS itself); as far as the running program is concerned, it has physical memory all to itself. The reality, however, is that physical memory is a shared resource, managed by the operating system. Exactly how all of this is accomplished is also the subject of the first part of this book, on the topic of **virtualization**.

⁵For this example to work, you need to make sure address-space randomization is disabled; randomization, as it turns out, can be a good defense against certain kinds of security flaws. Read more about it on your own, especially if you want to learn how to break into computer systems via stack-smashing attacks. Not that we would recommend such a thing...

2.3 Concurrency

```

1  #include <stdio.h>
2  #include <stdlib.h>
3  #include "common.h"
4  #include "common_threads.h"
5
6  volatile int counter = 0;
7  int loops;
8
9  void *worker(void *arg) {
10     int i;
11     for (i = 0; i < loops; i++) {
12         counter++;
13     }
14     return NULL;
15 }
16
17 int main(int argc, char *argv[]) {
18     if (argc != 2) {
19         fprintf(stderr, "usage: threads <value>\n");
20         exit(1);
21     }
22     loops = atoi(argv[1]);
23     pthread_t p1, p2;
24     printf("Initial value : %d\n", counter);
25
26     Pthread_create(&p1, NULL, worker, NULL);
27     Pthread_create(&p2, NULL, worker, NULL);
28     Pthread_join(p1, NULL);
29     Pthread_join(p2, NULL);
30     printf("Final value   : %d\n", counter);
31     return 0;
32 }

```

Figure 2.5: A Multi-threaded Program (**threads.c**)

Another main theme of this book is **concurrency**. We use this conceptual term to refer to a host of problems that arise, and must be addressed, when working on many things at once (i.e., concurrently) in the same program. The problems of concurrency arose first within the operating system itself; as you can see in the examples above on virtualization, the OS is juggling many things at once, first running one process, then another, and so forth. As it turns out, doing so leads to some deep and interesting problems.

Unfortunately, the problems of concurrency are no longer limited just to the OS itself. Indeed, modern **multi-threaded** programs exhibit the same problems. Let us demonstrate with an example of a **multi-threaded** program (Figure 2.5).

Although you might not understand this example fully at the moment (and we'll learn a lot more about it in later chapters, in the section of the book on concurrency), the basic idea is simple. The main program creates two **threads** using `Pthread_create()`⁶. You can think of a thread as a function running within the same memory space as other functions, with more than one of them active at a time. In this example, each thread starts running in a routine called `worker()`, in which it simply increments a counter in a loop for `loops` number of times.

Below is a transcript of what happens when we run this program with the input value for the variable `loops` set to 1000. The value of `loops` determines how many times each of the two workers will increment the shared counter in a loop. When the program is run with the value of `loops` set to 1000, what do you expect the final value of `counter` to be?

```
prompt> gcc -o thread thread.c -Wall -pthread
prompt> ./thread 1000
Initial value : 0
Final value   : 2000
```

As you probably guessed, when the two threads are finished, the final value of the counter is 2000, as each thread incremented the counter 1000 times. Indeed, when the input value of `loops` is set to N , we would expect the final output of the program to be $2N$. But life is not so simple, as it turns out. Let's run the same program, but with higher values for `loops`, and see what happens:

```
prompt> ./thread 100000
Initial value : 0
Final value   : 143012 // huh??
prompt> ./thread 100000
Initial value : 0
Final value   : 137298 // what the??
```

In this run, when we gave an input value of 100,000, instead of getting a final value of 200,000, we instead first get 143,012. Then, when we run the program a second time, we not only again get the *wrong* value, but also a *different* value than the last time. In fact, if you run the program over and over with high values of `loops`, you may find that sometimes you even get the right answer! So why is this happening?

As it turns out, the reason for these odd and unusual outcomes relate to how instructions are executed, which is one at a time. Unfortunately, a key part of the program above, where the shared counter is incremented,

⁶The actual call should be to lower-case `pthread_create()`; the upper-case version is our own wrapper that calls `pthread_create()` and makes sure that the return code indicates that the call succeeded. See the code for details.

THE CRUX OF THE PROBLEM:

HOW TO BUILD CORRECT CONCURRENT PROGRAMS

When there are many concurrently executing threads within the same memory space, how can we build a correctly working program? What primitives are needed from the OS? What mechanisms should be provided by the hardware? How can we use them to solve the problems of concurrency?

takes three instructions: one to load the value of the counter from memory into a register, one to increment it, and one to store it back into memory. Because these three instructions do not execute **atomically** (all at once), strange things can happen. It is this problem of **concurrency** that we will address in great detail in the second part of this book.

2.4 Persistence

The third major theme of the course is **persistence**. In system memory, data can be easily lost, as devices such as DRAM store values in a **volatile** manner; when power goes away or the system crashes, any data in memory is lost. Thus, we need hardware and software to be able to store data **persistently**; such storage is thus critical to any system as users care a great deal about their data.

The hardware comes in the form of some kind of **input/output** or **I/O** device; in modern systems, a **hard drive** is a common repository for long-lived information, although **solid-state drives (SSDs)** are making headway in this arena as well.

The software in the operating system that usually manages the disk is called the **file system**; it is thus responsible for storing any **files** the user creates in a reliable and efficient manner on the disks of the system.

Unlike the abstractions provided by the OS for the CPU and memory, the OS does not create a private, virtualized disk for each application. Rather, it is assumed that often times, users will want to **share** information that is in files. For example, when writing a C program, you might first use an editor (e.g., Emacs⁷) to create and edit the C file (`emacs -nw main.c`). Once done, you might use the compiler to turn the source code into an executable (e.g., `gcc -o main main.c`). When you're finished, you might run the new executable (e.g., `./main`). Thus, you can see how files are shared across different processes. First, Emacs creates a file that serves as input to the compiler; the compiler uses that input file to create a new executable file (in many steps — take a compiler course for details); finally, the new executable is then run. And thus a new program is born!

⁷You should be using Emacs. If you are using vi, there is probably something wrong with you. If you are using something that is not a real code editor, that is even worse.

```
1 #include <stdio.h>
2 #include <unistd.h>
3 #include <assert.h>
4 #include <fcntl.h>
5 #include <sys/types.h>
6
7 int main(int argc, char *argv[]) {
8     int fd = open("/tmp/file", O_WRONLY|O_CREAT|O_TRUNC,
9                  S_IRWXU);
10    assert(fd > -1);
11    int rc = write(fd, "hello world\n", 13);
12    assert(rc == 13);
13    close(fd);
14    return 0;
15 }
```

Figure 2.6: A Program That Does I/O (`io.c`)

To understand this better, let's look at some code. Figure 2.6 presents code to create a file (`/tmp/file`) that contains the string "hello world".

To accomplish this task, the program makes three calls into the operating system. The first, a call to `open()`, opens the file and creates it; the second, `write()`, writes some data to the file; the third, `close()`, simply closes the file thus indicating the program won't be writing any more data to it. These **system calls** are routed to the part of the operating system called the **file system**, which then handles the requests and returns some kind of error code to the user.

You might be wondering what the OS does in order to actually write to disk. We would show you but you'd have to promise to close your eyes first; it is that unpleasant. The file system has to do a fair bit of work: first figuring out where on disk this new data will reside, and then keeping track of it in various structures the file system maintains. Doing so requires issuing I/O requests to the underlying storage device, to either read existing structures or update (write) them. As anyone who has written a **device driver**⁸ knows, getting a device to do something on your behalf is an intricate and detailed process. It requires a deep knowledge of the low-level device interface and its exact semantics. Fortunately, the OS provides a standard and simple way to access devices through its system calls. Thus, the OS is sometimes seen as a **standard library**.

Of course, there are many more details in how devices are accessed, and how file systems manage data persistently atop said devices. For performance reasons, most file systems first delay such writes for a while, hoping to batch them into larger groups. To handle the problems of system crashes during writes, most file systems incorporate some kind of intricate write protocol, such as **journaling** or **copy-on-write**, carefully

⁸A device driver is some code in the operating system that knows how to deal with a specific device. We will talk more about devices and device drivers later.

THE CRUX OF THE PROBLEM:
HOW TO STORE DATA PERSISTENTLY

The file system is the part of the OS in charge of managing persistent data. What techniques are needed to do so correctly? What mechanisms and policies are required to do so with high performance? How is reliability achieved, in the face of failures in hardware and software?

ordering writes to disk to ensure that if a failure occurs during the write sequence, the system can recover to reasonable state afterwards. To make different common operations efficient, file systems employ many different data structures and access methods, from simple lists to complex b-trees. If all of this doesn't make sense yet, good! We'll be talking about all of this quite a bit more in the third part of this book on **persistence**, where we'll discuss devices and I/O in general, and then disks, RAID's, and file systems in great detail.

2.5 Design Goals

So now you have some idea of what an OS actually does: it takes physical **resources**, such as a CPU, memory, or disk, and **virtualizes** them. It handles tough and tricky issues related to **concurrency**. And it stores files **persistently**, thus making them safe over the long-term. Given that we want to build such a system, we want to have some goals in mind to help focus our design and implementation and make trade-offs as necessary; finding the right set of trade-offs is a key to building systems.

One of the most basic goals is to build up some **abstractions** in order to make the system convenient and easy to use. Abstractions are fundamental to everything we do in computer science. Abstraction makes it possible to write a large program by dividing it into small and understandable pieces, to write such a program in a high-level language like C⁹ without thinking about assembly, to write code in assembly without thinking about logic gates, and to build a processor out of gates without thinking too much about transistors. Abstraction is so fundamental that sometimes we forget its importance, but we won't here; thus, in each section, we'll discuss some of the major abstractions that have developed over time, giving you a way to think about pieces of the OS.

One goal in designing and implementing an operating system is to provide high **performance**; another way to say this is our goal is to **minimize the overheads** of the OS. Virtualization and making the system easy to use are well worth it, but not at any cost; thus, we must strive to provide virtualization and other OS features without excessive overheads.

⁹Some of you might object to calling C a high-level language. Remember this is an OS course, though, where we're simply happy not to have to code in assembly all the time!

These overheads arise in a number of forms: extra time (more instructions) and extra space (in memory or on disk). We'll seek solutions that minimize one or the other or both, if possible. Perfection, however, is not always attainable, something we will learn to notice and (where appropriate) tolerate.

Another goal will be to provide **protection** between applications, as well as between the OS and applications. Because we wish to allow many programs to run at the same time, we want to make sure that the malicious or accidental bad behavior of one does not harm others; we certainly don't want an application to be able to harm the OS itself (as that would affect *all* programs running on the system). Protection is at the heart of one of the main principles underlying an operating system, which is that of **isolation**; isolating processes from one another is the key to protection and thus underlies much of what an OS must do.

The operating system must also run non-stop; when it fails, *all* applications running on the system fail as well. Because of this dependence, operating systems often strive to provide a high degree of **reliability**. As operating systems grow evermore complex (sometimes containing millions of lines of code), building a reliable operating system is quite a challenge — and indeed, much of the on-going research in the field (including some of our own work [BS+09, SS+10]) focuses on this exact problem.

Other goals make sense: **energy-efficiency** is important in our increasingly green world; **security** (an extension of protection, really) against malicious applications is critical, especially in these highly-networked times; **mobility** is increasingly important as OSes are run on smaller and smaller devices. Depending on how the system is used, the OS will have different goals and thus likely be implemented in at least slightly different ways. However, as we will see, many of the principles we will present on how to build an OS are useful on a range of different devices.

2.6 Some History

Before closing this introduction, let us present a brief history of how operating systems developed. Like any system built by humans, good ideas accumulated in operating systems over time, as engineers learned what was important in their design. Here, we discuss a few major developments. For a richer treatment, see Brinch Hansen's excellent history of operating systems [BH00].

Early Operating Systems: Just Libraries

In the beginning, the operating system didn't do too much. Basically, it was just a set of libraries of commonly-used functions; for example, instead of having each programmer of the system write low-level I/O handling code, the "OS" would provide such APIs, and thus make life easier for the developer.

Usually, on these old mainframe systems, one program ran at a time, as controlled by a human operator. Much of what you think a modern OS would do (e.g., deciding what order to run jobs in) was performed by this operator. If you were a smart developer, you would be nice to this operator, so that they might move your job to the front of the queue.

This mode of computing was known as **batch** processing, as a number of jobs were set up and then run in a “batch” by the operator. Computers, as of that point, were not used in an interactive manner, because of cost: it was simply too expensive to let a user sit in front of the computer and use it, as most of the time it would just sit idle then, costing the facility hundreds of thousands of dollars per hour [BH00].

Beyond Libraries: Protection

In moving beyond being a simple library of commonly-used services, operating systems took on a more central role in managing machines. One important aspect of this was the realization that code run on behalf of the OS was special; it had control of devices and thus should be treated differently than normal application code. Why is this? Well, imagine if you allowed any application to read from anywhere on the disk; the notion of privacy goes out the window, as any program could read any file. Thus, implementing a **file system** (to manage your files) as a library makes little sense. Instead, something else was needed.

Thus, the idea of a **system call** was invented, pioneered by the Atlas computing system [K+61,L78]. Instead of providing OS routines as a library (where you just make a **procedure call** to access them), the idea here was to add a special pair of hardware instructions and hardware state to make the transition into the OS a more formal, controlled process.

The key difference between a system call and a procedure call is that a system call transfers control (i.e., jumps) into the OS while simultaneously raising the **hardware privilege level**. User applications run in what is referred to as **user mode** which means the hardware restricts what applications can do; for example, an application running in user mode can’t typically initiate an I/O request to the disk, access any physical memory page, or send a packet on the network. When a system call is initiated (usually through a special hardware instruction called a **trap**), the hardware transfers control to a pre-specified **trap handler** (that the OS set up previously) and simultaneously raises the privilege level to **kernel mode**. In kernel mode, the OS has full access to the hardware of the system and thus can do things like initiate an I/O request or make more memory available to a program. When the OS is done servicing the request, it passes control back to the user via a special **return-from-trap** instruction, which reverts to user mode while simultaneously passing control back to where the application left off.

The Era of Multiprogramming

Where operating systems really took off was in the era of computing beyond the mainframe, that of the **minicomputer**. Classic machines like the PDP family from Digital Equipment made computers hugely more affordable; thus, instead of having one mainframe per large organization, now a smaller collection of people within an organization could likely have their own computer. Not surprisingly, one of the major impacts of this drop in cost was an increase in developer activity; more smart people got their hands on computers and thus made computer systems do more interesting and beautiful things.

In particular, **multiprogramming** became commonplace due to the desire to make better use of machine resources. Instead of just running one job at a time, the OS would load a number of jobs into memory and switch rapidly between them, thus improving CPU utilization. This switching was particularly important because I/O devices were slow; having a program wait on the CPU while its I/O was being serviced was a waste of CPU time. Instead, why not switch to another job and run it for a while?

The desire to support multiprogramming and overlap in the presence of I/O and interrupts forced innovation in the conceptual development of operating systems along a number of directions. Issues such as **memory protection** became important; we wouldn't want one program to be able to access the memory of another program. Understanding how to deal with the **concurrency** issues introduced by multiprogramming was also critical; making sure the OS was behaving correctly despite the presence of interrupts is a great challenge. We will study these issues and related topics later in the book.

One of the major practical advances of the time was the introduction of the UNIX operating system, primarily thanks to Ken Thompson (and Dennis Ritchie) at Bell Labs (yes, the phone company). UNIX took many good ideas from different operating systems (particularly from Multics [O72], and some from systems like TENEX [B+72] and the Berkeley Time-Sharing System [S+68]), but made them simpler and easier to use. Soon this team was shipping tapes containing UNIX source code to people around the world, many of whom then got involved and added to the system themselves; see the **Aside** (next page) for more detail¹⁰.

The Modern Era

Beyond the minicomputer came a new type of machine, cheaper, faster, and for the masses: the **personal computer**, or **PC** as we call it today. Led by Apple's early machines (e.g., the Apple II) and the IBM PC, this new breed of machine would soon become the dominant force in computing,

¹⁰We'll use asides and other related text boxes to call attention to various items that don't quite fit the main flow of the text. Sometimes, we'll even use them just to make a joke, because why not have a little fun along the way? Yes, many of the jokes are bad.

ASIDE: THE IMPORTANCE OF UNIX

It is difficult to overstate the importance of UNIX in the history of operating systems. Influenced by earlier systems (in particular, the famous **Multics** system from MIT), UNIX brought together many great ideas and made a system that was both simple and powerful.

Underlying the original “Bell Labs” UNIX was the unifying principle of building small powerful programs that could be connected together to form larger workflows. The **shell**, where you type commands, provided primitives such as **pipes** to enable such meta-level programming, and thus it became easy to string together programs to accomplish a bigger task. For example, to find lines of a text file that have the word “foo” in them, and then to count how many such lines exist, you would type: `grep foo file.txt|wc -l`, thus using the `grep` and `wc` (word count) programs to achieve your task.

The UNIX environment was friendly for programmers and developers alike, also providing a compiler for the new **C programming language**. Making it easy for programmers to write their own programs, as well as share them, made UNIX enormously popular. And it probably helped a lot that the authors gave out copies for free to anyone who asked, an early form of **open-source software**.

Also of critical importance was the accessibility and readability of the code. Having a beautiful, small kernel written in C invited others to play with the kernel, adding new and cool features. For example, an enterprising group at Berkeley, led by **Bill Joy**, made a wonderful distribution (the **Berkeley Systems Distribution**, or **BSD**) which had some advanced virtual memory, file system, and networking subsystems. Joy later co-founded **Sun Microsystems**.

Unfortunately, the spread of UNIX was slowed a bit as companies tried to assert ownership and profit from it, an unfortunate (but common) result of lawyers getting involved. Many companies had their own variants: **SunOS** from Sun Microsystems, **AIX** from IBM, **HPUX** (a.k.a. “H-Pucks”) from HP, and **IRIX** from SGI. The legal wrangling among AT&T/Bell Labs and these other players cast a dark cloud over UNIX, and many wondered if it would survive, especially as Windows was introduced and took over much of the PC market...

as their low-cost enabled one machine per desktop instead of a shared minicomputer per workgroup.

Unfortunately, for operating systems, the PC at first represented a great leap backwards, as early systems forgot (or never knew of) the lessons learned in the era of minicomputers. For example, early operating systems such as **DOS** (the **Disk Operating System**, from **Microsoft**) didn’t think memory protection was important; thus, a malicious (or perhaps just a poorly-programmed) application could scribble all over mem-

ASIDE: AND THEN CAME LINUX

Fortunately for UNIX, a young Finnish hacker named **Linus Torvalds** decided to write his own version of UNIX which borrowed heavily on the principles and ideas behind the original system, but not from the code base, thus avoiding issues of legality. He enlisted help from many others around the world, took advantage of the sophisticated GNU tools that already existed [G85], and soon **Linux** was born (as well as the modern open-source software movement).

As the internet era came into place, most companies (such as Google, Amazon, Facebook, and others) chose to run Linux, as it was free and could be readily modified to suit their needs; indeed, it is hard to imagine the success of these new companies had such a system not existed. As smart phones became a dominant user-facing platform, Linux found a stronghold there too (via Android), for many of the same reasons. And Steve Jobs took his UNIX-based **NeXTStep** operating environment with him to Apple, thus making UNIX popular on desktops (though many users of Apple technology are probably not even aware of this fact). Thus UNIX lives on, more important today than ever before. The computing gods, if you believe in them, should be thanked for this wonderful outcome.

ory. The first generations of the **Mac OS** (v9 and earlier) took a cooperative approach to job scheduling; thus, a thread that accidentally got stuck in an infinite loop could take over the entire system, forcing a reboot. The painful list of OS features missing in this generation of systems is long, too long for a full discussion here.

Fortunately, after some years of suffering, the old features of minicomputer operating systems started to find their way onto the desktop. For example, Mac OS X/macOS has UNIX at its core, including all of the features one would expect from such a mature system. Windows has similarly adopted many of the great ideas in computing history, starting in particular with Windows NT, a great leap forward in Microsoft OS technology. Even today's cell phones run operating systems (such as Linux) that are much more like what a minicomputer ran in the 1970s than what a PC ran in the 1980s (thank goodness); it is good to see that the good ideas developed in the heyday of OS development have found their way into the modern world. Even better is that these ideas continue to develop, providing more features and making modern systems even better for users and applications.

2.7 Summary

Thus, we have an introduction to the OS. Today's operating systems make systems relatively easy to use, and virtually all operating systems you use today have been influenced by the developments we will discuss throughout the book.

Unfortunately, due to time constraints, there are a number of parts of the OS we won't cover in the book. For example, there is a lot of **net-working** code in the operating system; we leave it to you to take the net-working class to learn more about that. Similarly, **graphics** devices are particularly important; take the graphics course to expand your knowledge in that direction. Finally, some operating system books talk a great deal about **security**; we will do so in the sense that the OS must provide protection between running programs and give users the ability to protect their files, but we won't delve into deeper security issues that one might find in a security course.

However, there are many important topics that we will cover, including the basics of virtualization of the CPU and memory, concurrency, and persistence via devices and file systems. Don't worry! While there is a lot of ground to cover, most of it is quite cool, and at the end of the road, you'll have a new appreciation for how computer systems really work. Now get to work!

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Homework

Most (and eventually, all) chapters of this book have homework sections at the end. Doing these homeworks is important, as each lets you, the reader, gain more experience with the concepts presented within the chapter.

There are two types of homeworks. The first is based on **simulation**. A simulation of a computer system is just a simple program that pretends to do some of the interesting parts of what a real system does, and then report some output metrics to show how the system behaves. For example, a hard drive simulator might take a series of requests, simulate how long they would take to get serviced by a hard drive with certain performance characteristics, and then report the average latency of the requests.

The cool thing about simulations is they let you easily explore how systems behave without the difficulty of running a real system. Indeed, they even let you create systems that cannot exist in the real world (for example, a hard drive with unimaginably fast performance), and thus see the potential impact of future technologies.

Of course, simulations are not without their downsides. By their very nature, simulations are just approximations of how a real system behaves. If an important aspect of real-world behavior is omitted, the simulation will report bad results. Thus, results from a simulation should always be treated with some suspicion. In the end, how a system behaves in the real world is what matters.

The second type of homework requires interaction with **real-world code**. Some of these homeworks are measurement focused, whereas others just require some small-scale development and experimentation. Both are just small forays into the larger world you should be getting into, which is how to write systems code in C on UNIX-based systems. Indeed, larger-scale projects, which go beyond these homeworks, are needed to push you in this direction; thus, beyond just doing homeworks, we strongly recommend you do projects to solidify your systems skills. See this page (<https://github.com/remzi-arpacidusseau/ostep-projects>) for some projects.

To do these homeworks, you likely have to be on a UNIX-based machine, running either Linux, macOS, or some similar system. It should also have a C compiler installed (e.g., **gcc**) as well as Python. You should also know how to edit code in a real code editor of some kind.

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 and some high-level intelligence. We call the low-level machinery **mechanisms**; mechanisms are low-level methods or protocols that implement a needed piece of functionality. For example, we'll learn later how to implement a **context**

TIP: USE TIME SHARING (AND SPACE SHARING)

Time sharing is a basic technique 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 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; once a block is assigned to a file, it is normally not assigned to another file until the user deletes the original file.

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 program will execute next; similarly a **stack pointer** and associated **frame**

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.

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.

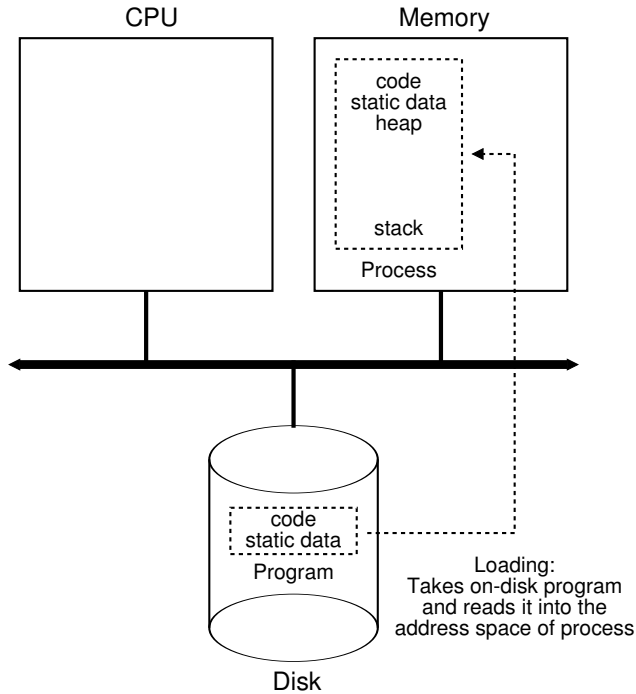


Figure 4.1: **Loading: From Program To Process**

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 and 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.

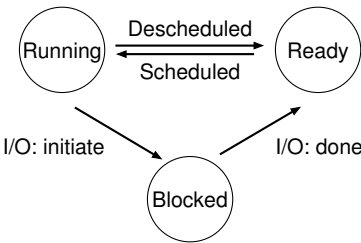


Figure 4.2: Process: State Transitions

- **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.

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

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

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, Process₀ initiates an I/O and becomes blocked waiting for it to complete; processes become blocked, for example, when reading from a disk or waiting for a packet from a network. The OS recognizes Process₀ is not using the CPU and starts running Process₁. While Process₁ is running, the I/O completes, moving Process₀ back to ready. Finally, Process₁ finishes, and Process₀ 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 Process₁ while Process₀ issued an I/O; doing so improves resource utilization by keeping the CPU busy. Second, the system decided not to switch back to Process₀ 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 and 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

```

// 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 !zero, sleeping on chan
    int killed;               // If !zero, has 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

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.

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

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** (also called the **task 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 (also sometimes called a **process descriptor**).

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.

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.

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

ASIDE: KEY PROCESS TERMS

- The **process** is the major OS abstraction of a running program. At any point in time, the process can be described by its state: the contents of memory in its **address space**, the contents of CPU registers (including the **program counter** and **stack pointer**, among others), and information about I/O (such as open files which can be read or written).
- The **process API** consists of calls programs can make related to processes. Typically, this includes creation, destruction, and other useful calls.
- Processes exist in one of many different **process states**, including running, ready to run, and blocked. Different events (e.g., getting scheduled or descheduled, or waiting for an I/O to complete) transition a process from one of these states to the other.
- A **process list** contains information about all processes in the system. Each entry is found in what is sometimes called a **process control block (PCB)**, which is really just a structure that contains information about a specific process.

References

- [BH70] “The Nucleus of a Multiprogramming System” by Per Brinch Hansen. Communications of the ACM, Volume 13:4, 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” by Russ Cox, Frans Kaashoek, Robert Morris, Nickolai Zeldovich. From: <https://github.com/mit-pdos/xv6-public>. *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. We have been using an older version (2012-01-30-1-g1c41342) and hence some examples in the book may not match the latest in the source.*
- [DV66] “Programming Semantics for Multiprogrammed Computations” by Jack B. Dennis, 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” by R. Levin, E. Cohen, W. Corwin, F. Pollack, W. Wulf. SOSP ’75, Austin, Texas, November 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” by 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 (Simulation)

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 `process-run.py` with the following flags: `-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. Switch the order of the processes: `-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 (`-l 1:0,4:100 -c -S SWITCH_ON_END`), one doing I/O and the other doing CPU work?
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 process 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? (Run `./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: `-s 1 -l 3:50,3:50` or `-s 2 -l 3:50,3:50` or `-s 3 -l 3:50,3:50`. See if you can predict how the trace will turn out. What happens when you use the flag `-I IO_RUN_IMMEDIATE` vs. `-I IO_RUN_LATER`? What happens when you use `-S SWITCH_ON_IO` vs. `-S SWITCH_ON_END`?

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 powerful functionality, ease of use, and high performance?

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 call¹. 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!

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

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.

```

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

```

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

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 receives a return code of zero. This differentiation is useful, because it is simple then to write the code that handles the two different cases (as above).

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 **non-determinism**, as it turns out, leads to some interesting problems, particularly in **multi-threaded programs**; hence, we'll see a lot more non-determinism 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 (rc_wait: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 exited². 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 call³. This system call is useful when you want to run a program that is different from the calling program. For example, calling `fork()`

²There 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."

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

```

1  #include <stdio.h>
2  #include <stdlib.h>
3  #include <unistd.h>
4  #include <string.h>
5  #include <sys/wait.h>
6
7  int main(int argc, char *argv[]) {
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         char *myargs[3];
16         myargs[0] = strdup("wc"); // program: "wc" (word count)
17         myargs[1] = strdup("p3.c"); // argument: file to count
18         myargs[2] = NULL;          // marks end of array
19         execvp(myargs[0], myargs); // runs word count
20         printf("this shouldn't print out");
21     } else {                    // parent goes down this path (main)
22         int rc_wait = wait(NULL);
23         printf("hello, I am parent of %d (rc_wait:%d) (pid:%d)\n",
24                rc, rc_wait, (int) getpid());
25     }
26     return 0;
27 }
28

```

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

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).

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 (rc_wait:29384) (pid:29383)
prompt>

```

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

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.

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.

The shell is just a user program⁴. 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
```

⁴And 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.

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 (page 8) 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>
```

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.

```

1  #include <stdio.h>
2  #include <stdlib.h>
3  #include <unistd.h>
4  #include <string.h>
5  #include <fcntl.h>
6  #include <sys/wait.h>
7
8  int main(int argc, char *argv[]) {
9      int rc = fork();
10     if (rc < 0) {
11         // fork failed
12         fprintf(stderr, "fork failed\n");
13         exit(1);
14     } else if (rc == 0) {
15         // child: redirect standard output to a file
16         close(STDOUT_FILENO);
17         open("./p4.output", O_CREAT|O_WRONLY|O_TRUNC, S_IRWXU);
18
19         // now exec "wc"...
20         char *myargs[3];
21         myargs[0] = strdup("wc"); // program: wc (word count)
22         myargs[1] = strdup("p4.c"); // arg: file to count
23         myargs[2] = NULL; // mark end of array
24         execvp(myargs[0], myargs); // runs word count
25     } else {
26         // parent goes down this path (main)
27         int rc_wait = wait(NULL);
28     }
29     return 0;
30 }

```

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

5.5 Process Control And Users

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 pause, die, and other useful imperatives. For convenience, in most UNIX shells, certain keystroke combinations are configured to deliver a specific signal to the currently running process; for example, control-c sends a `SIGINT` (interrupt) to the process (normally terminating it) and control-z sends a `SIGTSTP` (stop) signal thus pausing the process in mid-execution (you can resume it later with a command, e.g., the `fg` built-in command found in many shells).

The entire signals subsystem provides a rich infrastructure to deliver external events to processes, including ways to receive and process those signals within individual processes, and ways to send signals to individual processes as well as entire **process groups**. To use this form of com-

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...

munication, a process should use the `signal()` system call to "catch" various signals; doing so ensures that when a particular signal is delivered to a process, it will suspend its normal execution and run a particular piece of code in response to the signal. Read elsewhere [SR05] to learn more about signals and their many intricacies.

This naturally raises the question: who can send a signal to a process, and who cannot? Generally, the systems we use can have multiple people using them at the same time; if one of these people can arbitrarily send signals such as `SIGINT` (to interrupt a process, likely terminating it), the usability and security of the system will be compromised. As a result, modern systems include a strong conception of the notion of a **user**. The user, after entering a password to establish credentials, logs in to gain access to system resources. The user may then launch one or many processes, and exercise full control over them (pause them, kill them, etc.). Users generally can only control their own processes; it is the job of the operating system to parcel out resources (such as CPU, memory, and disk) to each user (and their processes) to meet overall system goals.

5.6 Useful Tools

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. The command `kill` can be used to send arbitrary

ASIDE: THE SUPERUSER (ROOT)

A system generally needs a user who can **administer** the system, and is not limited in the way most users are. Such a user should be able to kill an arbitrary process (e.g., if it is abusing the system in some way), even though that process was not started by this user. Such a user should also be able to run powerful commands such as `shutdown` (which, unsurprisingly, shuts down the system). In UNIX-based systems, these special abilities are given to the **superuser** (sometimes called **root**). While most users can't kill other users processes, the superuser can. Being root is much like being Spider-Man: with great power comes great responsibility [QI15]. Thus, to increase **security** (and avoid costly mistakes), it's usually better to be a regular user; if you do need to be root, tread carefully, as all of the destructive powers of the computing world are now at your fingertips.

signals to processes, as can the slightly more user friendly `killall`. Be sure to use these carefully; if you accidentally kill your window manager, the computer you are sitting in front of may become quite difficult to use.

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.

5.7 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.

While our passion for the UNIX process API remains strong, we should also note that such positivity is not uniform. For example, a recent paper by systems researchers from Microsoft, Boston University, and ETH in Switzerland details some problems with `fork()`, and advocates for other, simpler process creation APIs such as `spawn()` [B+19]. Read it, and the related work it refers to, to understand this different vantage point. While it's generally good to trust this book, remember too that the authors have opinions; those opinions may not (always) be as widely shared as you might think.

ASIDE: KEY PROCESS API TERMS

- Each process has a name; in most systems, that name is a number known as a **process ID (PID)**.
- The **fork()** system call is used in UNIX systems to create a new process. The creator is called the **parent**; the newly created process is called the **child**. As sometimes occurs in real life [J16], the child process is a nearly identical copy of the parent.
- The **wait()** system call allows a parent to wait for its child to complete execution.
- The **exec()** family of system calls allows a child to break free from its similarity to its parent and execute an entirely new program.
- A UNIX **shell** commonly uses `fork()`, `wait()`, and `exec()` to launch user commands; the separation of `fork` and `exec` enables features like **input/output redirection**, **pipes**, and other cool features, all without changing anything about the programs being run.
- Process control is available in the form of **signals**, which can cause jobs to stop, continue, or even terminate.
- Which processes can be controlled by a particular person is encapsulated in the notion of a **user**; the operating system allows multiple users onto the system, and ensures users can only control their own processes.
- A **superuser** can control all processes (and indeed do many other things); this role should be assumed infrequently and with caution for security reasons.

References

[B+19] “A fork() in the road” by Andrew Baumann, Jonathan Appavoo, Orran Krieger, Timothy Roscoe. HotOS ’19, Bertinoro, Italy. *A fun paper full of `fork()`ing rage. Read it to get an opposing viewpoint on the UNIX process API. Presented at the always lively HotOS workshop, where systems researchers go to present extreme opinions in the hopes of pushing the community in new directions.*

[C63] “A Multiprocessor System Design” by 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” by 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.*

[J16] “They could be twins!” by Phoebe Jackson-Edwards. The Daily Mail. March 1, 2016.. *This hard-hitting piece of journalism shows a bunch of weirdly similar child/parent photos and is frankly kind of mesmerizing. Go ahead, waste two minutes of your life and check it out. But don’t forget to come back here! This, in a microcosm, is the danger of surfing the web.*

[L83] “Hints for Computer Systems Design” by Butler Lampson. ACM Operating Systems Review, Volume 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.*

[QI15] “With Great Power Comes Great Responsibility” by The Quote Investigator. Available: <https://quoteinvestigator.com/2015/07/23/great-power>. *The quote investigator concludes that the earliest mention of this concept is 1793, in a collection of decrees made at the French National Convention. The specific quote: “Ils doivent envisager qu’une grande responsabilité est la suite inséparable d’un grand pouvoir”, which roughly translates to “They must consider that great responsibility follows inseparably from great power.” Only in 1962 did the following words appear in Spider-Man: “...with great power there must also come—great responsibility!” So it looks like the French Revolution gets credit for this one, not Stan Lee. Sorry, Stan.*

[SR05] “Advanced Programming in the UNIX Environment” by W. Richard Stevens, 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.*

Homework (Simulation)

This simulation homework focuses on `fork.py`, a simple process creation simulator that shows how processes are related in a single “familial” tree. Read the relevant README for details about how to run the simulator.

Questions

1. Run `./fork.py -s 10` and see which actions are taken. Can you predict what the process tree looks like at each step? Use the `-c` flag to check your answers. Try some different random seeds (`-s`) or add more actions (`-a`) to get the hang of it.
2. One control the simulator gives you is the `fork_percentage`, controlled by the `-f` flag. The higher it is, the more likely the next action is a fork; the lower it is, the more likely the action is an exit. Run the simulator with a large number of actions (e.g., `-a 100`) and vary the `fork_percentage` from 0.1 to 0.9. What do you think the resulting final process trees will look like as the percentage changes? Check your answer with `-c`.
3. Now, switch the output by using the `-t` flag (e.g., run `./fork.py -t`). Given a set of process trees, can you tell which actions were taken?
4. One interesting thing to note is what happens when a child exits; what happens to its children in the process tree? To study this, let's create a specific example: `./fork.py -A a+b,b+c,c+d,c+e,c-`. This example has process 'a' create 'b', which in turn creates 'c', which then creates 'd' and 'e'. However, then, 'c' exits. What do you think the process tree should look like after the exit? What if you use the `-R` flag? Learn more about what happens to orphaned processes on your own to add more context.
5. One last flag to explore is the `-F` flag, which skips intermediate steps and only asks to fill in the final process tree. Run `./fork.py -F` and see if you can write down the final tree by looking at the series of actions generated. Use different random seeds to try this a few times.
6. Finally, use both `-t` and `-F` together. This shows the final process tree, but then asks you to fill in the actions that took place. By looking at the tree, can you determine the exact actions that took place? In which cases can you tell? In which can't you tell? Try some different random seeds to delve into this question.

ASIDE: CODING HOMEWORKS

Coding homeworks are small exercises where you write code to run on a real machine to get some experience with some basic operating system APIs. After all, you are (probably) a computer scientist, and therefore should like to code, right? If you don't, there is always CS theory, but that's pretty hard. 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, 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 (on Linux) `execl()`, `execle()`, `execlp()`, `execv()`, `execvp()`, and `execvpe()`. 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?

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.

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 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?

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.

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

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 as instructions that allow the OS to tell the hardware where the **trap table** resides in memory.

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 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 **Very Bad Idea**¹. 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

¹Imagine 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]. In general, try to avoid Very Bad Ideas like this one.

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
Handle trap Do work of syscall return-from-trap	save regs (to kernel stack) move to kernel mode jump to trap handler	
	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

locations of these **trap handlers**, usually with some kind of special instruction. 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.

TIP: BE WARY OF USER INPUTS IN SECURE SYSTEMS

Even though we have taken great pains to protect the OS during system calls (by adding a hardware trapping mechanism, and ensuring all calls to the OS are routed through it), there are still many other aspects to implementing a **secure** operating system that we must consider. One of these is the handling of arguments at the system call boundary; the OS must check what the user passes in and ensure that arguments are properly specified, or otherwise reject the call.

For example, with a `write()` system call, the user specifies an address of a buffer as a source of the write call. If the user (either accidentally or maliciously) passes in a “bad” address (e.g., one inside the kernel’s portion of the address space), the OS must detect this and reject the call. Otherwise, it would be possible for a user to read all of kernel memory; given that kernel (virtual) memory also usually includes all of the physical memory of the system, this small slip would enable a program to read the memory of any other process in the system.

In general, a secure system must treat user inputs with great suspicion. Not doing so will undoubtedly lead to easily hacked software, a despairing sense that the world is an unsafe and scary place, and the loss of job security for the all-too-trusting OS developer.

To specify the exact system call, a **system-call number** is usually assigned to each system call. The user code is thus responsible for placing the desired system-call number in a register or at a specified location on the stack; the OS, when handling the system call inside the trap handler, examines this number, ensures it is valid, and, if it is, executes the corresponding code. This level of indirection serves as a form of **protection**; user code cannot specify an exact address to jump to, but rather must request a particular service via number.

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 limited direct execution (**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 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.

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

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?

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, and 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 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,

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.

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!

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 explicitly 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.

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) → k-stack(A) move to kernel mode jump to trap handler	
Handle the trap Call <code>switch()</code> routine save regs(A) → <code>proc.t(A)</code> restore regs(B) ← <code>proc.t(B)</code> switch to k-stack(B) return-from-trap (into B)	restore regs(B) ← k-stack(B) move to user mode jump to B's PC	
		Process B
		...

Figure 6.3: Limited Direct Execution Protocol (Timer Interrupt)

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.

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

```

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

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.

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.

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.

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.

ASIDE: KEY CPU VIRTUALIZATION TERMS (MECHANISMS)

- The CPU should support at least two modes of execution: a restricted **user mode** and a privileged (non-restricted) **kernel mode**.
- Typical user applications run in user mode, and use a **system call** to **trap** into the kernel to request operating system services.
- The trap instruction saves register state carefully, changes the hardware status to kernel mode, and jumps into the OS to a pre-specified destination: the **trap table**.
- When the OS finishes servicing a system call, it returns to the user program via another special **return-from-trap** instruction, which reduces privilege and returns control to the instruction after the trap that jumped into the OS.
- The trap tables must be set up by the OS at boot time, and make sure that they cannot be readily modified by user programs. All of this is part of the **limited direct execution** protocol which runs programs efficiently but without loss of OS control.
- Once a program is running, the OS must use hardware mechanisms to ensure the user program does not run forever, namely the **timer interrupt**. This approach is a **non-cooperative** approach to CPU scheduling.
- Sometimes the OS, during a timer interrupt or system call, might wish to switch from running the current process to a different one, a low-level technique known as a **context switch**.

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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.

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 $T_{\text{turnaround}}$ is:

$$T_{\text{turnaround}} = T_{\text{completion}} - T_{\text{arrival}} \quad (7.1)$$

Because we have assumed that all jobs arrive at the same time, for now $T_{\text{arrival}} = 0$ and hence $T_{\text{turnaround}} = T_{\text{completion}}$. 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)**.

¹Said 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?

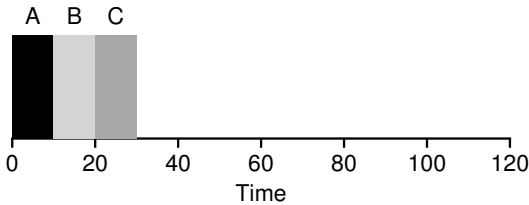


Figure 7.1: FIFO Simple Example

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.

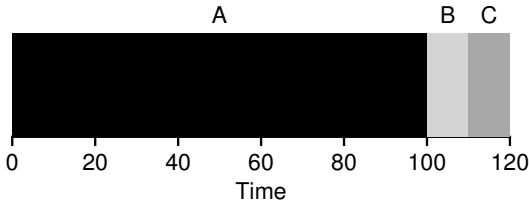


Figure 7.2: Why FIFO Is Not That Great

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

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.

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 you see the person in front of you with three carts full of provisions and a checkbook out; it’s going to be a while².

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.

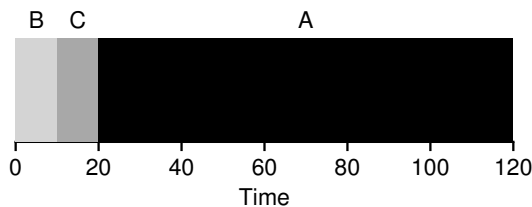


Figure 7.3: SJF Simple Example

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.

²Recommended 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.

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

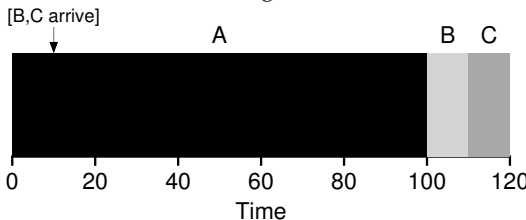


Figure 7.4: SJF With Late Arrivals From B and C

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

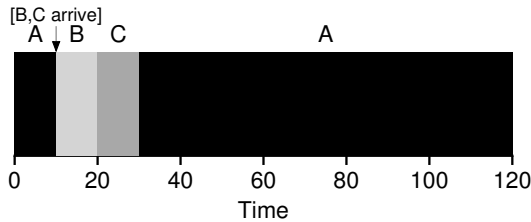


Figure 7.5: STCF Simple Example

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.

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**.

We define response time as the time from when the job arrives in a system to the first time it is scheduled³. More formally:

$$T_{\text{response}} = T_{\text{firstrun}} - T_{\text{arrival}} \quad (7.2)$$

³Some define it slightly differently, e.g., to also include the time until the job produces some kind of "response"; our definition is the best-case version of this, essentially assuming that the job produces a response instantaneously.

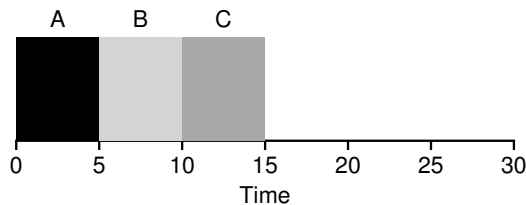


Figure 7.6: SJF Again (Bad for Response Time)

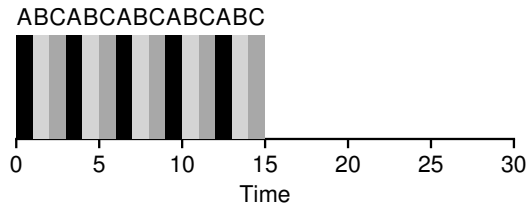


Figure 7.7: Round Robin (Good For Response Time)

For example, if we had the schedule from Figure 7.5 (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 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

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.

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.

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,

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.

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 too⁴.

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.

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).

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,

⁴A 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*.

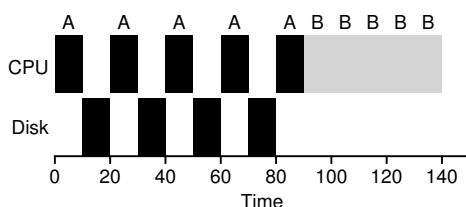


Figure 7.8: Poor Use Of Resources

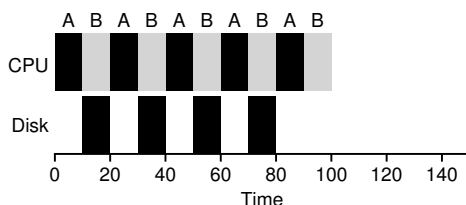


Figure 7.9: Overlap Allows Better Use Of Resources

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 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.

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Homework (Simulation)

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?

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

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

The key to MLFQ scheduling therefore 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.

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-

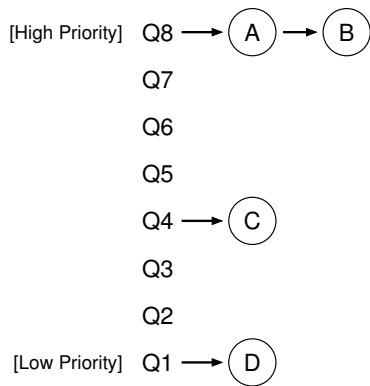


Figure 8.1: MLFQ Example

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.

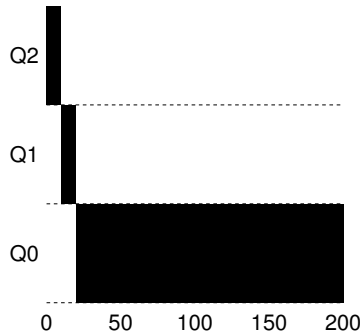


Figure 8.2: Long-running Job Over Time

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

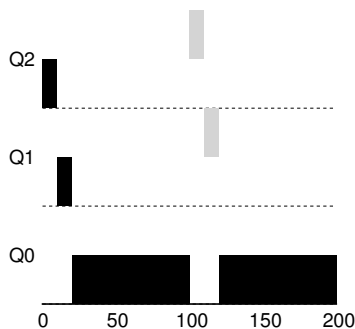


Figure 8.3: Along Came An Interactive Job

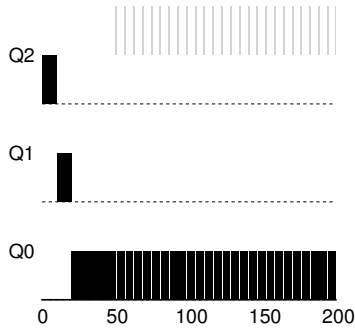


Figure 8.4: A Mixed I/O-intensive and CPU-intensive Workload

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)

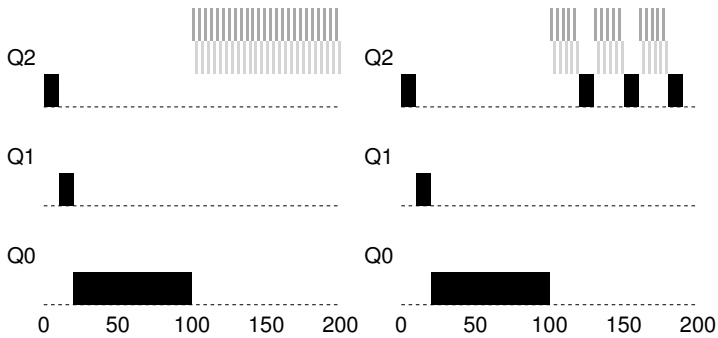


Figure 8.5: Without (Left) and With (Right) Priority Boost

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.

TIP: SCHEDULING MUST BE SECURE FROM ATTACK

You might think that a scheduling policy, whether inside the OS itself (as discussed herein), or in a broader context (e.g., in a distributed storage system’s I/O request handling [Y+18]), is not a **security** concern, but in increasingly many cases, it is exactly that. Consider the modern datacenter, in which users from around the world share CPUs, memories, networks, and storage systems; without care in policy design and enforcement, a single user may be able to adversely harm others and gain advantage for itself. Thus, scheduling policy forms an important part of the security of a system, and should be carefully constructed.

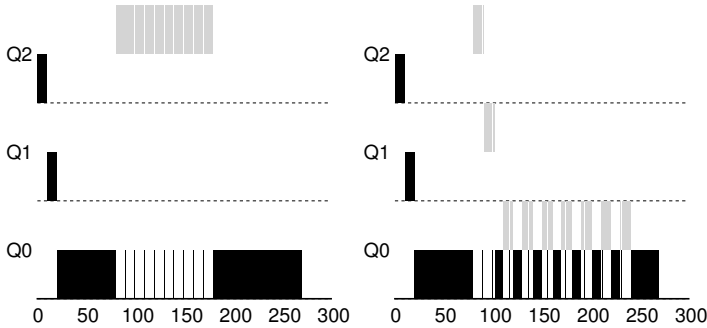


Figure 8.6: Without (Left) and With (Right) Gaming Tolerance

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 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.

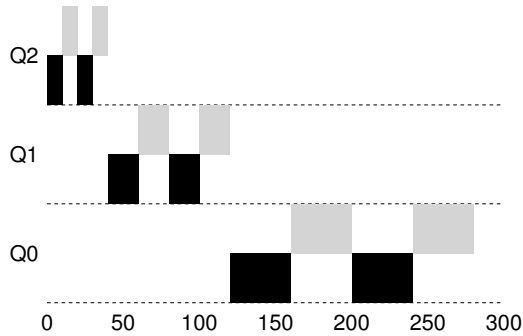


Figure 8.7: Lower Priority, Longer Quanta

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 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.

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**.

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 (page 8) shows an example in which two jobs run for 20 ms at the highest queue (with a 10-ms time slice), 40 ms in the middle (20-ms time slice), and with a 40-ms time slice at the lowest.

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.

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]).

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.

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

- **Rule 1:** If $\text{Priority}(A) > \text{Priority}(B)$, A runs (B doesn't).
- **Rule 2:** If $\text{Priority}(A) = \text{Priority}(B)$, A & B run in round-robin fashion using the time slice (quantum length) of the given queue.
- **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.

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Homework (Simulation)

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.

The Abstraction: Address Spaces

In the early days, building computer systems was easy. Why, you ask? Because users didn't expect much. It is those darned users with their expectations of "ease of use", "high performance", "reliability", etc., that really have led to all these headaches. Next time you meet one of those computer users, thank them for all the problems they have caused.

13.1 Early Systems

From the perspective of memory, early machines didn't provide much of an abstraction to users. Basically, the physical memory of the machine looked something like what you see in Figure 13.1 (page 2).

The OS was a set of routines (a library, really) that sat in memory (starting at physical address 0 in this example), and there would be one running program (a process) that currently sat in physical memory (starting at physical address 64k in this example) and used the rest of memory. There were few illusions here, and the user didn't expect much from the OS. Life was sure easy for OS developers in those days, wasn't it?

13.2 Multiprogramming and Time Sharing

After a time, because machines were expensive, people began to share machines more effectively. Thus the era of **multiprogramming** was born [DV66], in which multiple processes were ready to run at a given time, and the OS would switch between them, for example when one decided to perform an I/O. Doing so increased the effective **utilization** of the CPU. Such increases in **efficiency** were particularly important in those days where each machine cost hundreds of thousands or even millions of dollars (and you thought your Mac was expensive!).

Soon enough, however, people began demanding more of machines, and the era of **time sharing** was born [S59, L60, M62, M83]. Specifically, many realized the limitations of batch computing, particularly on programmers themselves [CV65], who were tired of long (and hence ineffec-

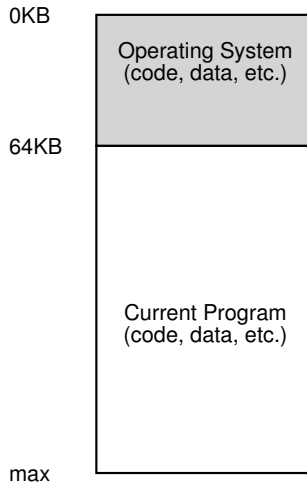


Figure 13.1: **Operating Systems: The Early Days**

tive) program-debug cycles. The notion of **interactivity** became important, as many users might be concurrently using a machine, each waiting for (or hoping for) a timely response from their currently-executing tasks.

One way to implement time sharing would be to run one process for a short while, giving it full access to all memory (Figure 13.1), then stop it, save all of its state to some kind of disk (including all of physical memory), load some other process's state, run it for a while, and thus implement some kind of crude sharing of the machine [M+63].

Unfortunately, this approach has a big problem: it is way too slow, particularly as memory grows. While saving and restoring register-level state (the PC, general-purpose registers, etc.) is relatively fast, saving the entire contents of memory to disk is brutally non-performant. Thus, what we'd rather do is leave processes in memory while switching between them, allowing the OS to implement time sharing efficiently (as shown in Figure 13.2, page 3).

In the diagram, there are three processes (A, B, and C) and each of them have a small part of the 512KB physical memory carved out for them. Assuming a single CPU, the OS chooses to run one of the processes (say A), while the others (B and C) sit in the ready queue waiting to run.

As time sharing became more popular, you can probably guess that new demands were placed on the operating system. In particular, allowing multiple programs to reside concurrently in memory makes **protection** an important issue; you don't want a process to be able to read, or worse, write some other process's memory.

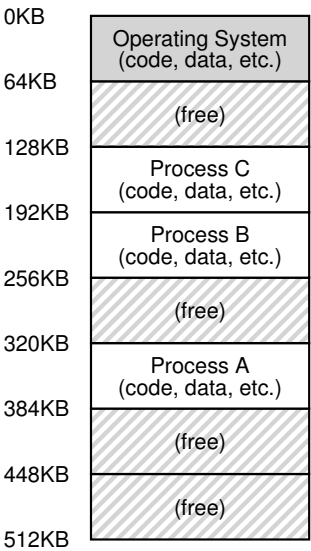


Figure 13.2: Three Processes: Sharing Memory

13.3 The Address Space

However, we have to keep those pesky users in mind, and doing so requires the OS to create an **easy to use** abstraction of physical memory. We call this abstraction the **address space**, and it is the running program’s view of memory in the system. Understanding this fundamental OS abstraction of memory is key to understanding how memory is virtualized.

The address space of a process contains all of the memory state of the running program. For example, the **code** of the program (the instructions) have to live in memory somewhere, and thus they are in the address space. The program, while it is running, uses a **stack** to keep track of where it is in the function call chain as well as to allocate local variables and pass parameters and return values to and from routines. Finally, the **heap** is used for dynamically-allocated, user-managed memory, such as that you might receive from a call to `malloc()` in C or `new` in an object-oriented language such as C++ or Java. Of course, there are other things in there too (e.g., statically-initialized variables), but for now let us just assume those three components: code, stack, and heap.

In the example in Figure 13.3 (page 4), we have a tiny address space (only 16KB)¹. The program code lives at the top of the address space

¹We will often use small examples like this because (a) it is a pain to represent a 32-bit address space and (b) the math is harder. We like simple math.

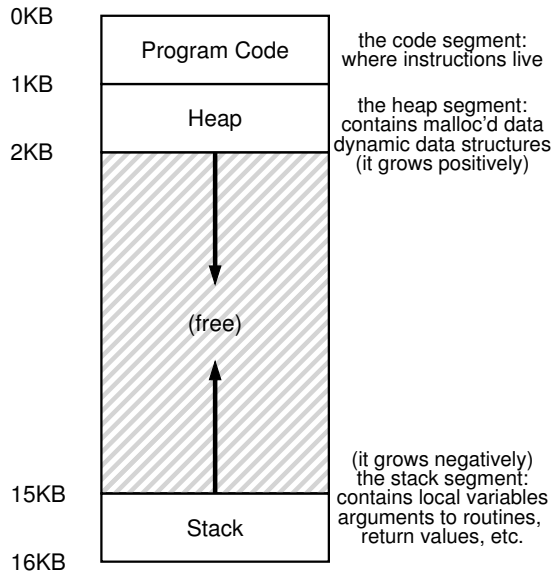


Figure 13.3: An Example Address Space

(starting at 0 in this example, and is packed into the first 1K of the address space). Code is static (and thus easy to place in memory), so we can place it at the top of the address space and know that it won't need any more space as the program runs.

Next, we have the two regions of the address space that may grow (and shrink) while the program runs. Those are the heap (at the top) and the stack (at the bottom). We place them like this because each wishes to be able to grow, and by putting them at opposite ends of the address space, we can allow such growth: they just have to grow in opposite directions. The heap thus starts just after the code (at 1KB) and grows downward (say when a user requests more memory via `malloc()`); the stack starts at 16KB and grows upward (say when a user makes a procedure call). However, this placement of stack and heap is just a convention; you could arrange the address space in a different way if you'd like (as we'll see later, when multiple **threads** co-exist in an address space, no nice way to divide the address space like this works anymore, alas).

Of course, when we describe the address space, what we are describing is the **abstraction** that the OS is providing to the running program. The program really isn't in memory at physical addresses 0 through 16KB; rather it is loaded at some arbitrary physical address(es). Examine processes A, B, and C in Figure 13.2; there you can see how each process is loaded into memory at a different address. And hence the problem:

THE CRUX: HOW TO VIRTUALIZE MEMORY

How can the OS build this abstraction of a private, potentially large address space for multiple running processes (all sharing memory) on top of a single, physical memory?

When the OS does this, we say the OS is **virtualizing memory**, because the running program thinks it is loaded into memory at a particular address (say 0) and has a potentially very large address space (say 32-bits or 64-bits); the reality is quite different.

When, for example, process A in Figure 13.2 tries to perform a load at address 0 (which we will call a **virtual address**), somehow the OS, in tandem with some hardware support, will have to make sure the load doesn't actually go to physical address 0 but rather to physical address 320KB (where A is loaded into memory). This is the key to virtualization of memory, which underlies every modern computer system in the world.

13.4 Goals

Thus we arrive at the job of the OS in this set of notes: to virtualize memory. The OS will not only virtualize memory, though; it will do so with style. To make sure the OS does so, we need some goals to guide us. We have seen these goals before (think of the Introduction), and we'll see them again, but they are certainly worth repeating.

One major goal of a virtual memory (VM) system is **transparency**². The OS should implement virtual memory in a way that is invisible to the running program. Thus, the program shouldn't be aware of the fact that memory is virtualized; rather, the program behaves as if it has its own private physical memory. Behind the scenes, the OS (and hardware) does all the work to multiplex memory among many different jobs, and hence implements the illusion.

Another goal of VM is **efficiency**. The OS should strive to make the virtualization as **efficient** as possible, both in terms of time (i.e., not making programs run much more slowly) and space (i.e., not using too much memory for structures needed to support virtualization). In implementing time-efficient virtualization, the OS will have to rely on hardware support, including hardware features such as TLBs (which we will learn about in due course).

Finally, a third VM goal is **protection**. The OS should make sure to **protect** processes from one another as well as the OS itself from pro-

²This usage of transparency is sometimes confusing; some students think that "being transparent" means keeping everything out in the open, i.e., what government should be like. Here, it means the opposite: that the illusion provided by the OS should not be visible to applications. Thus, in common usage, a transparent system is one that is hard to notice, not one that responds to requests as stipulated by the Freedom of Information Act.

TIP: THE PRINCIPLE OF ISOLATION

Isolation is a key principle in building reliable systems. If two entities are properly isolated from one another, this implies that one can fail without affecting the other. Operating systems strive to isolate processes from each other and in this way prevent one from harming the other. By using memory isolation, the OS further ensures that running programs cannot affect the operation of the underlying OS. Some modern OS's take isolation even further, by walling off pieces of the OS from other pieces of the OS. Such **microkernels** [BH70, R+89, S+03] thus may provide greater reliability than typical monolithic kernel designs.

cesses. When one process performs a load, a store, or an instruction fetch, it should not be able to access or affect in any way the memory contents of any other process or the OS itself (that is, anything *outside* its address space). Protection thus enables us to deliver the property of **isolation** among processes; each process should be running in its own isolated cocoon, safe from the ravages of other faulty or even malicious processes.

In the next chapters, we'll focus our exploration on the basic **mechanisms** needed to virtualize memory, including hardware and operating systems support. We'll also investigate some of the more relevant **policies** that you'll encounter in operating systems, including how to manage free space and which pages to kick out of memory when you run low on space. In doing so, we'll build up your understanding of how a modern virtual memory system really works³.

13.5 Summary

We have seen the introduction of a major OS subsystem: virtual memory. The VM system is responsible for providing the illusion of a large, sparse, private address space to programs, which hold all of their instructions and data therein. The OS, with some serious hardware help, will take each of these virtual memory references, and turn them into physical addresses, which can be presented to the physical memory in order to fetch the desired information. The OS will do this for many processes at once, making sure to protect programs from one another, as well as protect the OS. The entire approach requires a great deal of mechanism (lots of low-level machinery) as well as some critical policies to work; we'll start from the bottom up, describing the critical mechanisms first. And thus we proceed!

³Or, we'll convince you to drop the course. But hold on; if you make it through VM, you'll likely make it all the way!

ASIDE: EVERY ADDRESS YOU SEE IS VIRTUAL

Ever write a C program that prints out a pointer? The value you see (some large number, often printed in hexadecimal), is a **virtual address**. Ever wonder where the code of your program is found? You can print that out too, and yes, if you can print it, it also is a virtual address. In fact, any address you can see as a programmer of a user-level program is a virtual address. It's only the OS, through its tricky techniques of virtualizing memory, that knows where in the physical memory of the machine these instructions and data values lie. So never forget: if you print out an address in a program, it's a virtual one, an illusion of how things are laid out in memory; only the OS (and the hardware) knows the real truth.

Here's a little program (`va.c`) that prints out the locations of the `main()` routine (where code lives), the value of a heap-allocated value returned from `malloc()`, and the location of an integer on the stack:

```
1 #include <stdio.h>
2 #include <stdlib.h>
3 int main(int argc, char *argv[]) {
4     printf("location of code : %p\n", main);
5     printf("location of heap : %p\n", malloc(100e6));
6     int x = 3;
7     printf("location of stack: %p\n", &x);
8     return x;
9 }
```

When run on a 64-bit Mac, we get the following output:

```
location of code : 0x1095afe50
location of heap : 0x1096008c0
location of stack: 0x7fff691aea64
```

From this, you can see that code comes first in the address space, then the heap, and the stack is all the way at the other end of this large virtual space. All of these addresses are virtual, and will be translated by the OS and hardware in order to fetch values from their true physical locations.

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Homework (Code)

In this homework, we'll just learn about a few useful tools to examine virtual memory usage on Linux-based systems. This will only be a brief hint at what is possible; you'll have to dive deeper on your own to truly become an expert (as always!).

Questions

1. The first Linux tool you should check out is the very simple tool `free`. First, type `man free` and read its entire manual page; it's short, don't worry!
2. Now, run `free`, perhaps using some of the arguments that might be useful (e.g., `-m`, to display memory totals in megabytes). How much memory is in your system? How much is free? Do these numbers match your intuition?
3. Next, create a little program that uses a certain amount of memory, called `memory-user.c`. This program should take one command-line argument: the number of megabytes of memory it will use. When run, it should allocate an array, and constantly stream through the array, touching each entry. The program should do this indefinitely, or, perhaps, for a certain amount of time also specified at the command line.
4. Now, while running your `memory-user` program, also (in a different terminal window, but on the same machine) run the `free` tool. How do the memory usage totals change when your program is running? How about when you kill the `memory-user` program? Do the numbers match your expectations? Try this for different amounts of memory usage. What happens when you use really large amounts of memory?
5. Let's try one more tool, known as `pmap`. Spend some time, and read the `pmap` manual page in detail.
6. To use `pmap`, you have to know the **process ID** of the process you're interested in. Thus, first run `ps auxw` to see a list of all processes; then, pick an interesting one, such as a browser. You can also use your `memory-user` program in this case (indeed, you can even have that program call `getpid()` and print out its PID for your convenience).
7. Now run `pmap` on some of these processes, using various flags (like `-X`) to reveal many details about the process. What do you see? How many different entities make up a modern address space, as opposed to our simple conception of code/stack/heap?
8. Finally, let's run `pmap` on your `memory-user` program, with different amounts of used memory. What do you see here? Does the output from `pmap` match your expectations?

Interlude: Memory API

In this interlude, we discuss the memory allocation interfaces in UNIX systems. The interfaces provided are quite simple, and hence the chapter is short and to the point¹. The main problem we address is this:

CRUX: HOW TO ALLOCATE AND MANAGE MEMORY

In UNIX/C programs, understanding how to allocate and manage memory is critical in building robust and reliable software. What interfaces are commonly used? What mistakes should be avoided?

14.1 Types of Memory

In running a C program, there are two types of memory that are allocated. The first is called **stack** memory, and allocations and deallocations of it are managed *implicitly* by the compiler for you, the programmer; for this reason it is sometimes called **automatic** memory.

Declaring memory on the stack in C is easy. For example, let's say you need some space in a function `func()` for an integer, called `x`. To declare such a piece of memory, you just do something like this:

```
void func() {
    int x; // declares an integer on the stack
    ...
}
```

The compiler does the rest, making sure to make space on the stack when you call into `func()`. When you return from the function, the compiler deallocates the memory for you; thus, if you want some information to live beyond the call invocation, you had better not leave that information on the stack.

¹Indeed, we hope all chapters are! But this one is shorter and pointier, we think.

It is this need for long-lived memory that gets us to the second type of memory, called **heap** memory, where all allocations and deallocations are *explicitly* handled by you, the programmer. A heavy responsibility, no doubt! And certainly the cause of many bugs. But if you are careful and pay attention, you will use such interfaces correctly and without too much trouble. Here is an example of how one might allocate an integer on the heap:

```
void func() {  
    int *x = (int *) malloc(sizeof(int));  
    ...  
}
```

A couple of notes about this small code snippet. First, you might notice that both stack and heap allocation occur on this line: first the compiler knows to make room for a pointer to an integer when it sees your declaration of said pointer (`int *x`); subsequently, when the program calls `malloc()`, it requests space for an integer on the heap; the routine returns the address of such an integer (upon success, or `NULL` on failure), which is then stored on the stack for use by the program.

Because of its explicit nature, and because of its more varied usage, heap memory presents more challenges to both users and systems. Thus, it is the focus of the remainder of our discussion.

14.2 The `malloc()` Call

The **`malloc()`** call is quite simple: you pass it a size asking for some room on the heap, and it either succeeds and gives you back a pointer to the newly-allocated space, or fails and returns `NULL`².

The manual page shows what you need to do to use `malloc`; type `man malloc` at the command line and you will see:

```
#include <stdlib.h>  
...  
void *malloc(size_t size);
```

From this information, you can see that all you need to do is include the header file `stdlib.h` to use `malloc`. In fact, you don't really need to even do this, as the C library, which all C programs link with by default, has the code for `malloc()` inside of it; adding the header just lets the compiler check whether you are calling `malloc()` correctly (e.g., passing the right number of arguments to it, of the right type).

The single parameter `malloc()` takes is of type `size_t` which simply describes how many bytes you need. However, most programmers do not type in a number here directly (such as 10); indeed, it would be considered poor form to do so. Instead, various routines and macros are

²Note that `NULL` in C isn't really anything special at all, just a macro for the value zero.

TIP: WHEN IN DOUBT, TRY IT OUT

If you aren't sure how some routine or operator you are using behaves, there is no substitute for simply trying it out and making sure it behaves as you expect. While reading the manual pages or other documentation is useful, how it works in practice is what matters. Write some code and test it! That is no doubt the best way to make sure your code behaves as you desire. Indeed, that is what we did to double-check the things we were saying about `sizeof()` were actually true!

utilized. For example, to allocate space for a double-precision floating point value, you simply do this:

```
double *d = (double *) malloc(sizeof(double));
```

Wow, that's lot of double-ing! This invocation of `malloc()` uses the `sizeof()` operator to request the right amount of space; in C, this is generally thought of as a *compile-time* operator, meaning that the actual size is known at *compile time* and thus a number (in this case, 8, for a double) is substituted as the argument to `malloc()`. For this reason, `sizeof()` is correctly thought of as an operator and not a function call (a function call would take place at run time).

You can also pass in the name of a variable (and not just a type) to `sizeof()`, but in some cases you may not get the desired results, so be careful. For example, let's look at the following code snippet:

```
int *x = malloc(10 * sizeof(int));
printf("%d\n", sizeof(x));
```

In the first line, we've declared space for an array of 10 integers, which is fine and dandy. However, when we use `sizeof()` in the next line, it returns a small value, such as 4 (on 32-bit machines) or 8 (on 64-bit machines). The reason is that in this case, `sizeof()` thinks we are simply asking how big a *pointer* to an integer is, not how much memory we have dynamically allocated. However, sometimes `sizeof()` does work as you might expect:

```
int x[10];
printf("%d\n", sizeof(x));
```

In this case, there is enough static information for the compiler to know that 40 bytes have been allocated.

Another place to be careful is with strings. When declaring space for a string, use the following idiom: `malloc(strlen(s) + 1)`, which gets the length of the string using the function `strlen()`, and adds 1 to it in order to make room for the end-of-string character. Using `sizeof()` may lead to trouble here.

You might also notice that `malloc()` returns a pointer to type `void`. Doing so is just the way in C to pass back an address and let the programmer decide what to do with it. The programmer further helps out by using what is called a **cast**; in our example above, the programmer casts the return type of `malloc()` to a pointer to a `double`. Casting doesn't really accomplish anything, other than tell the compiler and other programmers who might be reading your code: "yeah, I know what I'm doing." By casting the result of `malloc()`, the programmer is just giving some reassurance; the cast is not needed for the correctness.

14.3 The `free()` Call

As it turns out, allocating memory is the easy part of the equation; knowing when, how, and even if to free memory is the hard part. To free heap memory that is no longer in use, programmers simply call **`free()`**:

```
int *x = malloc(10 * sizeof(int));
...
free(x);
```

The routine takes one argument, a pointer returned by `malloc()`. Thus, you might notice, the size of the allocated region is not passed in by the user, and must be tracked by the memory-allocation library itself.

14.4 Common Errors

There are a number of common errors that arise in the use of `malloc()` and `free()`. Here are some we've seen over and over again in teaching the undergraduate operating systems course. All of these examples compile and run with nary a peep from the compiler; while compiling a C program is necessary to build a correct C program, it is far from sufficient, as you will learn (often in the hard way).

Correct memory management has been such a problem, in fact, that many newer languages have support for **automatic memory management**. In such languages, while you call something akin to `malloc()` to allocate memory (usually **new** or something similar to allocate a new object), you never have to call something to free space; rather, a **garbage collector** runs and figures out what memory you no longer have references to and frees it for you.

Forgetting To Allocate Memory

Many routines expect memory to be allocated before you call them. For example, the routine `strcpy(dst, src)` copies a string from a source pointer to a destination pointer. However, if you are not careful, you might do this:

```
char *src = "hello";
char *dst;           // oops! unallocated
strcpy(dst, src);    // segfault and die
```

TIP: IT COMPILED OR IT RAN \neq IT IS CORRECT

Just because a program compiled(!) or even ran once or many times correctly does not mean the program is correct. Many events may have conspired to get you to a point where you believe it works, but then something changes and it stops. A common student reaction is to say (or yell) “But it worked before!” and then blame the compiler, operating system, hardware, or even (dare we say it) the professor. But the problem is usually right where you think it would be, in your code. Get to work and debug it before you blame those other components.

When you run this code, it will likely lead to a **segmentation fault**³, which is a fancy term for **YOU DID SOMETHING WRONG WITH MEMORY YOU FOOLISH PROGRAMMER AND I AM ANGRY**.

In this case, the proper code might instead look like this:

```
char *src = "hello";
char *dst = (char *) malloc(strlen(src) + 1);
strcpy(dst, src); // work properly
```

Alternately, you could use `strdup()` and make your life even easier. Read the `strdup` man page for more information.

Not Allocating Enough Memory

A related error is not allocating enough memory, sometimes called a **buffer overflow**. In the example above, a common error is to make *almost* enough room for the destination buffer.

```
char *src = "hello";
char *dst = (char *) malloc(strlen(src)); // too small!
strcpy(dst, src); // work properly
```

Oddly enough, depending on how `malloc` is implemented and many other details, this program will often run seemingly correctly. In some cases, when the string copy executes, it writes one byte too far past the end of the allocated space, but in some cases this is harmless, perhaps overwriting a variable that isn’t used anymore. In some cases, these overflows can be incredibly harmful, and in fact are the source of many security vulnerabilities in systems [W06]. In other cases, the `malloc` library allocated a little extra space anyhow, and thus your program actually doesn’t scribble on some other variable’s value and works quite fine. In even other cases, the program will indeed fault and crash. And thus we learn another valuable lesson: even though it ran correctly once, doesn’t mean it’s correct.

³Although it sounds arcane, you will soon learn why such an illegal memory access is called a segmentation fault; if that isn’t incentive to read on, what is?

Forgetting to Initialize Allocated Memory

With this error, you call `malloc()` properly, but forget to fill in some values into your newly-allocated data type. Don't do this! If you do forget, your program will eventually encounter an **uninitialized read**, where it reads from the heap some data of unknown value. Who knows what might be in there? If you're lucky, some value such that the program still works (e.g., zero). If you're not lucky, something random and harmful.

Forgetting To Free Memory

Another common error is known as a **memory leak**, and it occurs when you forget to free memory. In long-running applications or systems (such as the OS itself), this is a huge problem, as slowly leaking memory eventually leads one to run out of memory, at which point a restart is required. Thus, in general, when you are done with a chunk of memory, you should make sure to free it. Note that using a garbage-collected language doesn't help here: if you still have a reference to some chunk of memory, no garbage collector will ever free it, and thus memory leaks remain a problem even in more modern languages.

In some cases, it may seem like not calling `free()` is reasonable. For example, your program is short-lived, and will soon exit; in this case, when the process dies, the OS will clean up all of its allocated pages and thus no memory leak will take place per se. While this certainly "works" (see the aside on page 7), it is probably a bad habit to develop, so be wary of choosing such a strategy. In the long run, one of your goals as a programmer is to develop good habits; one of those habits is understanding how you are managing memory, and (in languages like C), freeing the blocks you have allocated. Even if you can get away with not doing so, it is probably good to get in the habit of freeing each and every byte you explicitly allocate.

Freeing Memory Before You Are Done With It

Sometimes a program will free memory before it is finished using it; such a mistake is called a **dangling pointer**, and it, as you can guess, is also a bad thing. The subsequent use can crash the program, or overwrite valid memory (e.g., you called `free()`, but then called `malloc()` again to allocate something else, which then recycles the errantly-freed memory).

Freeing Memory Repeatedly

Programs also sometimes free memory more than once; this is known as the **double free**. The result of doing so is undefined. As you can imagine, the memory-allocation library might get confused and do all sorts of weird things; crashes are a common outcome.

ASIDE: WHY NO MEMORY IS LEAKED ONCE YOUR PROCESS EXITS

When you write a short-lived program, you might allocate some space using `malloc()`. The program runs and is about to complete: is there need to call `free()` a bunch of times just before exiting? While it seems wrong not to, no memory will be “lost” in any real sense. The reason is simple: there are really two levels of memory management in the system. The first level of memory management is performed by the OS, which hands out memory to processes when they run, and takes it back when processes exit (or otherwise die). The second level of management is *within* each process, for example within the heap when you call `malloc()` and `free()`. Even if you fail to call `free()` (and thus leak memory in the heap), the operating system will reclaim *all* the memory of the process (including those pages for code, stack, and, as relevant here, heap) when the program is finished running. No matter what the state of your heap in your address space, the OS takes back all of those pages when the process dies, thus ensuring that no memory is lost despite the fact that you didn’t free it.

Thus, for short-lived programs, leaking memory often does not cause any operational problems (though it may be considered poor form). When you write a long-running server (such as a web server or database management system, which never exit), leaked memory is a much bigger issue, and will eventually lead to a crash when the application runs out of memory. And of course, leaking memory is an even larger issue inside one particular program: the operating system itself. Showing us once again: those who write the kernel code have the toughest job of all...

Calling `free()` Incorrectly

One last problem we discuss is the call of `free()` incorrectly. After all, `free()` expects you only to pass to it one of the pointers you received from `malloc()` earlier. When you pass in some other value, bad things can (and do) happen. Thus, such **invalid frees** are dangerous and of course should also be avoided.

Summary

As you can see, there are lots of ways to abuse memory. Because of frequent errors with memory, a whole ecosystem of tools have developed to help find such problems in your code. Check out both **purify** [HJ92] and **valgrind** [SN05]; both are excellent at helping you locate the source of your memory-related problems. Once you become accustomed to using these powerful tools, you will wonder how you survived without them.

14.5 Underlying OS Support

You might have noticed that we haven't been talking about system calls when discussing `malloc()` and `free()`. The reason for this is simple: they are not system calls, but rather library calls. Thus the `malloc` library manages space within your virtual address space, but itself is built on top of some system calls which call into the OS to ask for more memory or release some back to the system.

One such system call is called `brk`, which is used to change the location of the program's **break**: the location of the end of the heap. It takes one argument (the address of the new break), and thus either increases or decreases the size of the heap based on whether the new break is larger or smaller than the current break. An additional call `sbrk` is passed an increment but otherwise serves a similar purpose.

Note that you should never directly call either `brk` or `sbrk`. They are used by the memory-allocation library; if you try to use them, you will likely make something go (horribly) wrong. Stick to `malloc()` and `free()` instead.

Finally, you can also obtain memory from the operating system via the `mmap()` call. By passing in the correct arguments, `mmap()` can create an **anonymous** memory region within your program — a region which is not associated with any particular file but rather with **swap space**, something we'll discuss in detail later on in virtual memory. This memory can then also be treated like a heap and managed as such. Read the manual page of `mmap()` for more details.

14.6 Other Calls

There are a few other calls that the memory-allocation library supports. For example, `calloc()` allocates memory and also zeroes it before returning; this prevents some errors where you assume that memory is zeroed and forget to initialize it yourself (see the paragraph on “uninitialized reads” above). The routine `realloc()` can also be useful, when you've allocated space for something (say, an array), and then need to add something to it: `realloc()` makes a new larger region of memory, copies the old region into it, and returns the pointer to the new region.

14.7 Summary

We have introduced some of the APIs dealing with memory allocation. As always, we have just covered the basics; more details are available elsewhere. Read the C book [KR88] and Stevens [SR05] (Chapter 7) for more information. For a cool modern paper on how to detect and correct many of these problems automatically, see Novark et al. [N+07]; this paper also contains a nice summary of common problems and some neat ideas on how to find and fix them.

References

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- [W06] “Survey on Buffer Overflow Attacks and Countermeasures” by T. Werthman. Available: www.nds.rub.de/lehre/seminar/SS06/Werthmann.BufferOverflow.pdf. *A nice survey of buffer overflows and some of the security problems they cause. Refers to many of the famous exploits.*

Homework (Code)

In this homework, you will gain some familiarity with memory allocation. First, you'll write some buggy programs (fun!). Then, you'll use some tools to help you find the bugs you inserted. Then, you will realize how awesome these tools are and use them in the future, thus making yourself more happy and productive. The tools are the debugger (e.g., `gdb`) and a memory-bug detector called `valgrind` [SN05].

Questions

1. First, write a simple program called `null.c` that creates a pointer to an integer, sets it to `NULL`, and then tries to dereference it. Compile this into an executable called `null`. What happens when you run this program?
2. Next, compile this program with symbol information included (with the `-g` flag). Doing so let's put more information into the executable, enabling the debugger to access more useful information about variable names and the like. Run the program under the debugger by typing `gdb null` and then, once `gdb` is running, typing `run`. What does `gdb` show you?
3. Finally, use the `valgrind` tool on this program. We'll use the `memcheck` tool that is a part of `valgrind` to analyze what happens. Run this by typing in the following: `valgrind --leak-check=yes null`. What happens when you run this? Can you interpret the output from the tool?
4. Write a simple program that allocates memory using `malloc()` but forgets to free it before exiting. What happens when this program runs? Can you use `gdb` to find any problems with it? How about `valgrind` (again with the `--leak-check=yes` flag)?
5. Write a program that creates an array of integers called `data` of size 100 using `malloc`; then, set `data[100]` to zero. What happens when you run this program? What happens when you run this program using `valgrind`? Is the program correct?
6. Create a program that allocates an array of integers (as above), frees them, and then tries to print the value of one of the elements of the array. Does the program run? What happens when you use `valgrind` on it?
7. Now pass a funny value to free (e.g., a pointer in the middle of the array you allocated above). What happens? Do you need tools to find this type of problem?

8. Try out some of the other interfaces to memory allocation. For example, create a simple vector-like data structure and related routines that use `realloc()` to manage the vector. Use an array to store the vectors elements; when a user adds an entry to the vector, use `realloc()` to allocate more space for it. How well does such a vector perform? How does it compare to a linked list? Use `valgrind` to help you find bugs.
9. Spend more time and read about using `gdb` and `valgrind`. Knowing your tools is critical; spend the time and learn how to become an expert debugger in the UNIX and C environment.

Mechanism: Address Translation

In developing the virtualization of the CPU, we focused on a general mechanism known as **limited direct execution** (or **LDE**). The idea behind LDE is simple: for the most part, let the program run directly on the hardware; however, at certain key points in time (such as when a process issues a system call, or a timer interrupt occurs), arrange so that the OS gets involved and makes sure the “right” thing happens. Thus, the OS, with a little hardware support, tries its best to get out of the way of the running program, to deliver an *efficient* virtualization; however, by **interposing** at those critical points in time, the OS ensures that it maintains *control* over the hardware. Efficiency and control together are two of the main goals of any modern operating system.

In virtualizing memory, we will pursue a similar strategy, attaining both efficiency and control while providing the desired virtualization. Efficiency dictates that we make use of hardware support, which at first will be quite rudimentary (e.g., just a few registers) but will grow to be fairly complex (e.g., TLBs, page-table support, and so forth, as you will see). Control implies that the OS ensures that no application is allowed to access any memory but its own; thus, to protect applications from one another, and the OS from applications, we will need help from the hardware here too. Finally, we will need a little more from the VM system, in terms of *flexibility*; specifically, we’d like for programs to be able to use their address spaces in whatever way they would like, thus making the system easier to program. And thus we arrive at the refined crux:

THE CRUX:

HOW TO EFFICIENTLY AND FLEXIBLY VIRTUALIZE MEMORY

How can we build an efficient virtualization of memory? How do we provide the flexibility needed by applications? How do we maintain control over which memory locations an application can access, and thus ensure that application memory accesses are properly restricted? How do we do all of this efficiently?

The generic technique we will use, which you can consider an addition to our general approach of limited direct execution, is something that is referred to as **hardware-based address translation**, or just **address translation** for short. With address translation, the hardware transforms each memory access (e.g., an instruction fetch, load, or store), changing the **virtual** address provided by the instruction to a **physical** address where the desired information is actually located. Thus, on each and every memory reference, an address translation is performed by the hardware to redirect application memory references to their actual locations in memory.

Of course, the hardware alone cannot virtualize memory, as it just provides the low-level mechanism for doing so efficiently. The OS must get involved at key points to set up the hardware so that the correct translations take place; it must thus **manage memory**, keeping track of which locations are free and which are in use, and judiciously intervening to maintain control over how memory is used.

Once again the goal of all of this work is to create a beautiful **illusion**: that the program has its own private memory, where its own code and data reside. Behind that virtual reality lies the ugly physical truth: that many programs are actually sharing memory at the same time, as the CPU (or CPUs) switches between running one program and the next. Through virtualization, the OS (with the hardware's help) turns the ugly machine reality into a useful, powerful, and easy to use abstraction.

15.1 Assumptions

Our first attempts at virtualizing memory will be very simple, almost laughably so. Go ahead, laugh all you want; pretty soon it will be the OS laughing at you, when you try to understand the ins and outs of TLBs, multi-level page tables, and other technical wonders. Don't like the idea of the OS laughing at you? Well, you may be out of luck then; that's just how the OS rolls.

Specifically, we will assume for now that the user's address space must be placed *contiguously* in physical memory. We will also assume, for simplicity, that the size of the address space is not too big; specifically, that it is *less than the size of physical memory*. Finally, we will also assume that each address space is exactly the *same size*. Don't worry if these assumptions sound unrealistic; we will relax them as we go, thus achieving a realistic virtualization of memory.

15.2 An Example

To understand better what we need to do to implement address translation, and why we need such a mechanism, let's look at a simple example. Imagine there is a process whose address space is as indicated in Figure 15.1. What we are going to examine here is a short code sequence that loads a value from memory, increments it by three, and then stores the value back into memory. You can imagine the C-language representation of this code might look like this:

TIP: INTERPOSITION IS POWERFUL

Interposition is a generic and powerful technique that is often used to great effect in computer systems. In virtualizing memory, the hardware will interpose on each memory access, and translate each virtual address issued by the process to a physical address where the desired information is actually stored. However, the general technique of interposition is much more broadly applicable; indeed, almost any well-defined interface can be interposed upon, to add new functionality or improve some other aspect of the system. One of the usual benefits of such an approach is **transparency**; the interposition often is done without changing the interface of the client, thus requiring no changes to said client.

```
void func() {  
    int x = 3000; // thanks, Perry.  
    x = x + 3;    // line of code we are interested in  
    ...  
}
```

The compiler turns this line of code into assembly, which might look something like this (in x86 assembly). Use `objdump` on Linux or `otool` on a Mac to disassemble it:

```
128: movl 0x0(%ebx), %eax    ;load 0+ebx into eax  
132: addl $0x03, %eax        ;add 3 to eax register  
135: movl %eax, 0x0(%ebx)    ;store eax back to mem
```

This code snippet is relatively straightforward; it presumes that the address of `x` has been placed in the register `ebx`, and then loads the value at that address into the general-purpose register `eax` using the `movl` instruction (for “longword” move). The next instruction adds 3 to `eax`, and the final instruction stores the value in `eax` back into memory at that same location.

In Figure 15.1 (page 4), observe how both the code and data are laid out in the process’s address space; the three-instruction code sequence is located at address 128 (in the code section near the top), and the value of the variable `x` at address 15 KB (in the stack near the bottom). In the figure, the initial value of `x` is 3000, as shown in its location on the stack.

When these instructions run, from the perspective of the process, the following memory accesses take place.

- Fetch instruction at address 128
- Execute this instruction (load from address 15 KB)
- Fetch instruction at address 132
- Execute this instruction (no memory reference)
- Fetch the instruction at address 135
- Execute this instruction (store to address 15 KB)

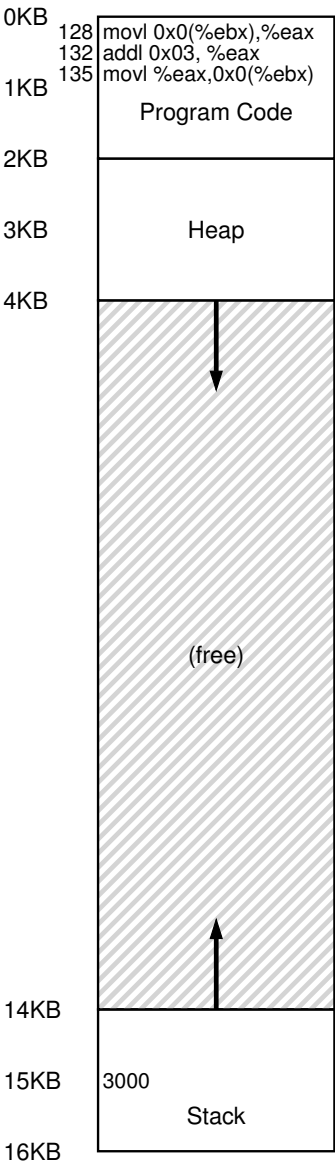


Figure 15.1: A Process And Its Address Space

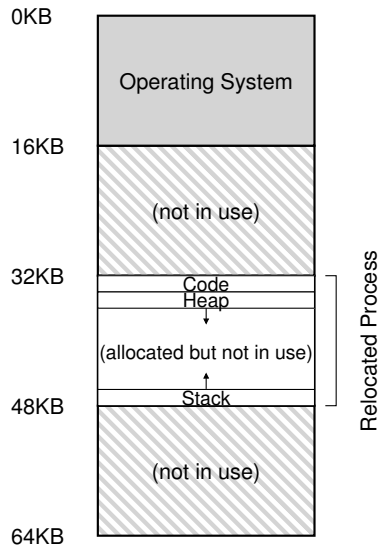


Figure 15.2: Physical Memory with a Single Relocated Process

From the program’s perspective, its **address space** starts at address 0 and grows to a maximum of 16 KB; all memory references it generates should be within these bounds. However, to virtualize memory, the OS wants to place the process somewhere else in physical memory, not necessarily at address 0. Thus, we have the problem: how can we **relocate** this process in memory in a way that is **transparent** to the process? How can we provide the illusion of a virtual address space starting at 0, when in reality the address space is located at some other physical address?

An example of what physical memory might look like once this process’s address space has been placed in memory is found in Figure 15.2. In the figure, you can see the OS using the first slot of physical memory for itself, and that it has relocated the process from the example above into the slot starting at physical memory address 32 KB. The other two slots are free (16 KB-32 KB and 48 KB-64 KB).

15.3 Dynamic (Hardware-based) Relocation

To gain some understanding of hardware-based address translation, we’ll first discuss its first incarnation. Introduced in the first time-sharing machines of the late 1950’s is a simple idea referred to as **base and bounds**; the technique is also referred to as **dynamic relocation**; we’ll use both terms interchangeably [SS74].

Specifically, we’ll need two hardware registers within each CPU: one is called the **base** register, and the other the **bounds** (sometimes called a **limit** register). This base-and-bounds pair is going to allow us to place the

ASIDE: SOFTWARE-BASED RELOCATION

In the early days, before hardware support arose, some systems performed a crude form of relocation purely via software methods. The basic technique is referred to as **static relocation**, in which a piece of software known as the **loader** takes an executable that is about to be run and rewrites its addresses to the desired offset in physical memory.

For example, if an instruction was a load from address 1000 into a register (e.g., `movl 1000, %eax`), and the address space of the program was loaded starting at address 3000 (and not 0, as the program thinks), the loader would rewrite the instruction to offset each address by 3000 (e.g., `movl 4000, %eax`). In this way, a simple static relocation of the process's address space is achieved.

However, static relocation has numerous problems. First and most importantly, it does not provide protection, as processes can generate bad addresses and thus illegally access other process's or even OS memory; in general, hardware support is likely needed for true protection [WL+93]. Another negative is that once placed, it is difficult to later relocate an address space to another location [M65].

address space anywhere we'd like in physical memory, and do so while ensuring that the process can only access its own address space.

In this setup, each program is written and compiled as if it is loaded at address zero. However, when a program starts running, the OS decides where in physical memory it should be loaded and sets the base register to that value. In the example above, the OS decides to load the process at physical address 32 KB and thus sets the base register to this value.

Interesting things start to happen when the process is running. Now, when any memory reference is generated by the process, it is **translated** by the processor in the following manner:

$$\text{physical address} = \text{virtual address} + \text{base}$$

Each memory reference generated by the process is a **virtual address**; the hardware in turn adds the contents of the base register to this address and the result is a **physical address** that can be issued to the memory system.

To understand this better, let's trace through what happens when a single instruction is executed. Specifically, let's look at one instruction from our earlier sequence:

```
128: movl 0x0(%ebx), %eax
```

The program counter (PC) is set to 128; when the hardware needs to fetch this instruction, it first adds the value to the base register value of 32 KB (32768) to get a physical address of 32896; the hardware then fetches the instruction from that physical address. Next, the processor begins executing the instruction. At some point, the process then issues

TIP: HARDWARE-BASED DYNAMIC RELOCATION

With dynamic relocation, a little hardware goes a long way. Namely, a **base** register is used to transform virtual addresses (generated by the program) into physical addresses. A **bounds** (or **limit**) register ensures that such addresses are within the confines of the address space. Together they provide a simple and efficient virtualization of memory.

the load from virtual address 15 KB, which the processor takes and again adds to the base register (32 KB), getting the final physical address of 47 KB and thus the desired contents.

Transforming a virtual address into a physical address is exactly the technique we refer to as **address translation**; that is, the hardware takes a virtual address the process thinks it is referencing and transforms it into a physical address which is where the data actually resides. Because this relocation of the address happens at runtime, and because we can move address spaces even after the process has started running, the technique is often referred to as **dynamic relocation** [M65].

Now you might be asking: what happened to that bounds (limit) register? After all, isn't this the base *and* bounds approach? Indeed, it is. As you might have guessed, the bounds register is there to help with protection. Specifically, the processor will first check that the memory reference is *within bounds* to make sure it is legal; in the simple example above, the bounds register would always be set to 16 KB. If a process generates a virtual address that is greater than the bounds, or one that is negative, the CPU will raise an exception, and the process will likely be terminated. The point of the bounds is thus to make sure that all addresses generated by the process are legal and within the "bounds" of the process.

We should note that the base and bounds registers are hardware structures kept on the chip (one pair per CPU). Sometimes people call the part of the processor that helps with address translation the **memory management unit (MMU)**; as we develop more sophisticated memory-management techniques, we will be adding more circuitry to the MMU.

A small aside about bound registers, which can be defined in one of two ways. In one way (as above), it holds the *size* of the address space, and thus the hardware checks the virtual address against it first before adding the base. In the second way, it holds the *physical address* of the end of the address space, and thus the hardware first adds the base and then makes sure the address is within bounds. Both methods are logically equivalent; for simplicity, we'll usually assume the former method.

Example Translations

To understand address translation via base-and-bounds in more detail, let's take a look at an example. Imagine a process with an address space of size 4 KB (yes, unrealistically small) has been loaded at physical address 16 KB. Here are the results of a number of address translations:

Virtual Address		Physical Address
0	→	16 KB
1 KB	→	17 KB
3000	→	19384
4400	→	<i>Fault (out of bounds)</i>

As you can see from the example, it is easy for you to simply add the base address to the virtual address (which can rightly be viewed as an *offset* into the address space) to get the resulting physical address. Only if the virtual address is “too big” or negative will the result be a fault, causing an exception to be raised.

15.4 Hardware Support: A Summary

Let us now summarize the support we need from the hardware (also see Figure 15.3, page 9). First, as discussed in the chapter on CPU virtualization, we require two different CPU modes. The OS runs in **privileged mode** (or **kernel mode**), where it has access to the entire machine; applications run in **user mode**, where they are limited in what they can do. A single bit, perhaps stored in some kind of **processor status word**, indicates which mode the CPU is currently running in; upon certain special occasions (e.g., a system call or some other kind of exception or interrupt), the CPU switches modes.

The hardware must also provide the **base and bounds registers** themselves; each CPU thus has an additional pair of registers, part of the **memory management unit (MMU)** of the CPU. When a user program is running, the hardware will translate each address, by adding the base value to the virtual address generated by the user program. The hardware must also be able to check whether the address is valid, which is accomplished by using the bounds register and some circuitry within the CPU.

The hardware should provide special instructions to modify the base and bounds registers, allowing the OS to change them when different processes run. These instructions are **privileged**; only in kernel (or privileged) mode can the registers be modified. Imagine the havoc a user process could wreak¹ if it could arbitrarily change the base register while

¹Is there anything other than “havoc” that can be “wreaked”? [W17]

ASIDE: DATA STRUCTURE — THE FREE LIST

The OS must track which parts of free memory are not in use, so as to be able to allocate memory to processes. Many different data structures can of course be used for such a task; the simplest (which we will assume here) is a **free list**, which simply is a list of the ranges of the physical memory which are not currently in use.

Hardware Requirements	Notes
Privileged mode	<i>Needed to prevent user-mode processes from executing privileged operations</i>
Base/bounds registers	<i>Need pair of registers per CPU to support address translation and bounds checks</i>
Ability to translate virtual addresses and check if within bounds	<i>Circuitry to do translations and check limits; in this case, quite simple</i>
Privileged instruction(s) to update base/bounds	<i>OS must be able to set these values before letting a user program run</i>
Privileged instruction(s) to register exception handlers	<i>OS must be able to tell hardware what code to run if exception occurs</i>
Ability to raise exceptions	<i>When processes try to access privileged instructions or out-of-bounds memory</i>

Figure 15.3: **Dynamic Relocation: Hardware Requirements**

running. Imagine it! And then quickly flush such dark thoughts from your mind, as they are the ghastly stuff of which nightmares are made.

Finally, the CPU must be able to generate **exceptions** in situations where a user program tries to access memory illegally (with an address that is “out of bounds”); in this case, the CPU should stop executing the user program and arrange for the OS “out-of-bounds” **exception handler** to run. The OS handler can then figure out how to react, in this case likely terminating the process. Similarly, if a user program tries to change the values of the (privileged) base and bounds registers, the CPU should raise an exception and run the “tried to execute a privileged operation while in user mode” handler. The CPU also must provide a method to inform it of the location of these handlers; a few more privileged instructions are thus needed.

15.5 Operating System Issues

Just as the hardware provides new features to support dynamic relocation, the OS now has new issues it must handle; the combination of hardware support and OS management leads to the implementation of a simple virtual memory. Specifically, there are a few critical junctures where the OS must get involved to implement our base-and-bounds version of virtual memory.

First, the OS must take action when a process is created, finding space for its address space in memory. Fortunately, given our assumptions that each address space is (a) smaller than the size of physical memory and (b) the same size, this is quite easy for the OS; it can simply view physical memory as an array of slots, and track whether each one is free or in use. When a new process is created, the OS will have to search a data structure (often called a **free list**) to find room for the new address space and then mark it used. With variable-sized address spaces, life is more complicated, but we will leave that concern for future chapters.

OS Requirements	Notes
Memory management	<i>Need to allocate memory for new processes; Reclaim memory from terminated processes; Generally manage memory via free list</i>
Base/bounds management	<i>Must set base/bounds properly upon context switch</i>
Exception handling	<i>Code to run when exceptions arise; likely action is to terminate offending process</i>

Figure 15.4: **Dynamic Relocation: Operating System Responsibilities**

Let's look at an example. In Figure 15.2 (page 5), you can see the OS using the first slot of physical memory for itself, and that it has relocated the process from the example above into the slot starting at physical memory address 32 KB. The other two slots are free (16 KB-32 KB and 48 KB-64 KB); thus, the **free list** should consist of these two entries.

Second, the OS must do some work when a process is terminated (i.e., when it exits gracefully, or is forcefully killed because it misbehaved), reclaiming all of its memory for use in other processes or the OS. Upon termination of a process, the OS thus puts its memory back on the free list, and cleans up any associated data structures as need be.

Third, the OS must also perform a few additional steps when a context switch occurs. There is only one base and bounds register pair on each CPU, after all, and their values differ for each running program, as each program is loaded at a different physical address in memory. Thus, the OS must *save and restore* the base-and-bounds pair when it switches between processes. Specifically, when the OS decides to stop running a process, it must save the values of the base and bounds registers to memory, in some per-process structure such as the **process structure** or **process control block (PCB)**. Similarly, when the OS resumes a running process (or runs it the first time), it must set the values of the base and bounds on the CPU to the correct values for this process.

We should note that when a process is stopped (i.e., not running), it is possible for the OS to move an address space from one location in memory to another rather easily. To move a process's address space, the OS first deschedules the process; then, the OS copies the address space from the current location to the new location; finally, the OS updates the saved base register (in the process structure) to point to the new location. When the process is resumed, its (new) base register is restored, and it begins running again, oblivious that its instructions and data are now in a completely new spot in memory.

Fourth, the OS must provide **exception handlers**, or functions to be called, as discussed above; the OS installs these handlers at boot time (via privileged instructions). For example, if a process tries to access memory outside its bounds, the CPU will raise an exception; the OS must be prepared to take action when such an exception arises. The common reaction of the OS will be one of hostility: it will likely terminate the offending process. The OS should be highly protective of the machine it is running, and thus it does not take kindly to a process trying to access memory or

OS @ boot (kernel mode)	Hardware	(No Program Yet)
initialize trap table	remember addresses of... system call handler timer handler illegal mem-access handler illegal instruction handler	
start interrupt timer		
initialize process table	start timer; interrupt after X ms	
initialize free list		

Figure 15.5: **Limited Direct Execution (Dynamic Relocation) @ Boot**

execute instructions that it shouldn't. Bye bye, misbehaving process; it's been nice knowing you.

Figures 15.5 and 15.6 (page 12) illustrate much of the hardware/OS interaction in a timeline. The first figure shows what the OS does at boot time to ready the machine for use, and the second shows what happens when a process (Process A) starts running; note how its memory translations are handled by the hardware with no OS intervention. At some point (middle of second figure), a timer interrupt occurs, and the OS switches to Process B, which executes a "bad load" (to an illegal memory address); at that point, the OS must get involved, terminating the process and cleaning up by freeing B's memory and removing its entry from the process table. As you can see from the figures, we are still following the basic approach of **limited direct execution**. In most cases, the OS just sets up the hardware appropriately and lets the process run directly on the CPU; only when the process misbehaves does the OS have to become involved.

15.6 Summary

In this chapter, we have extended the concept of limited direct execution with a specific mechanism used in virtual memory, known as **address translation**. With address translation, the OS can control each and every memory access from a process, ensuring the accesses stay within the bounds of the address space. Key to the efficiency of this technique is hardware support, which performs the translation quickly for each access, turning virtual addresses (the process's view of memory) into physical ones (the actual view). All of this is performed in a way that is *transparent* to the process that has been relocated; the process has no idea its memory references are being translated, making for a wonderful illusion.

We have also seen one particular form of virtualization, known as base and bounds or dynamic relocation. Base-and-bounds virtualization is quite *efficient*, as only a little more hardware logic is required to add a

OS @ run (kernel mode)	Hardware	Program (user mode)
To start process A:		
allocate entry in process table alloc memory for process set base/bound registers return-from-trap (into A)	restore registers of A move to user mode jump to A's (initial) PC	
		Process A runs Fetch instruction
	translate virtual address perform fetch	
	if explicit load/store: ensure address is legal translate virtual address perform load/store	Execute instruction
		(A runs...)
	Timer interrupt move to kernel mode jump to handler	
Handle timer decide: stop A, run B call <code>switch()</code> routine save regs(A) to <code>proc-struct(A)</code> (including base/bounds) restore regs(B) from <code>proc-struct(B)</code> (including base/bounds) return-from-trap (into B)	restore registers of B move to user mode jump to B's PC	
		Process B runs Execute bad load
	Load is out-of-bounds; move to kernel mode jump to trap handler	
Handle the trap decide to kill process B deallocate B's memory free B's entry in process table		

Figure 15.6: **Limited Direct Execution (Dynamic Relocation) @ Runtime**

base register to the virtual address and check that the address generated by the process is in bounds. Base-and-bounds also offers *protection*; the OS and hardware combine to ensure no process can generate memory references outside its own address space. Protection is certainly one of the most important goals of the OS; without it, the OS could not control the machine (if processes were free to overwrite memory, they could easily do nasty things like overwrite the trap table and take over the system).

Unfortunately, this simple technique of dynamic relocation does have its inefficiencies. For example, as you can see in Figure 15.2 (page 5), the relocated process is using physical memory from 32 KB to 48 KB; however, because the process stack and heap are not too big, all of the space between the two is simply *wasted*. This type of waste is usually called **internal fragmentation**, as the space *inside* the allocated unit is not all used (i.e., is fragmented) and thus wasted. In our current approach, although there might be enough physical memory for more processes, we are currently restricted to placing an address space in a fixed-sized slot and thus internal fragmentation can arise². Thus, we are going to need more sophisticated machinery, to try to better utilize physical memory and avoid internal fragmentation. Our first attempt will be a slight generalization of base and bounds known as **segmentation**, which we will discuss next.

²A different solution might instead place a fixed-sized stack within the address space, just below the code region, and a growing heap below that. However, this limits flexibility by making recursion and deeply-nested function calls challenging, and thus is something we hope to avoid.

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Homework (Simulation)

The program `relocation.py` allows you to see how address translations are performed in a system with base and bounds registers. See the README for details.

Questions

1. Run with seeds 1, 2, and 3, and compute whether each virtual address generated by the process is in or out of bounds. If in bounds, compute the translation.
2. Run with these flags: `-s 0 -n 10`. What value do you have set `-1` (the bounds register) to in order to ensure that all the generated virtual addresses are within bounds?
3. Run with these flags: `-s 1 -n 10 -l 100`. What is the maximum value that base can be set to, such that the address space still fits into physical memory in its entirety?
4. Run some of the same problems above, but with larger address spaces (`-a`) and physical memories (`-p`).
5. What fraction of randomly-generated virtual addresses are valid, as a function of the value of the bounds register? Make a graph from running with different random seeds, with limit values ranging from 0 up to the maximum size of the address space.

Segmentation

So far we have been putting the entire address space of each process in memory. With the base and bounds registers, the OS can easily relocate processes to different parts of physical memory. However, you might have noticed something interesting about these address spaces of ours: there is a big chunk of “free” space right in the middle, between the stack and the heap.

As you can imagine from Figure 16.1, although the space between the stack and heap is not being used by the process, it is still taking up physical memory when we relocate the entire address space somewhere in physical memory; thus, the simple approach of using a base and bounds register pair to virtualize memory is wasteful. It also makes it quite hard to run a program when the entire address space doesn’t fit into memory; thus, base and bounds is not as flexible as we would like. And thus:

THE CRUX: HOW TO SUPPORT A LARGE ADDRESS SPACE

How do we support a large address space with (potentially) a lot of free space between the stack and the heap? Note that in our examples, with tiny (pretend) address spaces, the waste doesn’t seem too bad. Imagine, however, a 32-bit address space (4 GB in size); a typical program will only use megabytes of memory, but still would demand that the entire address space be resident in memory.

16.1 Segmentation: Generalized Base/Bounds

To solve this problem, an idea was born, and it is called **segmentation**. It is quite an old idea, going at least as far back as the very early 1960’s [H61, G62]. The idea is simple: instead of having just one base and bounds pair in our MMU, why not have a base and bounds pair per logical **segment** of the address space? A segment is just a contiguous portion of the address space of a particular length, and in our canonical

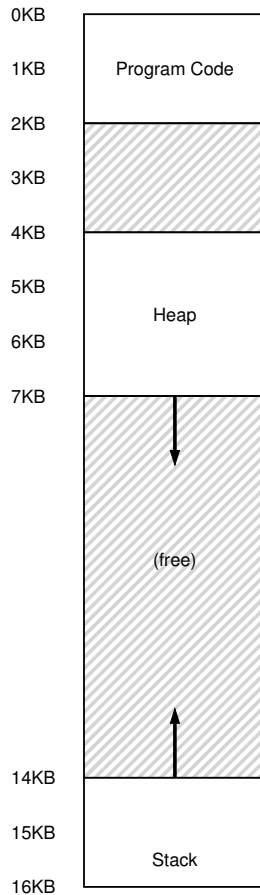


Figure 16.1: An Address Space (Again)

address space, we have three logically-different segments: code, stack, and heap. What segmentation allows the OS to do is to place each one of those segments in different parts of physical memory, and thus avoid filling physical memory with unused virtual address space.

Let's look at an example. Assume we want to place the address space from Figure 16.1 into physical memory. With a base and bounds pair per segment, we can place each segment *independently* in physical memory. For example, see Figure 16.2 (page 3); there you see a 64KB physical memory with those three segments in it (and 16KB reserved for the OS).

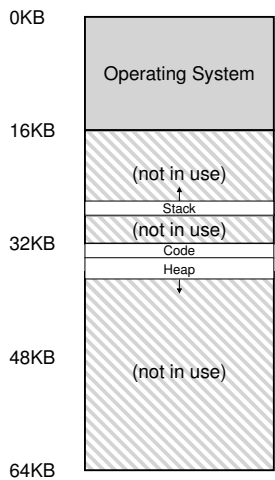


Figure 16.2: **Placing Segments In Physical Memory**

As you can see in the diagram, only used memory is allocated space in physical memory, and thus large address spaces with large amounts of unused address space (which we sometimes call **sparse address spaces**) can be accommodated.

The hardware structure in our MMU required to support segmentation is just what you’d expect: in this case, a set of three base and bounds register pairs. Figure 16.3 below shows the register values for the example above; each bounds register holds the size of a segment.

Segment	Base	Size
Code	32K	2K
Heap	34K	3K
Stack	28K	2K

Figure 16.3: **Segment Register Values**

You can see from the figure that the code segment is placed at physical address 32KB and has a size of 2KB and the heap segment is placed at 34KB and has a size of 3KB. The size segment here is exactly the same as the bounds register introduced previously; it tells the hardware exactly how many bytes are valid in this segment (and thus, enables the hardware to determine when a program has made an illegal access outside of those bounds).

Let’s do an example translation, using the address space in Figure 16.1. Assume a reference is made to virtual address 100 (which is in the code segment, as you can see visually in Figure 16.1, page 2). When the refer-

ASIDE: THE SEGMENTATION FAULT

The term **segmentation fault** or violation arises from a memory access on a segmented machine to an illegal address. Humorously, the term persists, even on machines with no support for segmentation at all. Or not so humorously, if you can't figure out why your code keeps faulting.

ence takes place (say, on an instruction fetch), the hardware will add the base value to the *offset* into this segment (100 in this case) to arrive at the desired physical address: $100 + 32\text{KB}$, or 32868. It will then check that the address is within bounds (100 is less than 2KB), find that it is, and issue the reference to physical memory address 32868.

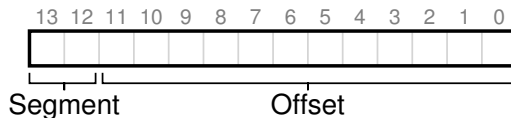
Now let's look at an address in the heap, virtual address 4200 (again refer to Figure 16.1). If we just add the virtual address 4200 to the base of the heap (34KB), we get a physical address of 39016, which is *not* the correct physical address. What we need to first do is extract the *offset* into the heap, i.e., which byte(s) *in this segment* the address refers to. Because the heap starts at virtual address 4KB (4096), the offset of 4200 is actually $4200 - 4096$, or 104. We then take this offset (104) and add it to the base register physical address (34K) to get the desired result: 34920.

What if we tried to refer to an illegal address (i.e., a virtual address of 7KB or greater), which is beyond the end of the heap? You can imagine what will happen: the hardware detects that the address is out of bounds, traps into the OS, likely leading to the termination of the offending process. And now you know the origin of the famous term that all C programmers learn to dread: the **segmentation violation** or **segmentation fault**.

16.2 Which Segment Are We Referring To?

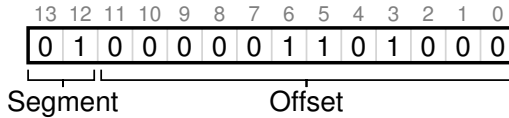
The hardware uses segment registers during translation. How does it know the offset into a segment, and to which segment an address refers?

One common approach, sometimes referred to as an **explicit** approach, is to chop up the address space into segments based on the top few bits of the virtual address; this technique was used in the VAX/VMS system [LL82]. In our example above, we have three segments; thus we need two bits to accomplish our task. If we use the top two bits of our 14-bit virtual address to select the segment, our virtual address looks like this:



In our example, then, if the top two bits are 00, the hardware knows the virtual address is in the code segment, and thus uses the code base and bounds pair to relocate the address to the correct physical location. If the top two bits are 01, the hardware knows the address is in the heap,

and thus uses the heap base and bounds. Let's take our example heap virtual address from above (4200) and translate it, just to make sure this is clear. The virtual address 4200, in binary form, can be seen here:



As you can see from the picture, the top two bits (01) tell the hardware which *segment* we are referring to. The bottom 12 bits are the *offset* into the segment: 0000 0110 1000, or hex 0x068, or 104 in decimal. Thus, the hardware simply takes the first two bits to determine which segment register to use, and then takes the next 12 bits as the offset into the segment. By adding the base register to the offset, the hardware arrives at the final physical address. Note the offset eases the bounds check too: we can simply check if the offset is less than the bounds; if not, the address is illegal. Thus, if base and bounds were arrays (with one entry per segment), the hardware would be doing something like this to obtain the desired physical address:

```

1 // get top 2 bits of 14-bit VA
2 Segment = (VirtualAddress & SEG_MASK) >> SEG_SHIFT
3 // now get offset
4 Offset = VirtualAddress & OFFSET_MASK
5 if (Offset >= Bounds[Segment])
6     RaiseException(PROTECTION_FAULT)
7 else
8     PhysAddr = Base[Segment] + Offset
9     Register = AccessMemory(PhysAddr)

```

In our running example, we can fill in values for the constants above. Specifically, `SEG_MASK` would be set to `0x3000`, `SEG_SHIFT` to 12, and `OFFSET_MASK` to `0xFFF`.

You may also have noticed that when we use the top two bits, and we only have three segments (code, heap, stack), one segment of the address space goes unused. To fully utilize the virtual address space (and avoid an unused segment), some systems put code in the same segment as the heap and thus use only one bit to select which segment to use [LL82].

Another issue with using the top so many bits to select a segment is that it limits use of the virtual address space. Specifically, each segment is limited to a *maximum size*, which in our example is 4KB (using the top two bits to choose segments implies the 16KB address space gets chopped into four pieces, or 4KB in this example). If a running program wishes to grow a segment (say the heap, or the stack) beyond that maximum, the program is out of luck.

There are other ways for the hardware to determine which segment a particular address is in. In the **implicit** approach, the hardware deter-

mines the segment by noticing how the address was formed. If, for example, the address was generated from the program counter (i.e., it was an instruction fetch), then the address is within the code segment; if the address is based off of the stack or base pointer, it must be in the stack segment; any other address must be in the heap.

16.3 What About The Stack?

Thus far, we've left out one important component of the address space: the stack. The stack has been relocated to physical address 28KB in the diagram above, but with one critical difference: *it grows backwards* (i.e., towards lower addresses). In physical memory, it "starts" at 28KB¹ and grows back to 26KB, corresponding to virtual addresses 16KB to 14KB; translation must proceed differently.

The first thing we need is a little extra hardware support. Instead of just base and bounds values, the hardware also needs to know which way the segment grows (a bit, for example, that is set to 1 when the segment grows in the positive direction, and 0 for negative). Our updated view of what the hardware tracks is seen in Figure 16.4:

Segment	Base	Size (max 4K)	Grows Positive?
Code ₀₀	32K	2K	1
Heap ₀₁	34K	3K	1
Stack ₁₁	28K	2K	0

Figure 16.4: **Segment Registers (With Negative-Growth Support)**

With the hardware understanding that segments can grow in the negative direction, the hardware must now translate such virtual addresses slightly differently. Let's take an example stack virtual address and translate it to understand the process.

In this example, assume we wish to access virtual address 15KB, which should map to physical address 27KB. Our virtual address, in binary form, thus looks like this: 11 1100 0000 0000 (hex 0x3C00). The hardware uses the top two bits (11) to designate the segment, but then we are left with an offset of 3KB. To obtain the correct negative offset, we must subtract the maximum segment size from 3KB: in this example, a segment can be 4KB, and thus the correct negative offset is 3KB minus 4KB which equals -1KB. We simply add the negative offset (-1KB) to the base (28KB) to arrive at the correct physical address: 27KB. The bounds check can be calculated by ensuring the absolute value of the negative offset is less than or equal to the segment's current size (in this case, 2KB).

¹ Although we say, for simplicity, that the stack "starts" at 28KB, this value is actually the byte just *below* the location of the backward growing region; the first valid byte is actually 28KB minus 1. In contrast, forward-growing regions start at the address of the first byte of the segment. We take this approach because it makes the math to compute the physical address straightforward: the physical address is just the base plus the negative offset.

16.4 Support for Sharing

As support for segmentation grew, system designers soon realized that they could realize new types of efficiencies with a little more hardware support. Specifically, to save memory, sometimes it is useful to **share** certain memory segments between address spaces. In particular, **code sharing** is common and still in use in systems today.

To support sharing, we need a little extra support from the hardware, in the form of **protection bits**. Basic support adds a few bits per segment, indicating whether or not a program can read or write a segment, or perhaps execute code that lies within the segment. By setting a code segment to read-only, the same code can be shared across multiple processes, without worry of harming isolation; while each process still thinks that it is accessing its own private memory, the OS is secretly sharing memory which cannot be modified by the process, and thus the illusion is preserved.

An example of the additional information tracked by the hardware (and OS) is shown in Figure 16.5. As you can see, the code segment is set to read and execute, and thus the same physical segment in memory could be mapped into multiple virtual address spaces.

Segment	Base	Size (max 4K)	Grows Positive?	Protection
Code ₀₀	32K	2K	1	Read-Execute
Heap ₀₁	34K	3K	1	Read-Write
Stack ₁₁	28K	2K	0	Read-Write

Figure 16.5: Segment Register Values (with Protection)

With protection bits, the hardware algorithm described earlier would also have to change. In addition to checking whether a virtual address is within bounds, the hardware also has to check whether a particular access is permissible. If a user process tries to write to a read-only segment, or execute from a non-executable segment, the hardware should raise an exception, and thus let the OS deal with the offending process.

16.5 Fine-grained vs. Coarse-grained Segmentation

Most of our examples thus far have focused on systems with just a few segments (i.e., code, stack, heap); we can think of this segmentation as **coarse-grained**, as it chops up the address space into relatively large, coarse chunks. However, some early systems (e.g., Multics [CV65,DD68]) were more flexible and allowed for address spaces to consist of a large number of smaller segments, referred to as **fine-grained** segmentation.

Supporting many segments requires even further hardware support, with a **segment table** of some kind stored in memory. Such segment tables usually support the creation of a very large number of segments, and thus enable a system to use segments in more flexible ways than we have thus far discussed. For example, early machines like the Burroughs B5000 had support for thousands of segments, and expected a compiler to chop

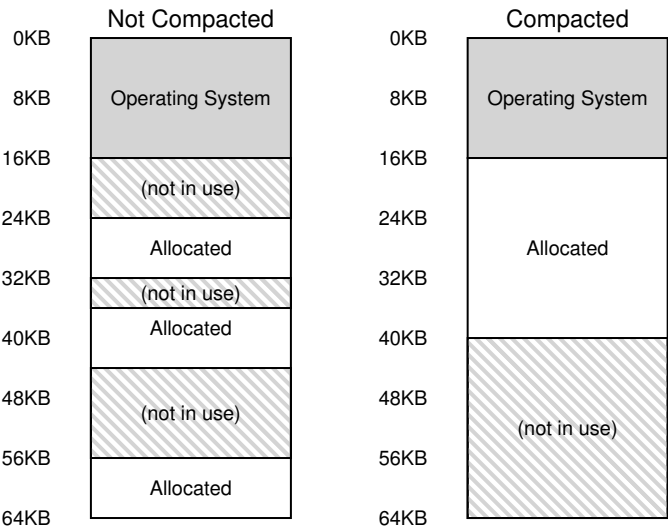


Figure 16.6: Non-compacted and Compacted Memory

code and data into separate segments which the OS and hardware would then support [RK68]. The thinking at the time was that by having fine-grained segments, the OS could better learn about which segments are in use and which are not and thus utilize main memory more effectively.

16.6 OS Support

You now should have a basic idea as to how segmentation works. Pieces of the address space are relocated into physical memory as the system runs, and thus a huge savings of physical memory is achieved relative to our simpler approach with just a single base/bounds pair for the entire address space. Specifically, all the unused space between the stack and the heap need not be allocated in physical memory, allowing us to fit more address spaces into physical memory and support a large and sparse virtual address space per process.

However, segmentation raises a number of new issues for the operating system. The first is an old one: what should the OS do on a context switch? You should have a good guess by now: the segment registers must be saved and restored. Clearly, each process has its own virtual address space, and the OS must make sure to set up these registers correctly before letting the process run again.

The second is OS interaction when segments grow (or perhaps shrink). For example, a program may call `malloc()` to allocate an object. In some cases, the existing heap will be able to service the request, and thus

TIP: IF 1000 SOLUTIONS EXIST, NO GREAT ONE DOES

The fact that so many different algorithms exist to try to minimize external fragmentation is indicative of a stronger underlying truth: there is no one “best” way to solve the problem. Thus, we settle for something reasonable and hope it is good enough. The only real solution (as we will see in forthcoming chapters) is to avoid the problem altogether, by never allocating memory in variable-sized chunks.

`malloc()` will find free space for the object and return a pointer to it to the caller. In others, however, the heap segment itself may need to grow. In this case, the memory-allocation library will perform a system call to grow the heap (e.g., the traditional UNIX `sbrk()` system call). The OS will then (usually) provide more space, updating the segment size register to the new (bigger) size, and informing the library of success; the library can then allocate space for the new object and return successfully to the calling program. Do note that the OS could reject the request, if no more physical memory is available, or if it decides that the calling process already has too much.

The last, and perhaps most important, issue is managing free space in physical memory. When a new address space is created, the OS has to be able to find space in physical memory for its segments. Previously, we assumed that each address space was the same size, and thus physical memory could be thought of as a bunch of slots where processes would fit in. Now, we have a number of segments per process, and each segment might be a different size.

The general problem that arises is that physical memory quickly becomes full of little holes of free space, making it difficult to allocate new segments, or to grow existing ones. We call this problem **external fragmentation** [R69]; see Figure 16.6 (left).

In the example, a process comes along and wishes to allocate a 20KB segment. In that example, there is 24KB free, but not in one contiguous segment (rather, in three non-contiguous chunks). Thus, the OS cannot satisfy the 20KB request. Similar problems could occur when a request to grow a segment arrives; if the next so many bytes of physical space are not available, the OS will have to reject the request, even though there may be free bytes available elsewhere in physical memory.

One solution to this problem would be to **compact** physical memory by rearranging the existing segments. For example, the OS could stop whichever processes are running, copy their data to one contiguous region of memory, change their segment register values to point to the new physical locations, and thus have a large free extent of memory with which to work. By doing so, the OS enables the new allocation request to succeed. However, compaction is expensive, as copying segments is memory-intensive and generally uses a fair amount of processor time; see

Figure 16.6 (right) for a diagram of compacted physical memory. Compaction also (ironically) makes requests to grow existing segments hard to serve, and may thus cause further rearrangement to accommodate such requests.

A simpler approach might instead be to use a free-list management algorithm that tries to keep large extents of memory available for allocation. There are literally hundreds of approaches that people have taken, including classic algorithms like **best-fit** (which keeps a list of free spaces and returns the one closest in size that satisfies the desired allocation to the requester), **worst-fit**, **first-fit**, and more complex schemes like **buddy algorithm** [K68]. An excellent survey by Wilson et al. is a good place to start if you want to learn more about such algorithms [W+95], or you can wait until we cover some of the basics in a later chapter. Unfortunately, though, no matter how smart the algorithm, external fragmentation will still exist; thus, a good algorithm simply attempts to minimize it.

16.7 Summary

Segmentation solves a number of problems, and helps us build a more effective virtualization of memory. Beyond just dynamic relocation, segmentation can better support sparse address spaces, by avoiding the huge potential waste of memory between logical segments of the address space. It is also fast, as doing the arithmetic segmentation requires is easy and well-suited to hardware; the overheads of translation are minimal. A fringe benefit arises too: code sharing. If code is placed within a separate segment, such a segment could potentially be shared across multiple running programs.

However, as we learned, allocating variable-sized segments in memory leads to some problems that we'd like to overcome. The first, as discussed above, is external fragmentation. Because segments are variable-sized, free memory gets chopped up into odd-sized pieces, and thus satisfying a memory-allocation request can be difficult. One can try to use smart algorithms [W+95] or periodically compact memory, but the problem is fundamental and hard to avoid.

The second and perhaps more important problem is that segmentation still isn't flexible enough to support our fully generalized, sparse address space. For example, if we have a large but sparsely-used heap all in one logical segment, the entire heap must still reside in memory in order to be accessed. In other words, if our model of how the address space is being used doesn't exactly match how the underlying segmentation has been designed to support it, segmentation doesn't work very well. We thus need to find some new solutions. Ready to find them?

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Homework (Simulation)

This program allows you to see how address translations are performed in a system with segmentation. See the README for details.

Questions

1. First let's use a tiny address space to translate some addresses. Here's a simple set of parameters with a few different random seeds; can you translate the addresses?

```
segmentation.py -a 128 -p 512 -b 0 -l 20 -B 512
-L 20 -s 0
segmentation.py -a 128 -p 512 -b 0 -l 20 -B 512
-L 20 -s 1
segmentation.py -a 128 -p 512 -b 0 -l 20 -B 512
-L 20 -s 2
```

2. Now, let's see if we understand this tiny address space we've constructed (using the parameters from the question above). What is the highest legal virtual address in segment 0? What about the lowest legal virtual address in segment 1? What are the lowest and highest *illegal* addresses in this entire address space? Finally, how would you run `segmentation.py` with the `-A` flag to test if you are right?
3. Let's say we have a tiny 16-byte address space in a 128-byte physical memory. What base and bounds would you set up so as to get the simulator to generate the following translation results for the specified address stream: valid, valid, violation, ..., violation, valid, valid? Assume the following parameters:

```
segmentation.py -a 16 -p 128
-A 0,1,2,3,4,5,6,7,8,9,10,11,12,13,14,15
--b0 ? --l0 ? --b1 ? --l1 ?
```

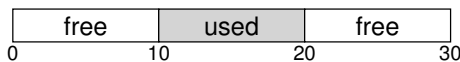
4. Assume we want to generate a problem where roughly 90% of the randomly-generated virtual addresses are valid (not segmentation violations). How should you configure the simulator to do so? Which parameters are important to getting this outcome?
5. Can you run the simulator such that no virtual addresses are valid? How?

Free-Space Management

In this chapter, we take a small detour from our discussion of virtualizing memory to discuss a fundamental aspect of any memory management system, whether it be a malloc library (managing pages of a process's heap) or the OS itself (managing portions of the address space of a process). Specifically, we will discuss the issues surrounding **free-space management**.

Let us make the problem more specific. Managing free space can certainly be easy, as we will see when we discuss the concept of **paging**. It is easy when the space you are managing is divided into fixed-sized units; in such a case, you just keep a list of these fixed-sized units; when a client requests one of them, return the first entry.

Where free-space management becomes more difficult (and interesting) is when the free space you are managing consists of variable-sized units; this arises in a user-level memory-allocation library (as in `malloc()` and `free()`) and in an OS managing physical memory when using **segmentation** to implement virtual memory. In either case, the problem that exists is known as **external fragmentation**: the free space gets chopped into little pieces of different sizes and is thus fragmented; subsequent requests may fail because there is no single contiguous space that can satisfy the request, even though the total amount of free space exceeds the size of the request.



The figure shows an example of this problem. In this case, the total free space available is 20 bytes; unfortunately, it is fragmented into two chunks of size 10 each. As a result, a request for 15 bytes will fail even though there are 20 bytes free. And thus we arrive at the problem addressed in this chapter.

CRUX: HOW TO MANAGE FREE SPACE

How should free space be managed, when satisfying variable-sized requests? What strategies can be used to minimize fragmentation? What are the time and space overheads of alternate approaches?

17.1 Assumptions

Most of this discussion will focus on the great history of allocators found in user-level memory-allocation libraries. We draw on Wilson's excellent survey [W+95] but encourage interested readers to go to the source document itself for more details¹.

We assume a basic interface such as that provided by `malloc()` and `free()`. Specifically, `void *malloc(size_t size)` takes a single parameter, `size`, which is the number of bytes requested by the application; it hands back a pointer (of no particular type, or a **void pointer** in C lingo) to a region of that size (or greater). The complementary routine `void free(void *ptr)` takes a pointer and frees the corresponding chunk. Note the implication of the interface: the user, when freeing the space, does not inform the library of its size; thus, the library must be able to figure out how big a chunk of memory is when handed just a pointer to it. We'll discuss how to do this a bit later on in the chapter.

The space that this library manages is known historically as the **heap**, and the generic data structure used to manage free space in the heap is some kind of **free list**. This structure contains references to all of the free chunks of space in the managed region of memory. Of course, this data structure need not be a list *per se*, but just some kind of data structure to track free space.

We further assume that primarily we are concerned with **external fragmentation**, as described above. Allocators could of course also have the problem of **internal fragmentation**; if an allocator hands out chunks of memory bigger than that requested, any unasked for (and thus unused) space in such a chunk is considered *internal* fragmentation (because the waste occurs inside the allocated unit) and is another example of space waste. However, for the sake of simplicity, and because it is the more interesting of the two types of fragmentation, we'll mostly focus on external fragmentation.

We'll also assume that once memory is handed out to a client, it cannot be relocated to another location in memory. For example, if a program calls `malloc()` and is given a pointer to some space within the heap, that memory region is essentially "owned" by the program (and cannot be moved by the library) until the program returns it via a corresponding call to `free()`. Thus, no **compaction** of free space is possible, which

¹It is nearly 80 pages long; thus, you really have to be interested!

would be useful to combat fragmentation². Compaction could, however, be used in the OS to deal with fragmentation when implementing **segmentation** (as discussed in said chapter on segmentation).

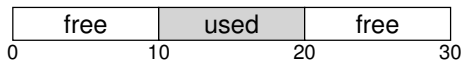
Finally, we'll assume that the allocator manages a contiguous region of bytes. In some cases, an allocator could ask for that region to grow; for example, a user-level memory-allocation library might call into the kernel to grow the heap (via a system call such as `sbrk`) when it runs out of space. However, for simplicity, we'll just assume that the region is a single fixed size throughout its life.

17.2 Low-level Mechanisms

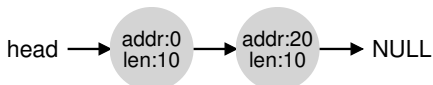
Before delving into some policy details, we'll first cover some common mechanisms used in most allocators. First, we'll discuss the basics of splitting and coalescing, common techniques in most any allocator. Second, we'll show how one can track the size of allocated regions quickly and with relative ease. Finally, we'll discuss how to build a simple list inside the free space to keep track of what is free and what isn't.

Splitting and Coalescing

A free list contains a set of elements that describe the free space still remaining in the heap. Thus, assume the following 30-byte heap:



The free list for this heap would have two elements on it. One entry describes the first 10-byte free segment (bytes 0-9), and one entry describes the other free segment (bytes 20-29):

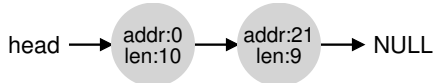


As described above, a request for anything greater than 10 bytes will fail (returning `NULL`); there just isn't a single contiguous chunk of memory of that size available. A request for exactly that size (10 bytes) could be satisfied easily by either of the free chunks. But what happens if the request is for something *smaller* than 10 bytes?

Assume we have a request for just a single byte of memory. In this case, the allocator will perform an action known as **splitting**: it will find

²Once you hand a pointer to a chunk of memory to a C program, it is generally difficult to determine all references (pointers) to that region, which may be stored in other variables or even in registers at a given point in execution. This may not be the case in more strongly-typed, garbage-collected languages, which would thus enable compaction as a technique to combat fragmentation.

a free chunk of memory that can satisfy the request and split it into two. The first chunk it will return to the caller; the second chunk will remain on the list. Thus, in our example above, if a request for 1 byte were made, and the allocator decided to use the second of the two elements on the list to satisfy the request, the call to `malloc()` would return 20 (the address of the 1-byte allocated region) and the list would end up looking like this:



In the picture, you can see the list basically stays intact; the only change is that the free region now starts at 21 instead of 20, and the length of that free region is now just 9³. Thus, the split is commonly used in allocators when requests are smaller than the size of any particular free chunk.

A corollary mechanism found in many allocators is known as **coalescing** of free space. Take our example from above once more (free 10 bytes, used 10 bytes, and another free 10 bytes).

Given this (tiny) heap, what happens when an application calls `free(10)`, thus returning the space in the middle of the heap? If we simply add this free space back into our list without too much thinking, we might end up with a list that looks like this:



Note the problem: while the entire heap is now free, it is seemingly divided into three chunks of 10 bytes each. Thus, if a user requests 20 bytes, a simple list traversal will not find such a free chunk, and return failure.

What allocators do in order to avoid this problem is coalesce free space when a chunk of memory is freed. The idea is simple: when returning a free chunk in memory, look carefully at the addresses of the chunk you are returning as well as the nearby chunks of free space; if the newly-freed space sits right next to one (or two, as in this example) existing free chunks, merge them into a single larger free chunk. Thus, with coalescing, our final list should look like this:



Indeed, this is what the heap list looked like at first, before any allocations were made. With coalescing, an allocator can better ensure that large free extents are available for the application.

³This discussion assumes that there are no headers, an unrealistic but simplifying assumption we make for now.

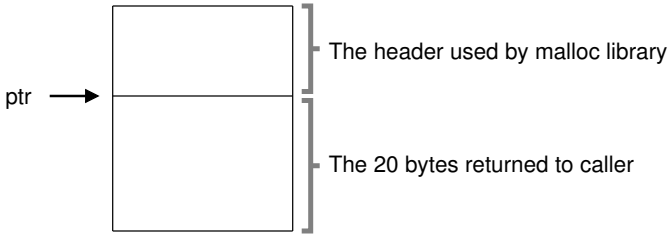


Figure 17.1: An Allocated Region Plus Header

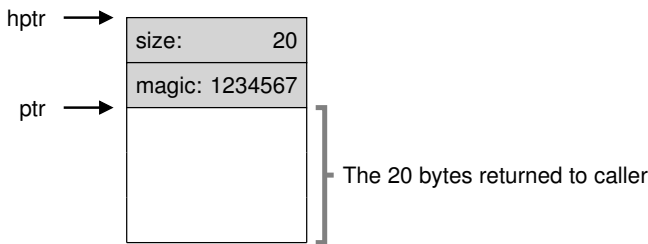


Figure 17.2: Specific Contents Of The Header

Tracking The Size Of Allocated Regions

You might have noticed that the interface to `free(void *ptr)` does not take a size parameter; thus it is assumed that given a pointer, the malloc library can quickly determine the size of the region of memory being freed and thus incorporate the space back into the free list.

To accomplish this task, most allocators store a little bit of extra information in a **header** block which is kept in memory, usually just before the handed-out chunk of memory. Let's look at an example again (Figure 17.1). In this example, we are examining an allocated block of size 20 bytes, pointed to by `ptr`; imagine the user called `malloc()` and stored the results in `ptr`, e.g., `ptr = malloc(20);`.

The header minimally contains the size of the allocated region (in this case, 20); it may also contain additional pointers to speed up deallocation, a magic number to provide additional integrity checking, and other information. Let's assume a simple header which contains the size of the region and a magic number, like this:

```
typedef struct {
    int size;
    int magic;
} header_t;
```

The example above would look like what you see in Figure 17.2. When the user calls `free(ptr)`, the library then uses simple pointer arithmetic to figure out where the header begins:

```
void free(void *ptr) {
    header_t *hptr = (header_t *) ptr - 1;
    ...
}
```

After obtaining such a pointer to the header, the library can easily determine whether the magic number matches the expected value as a sanity check (`assert(hptr->magic == 1234567)`) and calculate the total size of the newly-freed region via simple math (i.e., adding the size of the header to size of the region). Note the small but critical detail in the last sentence: the size of the free region is the size of the header plus the size of the space allocated to the user. Thus, when a user requests N bytes of memory, the library does not search for a free chunk of size N ; rather, it searches for a free chunk of size N plus the size of the header.

Embedding A Free List

Thus far we have treated our simple free list as a conceptual entity; it is just a list describing the free chunks of memory in the heap. But how do we build such a list inside the free space itself?

In a more typical list, when allocating a new node, you would just call `malloc()` when you need space for the node. Unfortunately, within the memory-allocation library, you can't do this! Instead, you need to build the list *inside* the free space itself. Don't worry if this sounds a little weird; it is, but not so weird that you can't do it!

Assume we have a 4096-byte chunk of memory to manage (i.e., the heap is 4KB). To manage this as a free list, we first have to initialize said list; initially, the list should have one entry, of size 4096 (minus the header size). Here is the description of a node of the list:

```
typedef struct __node_t {
    int             size;
    struct __node_t *next;
} node_t;
```

Now let's look at some code that initializes the heap and puts the first element of the free list inside that space. We are assuming that the heap is built within some free space acquired via a call to the system call `mmap()`; this is not the only way to build such a heap but serves us well in this example. Here is the code:

```
// mmap() returns a pointer to a chunk of free space
node_t *head = mmap(NULL, 4096, PROT_READ|PROT_WRITE,
                    MAP_ANON|MAP_PRIVATE, -1, 0);
head->size     = 4096 - sizeof(node_t);
head->next     = NULL;
```

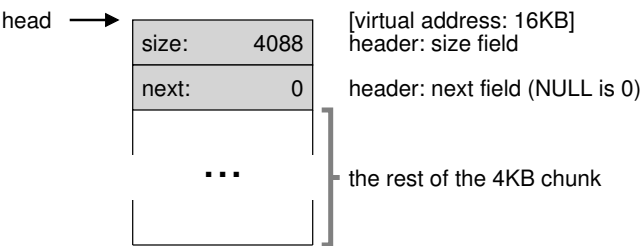


Figure 17.3: A Heap With One Free Chunk

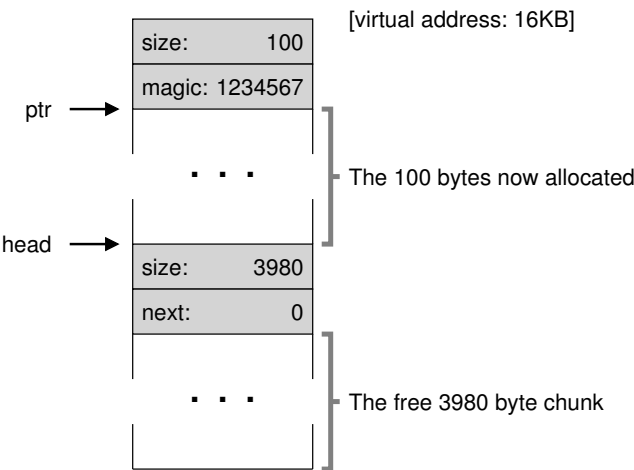


Figure 17.4: A Heap: After One Allocation

After running this code, the status of the list is that it has a single entry, of size 4088. Yes, this is a tiny heap, but it serves as a fine example for us here. The `head` pointer contains the beginning address of this range; let's assume it is 16KB (though any virtual address would be fine). Visually, the heap thus looks like what you see in Figure 17.3.

Now, let's imagine that a chunk of memory is requested, say of size 100 bytes. To service this request, the library will first find a chunk that is large enough to accommodate the request; because there is only one free chunk (size: 4088), this chunk will be chosen. Then, the chunk will be **split** into two: one chunk big enough to service the request (and header, as described above), and the remaining free chunk. Assuming an 8-byte header (an integer size and an integer magic number), the space in the heap now looks like what you see in Figure 17.4.

Thus, upon the request for 100 bytes, the library allocated 108 bytes

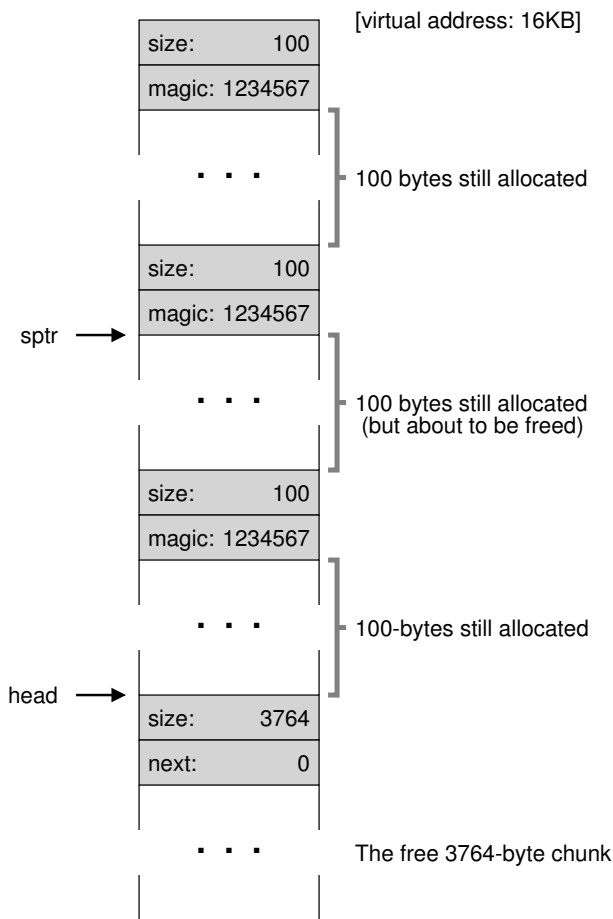


Figure 17.5: Free Space With Three Chunks Allocated

out of the existing one free chunk, returns a pointer (marked `ptr` in the figure above) to it, stashes the header information immediately before the allocated space for later use upon `free()`, and shrinks the one free node in the list to 3980 bytes (4088 minus 108).

Now let's look at the heap when there are three allocated regions, each of 100 bytes (or 108 including the header). A visualization of this heap is shown in Figure 17.5.

As you can see therein, the first 324 bytes of the heap are now allocated, and thus we see three headers in that space as well as three 100-byte regions being used by the calling program. The free list remains uninteresting: just a single node (pointed to by `head`), but now only 3764

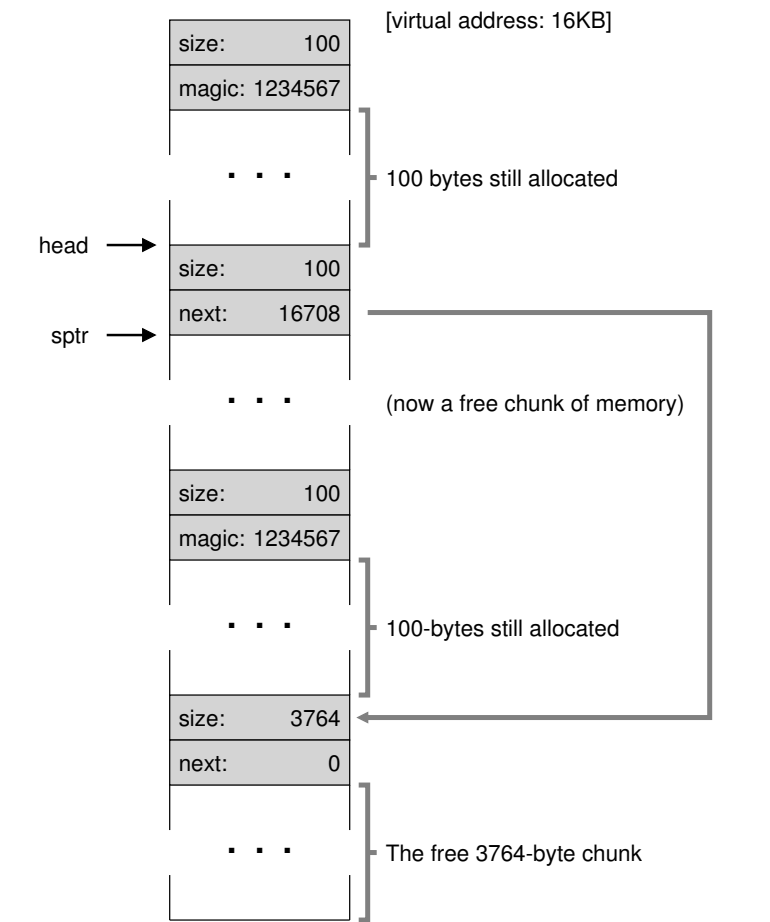


Figure 17.6: Free Space With Two Chunks Allocated

bytes in size after the three splits. But what happens when the calling program returns some memory via `free()`?

In this example, the application returns the middle chunk of allocated memory, by calling `free(16500)` (the value 16500 is arrived upon by adding the start of the memory region, 16384, to the 108 of the previous chunk and the 8 bytes of the header for this chunk). This value is shown in the previous diagram by the pointer `sptr`.

The library immediately figures out the size of the free region, and then adds the free chunk back onto the free list. Assuming we insert at the head of the free list, the space now looks like this (Figure 17.6).

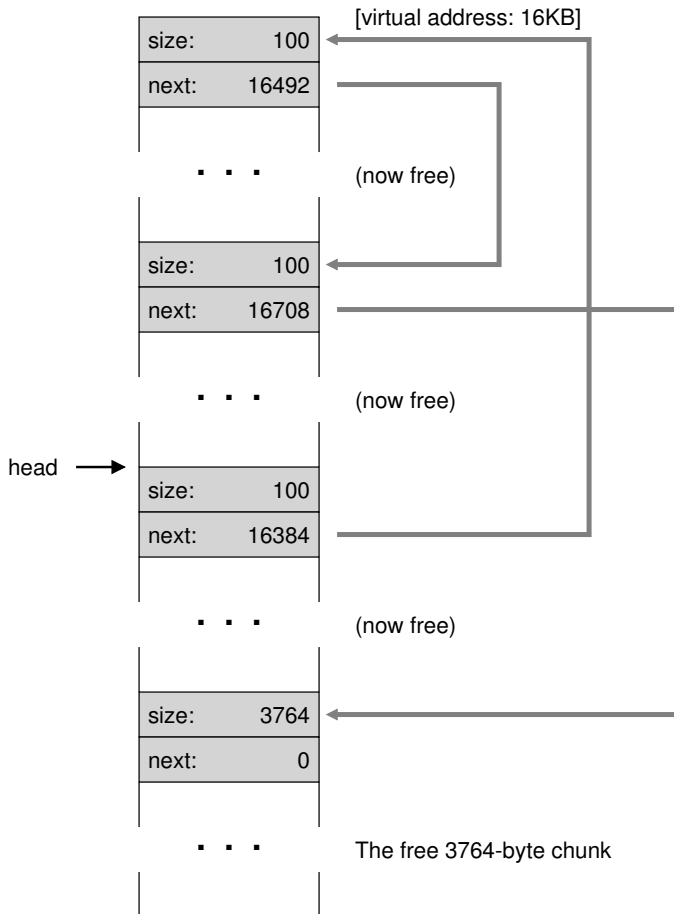


Figure 17.7: A Non-Coalesced Free List

Now we have a list that starts with a small free chunk (100 bytes, pointed to by the head of the list) and a large free chunk (3764 bytes). Our list finally has more than one element on it! And yes, the free space is fragmented, an unfortunate but common occurrence.

One last example: let's assume now that the last two in-use chunks are freed. Without coalescing, you end up with fragmentation (Figure 17.7).

As you can see from the figure, we now have a big mess! Why? Simple, we forgot to **coalesce** the list. Although all of the memory is free, it is chopped up into pieces, thus appearing as a fragmented memory despite not being one. The solution is simple: go through the list and **merge** neighboring chunks; when finished, the heap will be whole again.

Growing The Heap

We should discuss one last mechanism found within many allocation libraries. Specifically, what should you do if the heap runs out of space? The simplest approach is just to fail. In some cases this is the only option, and thus returning NULL is an honorable approach. Don't feel bad! You tried, and though you failed, you fought the good fight.

Most traditional allocators start with a small-sized heap and then request more memory from the OS when they run out. Typically, this means they make some kind of system call (e.g., `sbrk` in most UNIX systems) to grow the heap, and then allocate the new chunks from there. To service the `sbrk` request, the OS finds free physical pages, maps them into the address space of the requesting process, and then returns the value of the end of the new heap; at that point, a larger heap is available, and the request can be successfully serviced.

17.3 Basic Strategies

Now that we have some machinery under our belt, let's go over some basic strategies for managing free space. These approaches are mostly based on pretty simple policies that you could think up yourself; try it before reading and see if you come up with all of the alternatives (or maybe some new ones!).

The ideal allocator is both fast and minimizes fragmentation. Unfortunately, because the stream of allocation and free requests can be arbitrary (after all, they are determined by the programmer), any particular strategy can do quite badly given the wrong set of inputs. Thus, we will not describe a "best" approach, but rather talk about some basics and discuss their pros and cons.

Best Fit

The **best fit** strategy is quite simple: first, search through the free list and find chunks of free memory that are as big or bigger than the requested size. Then, return the one that is the smallest in that group of candidates; this is the so called best-fit chunk (it could be called smallest fit too). One pass through the free list is enough to find the correct block to return.

The intuition behind best fit is simple: by returning a block that is close to what the user asks, best fit tries to reduce wasted space. However, there is a cost; naive implementations pay a heavy performance penalty when performing an exhaustive search for the correct free block.

Worst Fit

The **worst fit** approach is the opposite of best fit; find the largest chunk and return the requested amount; keep the remaining (large) chunk on the free list. Worst fit tries to thus leave big chunks free instead of lots of

small chunks that can arise from a best-fit approach. Once again, however, a full search of free space is required, and thus this approach can be costly. Worse, most studies show that it performs badly, leading to excess fragmentation while still having high overheads.

First Fit

The **first fit** method simply finds the first block that is big enough and returns the requested amount to the user. As before, the remaining free space is kept free for subsequent requests.

First fit has the advantage of speed — no exhaustive search of all the free spaces are necessary — but sometimes pollutes the beginning of the free list with small objects. Thus, how the allocator manages the free list's order becomes an issue. One approach is to use **address-based ordering**; by keeping the list ordered by the address of the free space, coalescing becomes easier, and fragmentation tends to be reduced.

Next Fit

Instead of always beginning the first-fit search at the beginning of the list, the **next fit** algorithm keeps an extra pointer to the location within the list where one was looking last. The idea is to spread the searches for free space throughout the list more uniformly, thus avoiding splintering of the beginning of the list. The performance of such an approach is quite similar to first fit, as an exhaustive search is once again avoided.

Examples

Here are a few examples of the above strategies. Envision a free list with three elements on it, of sizes 10, 30, and 20 (we'll ignore headers and other details here, instead just focusing on how strategies operate):



Assume an allocation request of size 15. A best-fit approach would search the entire list and find that 20 was the best fit, as it is the smallest free space that can accommodate the request. The resulting free list:



As happens in this example, and often happens with a best-fit approach, a small free chunk is now left over. A worst-fit approach is similar but instead finds the largest chunk, in this example 30. The resulting list:



The first-fit strategy, in this example, does the same thing as worst-fit, also finding the first free block that can satisfy the request. The difference is in the search cost; both best-fit and worst-fit look through the entire list; first-fit only examines free chunks until it finds one that fits, thus reducing search cost.

These examples just scratch the surface of allocation policies. More detailed analysis with real workloads and more complex allocator behaviors (e.g., coalescing) are required for a deeper understanding. Perhaps something for a homework section, you say?

17.4 Other Approaches

Beyond the basic approaches described above, there have been a host of suggested techniques and algorithms to improve memory allocation in some way. We list a few of them here for your consideration (i.e., to make you think about a little more than just best-fit allocation).

Segregated Lists

One interesting approach that has been around for some time is the use of **segregated lists**. The basic idea is simple: if a particular application has one (or a few) popular-sized request that it makes, keep a separate list just to manage objects of that size; all other requests are forwarded to a more general memory allocator.

The benefits of such an approach are obvious. By having a chunk of memory dedicated for one particular size of requests, fragmentation is much less of a concern; moreover, allocation and free requests can be served quite quickly when they are of the right size, as no complicated search of a list is required.

Just like any good idea, this approach introduces new complications into a system as well. For example, how much memory should one dedicate to the pool of memory that serves specialized requests of a given size, as opposed to the general pool? One particular allocator, the **slab allocator** by uber-engineer Jeff Bonwick (which was designed for use in the Solaris kernel), handles this issue in a rather nice way [B94].

Specifically, when the kernel boots up, it allocates a number of **object caches** for kernel objects that are likely to be requested frequently (such as locks, file-system inodes, etc.); the object caches thus are each segregated free lists of a given size and serve memory allocation and free requests quickly. When a given cache is running low on free space, it requests some **slabs** of memory from a more general memory allocator (the total amount requested being a multiple of the page size and the object in question). Conversely, when the reference counts of the objects within a given slab all go to zero, the general allocator can reclaim them from the specialized allocator, which is often done when the VM system needs more memory.

ASIDE: GREAT ENGINEERS ARE REALLY GREAT

Engineers like Jeff Bonwick (who not only wrote the slab allocator mentioned herein but also was the lead of an amazing file system, ZFS) are the heart of Silicon Valley. Behind almost any great product or technology is a human (or small group of humans) who are way above average in their talents, abilities, and dedication. As Mark Zuckerberg (of Facebook) says: “Someone who is exceptional in their role is not just a little better than someone who is pretty good. They are 100 times better.” This is why, still today, one or two people can start a company that changes the face of the world forever (think Google, Apple, or Facebook). Work hard and you might become such a “100x” person as well. Failing that, work *with* such a person; you’ll learn more in a day than most learn in a month. Failing that, feel sad.

The slab allocator also goes beyond most segregated list approaches by keeping free objects on the lists in a pre-initialized state. Bonwick shows that initialization and destruction of data structures is costly [B94]; by keeping freed objects in a particular list in their initialized state, the slab allocator thus avoids frequent initialization and destruction cycles per object and thus lowers overheads noticeably.

Buddy Allocation

Because coalescing is critical for an allocator, some approaches have been designed around making coalescing simple. One good example is found in the **binary buddy allocator** [K65].

In such a system, free memory is first conceptually thought of as one big space of size 2^N . When a request for memory is made, the search for free space recursively divides free space by two until a block that is big enough to accommodate the request is found (and a further split into two would result in a space that is too small). At this point, the requested block is returned to the user. Here is an example of a 64KB free space getting divided in the search for a 7KB block (Figure 17.8, page 15).

In the example, the leftmost 8KB block is allocated (as indicated by the darker shade of gray) and returned to the user; note that this scheme can suffer from **internal fragmentation**, as you are only allowed to give out power-of-two-sized blocks.

The beauty of buddy allocation is found in what happens when that block is freed. When returning the 8KB block to the free list, the allocator checks whether the “buddy” 8KB is free; if so, it coalesces the two blocks into a 16KB block. The allocator then checks if the buddy of the 16KB block is still free; if so, it coalesces those two blocks. This recursive coalescing process continues up the tree, either restoring the entire free space or stopping when a buddy is found to be in use.

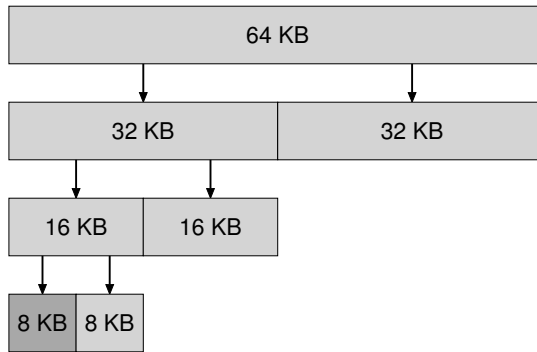


Figure 17.8: Example Buddy-managed Heap

The reason buddy allocation works so well is that it is simple to determine the buddy of a particular block. How, you ask? Think about the addresses of the blocks in the free space above. If you think carefully enough, you'll see that the address of each buddy pair only differs by a single bit; which bit is determined by the level in the buddy tree. And thus you have a basic idea of how binary buddy allocation schemes work. For more detail, as always, see the Wilson survey [W+95].

Other Ideas

One major problem with many of the approaches described above is their lack of **scaling**. Specifically, searching lists can be quite slow. Thus, advanced allocators use more complex data structures to address these costs, trading simplicity for performance. Examples include balanced binary trees, splay trees, or partially-ordered trees [W+95].

Given that modern systems often have multiple processors and run multi-threaded workloads (something you'll learn about in great detail in the section of the book on Concurrency), it is not surprising that a lot of effort has been spent making allocators work well on multiprocessor-based systems. Two wonderful examples are found in Berger et al. [B+00] and Evans [E06]; check them out for the details.

These are but two of the thousands of ideas people have had over time about memory allocators; read on your own if you are curious. Failing that, read about how the glibc allocator works [S15], to give you a sense of what the real world is like.

17.5 Summary

In this chapter, we've discussed the most rudimentary forms of memory allocators. Such allocators exist everywhere, linked into every C program you write, as well as in the underlying OS which is managing memory for its own data structures. As with many systems, there are many

trade-offs to be made in building such a system, and the more you know about the exact workload presented to an allocator, the more you could do to tune it to work better for that workload. Making a fast, space-efficient, scalable allocator that works well for a broad range of workloads remains an on-going challenge in modern computer systems.

References

- [B+00] “Hoard: A Scalable Memory Allocator for Multithreaded Applications” by Emery D. Berger, Kathryn S. McKinley, Robert D. Blumofe, Paul R. Wilson. ASPLOS-IX, November 2000. *Berger and company’s excellent allocator for multiprocessor systems. Beyond just being a fun paper, also used in practice!*
- [B94] “The Slab Allocator: An Object-Caching Kernel Memory Allocator” by Jeff Bonwick. USENIX ’94. *A cool paper about how to build an allocator for an operating system kernel, and a great example of how to specialize for particular common object sizes.*
- [E06] “A Scalable Concurrent malloc(3) Implementation for FreeBSD” by Jason Evans. April, 2006. <http://people.freebsd.org/~jasone/jemalloc/bsdcan2006/jemalloc.pdf>. *A detailed look at how to build a real modern allocator for use in multiprocessors. The “jemalloc” allocator is in widespread use today, within FreeBSD, NetBSD, Mozilla Firefox, and within Facebook.*
- [K65] “A Fast Storage Allocator” by Kenneth C. Knowlton. Communications of the ACM, Volume 8:10, October 1965. *The common reference for buddy allocation. Random strange fact: Knuth gives credit for the idea not to Knowlton but to Harry Markowitz, a Nobel-prize winning economist. Another strange fact: Knuth communicates all of his emails via a secretary; he doesn’t send email himself, rather he tells his secretary what email to send and then the secretary does the work of emailing. Last Knuth fact: he created TeX, the tool used to typeset this book. It is an amazing piece of software⁴.*
- [S15] “Understanding glibc malloc” by Sploitfun. February, 2015. sploitfun.wordpress.com/2015/02/10/understanding-glibc-malloc/. *A deep dive into how glibc malloc works. Amazingly detailed and a very cool read.*
- [W+95] “Dynamic Storage Allocation: A Survey and Critical Review” by Paul R. Wilson, Mark S. Johnstone, Michael Neely, David Boles. International Workshop on Memory Management, Scotland, UK, September 1995. *An excellent and far-reaching survey of many facets of memory allocation. Far too much detail to go into in this tiny chapter!*

⁴Actually we use LaTeX, which is based on Lamport’s additions to TeX, but close enough.

Homework (Simulation)

The program, `malloc.py`, lets you explore the behavior of a simple free-space allocator as described in the chapter. See the README for details of its basic operation.

Questions

1. First run with the flags `-n 10 -H 0 -p BEST -s 0` to generate a few random allocations and frees. Can you predict what `alloc()/free()` will return? Can you guess the state of the free list after each request? What do you notice about the free list over time?
2. How are the results different when using a WORST fit policy to search the free list (`-p WORST`)? What changes?
3. What about when using FIRST fit (`-p FIRST`)? What speeds up when you use first fit?
4. For the above questions, how the list is kept ordered can affect the time it takes to find a free location for some of the policies. Use the different free list orderings (`-l ADDRSORT`, `-l SIZESORT+`, `-l SIZESORT-`) to see how the policies and the list orderings interact.
5. Coalescing of a free list can be quite important. Increase the number of random allocations (say to `-n 1000`). What happens to larger allocation requests over time? Run with and without coalescing (i.e., without and with the `-C` flag). What differences in outcome do you see? How big is the free list over time in each case? Does the ordering of the list matter in this case?
6. What happens when you change the percent allocated fraction `-P` to higher than 50? What happens to allocations as it nears 100? What about as the percent nears 0?
7. What kind of specific requests can you make to generate a highly-fragmented free space? Use the `-A` flag to create fragmented free lists, and see how different policies and options change the organization of the free list.

Paging: Introduction

It is sometimes said that the operating system takes one of two approaches when solving most any space-management problem. The first approach is to chop things up into *variable-sized* pieces, as we saw with **segmentation** in virtual memory. Unfortunately, this solution has inherent difficulties. In particular, when dividing a space into different-size chunks, the space itself can become **fragmented**, and thus allocation becomes more challenging over time.

Thus, it may be worth considering the second approach: to chop up space into *fixed-sized* pieces. In virtual memory, we call this idea **paging**, and it goes back to an early and important system, the Atlas [KE+62, L78]. Instead of splitting up a process's address space into some number of variable-sized logical segments (e.g., code, heap, stack), we divide it into fixed-sized units, each of which we call a **page**. Correspondingly, we view physical memory as an array of fixed-sized slots called **page frames**; each of these frames can contain a single virtual-memory page. Our challenge:

THE CRUX:

HOW TO VIRTUALIZE MEMORY WITH PAGES

How can we virtualize memory with pages, so as to avoid the problems of segmentation? What are the basic techniques? How do we make those techniques work well, with minimal space and time overheads?

18.1 A Simple Example And Overview

To help make this approach more clear, let's illustrate it with a simple example. Figure 18.1 (page 2) presents an example of a tiny address space, only 64 bytes total in size, with four 16-byte pages (virtual pages 0, 1, 2, and 3). Real address spaces are much bigger, of course, commonly 32 bits and thus 4-GB of address space, or even 64 bits¹; in the book, we'll often use tiny examples to make them easier to digest.

¹A 64-bit address space is hard to imagine, it is so amazingly large. An analogy might help: if you think of a 32-bit address space as the size of a tennis court, a 64-bit address space is about the size of Europe(!).

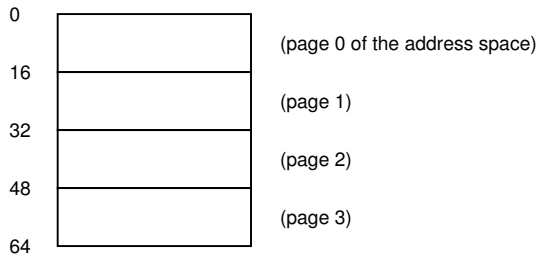


Figure 18.1: A Simple 64-byte Address Space

Physical memory, as shown in Figure 18.2, also consists of a number of fixed-sized slots, in this case eight page frames (making for a 128-byte physical memory, also ridiculously small). As you can see in the diagram, the pages of the virtual address space have been placed at different locations throughout physical memory; the diagram also shows the OS using some of physical memory for itself.

Paging, as we will see, has a number of advantages over our previous approaches. Probably the most important improvement will be *flexibility*: with a fully-developed paging approach, the system will be able to support the abstraction of an address space effectively, regardless of how a process uses the address space; we won't, for example, make assumptions about the direction the heap and stack grow and how they are used.

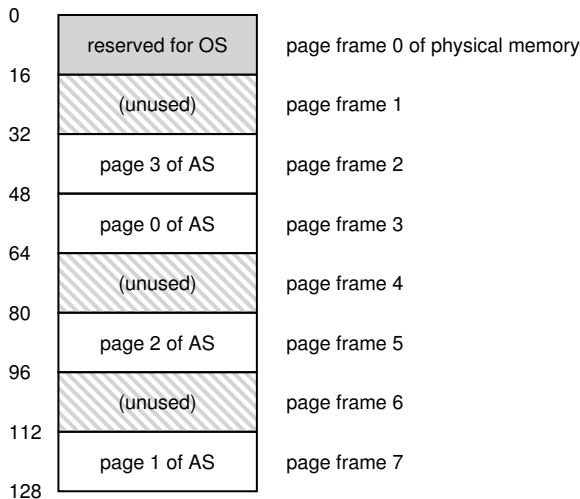


Figure 18.2: A 64-Byte Address Space In A 128-Byte Physical Memory

Another advantage is the *simplicity* of free-space management that paging affords. For example, when the OS wishes to place our tiny 64-byte address space into our eight-page physical memory, it simply finds four free pages; perhaps the OS keeps a **free list** of all free pages for this, and just grabs the first four free pages off of this list. In the example, the OS has placed virtual page 0 of the address space (AS) in physical frame 3, virtual page 1 of the AS in physical frame 7, page 2 in frame 5, and page 3 in frame 2. Page frames 1, 4, and 6 are currently free.

To record where each virtual page of the address space is placed in physical memory, the operating system usually keeps a *per-process* data structure known as a **page table**. The major role of the page table is to store **address translations** for each of the virtual pages of the address space, thus letting us know where in physical memory each page resides. For our simple example (Figure 18.2, page 2), the page table would thus have the following four entries: (Virtual Page 0 → Physical Frame 3), (VP 1 → PF 7), (VP 2 → PF 5), and (VP 3 → PF 2).

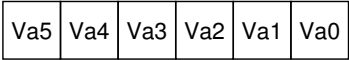
It is important to remember that this page table is a *per-process* data structure (most page table structures we discuss are per-process structures; an exception we'll touch on is the **inverted page table**). If another process were to run in our example above, the OS would have to manage a different page table for it, as its virtual pages obviously map to *different* physical pages (modulo any sharing going on).

Now, we know enough to perform an address-translation example. Let's imagine the process with that tiny address space (64 bytes) is performing a memory access:

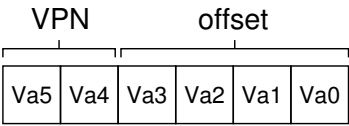
```
movl <virtual address>, %eax
```

Specifically, let's pay attention to the explicit load of the data from address <virtual address> into the register `eax` (and thus ignore the instruction fetch that must have happened prior).

To **translate** this virtual address that the process generated, we have to first split it into two components: the **virtual page number (VPN)**, and the **offset** within the page. For this example, because the virtual address space of the process is 64 bytes, we need 6 bits total for our virtual address ($2^6 = 64$). Thus, our virtual address can be conceptualized as follows:



In this diagram, Va5 is the highest-order bit of the virtual address, and Va0 the lowest-order bit. Because we know the page size (16 bytes), we can further divide the virtual address as follows:



The page size is 16 bytes in a 64-byte address space; thus we need to be able to select 4 pages, and the top 2 bits of the address do just that. Thus, we have a 2-bit virtual page number (VPN). The remaining bits tell us which byte of the page we are interested in, 4 bits in this case; we call this the offset.

When a process generates a virtual address, the OS and hardware must combine to translate it into a meaningful physical address. For example, let us assume the load above was to virtual address 21:

```
movl 21, %eax
```

Turning “21” into binary form, we get “010101”, and thus we can examine this virtual address and see how it breaks down into a virtual page number (VPN) and offset:



Thus, the virtual address “21” is on the 5th (“0101”th) byte of virtual page “01” (or 1). With our virtual page number, we can now index our page table and find which physical frame virtual page 1 resides within. In the page table above the **physical frame number** (PFN) (also sometimes called the **physical page number** or **PPN**) is 7 (binary 111). Thus, we can translate this virtual address by replacing the VPN with the PFN and then issue the load to physical memory (Figure 18.3).

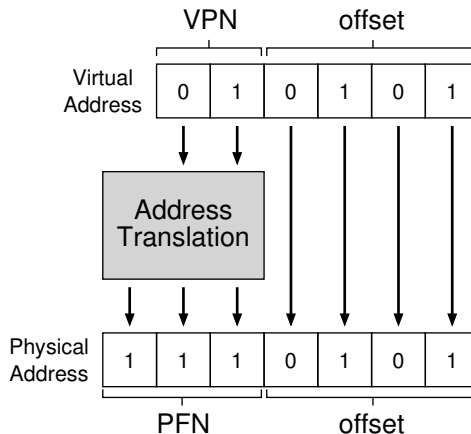


Figure 18.3: The Address Translation Process

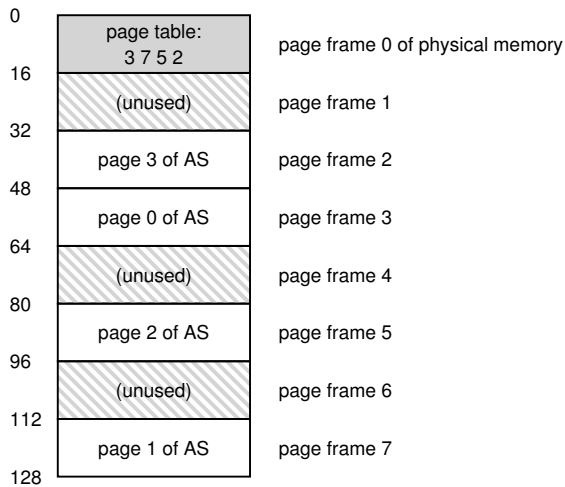


Figure 18.4: Example: Page Table in Kernel Physical Memory

Note the offset stays the same (i.e., it is not translated), because the offset just tells us which byte *within* the page we want. Our final physical address is 1110101 (117 in decimal), and is exactly where we want our load to fetch data from (Figure 18.2, page 2).

With this basic overview in mind, we can now ask (and hopefully, answer) a few basic questions you may have about paging. For example, where are these page tables stored? What are the typical contents of the page table, and how big are the tables? Does paging make the system (too) slow? These and other beguiling questions are answered, at least in part, in the text below. Read on!

18.2 Where Are Page Tables Stored?

Page tables can get terribly large, much bigger than the small segment table or base/bounds pair we have discussed previously. For example, imagine a typical 32-bit address space, with 4KB pages. This virtual address splits into a 20-bit VPN and 12-bit offset (recall that 10 bits would be needed for a 1KB page size, and just add two more to get to 4KB).

A 20-bit VPN implies that there are 2^{20} translations that the OS would have to manage for each process (that's roughly a million); assuming we need 4 bytes per **page table entry (PTE)** to hold the physical translation plus any other useful stuff, we get an immense 4MB of memory needed for each page table! That is pretty large. Now imagine there are 100 processes running: this means the OS would need 400MB of memory just for all those address translations! Even in the modern era, where

ASIDE: DATA STRUCTURE — THE PAGE TABLE

One of the most important data structures in the memory management subsystem of a modern OS is the **page table**. In general, a page table stores **virtual-to-physical address translations**, thus letting the system know where each page of an address space actually resides in physical memory. Because each address space requires such translations, in general there is one page table per process in the system. The exact structure of the page table is either determined by the hardware (older systems) or can be more flexibly managed by the OS (modern systems).

machines have gigabytes of memory, it seems a little crazy to use a large chunk of it just for translations, no? And we won't even think about how big such a page table would be for a 64-bit address space; that would be too gruesome and perhaps scare you off entirely.

Because page tables are so big, we don't keep any special on-chip hardware in the MMU to store the page table of the currently-running process. Instead, we store the page table for each process in *memory* somewhere. Let's assume for now that the page tables live in physical memory that the OS manages; later we'll see that much of OS memory itself can be virtualized, and thus page tables can be stored in OS virtual memory (and even swapped to disk), but that is too confusing right now, so we'll ignore it. In Figure 18.4 (page 5) is a picture of a page table in OS memory; see the tiny set of translations in there?

18.3 What's Actually In The Page Table?

Let's talk a little about page table organization. The page table is just a data structure that is used to map virtual addresses (or really, virtual page numbers) to physical addresses (physical frame numbers). Thus, any data structure could work. The simplest form is called a **linear page table**, which is just an array. The OS *indexes* the array by the virtual page number (VPN), and looks up the page-table entry (PTE) at that index in order to find the desired physical frame number (PFN). For now, we will assume this simple linear structure; in later chapters, we will make use of more advanced data structures to help solve some problems with paging.

As for the contents of each PTE, we have a number of different bits in there worth understanding at some level. A **valid bit** is common to indicate whether the particular translation is valid; for example, when a program starts running, it will have code and heap at one end of its address space, and the stack at the other. All the unused space in-between will be marked **invalid**, and if the process tries to access such memory, it will generate a trap to the OS which will likely terminate the process. Thus, the valid bit is crucial for supporting a sparse address space; by simply marking all the unused pages in the address space invalid, we remove the need to allocate physical frames for those pages and thus save a great deal of memory.

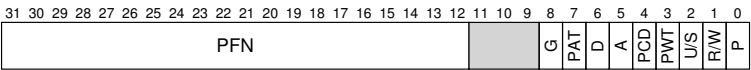


Figure 18.5: An x86 Page Table Entry (PTE)

We also might have **protection bits**, indicating whether the page could be read from, written to, or executed from. Again, accessing a page in a way not allowed by these bits will generate a trap to the OS.

There are a couple of other bits that are important but we won't talk about much for now. A **present bit** indicates whether this page is in physical memory or on disk (i.e., it has been **swapped out**). We will understand this machinery further when we study how to **swap** parts of the address space to disk to support address spaces that are larger than physical memory; swapping allows the OS to free up physical memory by moving rarely-used pages to disk. A **dirty bit** is also common, indicating whether the page has been modified since it was brought into memory.

A **reference bit** (a.k.a. **accessed bit**) is sometimes used to track whether a page has been accessed, and is useful in determining which pages are popular and thus should be kept in memory; such knowledge is critical during **page replacement**, a topic we will study in great detail in subsequent chapters.

Figure 18.5 shows an example page table entry from the x86 architecture [I09]. It contains a present bit (P); a read/write bit (R/W) which determines if writes are allowed to this page; a user/supervisor bit (U/S) which determines if user-mode processes can access the page; a few bits (PWT, PCD, PAT, and G) that determine how hardware caching works for these pages; an accessed bit (A) and a dirty bit (D); and finally, the page frame number (PFN) itself.

Read the Intel Architecture Manuals [I09] for more details on x86 paging support. Be forewarned, however; reading manuals such as these, while quite informative (and certainly necessary for those who write code to use such page tables in the OS), can be challenging at first. A little patience, and a lot of desire, is required.

ASIDE: WHY NO VALID BIT?

You may notice that in the Intel example, there are no separate valid and present bits, but rather just a present bit (P). If that bit is set (P=1), it means the page is both present and valid. If not (P=0), it means that the page may not be present in memory (but is valid), or may not be valid. An access to a page with P=0 will trigger a trap to the OS; the OS must then use additional structures it keeps to determine whether the page is valid (and thus perhaps should be swapped back in) or not (and thus the program is attempting to access memory illegally). This sort of judiciousness is common in hardware, which often just provide the minimal set of features upon which the OS can build a full service.

18.4 Paging: Also Too Slow

With page tables in memory, we already know that they might be too big. As it turns out, they can slow things down too. For example, take our simple instruction:

```
movl 21, %eax
```

Again, let's just examine the explicit reference to address 21 and not worry about the instruction fetch. In this example, we'll assume the hardware performs the translation for us. To fetch the desired data, the system must first **translate** the virtual address (21) into the correct physical address (117). Thus, before fetching the data from address 117, the system must first fetch the proper page table entry from the process's page table, perform the translation, and then load the data from physical memory.

To do so, the hardware must know where the page table is for the currently-running process. Let's assume for now that a single **page-table base register** contains the physical address of the starting location of the page table. To find the location of the desired PTE, the hardware will thus perform the following functions:

```
VPN      = (VirtualAddress & VPN_MASK) >> SHIFT
PTEAddr = PageTableBaseRegister + (VPN * sizeof(PTE))
```

In our example, `VPN_MASK` would be set to 0x30 (hex 30, or binary 110000) which picks out the VPN bits from the full virtual address; `SHIFT` is set to 4 (the number of bits in the offset), such that we move the VPN bits down to form the correct integer virtual page number. For example, with virtual address 21 (010101), and masking turns this value into 010000; the shift turns it into 01, or virtual page 1, as desired. We then use this value as an index into the array of PTEs pointed to by the page table base register.

Once this physical address is known, the hardware can fetch the PTE from memory, extract the PFN, and concatenate it with the offset from the virtual address to form the desired physical address. Specifically, you can think of the PFN being left-shifted by `SHIFT`, and then bitwise OR'd with the offset to form the final address as follows:

```
offset    = VirtualAddress & OFFSET_MASK
PhysAddr  = (PFN << SHIFT) | offset
```

Finally, the hardware can fetch the desired data from memory and put it into register `eax`. The program has now succeeded at loading a value from memory!

To summarize, we now describe the initial protocol for what happens on each memory reference. Figure 18.6 (page 9) shows the approach. For every memory reference (whether an instruction fetch or an explicit load or store), paging requires us to perform one extra memory reference in order to first fetch the translation from the page table. That is a lot of

```

1 // Extract the VPN from the virtual address
2 VPN = (VirtualAddress & VPN_MASK) >> SHIFT
3
4 // Form the address of the page-table entry (PTE)
5 PTEAddr = PTBR + (VPN * sizeof(PTE))
6
7 // Fetch the PTE
8 PTE = AccessMemory(PTEAddr)
9
10 // Check if process can access the page
11 if (PTE.Valid == False)
12     RaiseException(SEGMENTATION_FAULT)
13 else if (CanAccess(PTE.ProtectBits) == False)
14     RaiseException(PROTECTION_FAULT)
15 else
16     // Access is OK: form physical address and fetch it
17     offset = VirtualAddress & OFFSET_MASK
18     PhysAddr = (PTE.PFN << PFN_SHIFT) | offset
19     Register = AccessMemory(PhysAddr)

```

Figure 18.6: Accessing Memory With Paging

work! Extra memory references are costly, and in this case will likely slow down the process by a factor of two or more.

And now you can hopefully see that there are *two* real problems that we must solve. Without careful design of both hardware and software, page tables will cause the system to run too slowly, as well as take up too much memory. While seemingly a great solution for our memory virtualization needs, these two crucial problems must first be overcome.

18.5 A Memory Trace

Before closing, we now trace through a simple memory access example to demonstrate all of the resulting memory accesses that occur when using paging. The code snippet (in C, in a file called `array.c`) that we are interested in is as follows:

```

int array[1000];
...
for (i = 0; i < 1000; i++)
    array[i] = 0;

```

We compile `array.c` and run it with the following commands:

```

prompt> gcc -o array array.c -Wall -O
prompt> ./array

```

Of course, to truly understand what memory accesses this code snippet (which simply initializes an array) will make, we'll have to know (or assume) a few more things. First, we'll have to **disassemble** the resulting binary (using `objdump` on Linux, or `otool` on a Mac) to see what assembly instructions are used to initialize the array in a loop. Here is the resulting assembly code:

```
1024 movl $0x0, (%edi,%eax,4)
1028 incl %eax
1032 cmpl $0x03e8,%eax
1036 jne 0x1024
```

The code, if you know a little **x86**, is actually quite easy to understand². The first instruction moves the value zero (shown as `$0x0`) into the virtual memory address of the location of the array; this address is computed by taking the contents of `%edi` and adding `%eax` multiplied by four to it. Thus, `%edi` holds the base address of the array, whereas `%eax` holds the array index (`i`); we multiply by four because the array is an array of integers, each of size four bytes.

The second instruction increments the array index held in `%eax`, and the third instruction compares the contents of that register to the hex value `0x03e8`, or decimal 1000. If the comparison shows that two values are not yet equal (which is what the `jne` instruction tests), the fourth instruction jumps back to the top of the loop.

To understand which memory accesses this instruction sequence makes (at both the virtual and physical levels), we'll have to assume something about where in virtual memory the code snippet and array are found, as well as the contents and location of the page table.

For this example, we assume a virtual address space of size 64KB (unrealistically small). We also assume a page size of 1KB.

All we need to know now are the contents of the page table, and its location in physical memory. Let's assume we have a linear (array-based) page table and that it is located at physical address 1KB (1024).

As for its contents, there are just a few virtual pages we need to worry about having mapped for this example. First, there is the virtual page the code lives on. Because the page size is 1KB, virtual address 1024 resides on the second page of the virtual address space (`VPN=1`, as `VPN=0` is the first page). Let's assume this virtual page maps to physical frame 4 (`VPN 1 → PFN 4`).

Next, there is the array itself. Its size is 4000 bytes (1000 integers), and we assume that it resides at virtual addresses 40000 through 44000 (not including the last byte). The virtual pages for this decimal range are `VPN=39 ... VPN=42`. Thus, we need mappings for these pages. Let's assume these virtual-to-physical mappings for the example: (`VPN 39 → PFN 7`), (`VPN 40 → PFN 8`), (`VPN 41 → PFN 9`), (`VPN 42 → PFN 10`).

²We are cheating a little bit here, assuming each instruction is four bytes in size for simplicity; in actuality, x86 instructions are variable-sized.

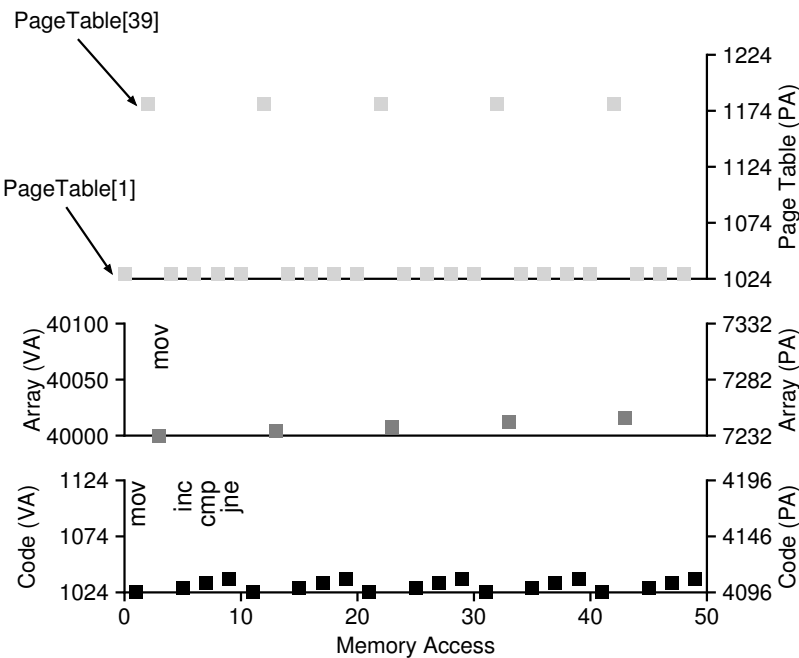


Figure 18.7: A Virtual (And Physical) Memory Trace

We are now ready to trace the memory references of the program. When it runs, each instruction fetch will generate two memory references: one to the page table to find the physical frame that the instruction resides within, and one to the instruction itself to fetch it to the CPU for processing. In addition, there is one explicit memory reference in the form of the `mov` instruction; this adds another page table access first (to translate the array virtual address to the correct physical one) and then the array access itself.

The entire process, for the first five loop iterations, is depicted in Figure 18.7 (page 11). The bottom most graph shows the instruction memory references on the y-axis in black (with virtual addresses on the left, and the actual physical addresses on the right); the middle graph shows array accesses in dark gray (again with virtual on left and physical on right); finally, the topmost graph shows page table memory accesses in light gray (just physical, as the page table in this example resides in physical memory). The x-axis, for the entire trace, shows memory accesses across the first five iterations of the loop; there are 10 memory accesses per loop, which includes four instruction fetches, one explicit update of memory, and five page table accesses to translate those four fetches and one explicit update.

See if you can make sense of the patterns that show up in this visualization. In particular, what will change as the loop continues to run beyond these first five iterations? Which new memory locations will be accessed? Can you figure it out?

This has just been the simplest of examples (only a few lines of C code), and yet you might already be able to sense the complexity of understanding the actual memory behavior of real applications. Don't worry: it definitely gets worse, because the mechanisms we are about to introduce only complicate this already complex machinery. Sorry³!

18.6 Summary

We have introduced the concept of **paging** as a solution to our challenge of virtualizing memory. Paging has many advantages over previous approaches (such as segmentation). First, it does not lead to external fragmentation, as paging (by design) divides memory into fixed-sized units. Second, it is quite flexible, enabling the sparse use of virtual address spaces.

However, implementing paging support without care will lead to a slower machine (with many extra memory accesses to access the page table) as well as memory waste (with memory filled with page tables instead of useful application data). We'll thus have to think a little harder to come up with a paging system that not only works, but works well. The next two chapters, fortunately, will show us how to do so.

³We're not really sorry. But, we are sorry about not being sorry, if that makes sense.

References

[KE+62] “One-level Storage System” by T. Kilburn, D.B.G. Edwards, M.J. Lanigan, F.H. Sumner. IRE Trans. EC-11, 2, 1962. Reprinted in Bell and Newell, “Computer Structures: Readings and Examples”. McGraw-Hill, New York, 1971. *The Atlas pioneered the idea of dividing memory into fixed-sized pages and in many senses was an early form of the memory-management ideas we see in modern computer systems.*

[I09] “Intel 64 and IA-32 Architectures Software Developer’s Manuals” Intel, 2009. Available: <http://www.intel.com/products/processor/manuals>. In particular, pay attention to “Volume 3A: System Programming Guide Part 1” and “Volume 3B: System Programming Guide Part 2”.

[L78] “The Manchester Mark I and Atlas: A Historical Perspective” by S. H. Lavington. Communications of the ACM, Volume 21:1, January 1978. *This paper is a great retrospective of some of the history of the development of some important computer systems. As we sometimes forget in the US, many of these new ideas came from overseas.*

Homework (Simulation)

In this homework, you will use a simple program, which is known as `paging-linear-translate.py`, to see if you understand how simple virtual-to-physical address translation works with linear page tables. See the README for details.

Questions

1. Before doing any translations, let's use the simulator to study how linear page tables change size given different parameters. Compute the size of linear page tables as different parameters change. Some suggested inputs are below; by using the `-v` flag, you can see how many page-table entries are filled. First, to understand how linear page table size changes as the address space grows, run with these flags:

```
-P 1k -a 1m -p 512m -v -n 0
-P 1k -a 2m -p 512m -v -n 0
-P 1k -a 4m -p 512m -v -n 0
```

Then, to understand how linear page table size changes as page size grows:

```
-P 1k -a 1m -p 512m -v -n 0
-P 2k -a 1m -p 512m -v -n 0
-P 4k -a 1m -p 512m -v -n 0
```

Before running any of these, try to think about the expected trends. How should page-table size change as the address space grows? As the page size grows? Why not use big pages in general?

2. Now let's do some translations. Start with some small examples, and change the number of pages that are allocated to the address space with the `-u` flag. For example:

```
-P 1k -a 16k -p 32k -v -u 0
-P 1k -a 16k -p 32k -v -u 25
-P 1k -a 16k -p 32k -v -u 50
-P 1k -a 16k -p 32k -v -u 75
-P 1k -a 16k -p 32k -v -u 100
```

What happens as you increase the percentage of pages that are allocated in each address space?

3. Now let's try some different random seeds, and some different (and sometimes quite crazy) address-space parameters, for variety:

```
-P 8 -a 32 -p 1024 -v -s 1
-P 8k -a 32k -p 1m -v -s 2
-P 1m -a 256m -p 512m -v -s 3
```

Which of these parameter combinations are unrealistic? Why?

4. Use the program to try out some other problems. Can you find the limits of where the program doesn't work anymore? For example, what happens if the address-space size is *bigger* than physical memory?

Paging: Smaller Tables

We now tackle the second problem that paging introduces: page tables are too big and thus consume too much memory. Let's start out with a linear page table. As you might recall¹, linear page tables get pretty big. Assume again a 32-bit address space (2^{32} bytes), with 4KB (2^{12} byte) pages and a 4-byte page-table entry. An address space thus has roughly one million virtual pages in it ($\frac{2^{32}}{2^{12}}$); multiply by the page-table entry size and you see that our page table is 4MB in size. Recall also: we usually have one page table *for every process* in the system! With a hundred active processes (not uncommon on a modern system), we will be allocating hundreds of megabytes of memory just for page tables! As a result, we are in search of some techniques to reduce this heavy burden. There are a lot of them, so let's get going. But not before our crux:

CRUX: HOW TO MAKE PAGE TABLES SMALLER?

Simple array-based page tables (usually called linear page tables) are too big, taking up far too much memory on typical systems. How can we make page tables smaller? What are the key ideas? What inefficiencies arise as a result of these new data structures?

20.1 Simple Solution: Bigger Pages

We could reduce the size of the page table in one simple way: use bigger pages. Take our 32-bit address space again, but this time assume 16KB pages. We would thus have an 18-bit VPN plus a 14-bit offset. Assuming the same size for each PTE (4 bytes), we now have 2^{18} entries in our linear page table and thus a total size of 1MB per page table, a factor

¹Or indeed, you might not; this paging thing is getting out of control, no? That said, always make sure you understand the *problem* you are solving before moving onto the solution; indeed, if you understand the problem, you can often derive the solution yourself. Here, the problem should be clear: simple linear (array-based) page tables are too big.

ASIDE: MULTIPLE PAGE SIZES

As an aside, do note that many architectures (e.g., MIPS, SPARC, x86-64) now support multiple page sizes. Usually, a small (4KB or 8KB) page size is used. However, if a “smart” application requests it, a single large page (e.g., of size 4MB) can be used for a specific portion of the address space, enabling such applications to place a frequently-used (and large) data structure in such a space while consuming only a single TLB entry. This type of large page usage is common in database management systems and other high-end commercial applications. The main reason for multiple page sizes is not to save page table space, however; it is to reduce pressure on the TLB, enabling a program to access more of its address space without suffering from too many TLB misses. However, as researchers have shown [N+02], using multiple page sizes makes the OS virtual memory manager notably more complex, and thus large pages are sometimes most easily used simply by exporting a new interface to applications to request large pages directly.

of four reduction in size of the page table (not surprisingly, the reduction exactly mirrors the factor of four increase in page size).

The major problem with this approach, however, is that big pages lead to waste *within* each page, a problem known as **internal fragmentation** (as the waste is **internal** to the unit of allocation). Applications thus end up allocating pages but only using little bits and pieces of each, and memory quickly fills up with these overly-large pages. Thus, most systems use relatively small page sizes in the common case: 4KB (as in x86) or 8KB (as in SPARCv9). Our problem will not be solved so simply, alas.

20.2 Hybrid Approach: Paging and Segments

Whenever you have two reasonable but different approaches to something in life, you should always examine the combination of the two to see if you can obtain the best of both worlds. We call such a combination a **hybrid**. For example, why eat just chocolate or plain peanut butter when you can instead combine the two in a lovely hybrid known as the Reese’s Peanut Butter Cup [M28]?

Years ago, the creators of Multics (in particular Jack Dennis) chanced upon such an idea in the construction of the Multics virtual memory system [M07]. Specifically, Dennis had the idea of combining paging and segmentation in order to reduce the memory overhead of page tables. We can see why this might work by examining a typical linear page table in more detail. Assume we have an address space in which the used portions of the heap and stack are small. For the example, we use a tiny 16KB address space with 1KB pages (Figure 20.1); the page table for this address space is in Figure 20.2.

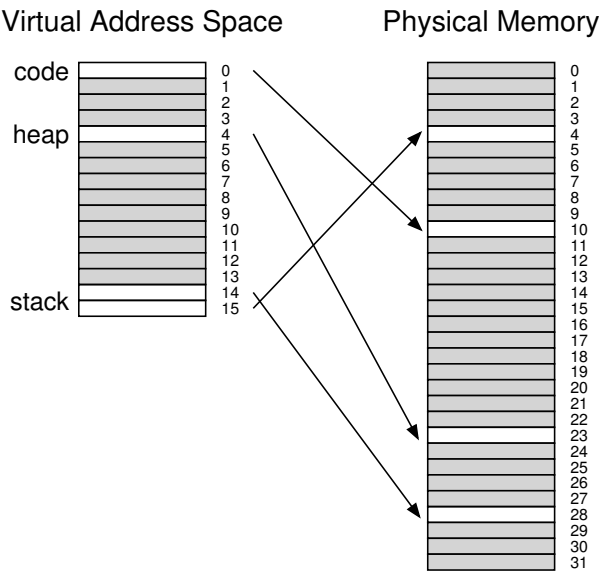


Figure 20.1: A 16KB Address Space With 1KB Pages

PFN	valid	prot	present	dirty
10	1	r-x	1	0
-	0	—	-	-
-	0	—	-	-
-	0	—	-	-
23	1	rw-	1	1
-	0	—	-	-
-	0	—	-	-
-	0	—	-	-
-	0	—	-	-
-	0	—	-	-
-	0	—	-	-
-	0	—	-	-
-	0	—	-	-
-	0	—	-	-
28	1	rw-	1	1
4	1	rw-	1	1

Figure 20.2: A Page Table For 16KB Address Space

This example assumes the single code page (VPN 0) is mapped to physical page 10, the single heap page (VPN 4) to physical page 23, and the two stack pages at the other end of the address space (VPNs 14 and

TIP: USE HYBRIDS

When you have two good and seemingly opposing ideas, you should always see if you can combine them into a **hybrid** that manages to achieve the best of both worlds. Hybrid corn species, for example, are known to be more robust than any naturally-occurring species. Of course, not all hybrids are a good idea; see the Zeedonk (or Zonkey), which is a cross of a Zebra and a Donkey. If you don't believe such a creature exists, look it up, and prepare to be amazed.

The critical difference in our hybrid scheme is the presence of a bounds register per segment; each bounds register holds the value of the maximum valid page in the segment. For example, if the code segment is using its first three pages (0, 1, and 2), the code segment page table will only have three entries allocated to it and the bounds register will be set to 3; memory accesses beyond the end of the segment will generate an exception and likely lead to the termination of the process. In this manner, our hybrid approach realizes a significant memory savings compared to the linear page table; unallocated pages between the stack and the heap no longer take up space in a page table (just to mark them as not valid).

However, as you might notice, this approach is not without problems. First, it still requires us to use segmentation; as we discussed before, segmentation is not quite as flexible as we would like, as it assumes a certain usage pattern of the address space; if we have a large but sparsely-used heap, for example, we can still end up with a lot of page table waste. Second, this hybrid causes external fragmentation to arise again. While most of memory is managed in page-sized units, page tables now can be of arbitrary size (in multiples of PTEs). Thus, finding free space for them in memory is more complicated. For these reasons, people continued to look for better ways to implement smaller page tables.

20.3 Multi-level Page Tables

A different approach doesn't rely on segmentation but attacks the same problem: how to get rid of all those invalid regions in the page table instead of keeping them all in memory? We call this approach a **multi-level page table**, as it turns the linear page table into something like a tree. This approach is so effective that many modern systems employ it (e.g., x86 [BOH10]). We now describe this approach in detail.

The basic idea behind a multi-level page table is simple. First, chop up the page table into page-sized units; then, if an entire page of page-table entries (PTEs) is invalid, don't allocate that page of the page table at all. To track whether a page of the page table is valid (and if valid, where it is in memory), use a new structure, called the **page directory**. The page directory thus either can be used to tell you where a page of the page table is, or that the entire page of the page table contains no valid pages.

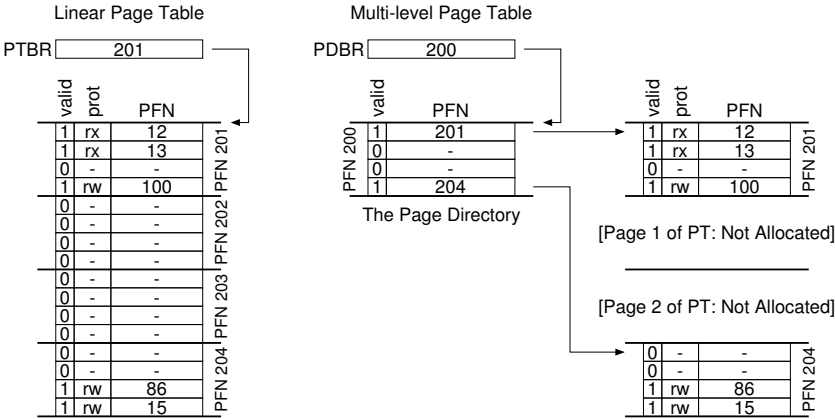


Figure 20.3: Linear (Left) And Multi-Level (Right) Page Tables

Figure 20.3 shows an example. On the left of the figure is the classic linear page table; even though most of the middle regions of the address space are not valid, we still require page-table space allocated for those regions (i.e., the middle two pages of the page table). On the right is a multi-level page table. The page directory marks just two pages of the page table as valid (the first and last); thus, just those two pages of the page table reside in memory. And thus you can see one way to visualize what a multi-level table is doing: it just makes parts of the linear page table disappear (freeing those frames for other uses), and tracks which pages of the page table are allocated with the page directory.

The page directory, in a simple two-level table, contains one entry per page of the page table. It consists of a number of **page directory entries (PDE)**. A PDE (minimally) has a **valid bit** and a **page frame number (PFN)**, similar to a PTE. However, as hinted at above, the meaning of this valid bit is slightly different: if the PDE is valid, it means that at least one of the pages of the page table that the entry points to (via the PFN) is valid, i.e., in at least one PTE on that page pointed to by this PDE, the valid bit in that PTE is set to one. If the PDE is not valid (i.e., equal to zero), the rest of the PDE is not defined.

Multi-level page tables have some obvious advantages over approaches we’ve seen thus far. First, and perhaps most obviously, the multi-level table only allocates page-table space in proportion to the amount of address space you are using; thus it is generally compact and supports sparse address spaces.

Second, if carefully constructed, each portion of the page table fits neatly within a page, making it easier to manage memory; the OS can simply grab the next free page when it needs to allocate or grow a page

TIP: UNDERSTAND TIME-SPACE TRADE-OFFS

When building a data structure, one should always consider **time-space trade-offs** in its construction. Usually, if you wish to make access to a particular data structure faster, you will have to pay a space-usage penalty for the structure.

table. Contrast this to a simple (non-paged) linear page table², which is just an array of PTEs indexed by VPN; with such a structure, the entire linear page table must reside contiguously in physical memory. For a large page table (say 4MB), finding such a large chunk of unused contiguous free physical memory can be quite a challenge. With a multi-level structure, we add a **level of indirection** through use of the page directory, which points to pieces of the page table; that indirection allows us to place page-table pages wherever we would like in physical memory.

It should be noted that there is a cost to multi-level tables; on a TLB miss, two loads from memory will be required to get the right translation information from the page table (one for the page directory, and one for the PTE itself), in contrast to just one load with a linear page table. Thus, the multi-level table is a small example of a **time-space trade-off**. We wanted smaller tables (and got them), but not for free; although in the common case (TLB hit), performance is obviously identical, a TLB miss suffers from a higher cost with this smaller table.

Another obvious negative is *complexity*. Whether it is the hardware or OS handling the page-table lookup (on a TLB miss), doing so is undoubtedly more involved than a simple linear page-table lookup. Often we are willing to increase complexity in order to improve performance or reduce overheads; in the case of a multi-level table, we make page-table lookups more complicated in order to save valuable memory.

A Detailed Multi-Level Example

To understand the idea behind multi-level page tables better, let's do an example. Imagine a small address space of size 16KB, with 64-byte pages. Thus, we have a 14-bit virtual address space, with 8 bits for the VPN and 6 bits for the offset. A linear page table would have 2^8 (256) entries, even if only a small portion of the address space is in use. Figure 20.4 (page 8) presents one example of such an address space.

In this example, virtual pages 0 and 1 are for code, virtual pages 4 and 5 for the heap, and virtual pages 254 and 255 for the stack; the rest of the pages of the address space are unused.

To build a two-level page table for this address space, we start with our full linear page table and break it up into page-sized units. Recall our full table (in this example) has 256 entries; assume each PTE is 4 bytes

²We are making some assumptions here, i.e., that all page tables reside in their entirety in physical memory (i.e., they are not swapped to disk); we'll soon relax this assumption.

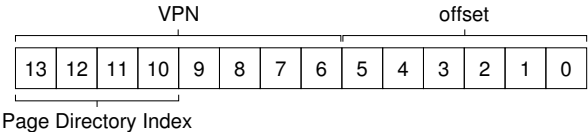
0000 0000	code
0000 0001	code
0000 0010	(free)
0000 0011	(free)
0000 0100	heap
0000 0101	heap
0000 0110	(free)
0000 0111	(free)
.....	... all free ...
1111 1100	(free)
1111 1101	(free)
1111 1110	stack
1111 1111	stack

Figure 20.4: A 16KB Address Space With 64-byte Pages

in size. Thus, our page table is 1KB (256×4 bytes) in size. Given that we have 64-byte pages, the 1KB page table can be divided into 16 64-byte pages; each page can hold 16 PTEs.

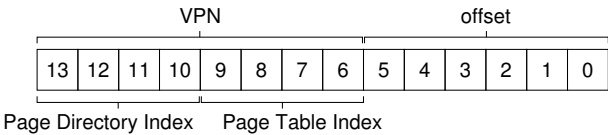
What we need to understand now is how to take a VPN and use it to index first into the page directory and then into the page of the page table. Remember that each is an array of entries; thus, all we need to figure out is how to construct the index for each from pieces of the VPN.

Let's first index into the page directory. Our page table in this example is small: 256 entries, spread across 16 pages. The page directory needs one entry per page of the page table; thus, it has 16 entries. As a result, we need four bits of the VPN to index into the directory; we use the top four bits of the VPN, as follows:



Once we extract the **page-directory index** (PDI_{index} for short) from the VPN, we can use it to find the address of the page-directory entry (PDE) with a simple calculation: $PDEAddr = PageDirBase + (PDI_{index} * sizeof(PDE))$. This results in our page directory, which we now examine to make further progress in our translation.

If the page-directory entry is marked invalid, we know that the access is invalid, and thus raise an exception. If, however, the PDE is valid, we have more work to do. Specifically, we now have to fetch the page-table entry (PTE) from the page of the page table pointed to by this page-directory entry. To find this PTE, we have to index into the portion of the page table using the remaining bits of the VPN:



This **page-table index** (PTIndex for short) can then be used to index into the page table itself, giving us the address of our PTE:

$$\text{PTEAddr} = (\text{PDE.PFN} \ll \text{SHIFT}) + (\text{PTIndex} * \text{sizeof}(\text{PTE}))$$

Note that the page-frame number (PFN) obtained from the page-directory entry must be left-shifted into place before combining it with the page-table index to form the address of the PTE.

To see if this all makes sense, we'll now fill in a multi-level page table with some actual values, and translate a single virtual address. Let's begin with the **page directory** for this example (left side of Figure 20.5).

In the figure, you can see that each page directory entry (PDE) describes something about a page of the page table for the address space. In this example, we have two valid regions in the address space (at the beginning and end), and a number of invalid mappings in-between.

In physical page 100 (the physical frame number of the 0th page of the page table), we have the first page of 16 page table entries for the first 16 VPNs in the address space. See Figure 20.5 (middle part) for the contents of this portion of the page table.

This page of the page table contains the mappings for the first 16 VPNs; in our example, VPNs 0 and 1 are valid (the code segment), as

Page Directory		Page of PT (@PFN:100)			Page of PT (@PFN:101)		
PFN	valid?	PFN	valid	prot	PFN	valid	prot
100	1	10	1	r-x	—	0	—
—	0	23	1	r-x	—	0	—
—	0	—	0	—	—	0	—
—	0	—	0	—	—	0	—
—	0	80	1	rw-	—	0	—
—	0	59	1	rw-	—	0	—
—	0	—	0	—	—	0	—
—	0	—	0	—	—	0	—
—	0	—	0	—	—	0	—
—	0	—	0	—	—	0	—
—	0	—	0	—	—	0	—
—	0	—	0	—	—	0	—
—	0	—	0	—	—	0	—
—	0	—	0	—	55	1	rw-
101	1	—	0	—	45	1	rw-

Figure 20.5: A Page Directory, And Pieces Of Page Table

TIP: BE WARY OF COMPLEXITY

System designers should be wary of adding complexity into their system. What a good systems builder does is implement the least complex system that achieves the task at hand. For example, if disk space is abundant, you shouldn't design a file system that works hard to use as few bytes as possible; similarly, if processors are fast, it is better to write a clean and understandable module within the OS than perhaps the most CPU-optimized, hand-assembled code for the task at hand. Be wary of needless complexity, in prematurely-optimized code or other forms; such approaches make systems harder to understand, maintain, and debug. As Antoine de Saint-Exupery famously wrote: "Perfection is finally attained not when there is no longer anything to add, but when there is no longer anything to take away." What he didn't write: "It's a lot easier to say something about perfection than to actually achieve it."

are 4 and 5 (the heap). Thus, the table has mapping information for each of those pages. The rest of the entries are marked invalid.

The other valid page of the page table is found inside PFN 101. This page contains mappings for the last 16 VPNs of the address space; see Figure 20.5 (right) for details.

In the example, VPNs 254 and 255 (the stack) have valid mappings. Hopefully, what we can see from this example is how much space savings are possible with a multi-level indexed structure. In this example, instead of allocating the full *sixteen* pages for a linear page table, we allocate only *three*: one for the page directory, and two for the chunks of the page table that have valid mappings. The savings for large (32-bit or 64-bit) address spaces could obviously be much greater.

Finally, let's use this information in order to perform a translation. Here is an address that refers to the 0th byte of VPN 254: $0x3F80$, or `11 1111 1000 0000` in binary.

Recall that we will use the top 4 bits of the VPN to index into the page directory. Thus, `1111` will choose the last (15th, if you start at the 0th) entry of the page directory above. This points us to a valid page of the page table located at address 101. We then use the next 4 bits of the VPN (`1110`) to index into that page of the page table and find the desired PTE. `1110` is the next-to-last (14th) entry on the page, and tells us that page 254 of our virtual address space is mapped at physical page 55. By concatenating $\text{PFN}=55$ (or hex $0x37$) with $\text{offset}=000000$, we can thus form our desired physical address and issue the request to the memory system: $\text{PhysAddr} = (\text{PTE.PFN} \ll \text{SHIFT}) + \text{offset} = 00\ 1101\ 1100\ 0000 = 0x0DC0$.

You should now have some idea of how to construct a two-level page table, using a page directory which points to pages of the page table. Unfortunately, however, our work is not done. As we'll now discuss, sometimes two levels of page table is not enough!

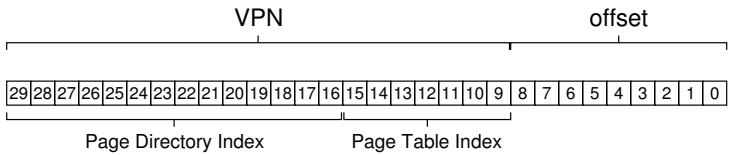
More Than Two Levels

In our example thus far, we’ve assumed that multi-level page tables only have two levels: a page directory and then pieces of the page table. In some cases, a deeper tree is possible (and indeed, needed).

Let’s take a simple example and use it to show why a deeper multi-level table can be useful. In this example, assume we have a 30-bit virtual address space, and a small (512 byte) page. Thus our virtual address has a 21-bit virtual page number component and a 9-bit offset.

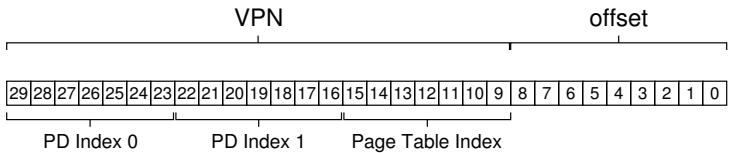
Remember our goal in constructing a multi-level page table: to make each piece of the page table fit within a single page. Thus far, we’ve only considered the page table itself; however, what if the page directory gets too big?

To determine how many levels are needed in a multi-level table to make all pieces of the page table fit within a page, we start by determining how many page-table entries fit within a page. Given our page size of 512 bytes, and assuming a PTE size of 4 bytes, you should see that you can fit 128 PTEs on a single page. When we index into a page of the page table, we can thus conclude we’ll need the least significant 7 bits ($\log_2 128$) of the VPN as an index:



What you also might notice from the diagram above is how many bits are left into the (large) page directory: 14. If our page directory has 2^{14} entries, it spans not one page but 128, and thus our goal of making every piece of the multi-level page table fit into a page vanishes.

To remedy this problem, we build a further level of the tree, by splitting the page directory itself into multiple pages, and then adding another page directory on top of that, to point to the pages of the page directory. We can thus split up our virtual address as follows:



Now, when indexing the upper-level page directory, we use the very top bits of the virtual address (PD Index 0 in the diagram); this index can be used to fetch the page-directory entry from the top-level page directory. If valid, the second level of the page directory is consulted by combining the physical frame number from the top-level PDE and the

```

1  VPN = (VirtualAddress & VPN_MASK) >> SHIFT
2  (Success, TlbEntry) = TLB_Lookup(VPN)
3  if (Success == True)    // TLB Hit
4      if (CanAccess(TlbEntry.ProtectBits) == True)
5          Offset = VirtualAddress & OFFSET_MASK
6          PhysAddr = (TlbEntry.PFN << SHIFT) | Offset
7          Register = AccessMemory(PhysAddr)
8      else
9          RaiseException(PROTECTION_FAULT)
10 else    // TLB Miss
11     // first, get page directory entry
12     PDIndex = (VPN & PD_MASK) >> PD_SHIFT
13     PDEAddr = PDBR + (PDIndex * sizeof(PDE))
14     PDE = AccessMemory(PDEAddr)
15     if (PDE.Valid == False)
16         RaiseException(SEGMENTATION_FAULT)
17     else
18         // PDE is valid: now fetch PTE from page table
19         PTIndex = (VPN & PT_MASK) >> PT_SHIFT
20         PTEAddr = (PDE.PFN << SHIFT) + (PTIndex * sizeof(PTE))
21         PTE = AccessMemory(PTEAddr)
22         if (PTE.Valid == False)
23             RaiseException(SEGMENTATION_FAULT)
24         else if (CanAccess(PTE.ProtectBits) == False)
25             RaiseException(PROTECTION_FAULT)
26         else
27             TLB_Insert(VPN, PTE.PFN, PTE.ProtectBits)
28             RetryInstruction()

```

Figure 20.6: Multi-level Page Table Control Flow

next part of the VPN (PD Index 1). Finally, if valid, the PTE address can be formed by using the page-table index combined with the address from the second-level PDE. Whew! That's a lot of work. And all just to look something up in a multi-level table.

The Translation Process: Remember the TLB

To summarize the entire process of address translation using a two-level page table, we once again present the control flow in algorithmic form (Figure 20.6). The figure shows what happens in hardware (assuming a hardware-managed TLB) upon *every* memory reference.

As you can see from the figure, before any of the complicated multi-level page table access occurs, the hardware first checks the TLB; upon a hit, the physical address is formed directly *without* accessing the page table at all, as before. Only upon a TLB miss does the hardware need to perform the full multi-level lookup. On this path, you can see the cost of our traditional two-level page table: two additional memory accesses to look up a valid translation.

20.4 Inverted Page Tables

An even more extreme space savings in the world of page tables is found with **inverted page tables**. Here, instead of having many page tables (one per process of the system), we keep a single page table that has an entry for each *physical page* of the system. The entry tells us which process is using this page, and which virtual page of that process maps to this physical page.

Finding the correct entry is now a matter of searching through this data structure. A linear scan would be expensive, and thus a hash table is often built over the base structure to speed up lookups. The PowerPC is one example of such an architecture [JM98].

More generally, inverted page tables illustrate what we've said from the beginning: page tables are just data structures. You can do lots of crazy things with data structures, making them smaller or bigger, making them slower or faster. Multi-level and inverted page tables are just two examples of the many things one could do.

20.5 Swapping the Page Tables to Disk

Finally, we discuss the relaxation of one final assumption. Thus far, we have assumed that page tables reside in kernel-owned physical memory. Even with our many tricks to reduce the size of page tables, it is still possible, however, that they may be too big to fit into memory all at once. Thus, some systems place such page tables in **kernel virtual memory**, thereby allowing the system to **swap** some of these page tables to disk when memory pressure gets a little tight. We'll talk more about this in a future chapter (namely, the case study on VAX/VMS), once we understand how to move pages in and out of memory in more detail.

20.6 Summary

We have now seen how real page tables are built; not necessarily just as linear arrays but as more complex data structures. The trade-offs such tables present are in time and space — the bigger the table, the faster a TLB miss can be serviced, as well as the converse — and thus the right choice of structure depends strongly on the constraints of the given environment.

In a memory-constrained system (like many older systems), small structures make sense; in a system with a reasonable amount of memory and with workloads that actively use a large number of pages, a bigger table that speeds up TLB misses might be the right choice. With software-managed TLBs, the entire space of data structures opens up to the delight of the operating system innovator (hint: that's you). What new structures can you come up with? What problems do they solve? Think of these questions as you fall asleep, and dream the big dreams that only operating-system developers can dream.

References

[BOH10] “Computer Systems: A Programmer’s Perspective” by Randal E. Bryant and David R. O’Hallaron. Addison-Wesley, 2010. *We have yet to find a good first reference to the multi-level page table. However, this great textbook by Bryant and O’Hallaron dives into the details of x86, which at least is an early system that used such structures. It’s also just a great book to have.*

[JM98] “Virtual Memory: Issues of Implementation” by Bruce Jacob, Trevor Mudge. IEEE Computer, June 1998. *An excellent survey of a number of different systems and their approach to virtualizing memory. Plenty of details on x86, PowerPC, MIPS, and other architectures.*

[LL82] “Virtual Memory Management in the VAX/VMS Operating System” by Hank Levy, P. Lipman. IEEE Computer, Vol. 15, No. 3, March 1982. *A terrific paper about a real virtual memory manager in a classic operating system, VMS. So terrific, in fact, that we’ll use it to review everything we’ve learned about virtual memory thus far a few chapters from now.*

[M28] “Reese’s Peanut Butter Cups” by Mars Candy Corporation. Published at stores near you. *Apparently these fine confections were invented in 1928 by Harry Burnett Reese, a former dairy farmer and shipping foreman for one Milton S. Hershey. At least, that is what it says on Wikipedia. If true, Hershey and Reese probably hate each other’s guts, as any two chocolate barons should.*

[N+02] “Practical, Transparent Operating System Support for Superpages” by Juan Navarro, Sitararam Iyer, Peter Druschel, Alan Cox. OSDI ’02, Boston, Massachusetts, October 2002. *A nice paper showing all the details you have to get right to incorporate large pages, or **superpages**, into a modern OS. Not as easy as you might think, alas.*

[M07] “Multics: History” Available: <http://www.multicians.org/history.html>. *This amazing web site provides a huge amount of history on the Multics system, certainly one of the most influential systems in OS history. The quote from therein: “Jack Dennis of MIT contributed influential architectural ideas to the beginning of Multics, especially the idea of combining paging and segmentation.” (from Section 1.2.1)*

Homework (Simulation)

This fun little homework tests if you understand how a multi-level page table works. And yes, there is some debate over the use of the term “fun” in the previous sentence. The program is called, perhaps unsurprisingly: `paging-multilevel-translate.py`; see the README for details.

Questions

1. With a linear page table, you need a single register to locate the page table, assuming that hardware does the lookup upon a TLB miss. How many registers do you need to locate a two-level page table? A three-level table?
2. Use the simulator to perform translations given random seeds 0, 1, and 2, and check your answers using the `-c` flag. How many memory references are needed to perform each lookup?
3. Given your understanding of how cache memory works, how do you think memory references to the page table will behave in the cache? Will they lead to lots of cache hits (and thus fast accesses?) Or lots of misses (and thus slow accesses)?

Concurrency: An Introduction

Thus far, we have seen the development of the basic abstractions that the OS performs. We have seen how to take a single physical CPU and turn it into multiple **virtual CPUs**, thus enabling the illusion of multiple programs running at the same time. We have also seen how to create the illusion of a large, private **virtual memory** for each process; this abstraction of the **address space** enables each program to behave as if it has its own memory when indeed the OS is secretly multiplexing address spaces across physical memory (and sometimes, disk).

In this note, we introduce a new abstraction for a single running process: that of a **thread**. Instead of our classic view of a single point of execution within a program (i.e., a single PC where instructions are being fetched from and executed), a **multi-threaded** program has more than one point of execution (i.e., multiple PCs, each of which is being fetched and executed from). Perhaps another way to think of this is that each thread is very much like a separate process, except for one difference: they *share* the same address space and thus can access the same data.

The state of a single thread is thus very similar to that of a process. It has a program counter (PC) that tracks where the program is fetching instructions from. Each thread has its own private set of registers it uses for computation; thus, if there are two threads that are running on a single processor, when switching from running one (T1) to running the other (T2), a **context switch** must take place. The context switch between threads is quite similar to the context switch between processes, as the register state of T1 must be saved and the register state of T2 restored before running T2. With processes, we saved state to a **process control block (PCB)**; now, we'll need one or more **thread control blocks (TCBs)** to store the state of each thread of a process. There is one major difference, though, in the context switch we perform between threads as compared to processes: the address space remains the same (i.e., there is no need to switch which page table we are using).

One other major difference between threads and processes concerns the stack. In our simple model of the address space of a classic process

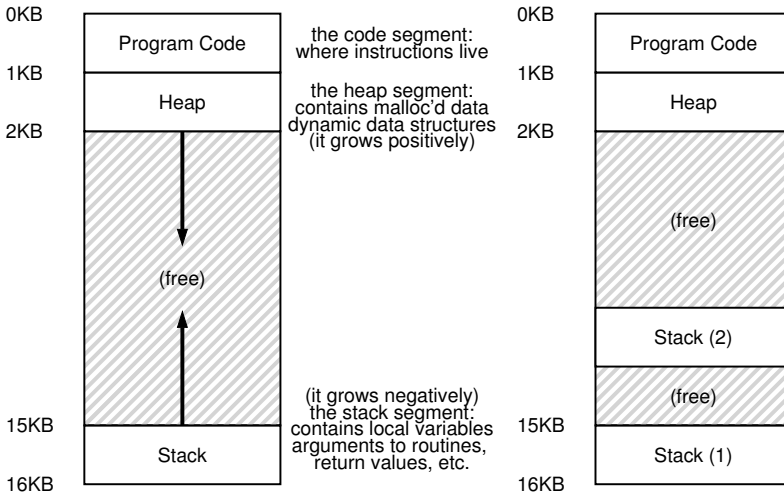


Figure 26.1: **Single-Threaded And Multi-Threaded Address Spaces**

(which we can now call a **single-threaded** process), there is a single stack, usually residing at the bottom of the address space (Figure 26.1, left).

However, in a multi-threaded process, each thread runs independently and of course may call into various routines to do whatever work it is doing. Instead of a single stack in the address space, there will be one per thread. Let's say we have a multi-threaded process that has two threads in it; the resulting address space looks different (Figure 26.1, right).

In this figure, you can see two stacks spread throughout the address space of the process. Thus, any stack-allocated variables, parameters, return values, and other things that we put on the stack will be placed in what is sometimes called **thread-local** storage, i.e., the stack of the relevant thread.

You might also notice how this ruins our beautiful address space layout. Before, the stack and heap could grow independently and trouble only arose when you ran out of room in the address space. Here, we no longer have such a nice situation. Fortunately, this is usually OK, as stacks do not generally have to be very large (the exception being in programs that make heavy use of recursion).

26.1 Why Use Threads?

Before getting into the details of threads and some of the problems you might have in writing multi-threaded programs, let's first answer a more simple question. Why should you use threads at all?

As it turns out, there are at least two major reasons you should use threads. The first is simple: **parallelism**. Imagine you are writing a program that performs operations on very large arrays, for example, adding two large arrays together, or incrementing the value of each element in the array by some amount. If you are running on just a single processor, the task is straightforward: just perform each operation and be done. However, if you are executing the program on a system with multiple processors, you have the potential of speeding up this process considerably by using the processors to each perform a portion of the work. The task of transforming your standard **single-threaded** program into a program that does this sort of work on multiple CPUs is called **parallelization**, and using a thread per CPU to do this work is a natural and typical way to make programs run faster on modern hardware.

The second reason is a bit more subtle: to avoid blocking program progress due to slow I/O. Imagine that you are writing a program that performs different types of I/O: either waiting to send or receive a message, for an explicit disk I/O to complete, or even (implicitly) for a page fault to finish. Instead of waiting, your program may wish to do something else, including utilizing the CPU to perform computation, or even issuing further I/O requests. Using threads is a natural way to avoid getting stuck; while one thread in your program waits (i.e., is blocked waiting for I/O), the CPU scheduler can switch to other threads, which are ready to run and do something useful. Threading enables **overlap** of I/O with other activities *within* a single program, much like **multiprogramming** did for processes *across* programs; as a result, many modern server-based applications (web servers, database management systems, and the like) make use of threads in their implementations.

Of course, in either of the cases mentioned above, you could use multiple *processes* instead of threads. However, threads share an address space and thus make it easy to share data, and hence are a natural choice when constructing these types of programs. Processes are a more sound choice for logically separate tasks where little sharing of data structures in memory is needed.

26.2 An Example: Thread Creation

Let's get into some of the details. Say we wanted to run a program that creates two threads, each of which does some independent work, in this case printing "A" or "B". The code is shown in Figure 26.2 (page 4).

The main program creates two threads, each of which will run the function `mythread()`, though with different arguments (the string A or B). Once a thread is created, it may start running right away (depending on the whims of the scheduler); alternately, it may be put in a "ready" but not "running" state and thus not run yet. Of course, on a multiprocessor, the threads could even be running at the same time, but let's not worry about this possibility quite yet.

```

1  #include <stdio.h>
2  #include <assert.h>
3  #include <pthread.h>
4  #include "common.h"
5  #include "common_threads.h"
6
7  void *mythread(void *arg) {
8      printf("%s\n", (char *) arg);
9      return NULL;
10 }
11
12 int
13 main(int argc, char *argv[]) {
14     pthread_t p1, p2;
15     int rc;
16     printf("main: begin\n");
17     Pthread_create(&p1, NULL, mythread, "A");
18     Pthread_create(&p2, NULL, mythread, "B");
19     // join waits for the threads to finish
20     Pthread_join(p1, NULL);
21     Pthread_join(p2, NULL);
22     printf("main: end\n");
23     return 0;
24 }

```

Figure 26.2: Simple Thread Creation Code (`t0.c`)

After creating the two threads (let's call them T1 and T2), the main thread calls `pthread_join()`, which waits for a particular thread to complete. It does so twice, thus ensuring T1 and T2 will run and complete before finally allowing the main thread to run again; when it does, it will print "main: end" and exit. Overall, three threads were employed during this run: the main thread, T1, and T2.

Let us examine the possible execution ordering of this little program. In the execution diagram (Figure 26.3, page 5), time increases in the downwards direction, and each column shows when a different thread (the main one, or Thread 1, or Thread 2) is running.

Note, however, that this ordering is not the only possible ordering. In fact, given a sequence of instructions, there are quite a few, depending on which thread the scheduler decides to run at a given point. For example, once a thread is created, it may run immediately, which would lead to the execution shown in Figure 26.4 (page 5).

We also could even see "B" printed before "A", if, say, the scheduler decided to run Thread 2 first even though Thread 1 was created earlier; there is no reason to assume that a thread that is created first will run first. Figure 26.5 (page 6) shows this final execution ordering, with Thread 2 getting to strut its stuff before Thread 1.

As you might be able to see, one way to think about thread creation

main	Thread 1	Thread2
starts running		
prints "main: begin"		
creates Thread 1		
creates Thread 2		
waits for T1	runs	
	prints "A"	
	returns	
waits for T2		runs
		prints "B"
		returns
prints "main: end"		

Figure 26.3: Thread Trace (1)

main	Thread 1	Thread2
starts running		
prints "main: begin"		
creates Thread 1		
	runs	
	prints "A"	
	returns	
creates Thread 2		runs
		prints "B"
		returns
waits for T1		
<i>returns immediately; T1 is done</i>		
waits for T2		
<i>returns immediately; T2 is done</i>		
prints "main: end"		

Figure 26.4: Thread Trace (2)

is that it is a bit like making a function call; however, instead of first executing the function and then returning to the caller, the system instead creates a new thread of execution for the routine that is being called, and it runs independently of the caller, perhaps before returning from the create, but perhaps much later. What runs next is determined by the OS **scheduler**, and although the scheduler likely implements some sensible algorithm, it is hard to know what will run at any given moment in time.

As you also might be able to tell from this example, threads make life complicated: it is already hard to tell what will run when! Computers are hard enough to understand without concurrency. Unfortunately, with concurrency, it simply gets worse. Much worse.

main	Thread 1	Thread2
starts running		
prints "main: begin"		
creates Thread 1		
creates Thread 2		
		runs
		prints "B"
		returns
waits for T1		
	runs	
	prints "A"	
	returns	
waits for T2		
<i>returns immediately; T2 is done</i>		
prints "main: end"		

Figure 26.5: Thread Trace (3)

26.3 Why It Gets Worse: Shared Data

The simple thread example we showed above was useful in showing how threads are created and how they can run in different orders depending on how the scheduler decides to run them. What it doesn't show you, though, is how threads interact when they access shared data.

Let us imagine a simple example where two threads wish to update a global shared variable. The code we'll study is in Figure 26.6 (page 7).

Here are a few notes about the code. First, as Stevens suggests [SR05], we wrap the thread creation and join routines to simply exit on failure; for a program as simple as this one, we want to at least notice an error occurred (if it did), but not do anything very smart about it (e.g., just exit). Thus, `Pthread.create()` simply calls `pthread.create()` and makes sure the return code is 0; if it isn't, `Pthread.create()` just prints a message and exits.

Second, instead of using two separate function bodies for the worker threads, we just use a single piece of code, and pass the thread an argument (in this case, a string) so we can have each thread print a different letter before its messages.

Finally, and most importantly, we can now look at what each worker is trying to do: add a number to the shared variable `counter`, and do so 10 million times ($1e7$) in a loop. Thus, the desired final result is: 20,000,000.

We now compile and run the program, to see how it behaves. Sometimes, everything works how we might expect:

```
prompt> gcc -o main main.c -Wall -pthread; ./main
main: begin (counter = 0)
A: begin
B: begin
A: done
B: done
main: done with both (counter = 20000000)
```

```
1  #include <stdio.h>
2  #include <pthread.h>
3  #include "common.h"
4  #include "common_threads.h"
5
6  static volatile int counter = 0;
7
8  // mythread()
9  //
10 // Simply adds 1 to counter repeatedly, in a loop
11 // No, this is not how you would add 10,000,000 to
12 // a counter, but it shows the problem nicely.
13 //
14 void *mythread(void *arg) {
15     printf("%s: begin\n", (char *) arg);
16     int i;
17     for (i = 0; i < 1e7; i++) {
18         counter = counter + 1;
19     }
20     printf("%s: done\n", (char *) arg);
21     return NULL;
22 }
23
24 // main()
25 //
26 // Just launches two threads (pthread_create)
27 // and then waits for them (pthread_join)
28 //
29 int main(int argc, char *argv[]) {
30     pthread_t p1, p2;
31     printf("main: begin (counter = %d)\n", counter);
32     Pthread_create(&p1, NULL, mythread, "A");
33     Pthread_create(&p2, NULL, mythread, "B");
34
35     // join waits for the threads to finish
36     Pthread_join(p1, NULL);
37     Pthread_join(p2, NULL);
38     printf("main: done with both (counter = %d)\n",
39           counter);
40     return 0;
41 }
```

Figure 26.6: Sharing Data: Uh Oh (t1.c)

Unfortunately, when we run this code, even on a single processor, we don't necessarily get the desired result. Sometimes, we get:

```
prompt> ./main
main: begin (counter = 0)
A: begin
B: begin
A: done
B: done
main: done with both (counter = 19345221)
```

Let's try it one more time, just to see if we've gone crazy. After all, aren't computers supposed to produce **deterministic** results, as you have been taught?! Perhaps your professors have been lying to you? (*gasp*)

```
prompt> ./main
main: begin (counter = 0)
A: begin
B: begin
A: done
B: done
main: done with both (counter = 19221041)
```

Not only is each run wrong, but also yields a *different* result! A big question remains: why does this happen?

TIP: KNOW AND USE YOUR TOOLS

You should always learn new tools that help you write, debug, and understand computer systems. Here, we use a neat tool called a **disassembler**. When you run a disassembler on an executable, it shows you what assembly instructions make up the program. For example, if we wish to understand the low-level code to update a counter (as in our example), we run `objdump` (Linux) to see the assembly code:

```
prompt> objdump -d main
```

Doing so produces a long listing of all the instructions in the program, neatly labeled (particularly if you compiled with the `-g` flag), which includes symbol information in the program. The `objdump` program is just one of many tools you should learn how to use; a debugger like `gdb`, memory profilers like `valgrind` or `purify`, and of course the compiler itself are others that you should spend time to learn more about; the better you are at using your tools, the better systems you'll be able to build.

26.4 The Heart Of The Problem: Uncontrolled Scheduling

To understand why this happens, we must understand the code sequence that the compiler generates for the update to `counter`. In this case, we wish to simply add a number (1) to `counter`. Thus, the code sequence for doing so might look something like this (in x86);

```
mov 0x8049a1c, %eax
add $0x1, %eax
mov %eax, 0x8049a1c
```

This example assumes that the variable `counter` is located at address 0x8049a1c. In this three-instruction sequence, the x86 `mov` instruction is used first to get the memory value at the address and put it into register `eax`. Then, the add is performed, adding 1 (0x1) to the contents of the `eax` register, and finally, the contents of `eax` are stored back into memory at the same address.

Let us imagine one of our two threads (Thread 1) enters this region of code, and is thus about to increment `counter` by one. It loads the value of `counter` (let's say it's 50 to begin with) into its register `eax`. Thus, `eax=50` for Thread 1. Then it adds one to the register; thus `eax=51`. Now, something unfortunate happens: a timer interrupt goes off; thus, the OS saves the state of the currently running thread (its PC, its registers including `eax`, etc.) to the thread's TCB.

Now something worse happens: Thread 2 is chosen to run, and it enters this same piece of code. It also executes the first instruction, getting the value of `counter` and putting it into its `eax` (remember: each thread when running has its own private registers; the registers are **virtualized** by the context-switch code that saves and restores them). The value of `counter` is still 50 at this point, and thus Thread 2 has `eax=50`. Let's then assume that Thread 2 executes the next two instructions, incrementing `eax` by 1 (thus `eax=51`), and then saving the contents of `eax` into `counter` (address 0x8049a1c). Thus, the global variable `counter` now has the value 51.

Finally, another context switch occurs, and Thread 1 resumes running. Recall that it had just executed the `mov` and `add`, and is now about to perform the final `mov` instruction. Recall also that `eax=51`. Thus, the final `mov` instruction executes, and saves the value to memory; the counter is set to 51 again.

Put simply, what has happened is this: the code to increment `counter` has been run twice, but `counter`, which started at 50, is now only equal to 51. A "correct" version of this program should have resulted in the variable `counter` equal to 52.

Let's look at a detailed execution trace to understand the problem better. Assume, for this example, that the above code is loaded at address 100 in memory, like the following sequence (note for those of you used to nice, RISC-like instruction sets: x86 has variable-length instructions; this `mov` instruction takes up 5 bytes of memory, and the `add` only 3):

OS	Thread 1	Thread 2	(after instruction)		
			PC	eax	counter
	<i>before critical section</i>		100	0	50
	mov 8049a1c,%eax		105	50	50
	add \$0x1,%eax		108	51	50
interrupt					
save T1					
restore T2			100	0	50
		mov 8049a1c,%eax	105	50	50
		add \$0x1,%eax	108	51	50
		mov %eax,8049a1c	113	51	51
interrupt					
save T2					
restore T1			108	51	51
	mov %eax,8049a1c		113	51	51

Figure 26.7: The Problem: Up Close and Personal

```

100 mov    0x8049a1c, %eax
105 add    $0x1, %eax
108 mov    %eax, 0x8049a1c

```

With these assumptions, what happens is shown in Figure 26.7 (page 10). Assume the counter starts at value 50, and trace through this example to make sure you understand what is going on.

What we have demonstrated here is called a **race condition** (or, more specifically, a **data race**): the results depend on the timing execution of the code. With some bad luck (i.e., context switches that occur at untimely points in the execution), we get the wrong result. In fact, we may get a different result each time; thus, instead of a nice **deterministic** computation (which we are used to from computers), we call this result **indeterminate**, where it is not known what the output will be and it is indeed likely to be different across runs.

Because multiple threads executing this code can result in a race condition, we call this code a **critical section**. A critical section is a piece of code that accesses a shared variable (or more generally, a shared resource) and must not be concurrently executed by more than one thread.

What we really want for this code is what we call **mutual exclusion**. This property guarantees that if one thread is executing within the critical section, the others will be prevented from doing so.

Virtually all of these terms, by the way, were coined by Edsger Dijkstra, who was a pioneer in the field and indeed won the Turing Award because of this and other work; see his 1968 paper on “Cooperating Sequential Processes” [D68] for an amazingly clear description of the problem. We’ll be hearing more about Dijkstra in this section of the book.

TIP: USE ATOMIC OPERATIONS

Atomic operations are one of the most powerful underlying techniques in building computer systems, from the computer architecture, to concurrent code (what we are studying here), to file systems (which we'll study soon enough), database management systems, and even distributed systems [L+93].

The idea behind making a series of actions **atomic** is simply expressed with the phrase “all or nothing”; it should either appear as if all of the actions you wish to group together occurred, or that none of them occurred, with no in-between state visible. Sometimes, the grouping of many actions into a single atomic action is called a **transaction**, an idea developed in great detail in the world of databases and transaction processing [GR92].

In our theme of exploring concurrency, we'll be using synchronization primitives to turn short sequences of instructions into atomic blocks of execution, but the idea of atomicity is much bigger than that, as we will see. For example, file systems use techniques such as journaling or copy-on-write in order to atomically transition their on-disk state, critical for operating correctly in the face of system failures. If that doesn't make sense, don't worry — it will, in some future chapter.

26.5 The Wish For Atomicity

One way to solve this problem would be to have more powerful instructions that, in a single step, did exactly whatever we needed done and thus removed the possibility of an untimely interrupt. For example, what if we had a super instruction that looked like this:

```
memory-add 0x8049a1c, $0x1
```

Assume this instruction adds a value to a memory location, and the hardware guarantees that it executes **atomically**; when the instruction executed, it would perform the update as desired. It could not be interrupted mid-instruction, because that is precisely the guarantee we receive from the hardware: when an interrupt occurs, either the instruction has not run at all, or it has run to completion; there is no in-between state. Hardware can be a beautiful thing, no?

Atomically, in this context, means “as a unit”, which sometimes we take as “all or none.” What we'd like is to execute the three instruction sequence atomically:

```
mov 0x8049a1c, %eax
add $0x1, %eax
mov %eax, 0x8049a1c
```

As we said, if we had a single instruction to do this, we could just issue that instruction and be done. But in the general case, we won't have such an instruction. Imagine we were building a concurrent B-tree, and wished to update it; would we really want the hardware to support an "atomic update of B-tree" instruction? Probably not, at least in a sane instruction set.

Thus, what we will instead do is ask the hardware for a few useful instructions upon which we can build a general set of what we call **synchronization primitives**. By using this hardware support, in combination with some help from the operating system, we will be able to build multi-threaded code that accesses critical sections in a synchronized and controlled manner, and thus reliably produces the correct result despite the challenging nature of concurrent execution. Pretty awesome, right?

This is the problem we will study in this section of the book. It is a wonderful and hard problem, and should make your mind hurt (a bit). If it doesn't, then you don't understand! Keep working until your head hurts; you then know you're headed in the right direction. At that point, take a break; we don't want your head hurting too much.

THE CRUX: HOW TO SUPPORT SYNCHRONIZATION

What support do we need from the hardware in order to build useful synchronization primitives? What support do we need from the OS? How can we build these primitives correctly and efficiently? How can programs use them to get the desired results?

26.6 One More Problem: Waiting For Another

This chapter has set up the problem of concurrency as if only one type of interaction occurs between threads, that of accessing shared variables and the need to support atomicity for critical sections. As it turns out, there is another common interaction that arises, where one thread must wait for another to complete some action before it continues. This interaction arises, for example, when a process performs a disk I/O and is put to sleep; when the I/O completes, the process needs to be roused from its slumber so it can continue.

Thus, in the coming chapters, we'll be not only studying how to build support for synchronization primitives to support atomicity but also for mechanisms to support this type of sleeping/waking interaction that is common in multi-threaded programs. If this doesn't make sense right now, that is OK! It will soon enough, when you read the chapter on **condition variables**. If it doesn't by then, well, then it is less OK, and you should read that chapter again (and again) until it does make sense.

ASIDE: KEY CONCURRENCY TERMS
CRITICAL SECTION, RACE CONDITION,
INDETERMINATE, MUTUAL EXCLUSION

These four terms are so central to concurrent code that we thought it worth while to call them out explicitly. See some of Dijkstra's early work [D65,D68] for more details.

- A **critical section** is a piece of code that accesses a *shared* resource, usually a variable or data structure.
- A **race condition** (or **data race** [NM92]) arises if multiple threads of execution enter the critical section at roughly the same time; both attempt to update the shared data structure, leading to a surprising (and perhaps undesirable) outcome.
- An **indeterminate** program consists of one or more race conditions; the output of the program varies from run to run, depending on which threads ran when. The outcome is thus not **deterministic**, something we usually expect from computer systems.
- To avoid these problems, threads should use some kind of **mutual exclusion** primitives; doing so guarantees that only a single thread ever enters a critical section, thus avoiding races, and resulting in deterministic program outputs.

26.7 Summary: Why in OS Class?

Before wrapping up, one question that you might have is: why are we studying this in OS class? "History" is the one-word answer; the OS was the first concurrent program, and many techniques were created for use *within* the OS. Later, with multi-threaded processes, application programmers also had to consider such things.

For example, imagine the case where there are two processes running. Assume they both call `write()` to write to the file, and both wish to append the data to the file (i.e., add the data to the end of the file, thus increasing its length). To do so, both must allocate a new block, record in the inode of the file where this block lives, and change the size of the file to reflect the new larger size (among other things; we'll learn more about files in the third part of the book). Because an interrupt may occur at any time, the code that updates these shared structures (e.g., a bitmap for allocation, or the file's inode) are critical sections; thus, OS designers, from the very beginning of the introduction of the interrupt, had to worry about how the OS updates internal structures. An untimely interrupt causes all of the problems described above. Not surprisingly, page tables, process lists, file system structures, and virtually every kernel data structure has to be carefully accessed, with the proper synchronization primitives, to work correctly.

References

[D65] “Solution of a problem in concurrent programming control” by E. W. Dijkstra. Communications of the ACM, 8(9):569, September 1965. *Pointed to as the first paper of Dijkstra’s where he outlines the mutual exclusion problem and a solution. The solution, however, is not widely used; advanced hardware and OS support is needed, as we will see in the coming chapters.*

[D68] “Cooperating sequential processes” by Edsger W. Dijkstra. 1968. Available at this site: <http://www.cs.utexas.edu/users/EWD/ewd01xx/EWD123.PDF>. *Dijkstra has an amazing number of his old papers, notes, and thoughts recorded (for posterity) on this website at the last place he worked, the University of Texas. Much of his foundational work, however, was done years earlier while he was at the Technische Hogeschool Eindhoven (THE), including this famous paper on “cooperating sequential processes”, which basically outlines all of the thinking that has to go into writing multi-threaded programs. Dijkstra discovered much of this while working on an operating system named after his school: the “THE” operating system (said “T”, “H”, “E”, and not like the word “the”).*

[GR92] “Transaction Processing: Concepts and Techniques” by Jim Gray and Andreas Reuter. Morgan Kaufmann, September 1992. *This book is the bible of transaction processing, written by one of the legends of the field, Jim Gray. It is, for this reason, also considered Jim Gray’s “brain dump”, in which he wrote down everything he knows about how database management systems work. Sadly, Gray passed away tragically a few years back, and many of us lost a friend and great mentor, including the co-authors of said book, who were lucky enough to interact with Gray during their graduate school years.*

[L+93] “Atomic Transactions” by Nancy Lynch, Michael Merritt, William Weihl, Alan Fekete. Morgan Kaufmann, August 1993. *A nice text on some of the theory and practice of atomic transactions for distributed systems. Perhaps a bit formal for some, but lots of good material is found herein.*

[NM92] “What Are Race Conditions? Some Issues and Formalizations” by Robert H. B. Netzer and Barton P. Miller. ACM Letters on Programming Languages and Systems, Volume 1:1, March 1992. *An excellent discussion of the different types of races found in concurrent programs. In this chapter (and the next few), we focus on data races, but later we will broaden to discuss **general races** as well.*

[SR05] “Advanced Programming in the UNIX Environment” by W. Richard Stevens and Stephen A. Rago. Addison-Wesley, 2005. *As we’ve said many times, buy this book, and read it, in little chunks, preferably before going to bed. This way, you will actually fall asleep more quickly; more importantly, you learn a little more about how to become a serious UNIX programmer.*

Homework (Simulation)

This program, `x86.py`, allows you to see how different thread interleavings either cause or avoid race conditions. See the README for details on how the program works, then answer the questions below.

Questions

1. Let's examine a simple program, "loop.s". First, just read and understand it. Then, run it with these arguments (`./x86.py -p loop.s -t 1 -i 100 -R dx`) This specifies a single thread, an interrupt every 100 instructions, and tracing of register `%dx`. What will `%dx` be during the run? Use the `-c` flag to check your answers; the answers, on the left, show the value of the register (or memory value) *after* the instruction on the right has run.
2. Same code, different flags: (`./x86.py -p loop.s -t 2 -i 100 -a dx=3, dx=3 -R dx`) This specifies two threads, and initializes each `%dx` to 3. What values will `%dx` see? Run with `-c` to check. Does the presence of multiple threads affect your calculations? Is there a race in this code?
3. Run this: `./x86.py -p loop.s -t 2 -i 3 -r -a dx=3, dx=3 -R dx` This makes the interrupt interval small/random; use different seeds (`-s`) to see different interleavings. Does the interrupt frequency change anything?
4. Now, a different program, `looping-race-nolock.s`, which accesses a shared variable located at address 2000; we'll call this variable `value`. Run it with a single thread to confirm your understanding: `./x86.py -p looping-race-nolock.s -t 1 -M 2000` What is `value` (i.e., at memory address 2000) throughout the run? Use `-c` to check.
5. Run with multiple iterations/threads: `./x86.py -p looping-race-nolock.s -t 2 -a bx=3 -M 2000` Why does each thread loop three times? What is final value of `value`?
6. Run with random interrupt intervals: `./x86.py -p looping-race-nolock.s -t 2 -M 2000 -i 4 -r -s 0` with different seeds (`-s 1`, `-s 2`, etc.) Can you tell by looking at the thread interleaving what the final value of `value` will be? Does the timing of the interrupt matter? Where can it safely occur? Where not? In other words, where is the critical section exactly?

7. Now examine fixed interrupt intervals: `./x86.py -p looping-race-nolock.s -a bx=1 -t 2 -M 2000 -i 1` What will the final value of the shared variable `value` be? What about when you change `-i 2`, `-i 3`, etc.? For which interrupt intervals does the program give the “correct” answer?
8. Run the same for more loops (e.g., set `-a bx=100`). What interrupt intervals (`-i`) lead to a correct outcome? Which intervals are surprising?
9. One last program: `wait-for-me.s`. Run: `./x86.py -p wait-for-me.s -a ax=1,ax=0 -R ax -M 2000` This sets the `%ax` register to 1 for thread 0, and 0 for thread 1, and watches `%ax` and memory location 2000. How should the code behave? How is the value at location 2000 being used by the threads? What will its final value be?
10. Now switch the inputs: `./x86.py -p wait-for-me.s -a ax=0,ax=1 -R ax -M 2000` How do the threads behave? What is thread 0 doing? How would changing the interrupt interval (e.g., `-i 1000`, or perhaps to use random intervals) change the trace outcome? Is the program efficiently using the CPU?

Interlude: Thread API

This chapter briefly covers the main portions of the thread API. Each part will be explained further in the subsequent chapters, as we show how to use the API. More details can be found in various books and online sources [B89, B97, B+96, K+96]. We should note that the subsequent chapters introduce the concepts of locks and condition variables more slowly, with many examples; this chapter is thus better used as a reference.

CRUX: HOW TO CREATE AND CONTROL THREADS

What interfaces should the OS present for thread creation and control? How should these interfaces be designed to enable ease of use as well as utility?

27.1 Thread Creation

The first thing you have to be able to do to write a multi-threaded program is to create new threads, and thus some kind of thread creation interface must exist. In POSIX, it is easy:

```
#include <pthread.h>
int
pthread_create(pthread_t      *thread,
               const pthread_attr_t *attr,
               void            *(*start_routine)(void*),
               void            *arg);
```

This declaration might look a little complex (particularly if you haven't used function pointers in C), but actually it's not too bad. There are four arguments: `thread`, `attr`, `start_routine`, and `arg`. The first, `thread`, is a pointer to a structure of type `pthread_t`; we'll use this structure to interact with this thread, and thus we need to pass it to `pthread_create()` in order to initialize it.

The second argument, `attr`, is used to specify any attributes this thread might have. Some examples include setting the stack size or perhaps information about the scheduling priority of the thread. An attribute is initialized with a separate call to `pthread_attr_init()`; see the manual page for details. However, in most cases, the defaults will be fine; in this case, we will simply pass the value `NULL` in.

The third argument is the most complex, but is really just asking: which function should this thread start running in? In C, we call this a **function pointer**, and this one tells us the following is expected: a function name (`start_routine`), which is passed a single argument of type `void *` (as indicated in the parentheses after `start_routine`), and which returns a value of type `void *` (i.e., a **void pointer**).

If this routine instead required an integer argument, instead of a void pointer, the declaration would look like this:

```
int pthread_create(..., // first two args are the same
                    void *(*start_routine)(int),
                    int arg);
```

If instead the routine took a void pointer as an argument, but returned an integer, it would look like this:

```
int pthread_create(..., // first two args are the same
                    int (*start_routine)(void *),
                    void *arg);
```

Finally, the fourth argument, `arg`, is exactly the argument to be passed to the function where the thread begins execution. You might ask: why do we need these void pointers? Well, the answer is quite simple: having a void pointer as an argument to the function `start_routine` allows us to pass in *any* type of argument; having it as a return value allows the thread to return *any* type of result.

Let's look at an example in Figure 27.1. Here we just create a thread that is passed two arguments, packaged into a single type we define ourselves (`myarg_t`). The thread, once created, can simply cast its argument to the type it expects and thus unpack the arguments as desired.

And there it is! Once you create a thread, you really have another live executing entity, complete with its own call stack, running within the *same* address space as all the currently existing threads in the program. The fun thus begins!

27.2 Thread Completion

The example above shows how to create a thread. However, what happens if you want to wait for a thread to complete? You need to do something special in order to wait for completion; in particular, you must call the routine `pthread_join()`.

```
int pthread_join(pthread_t thread, void **value_ptr);
```

```
1  #include <stdio.h>
2  #include <pthread.h>
3
4  typedef struct {
5      int a;
6      int b;
7  } myarg_t;
8
9  void *mythread(void *arg) {
10     myarg_t *args = (myarg_t *) arg;
11     printf("%d %d\n", args->a, args->b);
12     return NULL;
13 }
14
15 int main(int argc, char *argv[]) {
16     pthread_t p;
17     myarg_t args = { 10, 20 };
18
19     int rc = pthread_create(&p, NULL, mythread, &args);
20     ...
21 }
```

Figure 27.1: Creating a Thread

This routine takes two arguments. The first is of type `pthread_t`, and is used to specify which thread to wait for. This variable is initialized by the thread creation routine (when you pass a pointer to it as an argument to `pthread_create()`); if you keep it around, you can use it to wait for that thread to terminate.

The second argument is a pointer to the return value you expect to get back. Because the routine can return anything, it is defined to return a pointer to void; because the `pthread_join()` routine *changes* the value of the passed in argument, you need to pass in a pointer to that value, not just the value itself.

Let's look at another example (Figure 27.2, page 4). In the code, a single thread is again created, and passed a couple of arguments via the `myarg_t` structure. To return values, the `myret_t` type is used. Once the thread is finished running, the main thread, which has been waiting inside of the `pthread_join()` routine¹, then returns, and we can access the values returned from the thread, namely whatever is in `myret_t`.

A few things to note about this example. First, often times we don't have to do all of this painful packing and unpacking of arguments. For example, if we just create a thread with no arguments, we can pass `NULL` in as an argument when the thread is created. Similarly, we can pass `NULL` into `pthread_join()` if we don't care about the return value.

¹Note we use wrapper functions here; specifically, we call `Malloc()`, `Pthread.join()`, and `Pthread.create()`, which just call their similarly-named lower-case versions and make sure the

```

1  typedef struct { int a; int b; } myarg_t;
2  typedef struct { int x; int y; } myret_t;
3
4  void *mythread(void *arg) {
5      myret_t *rvals = Malloc(sizeof(myret_t));
6      rvals->x = 1;
7      rvals->y = 2;
8      return (void *) rvals;
9  }
10
11 int main(int argc, char *argv[]) {
12     pthread_t p;
13     myret_t *rvals;
14     myarg_t args = { 10, 20 };
15     Pthread_create(&p, NULL, mythread, &args);
16     Pthread_join(p, (void **) &rvals);
17     printf("returned %d %d\n", rvals->x, rvals->y);
18     free(rvals);
19     return 0;
20 }

```

Figure 27.2: Waiting for Thread Completion

Second, if we are just passing in a single value (e.g., a long long int), we don't have to package it up as an argument. Figure 27.3 (page 5) shows an example. In this case, life is a bit simpler, as we don't have to package arguments and return values inside of structures.

Third, we should note that one has to be extremely careful with how values are returned from a thread. Specifically, never return a pointer which refers to something allocated on the thread's call stack. If you do, what do you think will happen? (think about it!) Here is an example of a dangerous piece of code, modified from the example in Figure 27.2.

```

1  void *mythread(void *arg) {
2      myarg_t *args = (myarg_t *) arg;
3      printf("%d %d\n", args->a, args->b);
4      myret_t oops; // ALLOCATED ON STACK: BAD!
5      oops.x = 1;
6      oops.y = 2;
7      return (void *) &oops;
8  }

```

In this case, the variable `oops` is allocated on the stack of `mythread`. However, when it returns, the value is automatically deallocated (that's why the stack is so easy to use, after all!), and thus, passing back a pointer

routines did not return anything unexpected.

```
void *mythread(void *arg) {
    long long int value = (long long int) arg;
    printf("%lld\n", value);
    return (void *) (value + 1);
}

int main(int argc, char *argv[]) {
    pthread_t p;
    long long int rvalue;
    Pthread_create(&p, NULL, mythread, (void *) 100);
    Pthread_join(p, (void **) &rvalue);
    printf("returned %lld\n", rvalue);
    return 0;
}
```

Figure 27.3: **Simpler Argument Passing to a Thread**

to a now deallocated variable will lead to all sorts of bad results. Certainly, when you print out the values you think you returned, you'll probably (but not necessarily!) be surprised. Try it and find out for yourself²!

Finally, you might notice that the use of `pthread_create()` to create a thread, followed by an immediate call to `pthread_join()`, is a pretty strange way to create a thread. In fact, there is an easier way to accomplish this exact task; it's called a **procedure call**. Clearly, we'll usually be creating more than just one thread and waiting for it to complete, otherwise there is not much purpose to using threads at all.

We should note that not all code that is multi-threaded uses the join routine. For example, a multi-threaded web server might create a number of worker threads, and then use the main thread to accept requests and pass them to the workers, indefinitely. Such long-lived programs thus may not need to join. However, a parallel program that creates threads to execute a particular task (in parallel) will likely use join to make sure all such work completes before exiting or moving onto the next stage of computation.

27.3 Locks

Beyond thread creation and join, probably the next most useful set of functions provided by the POSIX threads library are those for providing mutual exclusion to a critical section via **locks**. The most basic pair of routines to use for this purpose is provided by the following:

```
int pthread_mutex_lock(pthread_mutex_t *mutex);
int pthread_mutex_unlock(pthread_mutex_t *mutex);
```

²Fortunately the compiler `gcc` will likely complain when you write code like this, which is yet another reason to pay attention to compiler warnings.

The routines should be easy to understand and use. When you have a region of code that is a **critical section**, and thus needs to be protected to ensure correct operation, locks are quite useful. You can probably imagine what the code looks like:

```
pthread_mutex_t lock;  
pthread_mutex_lock(&lock);  
x = x + 1; // or whatever your critical section is  
pthread_mutex_unlock(&lock);
```

The intent of the code is as follows: if no other thread holds the lock when `pthread_mutex_lock()` is called, the thread will acquire the lock and enter the critical section. If another thread does indeed hold the lock, the thread trying to grab the lock will not return from the call until it has acquired the lock (implying that the thread holding the lock has released it via the unlock call). Of course, many threads may be stuck waiting inside the lock acquisition function at a given time; only the thread with the lock acquired, however, should call unlock.

Unfortunately, this code is broken, in two important ways. The first problem is a **lack of proper initialization**. All locks must be properly initialized in order to guarantee that they have the correct values to begin with and thus work as desired when lock and unlock are called.

With POSIX threads, there are two ways to initialize locks. One way to do this is to use `PTHREAD_MUTEX_INITIALIZER`, as follows:

```
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;
```

Doing so sets the lock to the default values and thus makes the lock usable. The dynamic way to do it (i.e., at run time) is to make a call to `pthread_mutex_init()`, as follows:

```
int rc = pthread_mutex_init(&lock, NULL);  
assert(rc == 0); // always check success!
```

The first argument to this routine is the address of the lock itself, whereas the second is an optional set of attributes. Read more about the attributes yourself; passing `NULL` in simply uses the defaults. Either way works, but we usually use the dynamic (latter) method. Note that a corresponding call to `pthread_mutex_destroy()` should also be made, when you are done with the lock; see the manual page for all of details.

The second problem with the code above is that it fails to check error codes when calling lock and unlock. Just like virtually any library routine you call in a UNIX system, these routines can also fail! If your code doesn't properly check error codes, the failure will happen silently, which in this case could allow multiple threads into a critical section. Minimally, use wrappers, which assert that the routine succeeded, as shown in Figure 27.4 (page 7); more sophisticated (non-toy) programs, which can't simply exit when something goes wrong, should check for failure and do something appropriate when a call does not succeed.

```
// Keeps code clean; only use if exit() OK upon failure
void Pthread_mutex_lock(pthread_mutex_t *mutex) {
    int rc = pthread_mutex_lock(mutex);
    assert(rc == 0);
}
```

Figure 27.4: An Example Wrapper

The lock and unlock routines are not the only routines within the pthreads library to interact with locks. Two other routines of interest:

```
int pthread_mutex_trylock(pthread_mutex_t *mutex);
int pthread_mutex_timedlock(pthread_mutex_t *mutex,
                             struct timespec *abs_timeout);
```

These two calls are used in lock acquisition. The `trylock` version returns failure if the lock is already held; the `timedlock` version of acquiring a lock returns after a timeout or after acquiring the lock, whichever happens first. Thus, the `timedlock` with a timeout of zero degenerates to the `trylock` case. Both of these versions should generally be avoided; however, there are a few cases where avoiding getting stuck (perhaps indefinitely) in a lock acquisition routine can be useful, as we'll see in future chapters (e.g., when we study deadlock).

27.4 Condition Variables

The other major component of any threads library, and certainly the case with POSIX threads, is the presence of a **condition variable**. Condition variables are useful when some kind of signaling must take place between threads, if one thread is waiting for another to do something before it can continue. Two primary routines are used by programs wishing to interact in this way:

```
int pthread_cond_wait(pthread_cond_t *cond, pthread_mutex_t *mutex);
int pthread_cond_signal(pthread_cond_t *cond);
```

To use a condition variable, one has to in addition have a lock that is associated with this condition. When calling either of the above routines, this lock should be held.

The first routine, `pthread_cond_wait()`, puts the calling thread to sleep, and thus waits for some other thread to signal it, usually when something in the program has changed that the now-sleeping thread might care about. A typical usage looks like this:

```
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t cond = PTHREAD_COND_INITIALIZER;

Pthread_mutex_lock(&lock);
while (ready == 0)
    Pthread_cond_wait(&cond, &lock);
Pthread_mutex_unlock(&lock);
```

In this code, after initialization of the relevant lock and condition³, a thread checks to see if the variable `ready` has yet been set to something other than zero. If not, the thread simply calls the wait routine in order to sleep until some other thread wakes it.

The code to wake a thread, which would run in some other thread, looks like this:

```
Pthread_mutex_lock(&lock);
ready = 1;
Pthread_cond_signal(&cond);
Pthread_mutex_unlock(&lock);
```

A few things to note about this code sequence. First, when signaling (as well as when modifying the global variable `ready`), we always make sure to have the lock held. This ensures that we don't accidentally introduce a race condition into our code.

Second, you might notice that the wait call takes a lock as its second parameter, whereas the signal call only takes a condition. The reason for this difference is that the wait call, in addition to putting the calling thread to sleep, *releases* the lock when putting said caller to sleep. Imagine if it did not: how could the other thread acquire the lock and signal it to wake up? However, *before* returning after being woken, the `pthread_cond_wait()` re-acquires the lock, thus ensuring that any time the waiting thread is running between the lock acquire at the beginning of the wait sequence, and the lock release at the end, it holds the lock.

One last oddity: the waiting thread re-checks the condition in a while loop, instead of a simple if statement. We'll discuss this issue in detail when we study condition variables in a future chapter, but in general, using a while loop is the simple and safe thing to do. Although it rechecks the condition (perhaps adding a little overhead), there are some pthread implementations that could spuriously wake up a waiting thread; in such a case, without rechecking, the waiting thread will continue thinking that the condition has changed even though it has not. It is safer thus to view waking up as a hint that something might have changed, rather than an absolute fact.

Note that sometimes it is tempting to use a simple flag to signal between two threads, instead of a condition variable and associated lock. For example, we could rewrite the waiting code above to look more like this in the waiting code:

```
while (ready == 0)
    ; // spin
```

The associated signaling code would look like this:

```
ready = 1;
```

³One can use `pthread_cond_init()` (and `pthread_cond_destroy()`) instead of the static initializer `PTHREAD_COND_INITIALIZER`. Sound like more work? It is.

Don't ever do this, for the following reasons. First, it performs poorly in many cases (spinning for a long time just wastes CPU cycles). Second, it is error prone. As recent research shows [X+10], it is surprisingly easy to make mistakes when using flags (as above) to synchronize between threads; in that study, roughly half the uses of these *ad hoc* synchronizations were buggy! Don't be lazy; use condition variables even when you think you can get away without doing so.

If condition variables sound confusing, don't worry too much (yet) – we'll be covering them in great detail in a subsequent chapter. Until then, it should suffice to know that they exist and to have some idea how and why they are used.

27.5 Compiling and Running

All of the code examples in this chapter are relatively easy to get up and running. To compile them, you must include the header `pthread.h` in your code. On the link line, you must also explicitly link with the pthreads library, by adding the `-pthread` flag.

For example, to compile a simple multi-threaded program, all you have to do is the following:

```
prompt> gcc -o main main.c -Wall -pthread
```

As long as `main.c` includes the pthreads header, you have now successfully compiled a concurrent program. Whether it works or not, as usual, is a different matter entirely.

27.6 Summary

We have introduced the basics of the pthread library, including thread creation, building mutual exclusion via locks, and signaling and waiting via condition variables. You don't need much else to write robust and efficient multi-threaded code, except patience and a great deal of care!

We now end the chapter with a set of tips that might be useful to you when you write multi-threaded code (see the aside on the following page for details). There are other aspects of the API that are interesting; if you want more information, type `man -k pthread` on a Linux system to see over one hundred APIs that make up the entire interface. However, the basics discussed herein should enable you to build sophisticated (and hopefully, correct and performant) multi-threaded programs. The hard part with threads is not the APIs, but rather the tricky logic of how you build concurrent programs. Read on to learn more.

ASIDE: THREAD API GUIDELINES

There are a number of small but important things to remember when you use the POSIX thread library (or really, any thread library) to build a multi-threaded program. They are:

- **Keep it simple.** Above all else, any code to lock or signal between threads should be as simple as possible. Tricky thread interactions lead to bugs.
- **Minimize thread interactions.** Try to keep the number of ways in which threads interact to a minimum. Each interaction should be carefully thought out and constructed with tried and true approaches (many of which we will learn about in the coming chapters).
- **Initialize locks and condition variables.** Failure to do so will lead to code that sometimes works and sometimes fails in very strange ways.
- **Check your return codes.** Of course, in any C and UNIX programming you do, you should be checking each and every return code, and it's true here as well. Failure to do so will lead to bizarre and hard to understand behavior, making you likely to (a) scream, (b) pull some of your hair out, or (c) both.
- **Be careful with how you pass arguments to, and return values from, threads.** In particular, any time you are passing a reference to a variable allocated on the stack, you are probably doing something wrong.
- **Each thread has its own stack.** As related to the point above, please remember that each thread has its own stack. Thus, if you have a locally-allocated variable inside of some function a thread is executing, it is essentially *private* to that thread; no other thread can (easily) access it. To share data between threads, the values must be in the **heap** or otherwise some locale that is globally accessible.
- **Always use condition variables to signal between threads.** While it is often tempting to use a simple flag, don't do it.
- **Use the manual pages.** On Linux, in particular, the pthread man pages are highly informative and discuss much of the nuances presented here, often in even more detail. Read them carefully!

References

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[B97] “Programming with POSIX Threads” by David R. Butenhof. Addison-Wesley, May 1997. *Another one of these books on threads.*

[B+96] “PThreads Programming: by A POSIX Standard for Better Multiprocessing.” Dick Buttlar, Jacqueline Farrell, Bradford Nichols. O’Reilly, September 1996 *A reasonable book from the excellent, practical publishing house O’Reilly. Our bookshelves certainly contain a great deal of books from this company, including some excellent offerings on Perl, Python, and Javascript (particularly Crockford’s “Javascript: The Good Parts”).*

[K+96] “Programming With Threads” by Steve Kleiman, Devang Shah, Bart Smaalders. Prentice Hall, January 1996. *Probably one of the better books in this space. Get it at your local library. Or steal it from your mother. More seriously, just ask your mother for it – she’ll let you borrow it, don’t worry.*

[X+10] “Ad Hoc Synchronization Considered Harmful” by Weiwei Xiong, Soyeon Park, Jiaqi Zhang, Yuanyuan Zhou, Zhiqiang Ma. OSDI 2010, Vancouver, Canada. *This paper shows how seemingly simple synchronization code can lead to a surprising number of bugs. Use condition variables and do the signaling correctly!*

Homework (Code)

In this section, we'll write some simple multi-threaded programs and use a specific tool, called **helgrind**, to find problems in these programs.

Read the README in the homework download for details on how to build the programs and run `helgrind`.

Questions

1. First build `main-race.c`. Examine the code so you can see the (hopefully obvious) data race in the code. Now run `helgrind` (by typing `valgrind --tool=helgrind main-race`) to see how it reports the race. Does it point to the right lines of code? What other information does it give to you?
2. What happens when you remove one of the offending lines of code? Now add a lock around one of the updates to the shared variable, and then around both. What does `helgrind` report in each of these cases?
3. Now let's look at `main-deadlock.c`. Examine the code. This code has a problem known as **deadlock** (which we discuss in much more depth in a forthcoming chapter). Can you see what problem it might have?
4. Now run `helgrind` on this code. What does `helgrind` report?
5. Now run `helgrind` on `main-deadlock-global.c`. Examine the code; does it have the same problem that `main-deadlock.c` has? Should `helgrind` be reporting the same error? What does this tell you about tools like `helgrind`?
6. Let's next look at `main-signal.c`. This code uses a variable (`done`) to signal that the child is done and that the parent can now continue. Why is this code inefficient? (what does the parent end up spending its time doing, particularly if the child thread takes a long time to complete?)
7. Now run `helgrind` on this program. What does it report? Is the code correct?
8. Now look at a slightly modified version of the code, which is found in `main-signal-cv.c`. This version uses a condition variable to do the signaling (and associated lock). Why is this code preferred to the previous version? Is it correctness, or performance, or both?
9. Once again run `helgrind` on `main-signal-cv`. Does it report any errors?

Locks

From the introduction to concurrency, we saw one of the fundamental problems in concurrent programming: we would like to execute a series of instructions atomically, but due to the presence of interrupts on a single processor (or multiple threads executing on multiple processors concurrently), we couldn't. In this chapter, we thus attack this problem directly, with the introduction of something referred to as a **lock**. Programmers annotate source code with locks, putting them around critical sections, and thus ensure that any such critical section executes as if it were a single atomic instruction.

28.1 Locks: The Basic Idea

As an example, assume our critical section looks like this, the canonical update of a shared variable:

```
balance = balance + 1;
```

Of course, other critical sections are possible, such as adding an element to a linked list or other more complex updates to shared structures, but we'll just keep to this simple example for now. To use a lock, we add some code around the critical section like this:

```
1 lock_t mutex; // some globally-allocated lock 'mutex'
2 ...
3 lock(&mutex);
4 balance = balance + 1;
5 unlock(&mutex);
```

A lock is just a variable, and thus to use one, you must declare a **lock variable** of some kind (such as `mutex` above). This lock variable (or just "lock" for short) holds the state of the lock at any instant in time. It is either **available** (or **unlocked** or **free**) and thus no thread holds the lock, or **acquired** (or **locked** or **held**), and thus exactly one thread holds the lock and presumably is in a critical section. We could store other information in the data type as well, such as which thread holds the lock, or a queue

for ordering lock acquisition, but information like that is hidden from the user of the lock.

The semantics of the `lock()` and `unlock()` routines are simple. Calling the routine `lock()` tries to acquire the lock; if no other thread holds the lock (i.e., it is free), the thread will acquire the lock and enter the critical section; this thread is sometimes said to be the **owner** of the lock. If another thread then calls `lock()` on that same lock variable (`mutex` in this example), it will not return while the lock is held by another thread; in this way, other threads are prevented from entering the critical section while the first thread that holds the lock is in there.

Once the owner of the lock calls `unlock()`, the lock is now available (free) again. If no other threads are waiting for the lock (i.e., no other thread has called `lock()` and is stuck therein), the state of the lock is simply changed to free. If there are waiting threads (stuck in `lock()`), one of them will (eventually) notice (or be informed of) this change of the lock's state, acquire the lock, and enter the critical section.

Locks provide some minimal amount of control over scheduling to programmers. In general, we view threads as entities created by the programmer but scheduled by the OS, in any fashion that the OS chooses. Locks yield some of that control back to the programmer; by putting a lock around a section of code, the programmer can guarantee that no more than a single thread can ever be active within that code. Thus locks help transform the chaos that is traditional OS scheduling into a more controlled activity.

28.2 Pthread Locks

The name that the POSIX library uses for a lock is a **mutex**, as it is used to provide **mutual exclusion** between threads, i.e., if one thread is in the critical section, it excludes the others from entering until it has completed the section. Thus, when you see the following POSIX threads code, you should understand that it is doing the same thing as above (we again use our wrappers that check for errors upon lock and unlock):

```
1 pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;
2
3 Pthread_mutex_lock(&lock); // wrapper; exits on failure
4 balance = balance + 1;
5 Pthread_mutex_unlock(&lock);
```

You might also notice here that the POSIX version passes a variable to lock and unlock, as we may be using *different* locks to protect different variables. Doing so can increase concurrency: instead of one big lock that is used any time any critical section is accessed (a **coarse-grained** locking strategy), one will often protect different data and data structures with different locks, thus allowing more threads to be in locked code at once (a more **fine-grained** approach).

28.3 Building A Lock

By now, you should have some understanding of how a lock works, from the perspective of a programmer. But how should we build a lock? What hardware support is needed? What OS support? It is this set of questions we address in the rest of this chapter.

THE CRUX: HOW TO BUILD A LOCK

How can we build an efficient lock? Efficient locks provide mutual exclusion at low cost, and also might attain a few other properties we discuss below. What hardware support is needed? What OS support?

To build a working lock, we will need some help from our old friend, the hardware, as well as our good pal, the OS. Over the years, a number of different hardware primitives have been added to the instruction sets of various computer architectures; while we won't study how these instructions are implemented (that, after all, is the topic of a computer architecture class), we will study how to use them in order to build a mutual exclusion primitive like a lock. We will also study how the OS gets involved to complete the picture and enable us to build a sophisticated locking library.

28.4 Evaluating Locks

Before building any locks, we should first understand what our goals are, and thus we ask how to evaluate the efficacy of a particular lock implementation. To evaluate whether a lock works (and works well), we should establish some basic criteria. The first is whether the lock does its basic task, which is to provide **mutual exclusion**. Basically, does the lock work, preventing multiple threads from entering a critical section?

The second is **fairness**. Does each thread contending for the lock get a fair shot at acquiring it once it is free? Another way to look at this is by examining the more extreme case: does any thread contending for the lock **starve** while doing so, thus never obtaining it?

The final criterion is **performance**, specifically the time overheads added by using the lock. There are a few different cases that are worth considering here. One is the case of no contention; when a single thread is running and grabs and releases the lock, what is the overhead of doing so? Another is the case where multiple threads are contending for the lock on a single CPU; in this case, are there performance concerns? Finally, how does the lock perform when there are multiple CPUs involved, and threads on each contending for the lock? By comparing these different scenarios, we can better understand the performance impact of using various locking techniques, as described below.

28.5 Controlling Interrupts

One of the earliest solutions used to provide mutual exclusion was to disable interrupts for critical sections; this solution was invented for single-processor systems. The code would look like this:

```
1 void lock() {  
2     DisableInterrupts();  
3 }  
4 void unlock() {  
5     EnableInterrupts();  
6 }
```

Assume we are running on such a single-processor system. By turning off interrupts (using some kind of special hardware instruction) before entering a critical section, we ensure that the code inside the critical section will *not* be interrupted, and thus will execute as if it were atomic. When we are finished, we re-enable interrupts (again, via a hardware instruction) and thus the program proceeds as usual.

The main positive of this approach is its simplicity. You certainly don't have to scratch your head too hard to figure out why this works. Without interruption, a thread can be sure that the code it executes will execute and that no other thread will interfere with it.

The negatives, unfortunately, are many. First, this approach requires us to allow any calling thread to perform a *privileged* operation (turning interrupts on and off), and thus *trust* that this facility is not abused. As you already know, any time we are required to trust an arbitrary program, we are probably in trouble. Here, the trouble manifests in numerous ways: a greedy program could call `lock()` at the beginning of its execution and thus monopolize the processor; worse, an errant or malicious program could call `lock()` and go into an endless loop. In this latter case, the OS never regains control of the system, and there is only one recourse: restart the system. Using interrupt disabling as a general-purpose synchronization solution requires too much trust in applications.

Second, the approach does not work on multiprocessors. If multiple threads are running on different CPUs, and each try to enter the same critical section, it does not matter whether interrupts are disabled; threads will be able to run on other processors, and thus could enter the critical section. As multiprocessors are now commonplace, our general solution will have to do better than this.

Third, turning off interrupts for extended periods of time can lead to interrupts becoming lost, which can lead to serious systems problems. Imagine, for example, if the CPU missed the fact that a disk device has finished a read request. How will the OS know to wake the process waiting for said read?

Finally, and probably least important, this approach can be inefficient. Compared to normal instruction execution, code that masks or unmask interrupts tends to be executed slowly by modern CPUs.

```
1  typedef struct __lock_t { int flag; } lock_t;
2
3  void init(lock_t *mutex) {
4      // 0 -> lock is available, 1 -> held
5      mutex->flag = 0;
6  }
7
8  void lock(lock_t *mutex) {
9      while (mutex->flag == 1) // TEST the flag
10         ; // spin-wait (do nothing)
11     mutex->flag = 1;          // now SET it!
12 }
13
14 void unlock(lock_t *mutex) {
15     mutex->flag = 0;
16 }
```

Figure 28.1: **First Attempt: A Simple Flag**

For these reasons, turning off interrupts is only used in limited contexts as a mutual-exclusion primitive. For example, in some cases an operating system itself will use interrupt masking to guarantee atomicity when accessing its own data structures, or at least to prevent certain messy interrupt handling situations from arising. This usage makes sense, as the trust issue disappears inside the OS, which always trusts itself to perform privileged operations anyhow.

28.6 A Failed Attempt: Just Using Loads/Stores

To move beyond interrupt-based techniques, we will have to rely on CPU hardware and the instructions it provides us to build a proper lock. Let's first try to build a simple lock by using a single flag variable. In this failed attempt, we'll see some of the basic ideas needed to build a lock, and (hopefully) see why just using a single variable and accessing it via normal loads and stores is insufficient.

In this first attempt (Figure 28.1), the idea is quite simple: use a simple variable (`flag`) to indicate whether some thread has possession of a lock. The first thread that enters the critical section will call `lock()`, which **tests** whether the flag is equal to 1 (in this case, it is not), and then **sets** the flag to 1 to indicate that the thread now **holds** the lock. When finished with the critical section, the thread calls `unlock()` and clears the flag, thus indicating that the lock is no longer held.

If another thread happens to call `lock()` while that first thread is in the critical section, it will simply **spin-wait** in the while loop for that thread to call `unlock()` and clear the flag. Once that first thread does so, the waiting thread will fall out of the while loop, set the flag to 1 for itself, and proceed into the critical section.

Unfortunately, the code has two problems: one of correctness, and an-

Thread 1	Thread 2
call lock()	
while (flag == 1)	
interrupt: switch to Thread 2	
	call lock()
	while (flag == 1)
	flag = 1;
	interrupt: switch to Thread 1
flag = 1; // set flag to 1 (too!)	

Figure 28.2: Trace: No Mutual Exclusion

other of performance. The correctness problem is simple to see once you get used to thinking about concurrent programming. Imagine the code interleaving in Figure 28.2; assume `flag=0` to begin.

As you can see from this interleaving, with timely (untimely?) interrupts, we can easily produce a case where *both* threads set the flag to 1 and both threads are thus able to enter the critical section. This behavior is what professionals call “bad” – we have obviously failed to provide the most basic requirement: providing mutual exclusion.

The performance problem, which we will address more later on, is the fact that the way a thread waits to acquire a lock that is already held: it endlessly checks the value of `flag`, a technique known as **spin-waiting**. Spin-waiting wastes time waiting for another thread to release a lock. The waste is exceptionally high on a uniprocessor, where the thread that the waiter is waiting for cannot even run (at least, until a context switch occurs)! Thus, as we move forward and develop more sophisticated solutions, we should also consider ways to avoid this kind of waste.

28.7 Building Working Spin Locks with Test-And-Set

Because disabling interrupts does not work on multiple processors, and because simple approaches using loads and stores (as shown above) don’t work, system designers started to invent hardware support for locking. The earliest multiprocessor systems, such as the Burroughs B5000 in the early 1960’s [M82], had such support; today all systems provide this type of support, even for single CPU systems.

The simplest bit of hardware support to understand is known as a **test-and-set** (or **atomic exchange**¹) instruction. We define what the test-and-set instruction does via the following C code snippet:

```

1 int TestAndSet(int *old_ptr, int new) {
2     int old = *old_ptr; // fetch old value at old_ptr
3     *old_ptr = new;      // store 'new' into old_ptr
4     return old;          // return the old value
5 }
```

¹Each architecture that supports test-and-set calls it by a different name. On SPARC it is called the load/store unsigned byte instruction (`ldstub`); on x86 it is the locked version of the atomic exchange (`xchg`).

ASIDE: DEKKER'S AND PETERSON'S ALGORITHMS

In the 1960's, Dijkstra posed the concurrency problem to his friends, and one of them, a mathematician named Theodorus Jozef Dekker, came up with a solution [D68]. Unlike the solutions we discuss here, which use special hardware instructions and even OS support, **Dekker's algorithm** uses just loads and stores (assuming they are atomic with respect to each other, which was true on early hardware).

Dekker's approach was later refined by Peterson [P81]. Once again, just loads and stores are used, and the idea is to ensure that two threads never enter a critical section at the same time. Here is **Peterson's algorithm** (for two threads); see if you can understand the code. What are the `flag` and `turn` variables used for?

```
int flag[2];
int turn;

void init() {
    // indicate you intend to hold the lock w/ 'flag'
    flag[0] = flag[1] = 0;
    // whose turn is it? (thread 0 or 1)
    turn = 0;
}

void lock() {
    // 'self' is the thread ID of caller
    flag[self] = 1;
    // make it other thread's turn
    turn = 1 - self;
    while ((flag[1-self] == 1) && (turn == 1 - self))
        ; // spin-wait while it's not your turn
}

void unlock() {
    // simply undo your intent
    flag[self] = 0;
}
```

For some reason, developing locks that work without special hardware support became all the rage for a while, giving theory-types a lot of problems to work on. Of course, this line of work became quite useless when people realized it is much easier to assume a little hardware support (and indeed that support had been around from the earliest days of multiprocessing). Further, algorithms like the ones above don't work on modern hardware (due to relaxed memory consistency models), thus making them even less useful than they were before. Yet more research relegated to the dustbin of history...

```
1 typedef struct __lock_t {
2     int flag;
3 } lock_t;
4
5 void init(lock_t *lock) {
6     // 0: lock is available, 1: lock is held
7     lock->flag = 0;
8 }
9
10 void lock(lock_t *lock) {
11     while (TestAndSet(&lock->flag, 1) == 1)
12         ; // spin-wait (do nothing)
13 }
14
15 void unlock(lock_t *lock) {
16     lock->flag = 0;
17 }
```

Figure 28.3: A Simple Spin Lock Using Test-and-set

What the test-and-set instruction does is as follows. It returns the old value pointed to by the `old_ptr`, and simultaneously updates said value to `new`. The key, of course, is that this sequence of operations is performed **atomically**. The reason it is called “test and set” is that it enables you to “test” the old value (which is what is returned) while simultaneously “setting” the memory location to a new value; as it turns out, this slightly more powerful instruction is enough to build a simple **spin lock**, as we now examine in Figure 28.3. Or better yet: figure it out first yourself!

Let’s make sure we understand why this lock works. Imagine first the case where a thread calls `lock()` and no other thread currently holds the lock; thus, `flag` should be 0. When the thread calls `TestAndSet(flag, 1)`, the routine will return the old value of `flag`, which is 0; thus, the calling thread, which is *testing* the value of `flag`, will not get caught spinning in the while loop and will acquire the lock. The thread will also atomically *set* the value to 1, thus indicating that the lock is now held. When the thread is finished with its critical section, it calls `unlock()` to set the flag back to zero.

The second case we can imagine arises when one thread already has the lock held (i.e., `flag` is 1). In this case, this thread will call `lock()` and then call `TestAndSet(flag, 1)` as well. This time, `TestAndSet()` will return the old value at `flag`, which is 1 (because the lock is held), while simultaneously setting it to 1 again. As long as the lock is held by another thread, `TestAndSet()` will repeatedly return 1, and thus this thread will spin and spin until the lock is finally released. When the flag is finally set to 0 by some other thread, this thread will call `TestAndSet()` again, which will now return 0 while atomically setting the value to 1 and thus acquire the lock and enter the critical section.

By making both the **test** (of the old lock value) and **set** (of the new

TIP: THINK ABOUT CONCURRENCY AS A MALICIOUS SCHEDULER

From this example, you might get a sense of the approach you need to take to understand concurrent execution. What you should try to do is to pretend you are a **malicious scheduler**, one that interrupts threads at the most inopportune of times in order to foil their feeble attempts at building synchronization primitives. What a mean scheduler you are! Although the exact sequence of interrupts may be *improbable*, it is *possible*, and that is all we need to demonstrate that a particular approach does not work. It can be useful to think maliciously! (at least, sometimes)

value) a single atomic operation, we ensure that only one thread acquires the lock. And that's how to build a working mutual exclusion primitive!

You may also now understand why this type of lock is usually referred to as a **spin lock**. It is the simplest type of lock to build, and simply spins, using CPU cycles, until the lock becomes available. To work correctly on a single processor, it requires a **preemptive scheduler** (i.e., one that will interrupt a thread via a timer, in order to run a different thread, from time to time). Without preemption, spin locks don't make much sense on a single CPU, as a thread spinning on a CPU will never relinquish it.

28.8 Evaluating Spin Locks

Given our basic spin lock, we can now evaluate how effective it is along our previously described axes. The most important aspect of a lock is **correctness**: does it provide mutual exclusion? The answer here is yes: the spin lock only allows a single thread to enter the critical section at a time. Thus, we have a correct lock.

The next axis is **fairness**. How fair is a spin lock to a waiting thread? Can you guarantee that a waiting thread will ever enter the critical section? The answer here, unfortunately, is bad news: spin locks don't provide any fairness guarantees. Indeed, a thread spinning may spin forever, under contention. Simple spin locks (as discussed thus far) are not fair and may lead to starvation.

The final axis is **performance**. What are the costs of using a spin lock? To analyze this more carefully, we suggest thinking about a few different cases. In the first, imagine threads competing for the lock on a single processor; in the second, consider threads spread out across many CPUs.

For spin locks, in the single CPU case, performance overheads can be quite painful; imagine the case where the thread holding the lock is preempted within a critical section. The scheduler might then run every other thread (imagine there are $N - 1$ others), each of which tries to acquire the lock. In this case, each of those threads will spin for the duration of a time slice before giving up the CPU, a waste of CPU cycles.

However, on multiple CPUs, spin locks work reasonably well (if the number of threads roughly equals the number of CPUs). The thinking

```

1 int CompareAndSwap(int *ptr, int expected, int new) {
2     int original = *ptr;
3     if (original == expected)
4         *ptr = new;
5     return original;
6 }

```

Figure 28.4: **Compare-and-swap**

goes as follows: imagine Thread A on CPU 1 and Thread B on CPU 2, both contending for a lock. If Thread A (CPU 1) grabs the lock, and then Thread B tries to, B will spin (on CPU 2). However, presumably the critical section is short, and thus soon the lock becomes available, and is acquired by Thread B. Spinning to wait for a lock held on another processor doesn't waste many cycles in this case, and thus can be effective.

28.9 Compare-And-Swap

Another hardware primitive that some systems provide is known as the **compare-and-swap** instruction (as it is called on SPARC, for example), or **compare-and-exchange** (as it called on x86). The C pseudocode for this single instruction is found in Figure 28.4.

The basic idea is for compare-and-swap to test whether the value at the address specified by `ptr` is equal to `expected`; if so, update the memory location pointed to by `ptr` with the new value. If not, do nothing. In either case, return the original value at that memory location, thus allowing the code calling compare-and-swap to know whether it succeeded or not.

With the compare-and-swap instruction, we can build a lock in a manner quite similar to that with test-and-set. For example, we could just replace the `lock()` routine above with the following:

```

1 void lock(lock_t *lock) {
2     while (CompareAndSwap(&lock->flag, 0, 1) == 1)
3         ; // spin
4 }

```

The rest of the code is the same as the test-and-set example above. This code works quite similarly; it simply checks if the flag is 0 and if so, atomically swaps in a 1 thus acquiring the lock. Threads that try to acquire the lock while it is held will get stuck spinning until the lock is finally released.

If you want to see how to really make a C-callable x86-version of compare-and-swap, the code sequence (from [S05]) might be useful².

Finally, as you may have sensed, compare-and-swap is a more powerful instruction than test-and-set. We will make some use of this power in

²github.com/remzi-arpacidusseau/ostep-code/tree/master/threads-locks

the future when we briefly delve into topics such as **lock-free synchronization** [H91]. However, if we just build a simple spin lock with it, its behavior is identical to the spin lock we analyzed above.

28.10 Load-Linked and Store-Conditional

Some platforms provide a pair of instructions that work in concert to help build critical sections. On the MIPS architecture [H93], for example, the **load-linked** and **store-conditional** instructions can be used in tandem to build locks and other concurrent structures. The C pseudocode for these instructions is as found in Figure 28.5. Alpha, PowerPC, and ARM provide similar instructions [W09].

The load-linked operates much like a typical load instruction, and simply fetches a value from memory and places it in a register. The key difference comes with the store-conditional, which only succeeds (and updates the value stored at the address just load-linked from) if no intervening store to the address has taken place. In the case of success, the store-conditional returns 1 and updates the value at `ptr` to `value`; if it fails, the value at `ptr` is *not* updated and 0 is returned.

As a challenge to yourself, try thinking about how to build a lock using load-linked and store-conditional. Then, when you are finished, look at the code below which provides one simple solution. Do it! The solution is in Figure 28.6.

The `lock()` code is the only interesting piece. First, a thread spins waiting for the flag to be set to 0 (and thus indicate the lock is not held). Once so, the thread tries to acquire the lock via the store-conditional; if it succeeds, the thread has atomically changed the flag's value to 1 and thus can proceed into the critical section.

Note how failure of the store-conditional might arise. One thread calls `lock()` and executes the load-linked, returning 0 as the lock is not held. Before it can attempt the store-conditional, it is interrupted and another thread enters the lock code, also executing the load-linked instruction,

```
1  int LoadLinked(int *ptr) {
2      return *ptr;
3  }
4
5  int StoreConditional(int *ptr, int value) {
6      if (no update to *ptr since LoadLinked to this address) {
7          *ptr = value;
8          return 1; // success!
9      } else {
10         return 0; // failed to update
11     }
12 }
```

Figure 28.5: Load-linked And Store-conditional

```

1 void lock(lock_t *lock) {
2     while (1) {
3         while (LoadLinked(&lock->flag) == 1)
4             ; // spin until it's zero
5         if (StoreConditional(&lock->flag, 1) == 1)
6             return; // if set-it-to-1 was a success: all done
7                     // otherwise: try it all over again
8     }
9 }
10
11 void unlock(lock_t *lock) {
12     lock->flag = 0;
13 }

```

Figure 28.6: Using LL/SC To Build A Lock

and also getting a 0 and continuing. At this point, two threads have each executed the load-linked and each are about to attempt the store-conditional. The key feature of these instructions is that only one of these threads will succeed in updating the flag to 1 and thus acquire the lock; the second thread to attempt the store-conditional will fail (because the other thread updated the value of flag between its load-linked and store-conditional) and thus have to try to acquire the lock again.

In class a few years ago, undergraduate student David Capel suggested a more concise form of the above, for those of you who enjoy short-circuiting boolean conditionals. See if you can figure out why it is equivalent. It certainly is shorter!

```

1 void lock(lock_t *lock) {
2     while (LoadLinked(&lock->flag) ||
3           !StoreConditional(&lock->flag, 1))
4         ; // spin
5 }

```

28.11 Fetch-And-Add

One final hardware primitive is the **fetch-and-add** instruction, which atomically increments a value while returning the old value at a particular address. The C pseudocode for the fetch-and-add instruction looks like this:

```

1 int FetchAndAdd(int *ptr) {
2     int old = *ptr;
3     *ptr = old + 1;
4     return old;
5 }

```

TIP: LESS CODE IS BETTER CODE (LAUER’S LAW)

Programmers tend to brag about how much code they wrote to do something. Doing so is fundamentally broken. What one should brag about, rather, is how *little* code one wrote to accomplish a given task. Short, concise code is always preferred; it is likely easier to understand and has fewer bugs. As Hugh Lauer said, when discussing the construction of the Pilot operating system: “If the same people had twice as much time, they could produce as good of a system in half the code.” [L81] We’ll call this **Lauer’s Law**, and it is well worth remembering. So next time you’re bragging about how much code you wrote to finish the assignment, think again, or better yet, go back, rewrite, and make the code as clear and concise as possible.

In this example, we’ll use fetch-and-add to build a more interesting **ticket lock**, as introduced by Mellor-Crummey and Scott [MS91]. The lock and unlock code is found in Figure 28.7 (page 14).

Instead of a single value, this solution uses a ticket and turn variable in combination to build a lock. The basic operation is pretty simple: when a thread wishes to acquire a lock, it first does an atomic fetch-and-add on the ticket value; that value is now considered this thread’s “turn” (`myturn`). The globally shared `lock->turn` is then used to determine which thread’s turn it is; when (`myturn == turn`) for a given thread, it is that thread’s turn to enter the critical section. Unlock is accomplished simply by incrementing the turn such that the next waiting thread (if there is one) can now enter the critical section.

Note one important difference with this solution versus our previous attempts: it ensures progress for all threads. Once a thread is assigned its ticket value, it will be scheduled at some point in the future (once those in front of it have passed through the critical section and released the lock). In our previous attempts, no such guarantee existed; a thread spinning on test-and-set (for example) could spin forever even as other threads acquire and release the lock.

28.12 Too Much Spinning: What Now?

Our simple hardware-based locks are simple (only a few lines of code) and they work (you could even prove that if you’d like to, by writing some code), which are two excellent properties of any system or code. However, in some cases, these solutions can be quite inefficient. Imagine you are running two threads on a single processor. Now imagine that one thread (thread 0) is in a critical section and thus has a lock held, and unfortunately gets interrupted. The second thread (thread 1) now tries to acquire the lock, but finds that it is held. Thus, it begins to spin. And spin. Then it spins some more. And finally, a timer interrupt goes off, thread 0 is run again, which releases the lock, and finally (the next time it runs,


```

1  typedef struct __lock_t {
2      int ticket;
3      int turn;
4  } lock_t;
5
6  void lock_init(lock_t *lock) {
7      lock->ticket = 0;
8      lock->turn   = 0;
9  }
10
11 void lock(lock_t *lock) {
12     int myturn = FetchAndAdd(&lock->ticket);
13     while (lock->turn != myturn)
14         ; // spin
15 }
16
17 void unlock(lock_t *lock) {
18     lock->turn = lock->turn + 1;
19 }

```

Figure 28.7: Ticket Locks

say), thread 1 won't have to spin so much and will be able to acquire the lock. Thus, any time a thread gets caught spinning in a situation like this, it wastes an entire time slice doing nothing but checking a value that isn't going to change! The problem gets worse with N threads contending for a lock; $N - 1$ time slices may be wasted in a similar manner, simply spinning and waiting for a single thread to release the lock. And thus, our next problem:

THE CRUX: HOW TO AVOID SPINNING

How can we develop a lock that doesn't needlessly waste time spinning on the CPU?

Hardware support alone cannot solve the problem. We'll need OS support too! Let's now figure out just how that might work.

28.13 A Simple Approach: Just Yield, Baby

Hardware support got us pretty far: working locks, and even (as with the case of the ticket lock) fairness in lock acquisition. However, we still have a problem: what to do when a context switch occurs in a critical section, and threads start to spin endlessly, waiting for the interrupted (lock-holding) thread to be run again?

Our first try is a simple and friendly approach: when you are going to spin, instead give up the CPU to another thread. As Al Davis might say, "just yield, baby!" [D91]. Figure 28.8 (page 15) shows the approach.

```
1 void init() {
2     flag = 0;
3 }
4
5 void lock() {
6     while (TestAndSet(&flag, 1) == 1)
7         yield(); // give up the CPU
8 }
9
10 void unlock() {
11     flag = 0;
12 }
```

Figure 28.8: Lock With Test-and-set And Yield

In this approach, we assume an operating system primitive `yield()` which a thread can call when it wants to give up the CPU and let another thread run. A thread can be in one of three states (running, ready, or blocked); `yield` is simply a system call that moves the caller from the **running** state to the **ready** state, and thus promotes another thread to running. Thus, the yielding thread essentially **deschedules** itself.

Think about the example with two threads on one CPU; in this case, our yield-based approach works quite well. If a thread happens to call `lock()` and find a lock held, it will simply yield the CPU, and thus the other thread will run and finish its critical section. In this simple case, the yielding approach works well.

Let us now consider the case where there are many threads (say 100) contending for a lock repeatedly. In this case, if one thread acquires the lock and is preempted before releasing it, the other 99 will each call `lock()`, find the lock held, and yield the CPU. Assuming some kind of round-robin scheduler, each of the 99 will execute this run-and-yield pattern before the thread holding the lock gets to run again. While better than our spinning approach (which would waste 99 time slices spinning), this approach is still costly; the cost of a context switch can be substantial, and there is thus plenty of waste.

Worse, we have not tackled the starvation problem at all. A thread may get caught in an endless yield loop while other threads repeatedly enter and exit the critical section. We clearly will need an approach that addresses this problem directly.

28.14 Using Queues: Sleeping Instead Of Spinning

The real problem with our previous approaches is that they leave too much to chance. The scheduler determines which thread runs next; if the scheduler makes a bad choice, a thread runs that must either spin waiting for the lock (our first approach), or yield the CPU immediately (our second approach). Either way, there is potential for waste and no prevention of starvation.

```

1  typedef struct __lock_t {
2      int flag;
3      int guard;
4      queue_t *q;
5  } lock_t;
6
7  void lock_init(lock_t *m) {
8      m->flag = 0;
9      m->guard = 0;
10     queue_init(m->q);
11 }
12
13 void lock(lock_t *m) {
14     while (TestAndSet(&m->guard, 1) == 1)
15         ; //acquire guard lock by spinning
16     if (m->flag == 0) {
17         m->flag = 1; // lock is acquired
18         m->guard = 0;
19     } else {
20         queue_add(m->q, gettid());
21         m->guard = 0;
22         park();
23     }
24 }
25
26 void unlock(lock_t *m) {
27     while (TestAndSet(&m->guard, 1) == 1)
28         ; //acquire guard lock by spinning
29     if (queue_empty(m->q))
30         m->flag = 0; // let go of lock; no one wants it
31     else
32         unpark(queue_remove(m->q)); // hold lock
33                                     // (for next thread!)
34     m->guard = 0;
35 }

```

Figure 28.9: **Lock With Queues, Test-and-set, Yield, And Wakeup**

Thus, we must explicitly exert some control over which thread next gets to acquire the lock after the current holder releases it. To do this, we will need a little more OS support, as well as a queue to keep track of which threads are waiting to acquire the lock.

For simplicity, we will use the support provided by Solaris, in terms of two calls: `park()` to put a calling thread to sleep, and `unpark(threadID)` to wake a particular thread as designated by `threadID`. These two routines can be used in tandem to build a lock that puts a caller to sleep if it tries to acquire a held lock and wakes it when the lock is free. Let's look at the code in Figure 28.9 to understand one possible use of such primitives.

ASIDE: MORE REASON TO AVOID SPINNING: PRIORITY INVERSION

One good reason to avoid spin locks is performance: as described in the main text, if a thread is interrupted while holding a lock, other threads that use spin locks will spend a large amount of CPU time just waiting for the lock to become available. However, it turns out there is another interesting reason to avoid spin locks on some systems: correctness. The problem to be wary of is known as **priority inversion**, which unfortunately is an intergalactic scourge, occurring on Earth [M15] and Mars [R97]!

Let's assume there are two threads in a system. Thread 2 (T2) has a high scheduling priority, and Thread 1 (T1) has lower priority. In this example, let's assume that the CPU scheduler will always run T2 over T1, if indeed both are runnable; T1 only runs when T2 is not able to do so (e.g., when T2 is blocked on I/O).

Now, the problem. Assume T2 is blocked for some reason. So T1 runs, grabs a spin lock, and enters a critical section. T2 now becomes unblocked (perhaps because an I/O completed), and the CPU scheduler immediately schedules it (thus descheduling T1). T2 now tries to acquire the lock, and because it can't (T1 holds the lock), it just keeps spinning. Because the lock is a spin lock, T2 spins forever, and the system is hung.

Just avoiding the use of spin locks, unfortunately, does not avoid the problem of inversion (alas). Imagine three threads, T1, T2, and T3, with T3 at the highest priority, and T1 the lowest. Imagine now that T1 grabs a lock. T3 then starts, and because it is higher priority than T1, runs immediately (preempting T1). T3 tries to acquire the lock that T1 holds, but gets stuck waiting, because T1 still holds it. If T2 starts to run, it will have higher priority than T1, and thus it will run. T3, which is higher priority than T2, is stuck waiting for T1, which may never run now that T2 is running. Isn't it sad that the mighty T3 can't run, while lowly T2 controls the CPU? Having high priority just ain't what it used to be.

You can address the priority inversion problem in a number of ways. In the specific case where spin locks cause the problem, you can avoid using spin locks (described more below). More generally, a higher-priority thread waiting for a lower-priority thread can temporarily boost the lower thread's priority, thus enabling it to run and overcoming the inversion, a technique known as **priority inheritance**. A last solution is simplest: ensure all threads have the same priority.

We do a couple of interesting things in this example. First, we combine the old test-and-set idea with an explicit queue of lock waiters to make a more efficient lock. Second, we use a queue to help control who gets the lock next and thus avoid starvation.

You might notice how the guard is used (Figure 28.9, page 16), basically as a spin-lock around the flag and queue manipulations the lock is using. This approach thus doesn't avoid spin-waiting entirely; a thread

might be interrupted while acquiring or releasing the lock, and thus cause other threads to spin-wait for this one to run again. However, the time spent spinning is quite limited (just a few instructions inside the lock and unlock code, instead of the user-defined critical section), and thus this approach may be reasonable.

You might also observe that in `lock()`, when a thread can not acquire the lock (it is already held), we are careful to add ourselves to a queue (by calling the `gettid()` function to get the thread ID of the current thread), set guard to 0, and yield the CPU. A question for the reader: What would happen if the release of the guard lock came *after* the `park()`, and not before? Hint: something bad.

You might further detect that the flag does not get set back to 0 when another thread gets woken up. Why is this? Well, it is not an error, but rather a necessity! When a thread is woken up, it will be as if it is returning from `park()`; however, it does not hold the guard at that point in the code and thus cannot even try to set the flag to 1. Thus, we just pass the lock directly from the thread releasing the lock to the next thread acquiring it; flag is not set to 0 in-between.

Finally, you might notice the perceived race condition in the solution, just before the call to `park()`. With just the wrong timing, a thread will be about to park, assuming that it should sleep until the lock is no longer held. A switch at that time to another thread (say, a thread holding the lock) could lead to trouble, for example, if that thread then released the lock. The subsequent park by the first thread would then sleep forever (potentially), a problem sometimes called the **wakeup/waiting race**.

Solaris solves this problem by adding a third system call: `setpark()`. By calling this routine, a thread can indicate it is *about to* park. If it then happens to be interrupted and another thread calls `unpark` before `park` is actually called, the subsequent park returns immediately instead of sleeping. The code modification, inside of `lock()`, is quite small:

```
1     queue_add(m->q, gettid());
2     setpark(); // new code
3     m->guard = 0;
```

A different solution could pass the guard into the kernel. In that case, the kernel could take precautions to atomically release the lock and dequeue the running thread.

28.15 Different OS, Different Support

We have thus far seen one type of support that an OS can provide in order to build a more efficient lock in a thread library. Other OS's provide similar support; the details vary.

For example, Linux provides a **futex** which is similar to the Solaris interface but provides more in-kernel functionality. Specifically, each futex has associated with it a specific physical memory location, as well as a

```

1 void mutex_lock (int *mutex) {
2     int v;
3     /* Bit 31 was clear, we got the mutex (the fastpath) */
4     if (atomic_bit_test_set (mutex, 31) == 0)
5         return;
6     atomic_increment (mutex);
7     while (1) {
8         if (atomic_bit_test_set (mutex, 31) == 0) {
9             atomic_decrement (mutex);
10            return;
11        }
12        /* We have to waitFirst make sure the futex value
13         we are monitoring is truly negative (locked). */
14        v = *mutex;
15        if (v >= 0)
16            continue;
17        futex_wait (mutex, v);
18    }
19 }
20
21 void mutex_unlock (int *mutex) {
22     /* Adding 0x80000000 to counter results in 0 if and
23      only if there are not other interested threads */
24     if (atomic_add_zero (mutex, 0x80000000))
25         return;
26
27     /* There are other threads waiting for this mutex,
28      wake one of them up. */
29     futex_wake (mutex);
30 }

```

Figure 28.10: Linux-based Futex Locks

per-futex in-kernel queue. Callers can use futex calls (described below) to sleep and wake as need be.

Specifically, two calls are available. The call to `futex_wait (address, expected)` puts the calling thread to sleep, assuming the value at `address` is equal to `expected`. If it is *not* equal, the call returns immediately. The call to the routine `futex_wake (address)` wakes one thread that is waiting on the queue. The usage of these calls in a Linux mutex is shown in Figure 28.10 (page 19).

This code snippet from `lowlevellock.h` in the `nptl` library (part of the `gnu libc` library) [L09] is interesting for a few reasons. First, it uses a single integer to track both whether the lock is held or not (the high bit of the integer) and the number of waiters on the lock (all the other bits). Thus, if the lock is negative, it is held (because the high bit is set and that bit determines the sign of the integer).

Second, the code snippet shows how to optimize for the common case,

specifically when there is no contention for the lock; with only one thread acquiring and releasing a lock, very little work is done (the atomic bit test-and-set to lock and an atomic add to release the lock).

See if you can puzzle through the rest of this “real-world” lock to understand how it works. Do it and become a master of Linux locking, or at least somebody who listens when a book tells you to do something³.

28.16 Two-Phase Locks

One final note: the Linux approach has the flavor of an old approach that has been used on and off for years, going at least as far back to Dahm Locks in the early 1960’s [M82], and is now referred to as a **two-phase lock**. A two-phase lock realizes that spinning can be useful, particularly if the lock is about to be released. So in the first phase, the lock spins for a while, hoping that it can acquire the lock.

However, if the lock is not acquired during the first spin phase, a second phase is entered, where the caller is put to sleep, and only woken up when the lock becomes free later. The Linux lock above is a form of such a lock, but it only spins once; a generalization of this could spin in a loop for a fixed amount of time before using **futex** support to sleep.

Two-phase locks are yet another instance of a **hybrid** approach, where combining two good ideas may indeed yield a better one. Of course, whether it does depends strongly on many things, including the hardware environment, number of threads, and other workload details. As always, making a single general-purpose lock, good for all possible use cases, is quite a challenge.

28.17 Summary

The above approach shows how real locks are built these days: some hardware support (in the form of a more powerful instruction) plus some operating system support (e.g., in the form of `park()` and `unpark()` primitives on Solaris, or **futex** on Linux). Of course, the details differ, and the exact code to perform such locking is usually highly tuned. Check out the Solaris or Linux code bases if you want to see more details; they are a fascinating read [L09, S09]. Also see David et al.’s excellent work for a comparison of locking strategies on modern multiprocessors [D+13].

³Like buy a print copy of OSTEP! Even though the book is available for free online, wouldn’t you just love a hard cover for your desk? Or, better yet, ten copies to share with friends and family? And maybe one extra copy to throw at an enemy? (the book is heavy, and thus chucking it is surprisingly effective)

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Homework (Simulation)

This program, `x86.py`, allows you to see how different thread interleavings either cause or avoid race conditions. See the README for details on how the program works and answer the questions below.

Questions

1. Examine `flag.s`. This code “implements” locking with a single memory flag. Can you understand the assembly?
2. When you run with the defaults, does `flag.s` work? Use the `-M` and `-R` flags to trace variables and registers (and turn on `-c` to see their values). Can you predict what value will end up in `flag`?
3. Change the value of the register `%bx` with the `-a` flag (e.g., `-a bx=2, bx=2` if you are running just two threads). What does the code do? How does it change your answer for the question above?
4. Set `bx` to a high value for each thread, and then use the `-i` flag to generate different interrupt frequencies; what values lead to a bad outcomes? Which lead to good outcomes?
5. Now let’s look at the program `test-and-set.s`. First, try to understand the code, which uses the `xchg` instruction to build a simple locking primitive. How is the lock acquired? How about lock release?
6. Now run the code, changing the value of the interrupt interval (`-i`) again, and making sure to loop for a number of times. Does the code always work as expected? Does it sometimes lead to an inefficient use of the CPU? How could you quantify that?
7. Use the `-P` flag to generate specific tests of the locking code. For example, run a schedule that grabs the lock in the first thread, but then tries to acquire it in the second. Does the right thing happen? What else should you test?
8. Now let’s look at the code in `peterson.s`, which implements Peterson’s algorithm (mentioned in a sidebar in the text). Study the code and see if you can make sense of it.
9. Now run the code with different values of `-i`. What kinds of different behavior do you see? Make sure to set the thread IDs appropriately (using `-a bx=0, bx=1` for example) as the code assumes it.
10. Can you control the scheduling (with the `-P` flag) to “prove” that the code works? What are the different cases you should show hold? Think about mutual exclusion and deadlock avoidance.
11. Now study the code for the ticket lock in `ticket.s`. Does it match the code in the chapter? Then run with the following flags: `-a bx=1000, bx=1000` (causing each thread to loop through the critical section 1000 times). Watch what happens; do the threads spend much time spin-waiting for the lock?
12. How does the code behave as you add more threads?
13. Now examine `yield.s`, in which a `yield` instruction enables one thread to yield control of the CPU (realistically, this would be an OS primitive, but for the simplicity, we assume an instruction does the task). Find a scenario where `test-and-set.s` wastes cycles spinning, but `yield.s` does not. How many instructions are saved? In what scenarios do these savings arise?
14. Finally, examine `test-and-test-and-set.s`. What does this lock do? What kind of savings does it introduce as compared to `test-and-set.s`?

Condition Variables

Thus far we have developed the notion of a lock and seen how one can be properly built with the right combination of hardware and OS support. Unfortunately, locks are not the only primitives that are needed to build concurrent programs.

In particular, there are many cases where a thread wishes to check whether a **condition** is true before continuing its execution. For example, a parent thread might wish to check whether a child thread has completed before continuing (this is often called a `join()`); how should such a wait be implemented? Let's look at Figure 30.1.

```
1 void *child(void *arg) {
2     printf("child\n");
3     // XXX how to indicate we are done?
4     return NULL;
5 }
6
7 int main(int argc, char *argv[]) {
8     printf("parent: begin\n");
9     pthread_t c;
10    Pthread_create(&c, NULL, child, NULL); // create child
11    // XXX how to wait for child?
12    printf("parent: end\n");
13    return 0;
14 }
```

Figure 30.1: A Parent Waiting For Its Child

What we would like to see here is the following output:

```
parent: begin
child
parent: end
```

We could try using a shared variable, as you see in Figure 30.2. This solution will generally work, but it is hugely inefficient as the parent spins

```

1 volatile int done = 0;
2
3 void *child(void *arg) {
4     printf("child\n");
5     done = 1;
6     return NULL;
7 }
8
9 int main(int argc, char *argv[]) {
10    printf("parent: begin\n");
11    pthread_t c;
12    Pthread_create(&c, NULL, child, NULL); // create child
13    while (done == 0)
14        ; // spin
15    printf("parent: end\n");
16    return 0;
17 }

```

Figure 30.2: Parent Waiting For Child: Spin-based Approach

and wastes CPU time. What we would like here instead is some way to put the parent to sleep until the condition we are waiting for (e.g., the child is done executing) comes true.

THE CRUX: HOW TO WAIT FOR A CONDITION

In multi-threaded programs, it is often useful for a thread to wait for some condition to become true before proceeding. The simple approach, of just spinning until the condition becomes true, is grossly inefficient and wastes CPU cycles, and in some cases, can be incorrect. Thus, how should a thread wait for a condition?

30.1 Definition and Routines

To wait for a condition to become true, a thread can make use of what is known as a **condition variable**. A **condition variable** is an explicit queue that threads can put themselves on when some state of execution (i.e., some **condition**) is not as desired (by **waiting** on the condition); some other thread, when it changes said state, can then wake one (or more) of those waiting threads and thus allow them to continue (by **signaling** on the condition). The idea goes back to Dijkstra's use of "private semaphores" [D68]; a similar idea was later named a "condition variable" by Hoare in his work on monitors [H74].

To declare such a condition variable, one simply writes something like this: `pthread_cond_t c;`, which declares `c` as a condition variable (note: proper initialization is also required). A condition variable has two operations associated with it: `wait()` and `signal()`. The `wait()` call is executed when a thread wishes to put itself to sleep; the `signal()` call

```

1  int done  = 0;
2  pthread_mutex_t m = PTHREAD_MUTEX_INITIALIZER;
3  pthread_cond_t c  = PTHREAD_COND_INITIALIZER;
4
5  void thr_exit() {
6      Pthread_mutex_lock(&m);
7      done = 1;
8      Pthread_cond_signal(&c);
9      Pthread_mutex_unlock(&m);
10 }
11
12 void *child(void *arg) {
13     printf("child\n");
14     thr_exit();
15     return NULL;
16 }
17
18 void thr_join() {
19     Pthread_mutex_lock(&m);
20     while (done == 0)
21         Pthread_cond_wait(&c, &m);
22     Pthread_mutex_unlock(&m);
23 }
24
25 int main(int argc, char *argv[]) {
26     printf("parent: begin\n");
27     pthread_t p;
28     Pthread_create(&p, NULL, child, NULL);
29     thr_join();
30     printf("parent: end\n");
31     return 0;
32 }

```

Figure 30.3: Parent Waiting For Child: Use A Condition Variable

is executed when a thread has changed something in the program and thus wants to wake a sleeping thread waiting on this condition. Specifically, the POSIX calls look like this:

```

pthread_cond_wait(pthread_cond_t *c, pthread_mutex_t *m);
pthread_cond_signal(pthread_cond_t *c);

```

We will often refer to these as `wait()` and `signal()` for simplicity. One thing you might notice about the `wait()` call is that it also takes a mutex as a parameter; it assumes that this mutex is locked when `wait()` is called. The responsibility of `wait()` is to release the lock and put the calling thread to sleep (atomically); when the thread wakes up (after some other thread has signaled it), it must re-acquire the lock before returning to the caller. This complexity stems from the desire to prevent certain

race conditions from occurring when a thread is trying to put itself to sleep. Let's take a look at the solution to the join problem (Figure 30.3) to understand this better.

There are two cases to consider. In the first, the parent creates the child thread but continues running itself (assume we have only a single processor) and thus immediately calls into `thr_join()` to wait for the child thread to complete. In this case, it will acquire the lock, check if the child is done (it is not), and put itself to sleep by calling `wait()` (hence releasing the lock). The child will eventually run, print the message "child", and call `thr_exit()` to wake the parent thread; this code just grabs the lock, sets the state variable `done`, and signals the parent thus waking it. Finally, the parent will run (returning from `wait()` with the lock held), unlock the lock, and print the final message "parent: end".

In the second case, the child runs immediately upon creation, sets `done` to 1, calls `signal` to wake a sleeping thread (but there is none, so it just returns), and is done. The parent then runs, calls `thr_join()`, sees that `done` is 1, and thus does not wait and returns.

One last note: you might observe the parent uses a `while` loop instead of just an `if` statement when deciding whether to wait on the condition. While this does not seem strictly necessary per the logic of the program, it is always a good idea, as we will see below.

To make sure you understand the importance of each piece of the `thr_exit()` and `thr_join()` code, let's try a few alternate implementations. First, you might be wondering if we need the state variable `done`. What if the code looked like the example below? (Figure 30.4)

Unfortunately this approach is broken. Imagine the case where the child runs immediately and calls `thr_exit()` immediately; in this case, the child will signal, but there is no thread asleep on the condition. When the parent runs, it will simply call `wait` and be stuck; no thread will ever wake it. From this example, you should appreciate the importance of the state variable `done`; it records the value the threads are interested in knowing. The sleeping, waking, and locking all are built around it.

```

1 void thr_exit() {
2     Pthread_mutex_lock(&m);
3     Pthread_cond_signal(&c);
4     Pthread_mutex_unlock(&m);
5 }
6
7 void thr_join() {
8     Pthread_mutex_lock(&m);
9     Pthread_cond_wait(&c, &m);
10    Pthread_mutex_unlock(&m);
11 }
```

Figure 30.4: Parent Waiting: No State Variable

```
1 void thr_exit() {
2     done = 1;
3     Pthread_cond_signal(&c);
4 }
5
6 void thr_join() {
7     if (done == 0)
8         Pthread_cond_wait(&c);
9 }
```

Figure 30.5: Parent Waiting: No Lock

Here (Figure 30.5) is another poor implementation. In this example, we imagine that one does not need to hold a lock in order to signal and wait. What problem could occur here? Think about it¹!

The issue here is a subtle race condition. Specifically, if the parent calls `thr_join()` and then checks the value of `done`, it will see that it is 0 and thus try to go to sleep. But just before it calls `wait` to go to sleep, the parent is interrupted, and the child runs. The child changes the state variable `done` to 1 and signals, but no thread is waiting and thus no thread is woken. When the parent runs again, it sleeps forever, which is sad.

Hopefully, from this simple join example, you can see some of the basic requirements of using condition variables properly. To make sure you understand, we now go through a more complicated example: the **producer/consumer** or **bounded-buffer** problem.

TIP: ALWAYS HOLD THE LOCK WHILE SIGNALING

Although it is strictly not necessary in all cases, it is likely simplest and best to hold the lock while signaling when using condition variables. The example above shows a case where you *must* hold the lock for correctness; however, there are some other cases where it is likely OK not to, but probably is something you should avoid. Thus, for simplicity, **hold the lock when calling signal**.

The converse of this tip, i.e., hold the lock when calling `wait`, is not just a tip, but rather mandated by the semantics of `wait`, because `wait` always (a) assumes the lock is held when you call it, (b) releases said lock when putting the caller to sleep, and (c) re-acquires the lock just before returning. Thus, the generalization of this tip is correct: **hold the lock when calling signal or wait**, and you will always be in good shape.

¹Note that this example is not “real” code, because the call to `pthread_cond_wait()` always requires a mutex as well as a condition variable; here, we just pretend that the interface does not do so for the sake of the negative example.

```

1  int buffer;
2  int count = 0; // initially, empty
3
4  void put(int value) {
5      assert(count == 0);
6      count = 1;
7      buffer = value;
8  }
9
10 int get() {
11     assert(count == 1);
12     count = 0;
13     return buffer;
14 }

```

Figure 30.6: The Put And Get Routines (v1)

30.2 The Producer/Consumer (Bounded Buffer) Problem

The next synchronization problem we will confront in this chapter is known as the **producer/consumer** problem, or sometimes as the **bounded buffer** problem, which was first posed by Dijkstra [D72]. Indeed, it was this very producer/consumer problem that led Dijkstra and his co-workers to invent the generalized semaphore (which can be used as either a lock or a condition variable) [D01]; we will learn more about semaphores later.

Imagine one or more producer threads and one or more consumer threads. Producers generate data items and place them in a buffer; consumers grab said items from the buffer and consume them in some way.

This arrangement occurs in many real systems. For example, in a multi-threaded web server, a producer puts HTTP requests into a work queue (i.e., the bounded buffer); consumer threads take requests out of this queue and process them.

A bounded buffer is also used when you pipe the output of one program into another, e.g., `grep foo file.txt | wc -l`. This example runs two processes concurrently; `grep` writes lines from `file.txt` with the string `foo` in them to what it thinks is standard output; the UNIX shell redirects the output to what is called a UNIX pipe (created by the **pipe** system call). The other end of this pipe is connected to the standard input of the process `wc`, which simply counts the number of lines in the input stream and prints out the result. Thus, the `grep` process is the producer; the `wc` process is the consumer; between them is an in-kernel bounded buffer; you, in this example, are just the happy user.

Because the bounded buffer is a shared resource, we must of course require synchronized access to it, lest² a race condition arise. To begin to understand this problem better, let us examine some actual code.

The first thing we need is a shared buffer, into which a producer puts data, and out of which a consumer takes data. Let's just use a single

²This is where we drop some serious Old English on you, and the subjunctive form.

```
1 void *producer(void *arg) {
2     int i;
3     int loops = (int) arg;
4     for (i = 0; i < loops; i++) {
5         put(i);
6     }
7 }
8
9 void *consumer(void *arg) {
10    while (1) {
11        int tmp = get();
12        printf("%d\n", tmp);
13    }
14 }
```

Figure 30.7: **Producer/Consumer Threads (v1)**

integer for simplicity (you can certainly imagine placing a pointer to a data structure into this slot instead), and the two inner routines to put a value into the shared buffer, and to get a value out of the buffer. See Figure 30.6 (page 6) for details.

Pretty simple, no? The `put()` routine assumes the buffer is empty (and checks this with an assertion), and then simply puts a value into the shared buffer and marks it full by setting `count` to 1. The `get()` routine does the opposite, setting the buffer to empty (i.e., setting `count` to 0) and returning the value. Don't worry that this shared buffer has just a single entry; later, we'll generalize it to a queue that can hold multiple entries, which will be even more fun than it sounds.

Now we need to write some routines that know when it is OK to access the buffer to either put data into it or get data out of it. The conditions for this should be obvious: only put data into the buffer when `count` is zero (i.e., when the buffer is empty), and only get data from the buffer when `count` is one (i.e., when the buffer is full). If we write the synchronization code such that a producer puts data into a full buffer, or a consumer gets data from an empty one, we have done something wrong (and in this code, an assertion will fire).

This work is going to be done by two types of threads, one set of which we'll call the **producer** threads, and the other set which we'll call **consumer** threads. Figure 30.7 shows the code for a producer that puts an integer into the shared buffer `loops` number of times, and a consumer that gets the data out of that shared buffer (forever), each time printing out the data item it pulled from the shared buffer.

A Broken Solution

Now imagine that we have just a single producer and a single consumer. Obviously the `put()` and `get()` routines have critical sections within them, as `put()` updates the buffer, and `get()` reads from it. However, putting a lock around the code doesn't work; we need something more.


```

1  int loops; // must initialize somewhere...
2  cond_t  cond;
3  mutex_t mutex;
4
5  void *producer(void *arg) {
6      int i;
7      for (i = 0; i < loops; i++) {
8          Pthread_mutex_lock(&mutex);           // p1
9          if (count == 1)                       // p2
10             Pthread_cond_wait(&cond, &mutex); // p3
11             put(i);                           // p4
12             Pthread_cond_signal(&cond);       // p5
13             Pthread_mutex_unlock(&mutex);     // p6
14         }
15     }
16
17 void *consumer(void *arg) {
18     int i;
19     for (i = 0; i < loops; i++) {
20         Pthread_mutex_lock(&mutex);           // c1
21         if (count == 0)                       // c2
22             Pthread_cond_wait(&cond, &mutex); // c3
23         int tmp = get();                      // c4
24         Pthread_cond_signal(&cond);           // c5
25         Pthread_mutex_unlock(&mutex);         // c6
26         printf("%d\n", tmp);
27     }
28 }

```

Figure 30.8: **Producer/Consumer: Single CV And If Statement**

Not surprisingly, that something more is some condition variables. In this (broken) first try (Figure 30.8), we have a single condition variable `cond` and associated lock `mutex`.

Let's examine the signaling logic between producers and consumers. When a producer wants to fill the buffer, it waits for it to be empty (p1–p3). The consumer has the exact same logic, but waits for a different condition: fullness (c1–c3).

With just a single producer and a single consumer, the code in Figure 30.8 works. However, if we have more than one of these threads (e.g., two consumers), the solution has two critical problems. What are they?

... (pause here to think) ...

Let's understand the first problem, which has to do with the `if` statement before the wait. Assume there are two consumers (T_{c1} and T_{c2}) and one producer (T_p). First, a consumer (T_{c1}) runs; it acquires the lock (c1), checks if any buffers are ready for consumption (c2), and finding that none are, waits (c3) (which releases the lock).

Then the producer (T_p) runs. It acquires the lock (p1), checks if all

T _{c1}	State	T _{c2}	State	T _p	State	Count	Comment
c1	Run		Ready		Ready	0	
c2	Run		Ready		Ready	0	
c3	Sleep		Ready		Ready	0	Nothing to get
	Sleep		Ready	p1	Run	0	
	Sleep		Ready	p2	Run	0	
	Sleep		Ready	p4	Run	1	Buffer now full
	Ready		Ready	p5	Run	1	T _{c1} awoken
	Ready		Ready	p6	Run	1	
	Ready		Ready	p1	Run	1	
	Ready		Ready	p2	Run	1	
	Ready		Ready	p3	Sleep	1	Buffer full; sleep
	Ready	c1	Run		Sleep	1	T _{c2} sneaks in ...
	Ready	c2	Run		Sleep	1	
	Ready	c4	Run		Sleep	0	... and grabs data
	Ready	c5	Run		Ready	0	T _p awoken
	Ready	c6	Run		Ready	0	
c4	Run		Ready		Ready	0	Oh oh! No data

Figure 30.9: Thread Trace: Broken Solution (v1)

buffers are full (p2), and finding that not to be the case, goes ahead and fills the buffer (p4). The producer then signals that a buffer has been filled (p5). Critically, this moves the first consumer (T_{c1}) from sleeping on a condition variable to the ready queue; T_{c1} is now able to run (but not yet running). The producer then continues until realizing the buffer is full, at which point it sleeps (p6, p1–p3).

Here is where the problem occurs: another consumer (T_{c2}) sneaks in and consumes the one existing value in the buffer (c1, c2, c4, c5, c6, skipping the wait at c3 because the buffer is full). Now assume T_{c1} runs; just before returning from the wait, it re-acquires the lock and then returns. It then calls `get ()` (c4), but there are no buffers to consume! An assertion triggers, and the code has not functioned as desired. Clearly, we should have somehow prevented T_{c1} from trying to consume because T_{c2} snuck in and consumed the one value in the buffer that had been produced. Figure 30.9 shows the action each thread takes, as well as its scheduler state (Ready, Running, or Sleeping) over time.

The problem arises for a simple reason: after the producer woke T_{c1} , but *before* T_{c1} ever ran, the state of the bounded buffer changed (thanks to T_{c2}). Signaling a thread only wakes them up; it is thus a *hint* that the state of the world has changed (in this case, that a value has been placed in the buffer), but there is no guarantee that when the woken thread runs, the state will *still* be as desired. This interpretation of what a signal means is often referred to as **Mesa semantics**, after the first research that built a condition variable in such a manner [LR80]; the contrast, referred to as

```

1  int loops;
2  cond_t  cond;
3  mutex_t mutex;
4
5  void *producer(void *arg) {
6      int i;
7      for (i = 0; i < loops; i++) {
8          Pthread_mutex_lock(&mutex);           // p1
9          while (count == 1)                    // p2
10             Pthread_cond_wait(&cond, &mutex); // p3
11             put(i);                            // p4
12             Pthread_cond_signal(&cond);        // p5
13             Pthread_mutex_unlock(&mutex);      // p6
14         }
15     }
16
17     void *consumer(void *arg) {
18         int i;
19         for (i = 0; i < loops; i++) {
20             Pthread_mutex_lock(&mutex);         // c1
21             while (count == 0)                  // c2
22                 Pthread_cond_wait(&cond, &mutex); // c3
23             int tmp = get();                    // c4
24             Pthread_cond_signal(&cond);        // c5
25             Pthread_mutex_unlock(&mutex);      // c6
26             printf("%d\n", tmp);
27         }
28     }

```

Figure 30.10: **Producer/Consumer: Single CV And While**

Hoare semantics, is harder to build but provides a stronger guarantee that the woken thread will run immediately upon being woken [H74]. Virtually every system ever built employs Mesa semantics.

Better, But Still Broken: While, Not If

Fortunately, this fix is easy (Figure 30.10): change the `if` to a `while`. Think about why this works; now consumer T_{c1} wakes up and (with the lock held) immediately re-checks the state of the shared variable (c2). If the buffer is empty at that point, the consumer simply goes back to sleep (c3). The corollary `if` is also changed to a `while` in the producer (p2).

Thanks to Mesa semantics, a simple rule to remember with condition variables is to **always use while loops**. Sometimes you don't have to re-check the condition, but it is always safe to do so; just do it and be happy.

However, this code still has a bug, the second of two problems mentioned above. Can you see it? It has something to do with the fact that there is only one condition variable. Try to figure out what the problem is, before reading ahead. **DO IT!** (*pause for you to think, or close your eyes...*)

T _{c1}	State	T _{c2}	State	T _p	State	Count	Comment
c1	Run		Ready		Ready	0	
c2	Run		Ready		Ready	0	
c3	Sleep		Ready		Ready	0	Nothing to get
	Sleep	c1	Run		Ready	0	
	Sleep	c2	Run		Ready	0	
	Sleep	c3	Sleep		Ready	0	Nothing to get
	Sleep		Sleep	p1	Run	0	
	Sleep		Sleep	p2	Run	0	
	Sleep		Sleep	p4	Run	1	Buffer now full
	Ready		Sleep	p5	Run	1	T _{c1} awoken
	Ready		Sleep	p6	Run	1	
	Ready		Sleep	p1	Run	1	
	Ready		Sleep	p2	Run	1	
	Ready		Sleep	p3	Sleep	1	Must sleep (full)
c2	Run		Sleep		Sleep	1	Recheck condition
c4	Run		Sleep		Sleep	0	T _{c1} grabs data
c5	Run		Ready		Sleep	0	Oops! Woke T _{c2}
c6	Run		Ready		Sleep	0	
c1	Run		Ready		Sleep	0	
c2	Run		Ready		Sleep	0	
c3	Sleep		Ready		Sleep	0	Nothing to get
	Sleep	c2	Run		Sleep	0	
	Sleep	c3	Sleep		Sleep	0	Everyone asleep...

Figure 30.11: Thread Trace: Broken Solution (v2)

Let’s confirm you figured it out correctly, or perhaps let’s confirm that you are now awake and reading this part of the book. The problem occurs when two consumers run first (T_{c1} and T_{c2}) and both go to sleep ($c3$). Then, the producer runs, puts a value in the buffer, and wakes one of the consumers (say T_{c1}). The producer then loops back (releasing and reacquiring the lock along the way) and tries to put more data in the buffer; because the buffer is full, the producer instead waits on the condition (thus sleeping). Now, one consumer is ready to run (T_{c1}), and two threads are sleeping on a condition (T_{c2} and T_p). We are about to cause a problem: things are getting exciting!

The consumer T_{c1} then wakes by returning from `wait()` ($c3$), re-checks the condition ($c2$), and finding the buffer full, consumes the value ($c4$). This consumer then, critically, signals on the condition ($c5$), waking *only one* thread that is sleeping. However, which thread should it wake?

Because the consumer has emptied the buffer, it clearly should wake the producer. However, if it wakes the consumer T_{c2} (which is definitely possible, depending on how the wait queue is managed), we have a problem. Specifically, the consumer T_{c2} will wake up and find the buffer empty ($c2$), and go back to sleep ($c3$). The producer T_p , which has a value

```

1  cond_t  empty, fill;
2  mutex_t mutex;
3
4  void *producer(void *arg) {
5      int i;
6      for (i = 0; i < loops; i++) {
7          Pthread_mutex_lock(&mutex);
8          while (count == 1)
9              Pthread_cond_wait(&empty, &mutex);
10         put(i);
11         Pthread_cond_signal(&fill);
12         Pthread_mutex_unlock(&mutex);
13     }
14 }
15
16 void *consumer(void *arg) {
17     int i;
18     for (i = 0; i < loops; i++) {
19         Pthread_mutex_lock(&mutex);
20         while (count == 0)
21             Pthread_cond_wait(&fill, &mutex);
22         int tmp = get();
23         Pthread_cond_signal(&empty);
24         Pthread_mutex_unlock(&mutex);
25         printf("%d\n", tmp);
26     }
27 }

```

Figure 30.12: **Producer/Consumer: Two CVs And While**

to put into the buffer, is left sleeping. The other consumer thread, T_{c1} , also goes back to sleep. All three threads are left sleeping, a clear bug; see Figure 30.11 for the brutal step-by-step of this terrible calamity.

Signaling is clearly needed, but must be more directed. A consumer should not wake other consumers, only producers, and vice-versa.

The Single Buffer Producer/Consumer Solution

The solution here is once again a small one: use *two* condition variables, instead of one, in order to properly signal which type of thread should wake up when the state of the system changes. Figure 30.12 shows the resulting code.

In the code, producer threads wait on the condition **empty**, and signals **fill**. Conversely, consumer threads wait on **fill** and signal **empty**. By doing so, the second problem above is avoided by design: a consumer can never accidentally wake a consumer, and a producer can never accidentally wake a producer.

```

1  int buffer[MAX];
2  int fill_ptr = 0;
3  int use_ptr  = 0;
4  int count    = 0;
5
6  void put(int value) {
7      buffer[fill_ptr] = value;
8      fill_ptr = (fill_ptr + 1) % MAX;
9      count++;
10 }
11
12 int get() {
13     int tmp = buffer[use_ptr];
14     use_ptr = (use_ptr + 1) % MAX;
15     count--;
16     return tmp;
17 }

```

Figure 30.13: The Correct Put And Get Routines

```

1  cond_t empty, fill;
2  mutex_t mutex;
3
4  void *producer(void *arg) {
5      int i;
6      for (i = 0; i < loops; i++) {
7          Pthread_mutex_lock(&mutex);           // p1
8          while (count == MAX)                  // p2
9              Pthread_cond_wait(&empty, &mutex); // p3
10         put(i);                               // p4
11         Pthread_cond_signal(&fill);           // p5
12         Pthread_mutex_unlock(&mutex);         // p6
13     }
14 }
15
16 void *consumer(void *arg) {
17     int i;
18     for (i = 0; i < loops; i++) {
19         Pthread_mutex_lock(&mutex);           // c1
20         while (count == 0)                    // c2
21             Pthread_cond_wait(&fill, &mutex); // c3
22         int tmp = get();                      // c4
23         Pthread_cond_signal(&empty);          // c5
24         Pthread_mutex_unlock(&mutex);         // c6
25         printf("%d\n", tmp);
26     }
27 }

```

Figure 30.14: The Correct Producer/Consumer Synchronization

TIP: USE WHILE (NOT IF) FOR CONDITIONS

When checking for a condition in a multi-threaded program, using a `while` loop is always correct; using an `if` statement only might be, depending on the semantics of signaling. Thus, always use `while` and your code will behave as expected.

Using `while` loops around conditional checks also handles the case where **spurious wakeups** occur. In some thread packages, due to details of the implementation, it is possible that two threads get woken up though just a single signal has taken place [L11]. Spurious wakeups are further reason to re-check the condition a thread is waiting on.

The Correct Producer/Consumer Solution

We now have a working producer/consumer solution, albeit not a fully general one. The last change we make is to enable more concurrency and efficiency; specifically, we add more buffer slots, so that multiple values can be produced before sleeping, and similarly multiple values can be consumed before sleeping. With just a single producer and consumer, this approach is more efficient as it reduces context switches; with multiple producers or consumers (or both), it even allows concurrent producing or consuming to take place, thus increasing concurrency. Fortunately, it is a small change from our current solution.

The first change for this correct solution is within the buffer structure itself and the corresponding `put()` and `get()` (Figure 30.13). We also slightly change the conditions that producers and consumers check in order to determine whether to sleep or not. We also show the correct waiting and signaling logic (Figure 30.14). A producer only sleeps if all buffers are currently filled (`p2`); similarly, a consumer only sleeps if all buffers are currently empty (`c2`). And thus we solve the producer/consumer problem; time to sit back and drink a cold one.

30.3 Covering Conditions

We'll now look at one more example of how condition variables can be used. This code study is drawn from Lampson and Redell's paper on Pilot [LR80], the same group who first implemented the **Mesa semantics** described above (the language they used was Mesa, hence the name).

The problem they ran into is best shown via simple example, in this case in a simple multi-threaded memory allocation library. Figure 30.15 shows a code snippet which demonstrates the issue.

As you might see in the code, when a thread calls into the memory allocation code, it might have to wait in order for more memory to become free. Conversely, when a thread frees memory, it signals that more memory is free. However, our code above has a problem: which waiting thread (there can be more than one) should be woken up?

```

1 // how many bytes of the heap are free?
2 int bytesLeft = MAX_HEAP_SIZE;
3
4 // need lock and condition too
5 cond_t c;
6 mutex_t m;
7
8 void *
9 allocate(int size) {
10     Pthread_mutex_lock(&m);
11     while (bytesLeft < size)
12         Pthread_cond_wait(&c, &m);
13     void *ptr = ...; // get mem from heap
14     bytesLeft -= size;
15     Pthread_mutex_unlock(&m);
16     return ptr;
17 }
18
19 void free(void *ptr, int size) {
20     Pthread_mutex_lock(&m);
21     bytesLeft += size;
22     Pthread_cond_signal(&c); // whom to signal??
23     Pthread_mutex_unlock(&m);
24 }

```

Figure 30.15: Covering Conditions: An Example

Consider the following scenario. Assume there are zero bytes free; thread T_a calls `allocate(100)`, followed by thread T_b which asks for less memory by calling `allocate(10)`. Both T_a and T_b thus wait on the condition and go to sleep; there aren't enough free bytes to satisfy either of these requests.

At that point, assume a third thread, T_c , calls `free(50)`. Unfortunately, when it calls `signal` to wake a waiting thread, it might not wake the correct waiting thread, T_b , which is waiting for only 10 bytes to be freed; T_a should remain waiting, as not enough memory is yet free. Thus, the code in the figure does not work, as the thread waking other threads does not know which thread (or threads) to wake up.

The solution suggested by Lampson and Redell is straightforward: replace the `pthread_cond_signal()` call in the code above with a call to `pthread_cond_broadcast()`, which wakes up *all* waiting threads. By doing so, we guarantee that any threads that should be woken are. The downside, of course, can be a negative performance impact, as we might needlessly wake up many other waiting threads that shouldn't (yet) be awake. Those threads will simply wake up, re-check the condition, and then go immediately back to sleep.

Lampson and Redell call such a condition a **covering condition**, as it covers all the cases where a thread needs to wake up (conservatively); the cost, as we've discussed, is that too many threads might be woken.

The astute reader might also have noticed we could have used this approach earlier (see the producer/consumer problem with only a single condition variable). However, in that case, a better solution was available to us, and thus we used it. In general, if you find that your program only works when you change your signals to broadcasts (but you don't think it should need to), you probably have a bug; fix it! But in cases like the memory allocator above, broadcast may be the most straightforward solution available.

30.4 Summary

We have seen the introduction of another important synchronization primitive beyond locks: condition variables. By allowing threads to sleep when some program state is not as desired, CVs enable us to neatly solve a number of important synchronization problems, including the famous (and still important) producer/consumer problem, as well as covering conditions. A more dramatic concluding sentence would go here, such as “He loved Big Brother” [O49].

References

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- [D72] “Information Streams Sharing a Finite Buffer” by E.W. Dijkstra. Information Processing Letters 1: 179–180, 1972. <http://www.cs.utexas.edu/users/EWD/ewd03xx/EWD329.PDF> *The famous paper that introduced the producer/consumer problem.*
- [D01] “My recollections of operating system design” by E.W. Dijkstra. April, 2001. Available: <http://www.cs.utexas.edu/users/EWD/ewd13xx/EWD1303.PDF>. *A fascinating read for those of you interested in how the pioneers of our field came up with some very basic and fundamental concepts, including ideas like “interrupts” and even “a stack”!*
- [H74] “Monitors: An Operating System Structuring Concept” by C.A.R. Hoare. Communications of the ACM, 17:10, pages 549–557, October 1974. *Hoare did a fair amount of theoretical work in concurrency. However, he is still probably most known for his work on Quicksort, the coolest sorting algorithm in the world, at least according to these authors.*
- [L11] “Pthread_cond_signal Man Page” by Mysterious author. March, 2011. Available online: http://linux.die.net/man/3/pthread_cond_signal. *The Linux man page shows a nice simple example of why a thread might get a spurious wakeup, due to race conditions within the signal/wakeup code.*
- [LR80] “Experience with Processes and Monitors in Mesa” by B.W. Lampson, D.R. Redell. Communications of the ACM. 23:2, pages 105–117, February 1980. *A classic paper about how to actually implement signaling and condition variables in a real system, leading to the term “Mesa” semantics for what it means to be woken up; the older semantics, developed by Tony Hoare [H74], then became known as “Hoare” semantics, which is a bit unfortunate of a name.*
- [O49] “1984” by George Orwell. Secker and Warburg, 1949. *A little heavy-handed, but of course a must read. That said, we kind of gave away the ending by quoting the last sentence. Sorry! And if the government is reading this, let us just say that we think that the government is “double plus good”. Hear that, our pals at the NSA?*

Homework (Code)

This homework lets you explore some real code that uses locks and condition variables to implement various forms of the producer/consumer queue discussed in the chapter. You'll look at the real code, run it in various configurations, and use it to learn about what works and what doesn't, as well as other intricacies. Read the README for details.

Questions

1. Our first question focuses on `main-two-cvs-while.c` (the working solution). First, study the code. Do you think you have an understanding of what should happen when you run the program?
2. Run with one producer and one consumer, and have the producer produce a few values. Start with a buffer (size 1), and then increase it. How does the behavior of the code change with larger buffers? (or does it?) What would you predict `num_full` to be with different buffer sizes (e.g., `-m 10`) and different numbers of produced items (e.g., `-l 100`), when you change the consumer sleep string from default (no sleep) to `-C 0,0,0,0,0,0,1`?
3. If possible, run the code on different systems (e.g., a Mac and Linux). Do you see different behavior across these systems?
4. Let's look at some timings. How long do you think the following execution, with one producer, three consumers, a single-entry shared buffer, and each consumer pausing at point `c3` for a second, will take? `./main-two-cvs-while -p 1 -c 3 -m 1 -C 0,0,0,1,0,0,0:0,0,0,1,0,0,0:0,0,0,1,0,0,0 -l 10 -v -t`
5. Now change the size of the shared buffer to 3 (`-m 3`). Will this make any difference in the total time?
6. Now change the location of the sleep to `c6` (this models a consumer taking something off the queue and then doing something with it), again using a single-entry buffer. What time do you predict in this case? `./main-two-cvs-while -p 1 -c 3 -m 1 -C 0,0,0,0,0,0,1:0,0,0,0,0,0,1:0,0,0,0,0,0,1 -l 10 -v -t`
7. Finally, change the buffer size to 3 again (`-m 3`). What time do you predict now?
8. Now let's look at `main-one-cv-while.c`. Can you configure a sleep string, assuming a single producer, one consumer, and a buffer of size 1, to cause a problem with this code?

9. Now change the number of consumers to two. Can you construct sleep strings for the producer and the consumers so as to cause a problem in the code?
10. Now examine `main-two-cvs-if.c`. Can you cause a problem to happen in this code? Again consider the case where there is only one consumer, and then the case where there is more than one.
11. Finally, examine `main-two-cvs-while-extra-unlock.c`. What problem arises when you release the lock before doing a put or a get? Can you reliably cause such a problem to happen, given the sleep strings? What bad thing can happen?