26

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). 多路复用

In this chapter, 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: threads 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

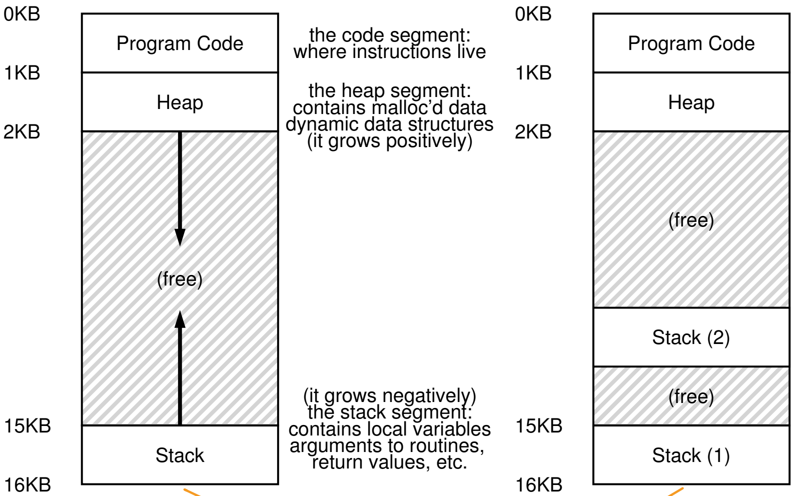

Figure 26.1: **Single-Threaded And Multi-Threaded Address Spaces**

(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).

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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.

```
#include <stdio.h>
#include <assert.h>
#include <pthread.h>
#include "common.h"
#include "common_threads.h"

void *mythread(void *arg) {
    printf("%s\n", (char *) arg);
    return NULL;
}

int
main(int argc, char *argv[]) {
    pthread_t p1, p2;
    int rc;
    printf("main: begin\n");
    Pthread_create(&p1, NULL, mythread, "A");
    Pthread_create(&p2, NULL, mythread, "B");
    // join waits for the threads to finish
    Pthread_join(p1, NULL);
    Pthread_join(p2, NULL);
    printf("main: end\n");
    return 0;
}
```

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.

趾高气昂地走

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		
returns immediately; T1 is done		
waits for T2		
returns immediately; T2 is done		
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		
returns immediately; T2 is done		
prints “main: end”		

strut

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).

包,裹

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)
```

```
#include <stdio.h>
#include <pthread.h>
#include "common.h"
#include "common_threads.h"

static volatile int counter = 0;

// mythread()
//
// Simply adds 1 to counter repeatedly, in a loop
// No, this is not how you would add 10,000,000 to
// a counter, but it shows the problem nicely.
//
void *mythread(void *arg) {
    printf("%s: begin\n", (char *) arg);
    int i;
    for (i = 0; i < 1e7; i++) {
        counter = counter + 1;
    }
    printf("%s: done\n", (char *) arg);
    return NULL;
}

// main()
//
// Just launches two threads (pthread_create)
// and then waits for them (pthread_join)
//
int main(int argc, char *argv[]) {
    pthread_t p1, p2;
    printf("main: begin (counter = %d)\n", counter);
    Pthread_create(&p1, NULL, mythread, "A");
    Pthread_create(&p2, NULL, mythread, "B");

    // join waits for the threads to finish
    Pthread_join(p1, NULL);
    Pthread_join(p2, NULL);
    printf("main: done with both (counter = %d)\n",
            counter);
    return 0;
}
```

共享变量

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)*

喘气

```
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:

反汇编器

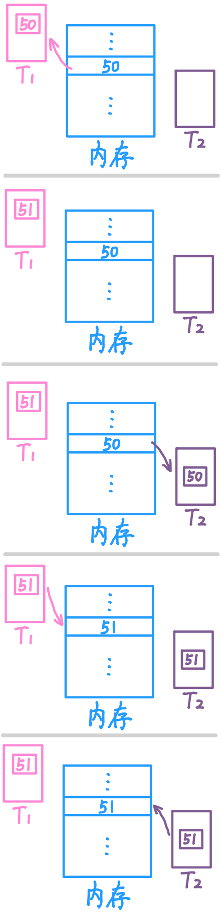
```
prompt> objdump -d main
```

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.

"TOCTTOU"

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):

			(after instruction)		
OS	**Thread 1**	**Thread 2**	**PC**	**eax**	**counter**
	before critical section		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. sequence

What we have demonstrated here is called a **race condition** (or, more specifically, a **data race**): the results depend on the timing of the code's execution. 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 threads

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. 被创造

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
沉睡 slumber so it can continue. 唤醒

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 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.*