The Little Book of Semaphores

Allen B. Downey

Version 2.1.5

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Second Edition

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Preface

Most undergraduate Operating Systems textbooks have a module on Synchronization, which usually presents a set of primitives (mutexes, semaphores, monitors, and sometimes condition variables), and classical problems like readers-writers and producers-consumers.

When I took the Operating Systems class at Berkeley, and taught it at Colby College, I got the impression that most students were able to understand the solutions to these problems, but few would have been able to produce them, or solve similar problems.

One reason students don't understand this material deeply is that it takes more time, and more practice, than most classes can spare. Synchronization is just one of the modules competing for space in an Operating Systems class, and I'm not sure I can argue that it is the most important. But I do think it is one of the most challenging, interesting, and (done right) fun.

I wrote the first edition this book with the goal of identifying synchronization idioms and patterns that could be understood in isolation and then assembled to solve complex problems. This was a challenge, because synchronization code doesn't compose well; as the number of components increases, the number of interactions grows unmanageably.

Nevertheless, I found patterns in the solutions I saw, and discovered at least some systematic approaches to assembling solutions that are demonstrably correct.

I had a chance to test this approach when I taught Operating Systems at Wellesley College. I used the first edition of *The Little Book of Semaphores* along with one of the standard textbooks, and I taught Synchronization as a concurrent thread for the duration of the course. Each week I gave the students a few pages from the book, ending with a puzzle, and sometimes a hint. I told them not to look at the hint unless they were stumped.

I also gave them some tools for testing their solutions: a small magnetic whiteboard where they could write code, and a stack of magnets to represent the threads executing the code.

The results were dramatic. Given more time to absorb the material, students demonstrated a depth of understanding I had not seen before. More importantly, most of them were able to solve most of the puzzles. In some cases they reinvented classical solutions; in other cases they found creative new approaches.

When I moved to Olin College, I took the next step and created a half-class, called Synchronization, which covered *The Little Book of Semaphores* and also the implementation of synchronization primitives in x86 Assembly Language, POSIX, and Python.

The students who took the class helped me find errors in the first edition and several of them contributed solutions that were better than mine. At the end of the semester, I asked each of them to write a new, original problem (preferably with a solution). I have added their contributions to the second edition.

Also since the first edition appeared, Kenneth Reek presented the article "Design Patterns for Semaphores" at the ACM Special Interest Group for Computer Science Education. He presents a problem, which I have cast as the Sushi Bar Problem, and two solutions that demonstrate patterns he calls "Pass the baton" and "I'll do it for you." Once I came to appreciate these patterns, I was able to apply them to some of the problems from the first edition and produce solutions that I think are better.

One other change in the second edition is the syntax. After I wrote the first edition, I learned Python, which is not only a great programming language; it also makes a great pseudocode language. So I switched from the C-like syntax in the first edition to syntax that is pretty close to executable Python[1]. In fact, I have written a simulator that can execute many of the solutions in this book.

Readers who are not familiar with Python will (I hope) find it mostly obvious. In cases where I use a Python-specific feature, I explain the syntax and what it means. I hope that these changes make the book more readable.

The pagination of this book might seem peculiar, but there is a method to my whitespace. After each puzzle, I leave enough space that the hint appears on the next sheet of paper and the solution on the next sheet after that. When I use this book in my class, I hand it out a few pages at a time, and students collect them in a binder. My pagination system makes it possible to hand out a problem without giving away the hint or the solution. Sometimes I fold and staple the hint and hand it out along with the problem so that students can decide whether and when to look at the hint. If you print the book single-sided, you can discard the blank pages and the system still works.

This is a Free Book, which means that anyone is welcome to read, copy, modify and redistribute it, subject to the restrictions of the license, which is the GNU Free Documentation License. I hope that people will find this book useful, but I also hope they will help continue to develop it by sending in corrections, suggestions, and additional material. Thanks!

Allen B. Downey
Needham, MA
June 1, 2005

[1] The primary difference is that I sometimes use indentation to indicate code that is protected by a mutex, which would cause syntax errors in Python.

Contributor's list

The following are some of the people who have contributed to this book:

- Many of the problems in this book are variations of classical problems that appeared first in technical articles and then in textbooks. Whenever I know the origin of a problem or solution, I acknowledge it in the text.
- I also thank the students at Wellesley College who worked with the first edition of the book, and the students at Olin College who worked with the second edition.
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Chapter 1

Introduction

1.1 Synchronization

In common use, "synchronization" means making two things happen at the same time. In computer systems, synchronization is a little more general; it refers to relationships among events—any number of events, and any kind of relationship (before, during, after).

Computer programmers are often concerned with **synchronization constraints**, which are requirements pertaining to the order of events. Examples include:

Serialization: Event A must happen before Event B.

Mutual exclusion: Events A and B must not happen at the same time.

In real life we often check and enforce synchronization constraints using a clock. How do we know if A happened before B? If we know what time both events occurred, we can just compare the times.

In computer systems, we often need to satisfy synchronization constraints without the benefit of a clock, either because there is no universal clock, or because we don't know with fine enough resolution when events occur.

That's what this book is about: software techniques for enforcing synchronization constraints.

1.2 Execution model

In order to understand software synchronization, you have to have a model of how computer programs run. In the simplest model, computers execute one instruction after another in sequence. In this model, synchronization is trivial; we can tell the order of events by looking at the program. If Statement A comes before Statement B, it will be executed first.

There are two ways things get more complicated. One possibility is that the computer is parallel, meaning that it has multiple processors running at the same time. In that case it is not easy to know if a statement on one processor is executed before a statement on another.

Another possibility is that a single processor is running multiple threads of execution. A thread is a sequence of instructions that execute sequentially. If there are multiple threads, then the processor can work on one for a while, then switch to another, and so on.

In general the programmer has no control over when each thread runs; the operating system (specifically, the scheduler) makes those decisions. As a result, again, the programmer can't tell when statements in different threads will be executed.

For purposes of synchronization, there is no difference between the parallel model and the multithread model. The issue is the same—within one processor (or one thread) we know the order of execution, but between processors (or threads) it is impossible to tell.

A real world example might make this clearer. Imagine that you and your friend Bob live in different cities, and one day, around dinner time, you start to wonder who ate lunch first that day, you or Bob. How would you find out?

Obviously you could call him and ask what time he ate lunch. But what if you started lunch at 11:59 by your clock and Bob started lunch at 12:01 by his clock? Can you be sure who started first? Unless you are both very careful to keep accurate clocks, you can't.

Computer systems face the same problem because, even though their clocks are usually accurate, there is always a limit to their precision. In addition, most of the time the computer does not keep track of what time things happen. There are just too many things happening, too fast, to record the exact time of everything.

Puzzle: Assuming that Bob is willing to follow simple instructions, is there any way you can *guarantee* that tomorrow you will eat lunch before Bob?

1.3 Serialization with messages

One solution is to instruct Bob not to eat lunch until you call. Then, make sure you don't call until after lunch. This approach may seem trivial, but the underlying idea, message passing, is a real solution for many synchronization problems. At the risk of belaboring the obvious, consider this timeline.

You

```
a1  Eat breakfast
a2  Work
a3  Eat lunch
a4  Call Bob
```

Bob

```
b1  Eat breakfast
b2  Wait for a call
b3  Eat lunch
```

The first column is a list of actions you perform; in other words, your thread of execution. The second column is Bob's thread of execution. Within a thread, we can always tell what order things happen. We can denote the order of events

$$a1 < a2 < a3 < a4$$
$$b1 < b2 < b3$$

where the relation $a1 < a2$ means that a1 happened before a2.

In general, though, there is no way to compare events from different threads; for example, we have no idea who ate breakfast first (is $a1 < b1$?).

But with message passing (the phone call) we *can* tell who ate lunch first ($a3 < b3$). Assuming that Bob has no other friends, he won't get a call until you call, so $b2 > a4$. Combining all the relations, we get

$$b3 > b2 > a4 > a3$$

which proves that you had lunch before Bob.

In this case, we would say that you and Bob ate lunch **sequentially**, because we know the order of events, and you ate breakfast **concurrently**, because we don't.

When we talk about concurrent events, it is tempting to say that they happen at the same time, or simultaneously. As a shorthand, that's fine, as long as you remember the strict definition:

> Two events are concurrent if we cannot tell by looking at the program which will happen first.

Sometimes we can tell, after the program runs, which happened first, but often not, and even if we can, there is no guarantee that we will get the same result the next time.

1.4 Non-determinism

Concurrent programs are often **non-deterministic**, which means it is not possible to tell, by looking at the program, what will happen when it executes. Here is a simple example of a non-deterministic program:

Thread A

```
a1  print "yes"
```

Thread B

```
b1  print "no"
```

Because the two threads run concurrently, the order of execution depends on the scheduler. During any given run of this program, the output might be "yes no" or "no yes".

Non-determinism is one of the things that makes concurrent programs hard to debug. A program might work correctly 1000 times in a row, and then crash on the 1001st run, depending on the particular decisions of the scheduler.

These kinds of bugs are almost impossible to find by testing; they can only be avoided by careful programming.

1.5 Shared variables

Most of the time, most variables in most threads are **local**, meaning that they belong to a single thread and no other threads can access them. As long as that's true, there tend to be few synchronization problems, because threads just don't interact.

But usually some variables are **shared** among two or more threads; this is one of the ways threads interact with each other. For example, one way to communicate information between threads is for one thread to read a value written by another thread.

If the threads are unsynchronized, then we cannot tell by looking at the program whether the reader will see the value the writer writes or an old value that was already there. Thus many applications enforce the constraint that the reader should not read until after the writer writes. This is exactly the serialization problem in Section 1.3.

Other ways that threads interact are concurrent writes (two or more writers) and concurrent updates (two or more threads performing a read followed by a write). The next two sections deal with these interactions. The other possible use of a shared variable, concurrent reads, does not generally create a synchronization problem.

1.5.1 Concurrent writes

In the following example, `x` is a shared variable accessed by two writers.

Thread A

```
a1  x = 5
a2  print x
```

Thread B

```
b1  x = 7
```

What value of `x` gets printed? What is the final value of `x` when all these statements have executed? It depends on the order in which the statements are executed, called the **execution path**. One possible path is $a1 < a2 < b1$, in which case the output of the program is `5`, but the final value is `7`.

Puzzle: What path yields output `5` and final value `5`?

Puzzle: What path yields output `7` and final value `7`?

Puzzle: Is there a path that yields output `7` and final value `5`? Can you prove it?

Answering questions like these is an important part of concurrent programming: What paths are possible and what are the possible effects? Can we prove that a given (desirable) effect is necessary or that an (undesirable) effect is impossible?

1.5.2 Concurrent updates

An update is an operation that reads the value of a variable, computes a new value based on the old value, and writes the new value. The most common kind of update is an increment, in which the new value is the old value plus one. The following example shows a shared variable, `count`, being updated concurrently by two threads.

Thread A

```
a1  count = count + 1
```

Thread B

```
b1  count = count + 1
```

At first glance, it is not obvious that there is a synchronization problem here. There are only two execution paths, and they yield the same result.

The problem is that these operations are translated into machine language before execution, and in machine language the update takes two steps, a read and a write. The problem is more obvious if we rewrite the code with a temporary variable, `temp`.

Thread A

```
a1  temp = count
a2  count = temp + 1
```

Thread B

```
b1  temp = count
b2  count = temp + 1
```

Now consider the following execution path

$$a1 < b1 < b2 < a2$$

Assuming that the initial value of `x` is `0`, what is its final value? Because both threads read the same initial value, they write the same value. The variable is only incremented once, which is probably not what the programmer had in mind.

This kind of problem is subtle because it is not always possible to tell, looking at a high-level program, which operations are performed in a single step and which can be interrupted. In fact, some computers provide an increment instruction that is implemented in hardware cannot be interrupted. An operation that cannot be interrupted is said to be **atomic**.

So how can we write concurrent programs if we don't know which operations are atomic? One possibility is to collect specific information about each operation on each hardware platform. The drawbacks of this approach are obvious.

The most common alternative is to make the conservative assumption that all updates and all writes are not atomic, and to use synchronization constraints to control concurrent access to shared variables.

The most common constraint is mutual exclusion, or mutex, which I mentioned in Section 1.1. Mutual exclusion guarantees that only one thread accesses a shared variable at a time, eliminating the kinds of synchronization errors in this section.

1.5.3 Mutual exclusion with messages

Like serialization, mutual exclusion can be implemented using message passing. For example, imagine that you and Bob operate a nuclear reactor that you monitor from remote stations. Most of the time, both of you are watching for warning lights, but you are both allowed to take a break for lunch. It doesn't matter who eats lunch first, but it is very important that you don't eat lunch at the same time, leaving the reactor unwatched!

Puzzle: Figure out a system of message passing (phone calls) that enforces these restraints. Assume there are no clocks, and you cannot predict when lunch will start or how long it will last. What is the minimum number of messages that is required?

Chapter 2

Semaphores

In real life a semaphore is a system of signals used to communicate visually, usually with flags, lights, or some other mechanism. In software, a semaphore is a data structure that is useful for solving a variety of synchronization problems.

Semaphores were invented by Edsger Dijkstra, a famously eccentric computer scientist. Some of the details have changed since the original design, but the basic idea is the same.

2.1 Definition

A semaphore is like an integer, with three differences:

1. When you create the semaphore, you can initialize its value to any integer, but after that the only operations you are allowed to perform are increment (increase by one) and decrement (decrease by one). You cannot read the current value of the semaphore.

2. When a thread decrements the semaphore, if the result is negative, the thread blocks itself and cannot continue until another thread increments the semaphore.

3. When a thread increments the semaphore, if there are other threads waiting, one of the waiting threads gets unblocked.

To say that a thread blocks itself (or simply "blocks") is to say that it notifies the scheduler that it cannot proceed. The scheduler will prevent the thread from running until an event occurs that causes the thread to become unblocked. In the tradition of mixed metaphors in computer science, unblocking is often called "waking".

That's all there is to the definition, but there are some consequences of the definition you might want to think about.

- In general, there is no way to know before a thread decrements a semaphore whether it will block or not (in specific cases you might be able to prove that it will or will not).
- After a thread increments a semaphore and another thread gets woken up, both threads continue running concurrently. There is no way to know which thread, if either, will continue immediately.
- When you signal a semaphore, you don't necessarily know whether another thread is waiting, so the number of unblocked threads may be zero or one.

Finally, you might want to think about what the value of the semaphore means. If the value is positive, then it represents the number of threads that can decrement without blocking. If it is negative, then it represents the number of threads that have blocked and are waiting. If the value is zero, it means there are no threads waiting, but if a thread tries to decrement, it will block.

2.2 Syntax

In most programming environments, an implementation of semaphores is available as part of the programming language or the operating system. Different implementations sometimes offer slightly different capabilities, and usually require different syntax.

In this book I will use a simple pseudo-language to demonstrate how semaphores work. The syntax for creating a new semaphore and initializing it is

Listing 2.1: Semaphore initialization syntax

```
fred = Semaphore(1)
```

The function `Semaphore` is a constructor; it creates and returns a new Semaphore. The initial value of the semaphore is passed as a parameter to the constructor.

The semaphore operations go by different names in different environments. The most common alternatives are

Listing 2.2: Semaphore operations

```
fred.increment()
fred.decrement()
```

and

Listing 2.3: Semaphore operations

```
fred.signal()
fred.wait()
```

and

Listing 2.4: Semaphore operations

```
fred.V()
fred.P()
```

It may be surprising that there are so many names, but there is a reason for the plurality. `increment` and `decrement` describe what the operations *do*. `signal` and `wait` describe what they are often *used for*. And `V` and `P` were the original names proposed by Dijkstra, who wisely realized that a meaningless name is better than a misleading name[1].

I consider the other pairs misleading because `increment` and `decrement` neglect to mention the possibility of blocking and waking, and semaphores are often used in ways that have nothing to do with `signal` and `wait`.

If you insist on meaningful names, then I would suggest these:

Listing 2.5: Semaphore operations

```
fred.increment_and_wake_a_waiting_process_if_any()
fred.decrement_and_block_if_the_result_is_negative()
```

I don't think the world is likely to embrace either of these names soon. In the meantime, I choose (more or less arbitrarily) to use `signal` and `wait`.

2.3 Why semaphores?

Looking at the definition of semaphores, it is not at all obvious why they are useful. It's true that we don't *need* semaphores to solve synchronization problems, but there are some advantages to using them:

- Semaphores impose deliberate constraints that help programmers avoid errors.
- Solutions using semaphores are often clean and organized, making it easy to demonstrate their correctness.
- Semaphores can be implemented efficiently on many systems, so solutions that use semaphores are portable and usually efficient.

[1] Actually, `V` and `P` aren't completely meaningless to people who speak Dutch.

Chapter 3

Basic synchronization patterns

This chapter presents a series of basic synchronization problems and shows ways of using semaphores to solve them. These problems include serialization and mutual exclusion, which we have already seen, along with others.

3.1 Signaling

Possibly the simplest use for a semaphore is **signaling**, which means that one thread sends a signal to another thread to indicate that something has happened.

Signaling makes it possible to guarantee that a section of code in one thread will run before a section of code in another thread; in other words, it solves the serialization problem.

Assume that we have a semaphore named `sem` with initial value 0, and that Threads A and B have shared access to it.

Thread A

```
statement a1
sem.signal()
```

Thread B

```
sem.wait()
statement b1
```

The word `statement` represents an arbitrary program statement. To make the example concrete, imagine that `a1` reads a line from a file, and `b1` displays the line on the screen. The semaphore in this program guarantees that Thread A has completed `a1` before Thread B begins `b1`.

Here's how it works: if thread B gets to the `wait` statement first, it will find the initial value, zero, and it will block. Then when Thread A signals, Thread B proceeds.

Similarly, if Thread A gets to the signal first then the value of the semaphore will be incremented, and when Thread B gets to the wait, it will proceed immediately. Either way, the order of `a1` and `b1` is guaranteed.

This use of semaphores is the basis of the names `signal` and `wait`, and in this case the names are conveniently mnemonic. Unfortunately, we will see other cases where the names are less helpful.

Speaking of meaningful names, `sem` isn't one. When possible, it is a good idea to give a semaphore a name that indicates what it represents. In this case a name like `a1Done` might be good, so that `a1done.signal()` means "signal that a1 is done," and `a1done.wait()` means "wait until a1 is done."

3.2 Rendezvous

Puzzle: Generalize the signal pattern so that it works both ways. Thread A has to wait for Thread B and vice versa. In other words, given this code

Thread A

```
statement a1
statement a2
```

Thread B

```
statement b1
statement b2
```

we want to guarantee that `a1` happens before `b2` and `b1` happens before `a2`. In writing your solution, be sure to specify the names and initial values of your semaphores (little hint there).

Your solution should not enforce too many constraints. For example, we don't care about the order of `a1` and `b1`. In your solution, either order should be possible.

This synchronization problem has a name; it's a rendezvous. The idea is that two threads rendezvous at a point of execution, and neither is allowed to proceed until both have arrived.

3.2.1 Rendezvous hint

The chances are good that you were able to figure out a solution, but if not, here is a hint. Create two semaphores, named `aArrived` and `bArrived`, and initialize them both to zero.

As the names suggest, `aArrived` indicates whether Thread A has arrived at the rendezvous, and `bArrived` likewise.

3.2.2 Rendezvous solution

Here is my solution, based on the previous hint:

Thread A

```
statement a1
aArrived.signal()
bArrived.wait()
statement a2
```

Thread B

```
statement b1
bArrived.signal()
aArrived.wait()
statement b2
```

While working on the previous problem, you might have tried something like this:

Thread A

```
statement a1
bArrived.wait()
aArrived.signal()
statement a2
```

Thread B

```
statement b1
bArrived.signal()
aArrived.wait()
statement b2
```

This solution also works, although it is probably less efficient, since it might have to switch between A and B one time more than necessary.

If A arrives first, it waits for B. When B arrives, it wakes A and might proceed immediately to its `wait` in which case it blocks, allowing A to reach its `signal`, after which both threads can proceed.

Think about the other possible paths through this code and convince yourself that in all cases neither thread can proceed until both have arrived.

3.2.3 Deadlock #1

Again, while working on the previous problem, you might have tried something like this:

Thread A

```
statement a1
bArrived.wait()
aArrived.signal()
statement a2
```

Thread B

```
statement b1
aArrived.wait()
bArrived.signal()
statement b2
```

If so, I hope you rejected it quickly, because it has a serious problem. Assuming that A arrives first, it will block at its `wait`. When B arrives, it will also block, since A wasn't able to signal `aArrived`. At this point, neither thread can proceed, and never will.

This situation is called a **deadlock** and, obviously, it is not a successful solution of the synchronization problem. In this case, the error is obvious, but often the possibility of deadlock is more subtle. We will see more examples later.

3.3 Mutex

A second common use for semaphores is to enforce mutual exclusion. We have already seen one use for mutual exclusion, controlling concurrent access to shared variables. The mutex guarantees that only one thread accesses the shared variable at a time.

A mutex is like a token that passes from one thread to another, allowing one thread at a time to proceed. For example, in *The Lord of the Flies* a group of children use a conch as a mutex. In order to speak, you have to hold the conch. As long as only one child holds the conch, only one can speak[1].

Similarly, in order for a thread to access a shared variable, it has to "get" the mutex; when it is done, it "releases" the mutex. Only one thread can hold the mutex at a time.

Puzzle: Add semaphores to the following example to enforce mutual exclusion to the shared variable `count`.

Thread A

```
count = count + 1
```

Thread B

```
count = count + 1
```

[1] Although this metaphor is helpful, for now, it can also be misleading, as you will see in Section 5.5

3.3.1 Mutual exclusion hint

Create a semaphore named `mutex` that is initialized to 1. A value of one means that a thread may proceed and access the shared variable; a value of zero means that it has to wait for another thread to release the mutex.

3.3.2 Mutual exclusion solution

Here is a solution:

Thread A

```
mutex.wait()
    # critical section
    count = count + 1
mutex.signal()
```

Thread B

```
mutex.wait()
    # critical section
    count = count + 1
mutex.signal()
```

Since `mutex` is initially 1, whichever thread gets to the `wait` first will be able to proceed immediately. Of course, the act of waiting on the semaphore has the effect of decrementing it, so the second thread to arrive will have to wait until the first signals.

I have indented the update operation to show that it is contained within the mutex.

In this example, both threads are running the same code. This is sometimes called a **symmetric** solution. If the threads have to run different code, the solution is **asymmetric**. Symmetric solutions are often easier to generalize. In this case, the mutex solution can handle any number of concurrent threads without modification. As long as every thread waits before performing an update and signals after, then no two threads will access `count` concurrently.

Often the code that needs to be protected is called the **critical section**, I suppose because it is critically important to prevent concurrent access.

In the tradition of computer science and mixed metaphors, there are several other ways people sometimes talk about mutexes. In the metaphor we have been using so far, the mutex is a token that is passed from one thread to another.

In an alternative metaphor, we think of the critical section as a room, and only one thread is allowed to be in the room at a time. In this metaphor, mutexes are called locks, and a thread is said to lock the mutex before entering and unlock it while exiting. Occasionally, though, people mix the metaphors and talk about "getting" or "releasing" a lock, which doesn't make much sense.

Both metaphors are potentially useful and potentially misleading. As you work on the next problem, try out both ways of thinking and see which one leads you to a solution.

3.4 Multiplex

Puzzle: Generalize the previous solution so that it allows multiple threads to run in the critical section at the same time, but it enforces an upper limit on the number of concurrent threads. In other words, no more than `n` threads can run in the critical section at the same time.

This pattern is called a **multiplex**. In real life, the multiplex problem occurs at busy nightclubs where there is a maximum number of people allowed in the building at a time, either to maintain fire safety or to create the illusion of exclusivity.

At such places a bouncer usually enforces the synchronization constraint by keeping track of the number of people inside and barring arrivals when the room is at capacity. Then, whenever one person leaves another is allowed to enter.

Enforcing this constraint with semaphores may sound difficult, but it is almost trivial.

3.4.1 Multiplex solution

To allow multiple threads to run in the critical section, just initialize the semaphore to `n`, which is the maximum number of threads that should be allowed.

At any time, the value of the semaphore represents the number of additional threads that may enter. If the value is zero, then the next thread will block until one of the threads inside exits and signals. When all threads have exited the value of the semaphore is restored to `n`.

Since the solution is symmetric, it's conventional to show only one copy of the code, but you should imagine multiple copies of the code running concurrently in multiple threads.

Listing 3.1: Multiplex solution

```
multiplex.wait()
    critical section
multiplex.signal()
```

What happens if the critical section is occupied and more than one thread arrives? Of course, what we want is for all the arrivals to wait. This solution does exactly that. Each time an arrival joins the queue, the semaphore is decremented, so that the value of the semaphore (negated) represents the number of threads in queue.

When a thread leaves, it signals the semaphore, incrementing its value and allowing one of the waiting threads to proceed.

Thinking again of metaphors, in this case I find it useful to think of the semaphore as a set of tokens (rather than a lock). As each thread invokes `wait`, it picks up one of the tokens; when it invokes `signal` it releases one. Only a thread that holds a token can enter the room. If no tokens are available when a thread arrives, it waits until another thread releases one.

In real life, ticket windows sometimes use a system like this. They hand out tokens (sometimes poker chips) to customers in line. Each token allows the holder to buy a ticket.

3.5 Barrier

Consider again the Rendezvous problem from Section 3.2. A limitation of the solution we presented is that it does not work with more than two threads.

Puzzle: Generalize the rendezvous solution. Every thread should run the following code:

Listing 3.2: Barrier code

```
rendezvous
critical point
```

The synchronization requirement is that no thread executes `critical point` until after all threads have executed `rendezvous`.

You can assume that there are n threads and that this value is stored in a variable, `n`, that is accessible from all threads.

When the first $n - 1$ threads arrive they should block until the nth thread arrives, at which point all the threads may proceed.

3.5.1 Barrier hint

For many of the problems in this book I will provide hints by presenting the variables I used in my solution and explaining their roles.

Listing 3.3: Barrier hint

```
n = the number of threads
count = 0
mutex = Semaphore(1)
barrier = Semaphore(0)
```

`count` keeps track of how many threads have arrived. `mutex` provides exclusive access to `count` so that threads can increment it safely.

`barrier` is locked (zero or negative) until all threads arrive; then it should be unlocked (1 or more).

3.5.2 Barrier non-solution

First I will present a solution that is not quite right, because it is useful to examine incorrect solutions and figure out what is wrong.

Listing 3.4: Barrier non-solution

```
rendezvous

mutex.wait()
    count = count + 1
mutex.signal()

if count == n: barrier.signal()

barrier.wait()

critical point
```

Since `count` is protected by a mutex, it counts the number of threads that pass. The first $n-1$ threads wait when they get to the barrier, which is initially locked. When the nth thread arrives, it unlocks the barrier.

Puzzle: What is wrong with this solution?

3.5.3 Deadlock #2

The problem is a deadlock.

An an example, imagine that $n = 5$ and that 4 threads are waiting at the barrier. The value of the semaphore is the number of threads in queue, negated, which is -4.

When the 5th thread signals the barrier, one of the waiting threads is allowed to proceed, and the semaphore is incremented to -3.

But then no one signals the semaphore again and none of the other threads can pass the barrier. This is a second example of a deadlock.

Puzzle: Does this code always create a deadlock? Can you find an execution path through this code that does *not* cause a deadlock?

Puzzle: Fix the problem.

3.5.4 Barrier solution

Finally, here is a working barrier:

Listing 3.5: Barrier solution

```
rendezvous

mutex.wait()
    count = count + 1
mutex.signal()

if count == n: barrier.signal()

barrier.wait()
barrier.signal()

critical point
```

The only change is another `signal` after waiting at the barrier. Now as each thread passes, it signals the semaphore so that the next thread can pass.

This pattern, a `wait` and a `signal` in rapid succession, occurs often enough that it has a name; it's called a **turnstile**, because it allows one thread to pass at a time, and it can be locked to bar all threads.

In its initial state (zero), the turnstile is locked. The nth thread unlocks it and then all n threads go through.

It might seem dangerous to read the value of `count` outside the mutex. In this case it is not a problem, but in general it is probably not a good idea. We will clean this up in a few pages, but in the meantime, you might want to consider these questions: After the nth thread, what state is the turnstile in? Is there any way the barrier might be signaled more than once?

3.5.5 Deadlock #3

Since only one thread at a time can pass through the mutex, and only one thread at a time can pass through the turnstile, it might seen reasonable to put the turnstile inside the mutex, like this:

Listing 3.6: Bad barrier solution

```
rendezvous

mutex.wait()
    count = count + 1
    if count == n: barrier.signal()

    barrier.wait()
    barrier.signal()
mutex.signal()

critical point
```

This turns out to be a bad idea because it can cause a deadlock.

Imagine that the first thread enters the mutex and then blocks when it reaches the turnstile. Since the mutex is locked, no other threads can enter, so the condition, `count==n`, will never be true and no one will ever unlock the turnstile.

In this case the deadlock is fairly obvious, but it demonstrates a common source of deadlocks: blocking on a semaphore while holding a mutex.

3.6 Reusable barrier

Often a set of cooperating threads will perform a series of steps in a loop and synchronize at a barrier after each step. For this application we need a reusable barrier that locks itself after all the threads have passed through.

Puzzle: Rewrite the barrier solution so that after all the threads have passed through, the turnstile is locked again.

3.6.1 Reusable barrier non-solution #1

Once again, we will start with a simple attempt at a solution and gradually improve it:

Listing 3.7: Reusable barrier non-solution

```
rendezvous

mutex.wait()
    count += 1
mutex.signal()

if count == n: turnstile.signal()

turnstile.wait()
turnstile.signal()

critical point

mutex.wait()
    count -= 1
mutex.signal()

if count == 0: turnstile.wait()
```

Notice that the code after the turnstile is pretty much the same as the code before it. Again, we have to use the mutex to protect access to the shared variable `count`. Tragically, though, this code is not quite correct.

Puzzle: What is the problem?

3.6.2 Reusable barrier problem #1

There is a problem spot at Line 7 of the previous code.

If the $n-1$th thread is interrupted at this point, and then the nth thread comes through the mutex, both threads will find that `count==n` and both threads will signal the turnstile. In fact, it is even possible that *all* the threads will signal the turnstile.

Similarly, at Line 18 it is possible for multiple threads to `wait`, which will cause a deadlock.

Puzzle: Fix the problem.

3.6.3 Reusable barrier non-solution #2

This attempt fixes the previous error, but a subtle problem remains.

Listing 3.8: Reusable barrier non-solution

```
rendezvous

mutex.wait()
    count += 1
    if count == n: turnstile.signal()
mutex.signal()

turnstile.wait()
turnstile.signal()

critical point

mutex.wait()
    count -= 1
    if count == 0: turnstile.wait()
mutex.signal()
```

In both cases the check is inside the mutex so that a thread cannot be interrupted after changing the counter and before checking it.

Tragically, this code is *still* not correct. Remember that this barrier will be inside a loop. So, after executing the last line, each thread will go back to the rendezvous.

Puzzle: Identify and fix the problem.

3.6.4 Reusable barrier hint

As it is currently written, this code allows a precocious thread to pass through the second mutex, then loop around and pass through the first mutex and the turnstile, effectively getting ahead of the other threads by a lap.

To solve this problem we can use two turnstiles.

Listing 3.9: Reusable barrier hint

```
turnstile = Semaphore(0)
turnstile2 = Semaphore(1)
mutex = Semaphore(1)
```

Initially the first is locked and the second is open. When all the threads arrive at the first, we lock the second and unlock the first. When all the threads arrive at the second we relock the first, which makes it safe for the threads to loop around to the beginning, and then open the second.

3.6.5 Reusable barrier solution

Listing 3.10: Reusable barrier solution

```
# rendezvous

mutex.wait()
    count += 1
    if count == n:
        turnstile2.wait()     # lock the second
        turnstile.signal()    # unlock the first
mutex.signal()

turnstile.wait()              # first turnstile
turnstile.signal()

# critical point

mutex.wait()
    count -= 1
    if count == 0:
        turnstile.wait()       # lock the first
        turnstile2.signal()    # unlock the second
mutex.signal()

turnstile2.wait()              # second turnstile
turnstile2.signal()
```

This solution is sometimes called a **two-phase barrier** because it forces all the threads to wait twice: once for all the threads to arrive and again for all the threads to execute the critical section.

Unfortunately, this solution is typical of most non-trivial synchronization code: it is difficult to be sure that a solution is correct. Often there is a subtle way that a particular path through the program can cause an error.

To make matters worse, testing an implementation of a solution is not much help. The error might occur very rarely because the particular path that causes it might require a spectacularly unlucky combination of circumstances. Such errors are almost impossible to reproduce and debug by conventional means.

The only alternative is to examine the code carefully and "prove" that it is correct. I put "prove" in quotation marks because I don't mean, necessarily, that you have to write a formal proof (although there are zealots who encourage such lunacy).

The kind of proof I have in mind is more informal. We can take advantage of the structure of the code, and the idioms we have developed, to assert, and then demonstrate, a number of intermediate-level claims about the program. For example:

1. Only the nth thread can lock or unlock the turnstiles.

2. Before a thread can unlock the first turnstile, it has to close the second, and vice versa; therefore it is impossible for one thread to get ahead of the others by more than one turnstile.

By finding the right kinds of statements to assert and prove, you can sometimes find a concise way to convince yourself (or a skeptical colleague) that your code is bulletproof.

3.6.6 Preloaded turnstile

One nice thing about a turnstile is that it is a versatile component you can use in a variety of solutions. But one drawback is that it forces threads to go through sequentially, which may cause more context switching than necessary.

In the reusable barrier solution, we can simplify the solution if the thread that unlocks the turnstile preloads the turnstile with enough signals to let the right number of threads through[2].

The syntax I am using here assumes that `signal` can take a parameter that specifies the number of signals. This is a non-standard feature, but it would be easy to implement with a loop. The only thing to keep in mind is that the multiple signals are not atomic; that is, the signaling thread might be interrupted in the loop. But in this case that is not a problem.

Listing 3.11: Reusable barrier solution

```
# rendezvous

mutex.wait()
    count += 1
    if count == n:
        turnstile.signal(n)    # unlock the first
mutex.signal()

turnstile.wait()               # first turnstile

# critical point

mutex.wait()
    count -= 1
    if count == 0:
        turnstile2.signal(n)   # unlock the second
mutex.signal()

turnstile2.wait()              # second turnstile
```

When the nth thread arrives, it preloads the first turnstile with one signal for each thread. When the nth thread passes the turnstile, it "takes the last token" and leaves the turnstile locked again.

The same thing happens at the second turnstile, which is unlocked when the last thread goes through the mutex.

[2]Thanks to Matt Tesch for this solution!

3.6.7 Barrier objects

It is natural to encapsulate a barrier in an object. I will borrow the Python syntax for defining a class:

Listing 3.12: Barrier class

```
class Barrier:
    def __init__(self, n):
        self.n = n
        self.count = 0
        self.mutex = Semaphore(1)
        self.turnstile = Semaphore(0)
        self.turnstile2 = Semaphore(0)

    def phase1(self):
        self.mutex.wait()
            self.count += 1
            if self.count == self.n:
                self.turnstile.signal(self.n)
        self.mutex.signal()
        self.turnstile.wait()

    def phase2(self):
        self.mutex.wait()
            self.count -= 1
            if self.count == 0:
                self.turnstile2.signal(self.n)
        self.mutex.signal()
        self.turnstile2.wait()

    def wait(self):
        self.phase1()
        self.phase2()
```

The `__init__` method runs when we create a new `Barrier` object, and initializes the instance variables. The parameter `n` is the number of threads that have to invoke `wait` before the Barrier opens.

The variable `self` refers to the object the method is operating on. Since each barrier object has its own mutex and turnstiles, `self.mutex` refers to the specific mutex of the current object.

Here is an example that creates a `Barrier` object and waits on it:

Listing 3.13: Barrier interface

```
barrier = Barrier(n)      # initialize a new barrier
barrier.wait()            # wait at a barrier
```

Optionally, code that uses a barrier can call `phase1` and `phase2` separately, if there is something else that should be done in between.

3.7 Queue

Semaphores can also be used to represent a queue. In this case, the initial value is 0, and usually the code is written so that it is not possible to signal unless there is a thread waiting, so the value of the semaphore is never positive.

For example, imagine that threads represent ballroom dancers and that two kinds of dancers, leaders and followers, wait in two queues before entering the dance floor. When a leader arrives, it checks to see if there is a follower waiting. If so, they can both proceed. Otherwise it waits.

Similarly, when a follower arrives, it checks for a leader and either proceeds or waits, accordingly.

Puzzle: write code for leaders and followers that enforces these constraints.

3.7.1 Queue hint

Here are the variables I used in my solution:

Listing 3.14: Queue hint

```
leaderQueue = Semaphore(0)
followerQueue = Semaphore(0)
```

`leaderQueue` is the queue where leaders wait and `followerQueue` is the queue where followers wait.

3.7.2 Queue solution

Here is the code for leaders:

Listing 3.15: Queue solution (leaders)

```
followerQueue.signal()
leaderQueue.wait()
dance()
```

And here is the code for followers:

Listing 3.16: Queue solution (followers)

```
leaderQueue.signal()
followerQueue.wait()
dance()
```

This solution is about as simple as it gets; it is just a Rendezvous. Each leader signals exactly one follower, and each follower signals one leader, so it is guaranteed that leaders and followers are allowed to proceed in pairs. But whether they actually proceed in pairs is not clear. It is possible for any number of threads to accumulate before executing `dance`, and so it is possible for any number of leaders to `dance` before any followers do. Depending on the semantics of `dance`, that behavior may or may not be problematic.

To make things more interesting, let's add the additional constraint that each leader can invoke `dance` concurrently with only one follower, and vice versa. In other words, you got to dance with the one that brought you[3].

Puzzle: write a solution to this "exclusive queue" problem.

[3]Song lyric performed by Shania Twain

3.7.3 Exclusive queue hint

Here are the variables I used in my solution:

Listing 3.17: Queue hint

```
leaders = followers = 0
mutex = Semaphore(1)
leaderQueue = Semaphore(0)
followerQueue = Semaphore(0)
rendezvous = Semaphore(0)
```

`leaders` and `followers` are counters that keep track of the number of dancers of each kinds that are waiting. The mutex guarantees exclusive access to the counters.

`leaderQueue` and `followerQueue` are the queues where dancers wait. `rendezvous` is used to check that both threads are done dancing.

3.7.4 Exclusive queue solution

Here is the code for leaders:

Listing 3.18: Queue solution (leaders)

```
mutex.wait()
if followers > 0:
    followers--
    followerQueue.signal()
else:
    leaders++
    mutex.signal()
    leaderQueue.wait()

dance()
rendezvous.wait()
mutex.signal()
```

When a leader arrives, it gets the mutex that protects `leaders` and `followers`. If there is a follower waiting, the leader decrements `followers`, signals a follower, and then invokes `dance`, all before releasing `mutex`. That guarantees that there can be only one follower thread running `dance` concurrently.

If there are no followers waiting, the leader has to give up the mutex before waiting on `leaderQueue`.

The code for followers is similar:

Listing 3.19: Queue solution (followers)

```
mutex.wait()
if leaders > 0:
    leaders--
    leaderQueue.signal()
else:
    followers++
    mutex.signal()
    followerQueue.wait()

dance()
rendezvous.signal()
```

When a follower arrives, it checks for a waiting leader. If there is one, the follower decrements `leaders`, signals a leader, and executes `dance`, all without releasing `mutex`. Actually, in this case the follower *never* releases `mutex`; the leader does. We don't have to keep track of which thread has the mutex because we know that one of them does, and either one of them can release it. In my solution it's always the leader.

When a semaphore is used as a queue[4], I find it useful to read "wait" as "wait for this queue" and signal as "let someone from this queue go."

In this code we never signal a queue unless someone is waiting, so the values of the queue semaphores are seldom positive. It is possible, though. See if you can figure out how.

[4] A semaphore used as a queue is very similar to a condition variable. The primary difference is that threads have to release the mutex explicitly before waiting, and reacquire it explicitly afterwards (but only if they need it).

3.8 Fifo queue

If there is more than one thread waiting in queue when a semaphore is signaled, there is usually no way to tell which thread will be woken. Some implementations wake threads up in a particular order, like first-in-first-out, but the semantics of semaphores don't require any particular order. Even if your environment doesn't provide first-in-first-out queueing, you can build it yourself.

Puzzle: use semaphores to build a first-in-first-out queue. Each time the Fifo is signaled, the thread at the head of the queue should proceed. If more than one thread is waiting on a semaphore, you should not make any assumptions about which thread will proceed when the semaphore is signaled.

For bonus points, your solution should define a class named `Fifo` that provides methods named `wait` and `signal`.

3.8.1 Fifo queue hint

A natural solution is to allocate one semaphore to each thread by having each thread run the following initialization:

Listing 3.20: Thread initialization

```
local mySem = Semaphore(0)
```

As each thread enters the Fifo, it adds its semaphore to a Queue data structure. When a thread signals the queue, it removes the semaphore at the head of the Queue and signals it.

Using Python syntax, here is what the Fifo class definition might look like:

Listing 3.21: Fifo class definition

```
class Fifo:
    def __init__(self):
        self.queue = Queue()
        self.mutex = Semaphore(1)
```

You can assume that there is a data structure named `Queue` that provides methods named `add` and `remove`, but you should not assume that the Queue is thread-safe; in other words, you have to enforce exclusive access to the Queue.

3.8.2 Fifo queue solution

Here is my solution:

Listing 3.22: Fifo queue solution

```
class Fifo:
    def __init__(self):
        self.queue = Queue()
        self.mutex = Semaphore(1)

    def wait():
        self.mutex.wait()
        self.queue.add(mySem)
        self.mutex.signal()
        mySem.wait()

    def signal():
        self.mutex.wait()
        sem = self.queue.remove()
        self.mutex.signal()
        sem.signal()
```

We use the `mutex` to protect the Queue, but release it as soon as possible to minimize contention (and context switches).

Chapter 4

Classical synchronization problems

In this chapter we examine the classical problems that appear in nearly every operating systems textbook. They are usually presented in terms of real-world problems, so that the statement of the problem is clear and so that students can bring their intuition to bear.

For the most part, though, these problems do not happen in the real world, or if they do, the real-world solutions are not much like the kind of synchronization code we are working with.

The reason we are interested in these problems is that they are analogous to common problems that operating systems (and some applications) need to solve. For each classical problem I will present the classical formulation, and also explain the analogy to the corresponding OS problem.

4.1 Producer-consumer problem

In multithreaded programs there is often a division of labor between threads. In one common pattern, some threads are producers and some are consumers. Producers create items of some kind and add them to a data structure; consumers remove the items and process them.

Event-driven programs are a good example. An "event" is something that happens that requires the program to respond: the user presses a key or moves the mouse, a block of data arrives from the disk, a packet arrives from the network, a pending operation completes.

Whenever an event occurs, a producer thread creates an event object and adds it to the event buffer. Concurrently, consumer threads take events out of the buffer and process them. In this case, the consumers are called "event handlers."

There are several synchronization constraints that we need to enforce to make this system work correctly:

- While an item is being added to or removed from the buffer, the buffer is in an inconsistent state. Therefore, threads must have exclusive access to the buffer.
- If a consumer thread arrives while the buffer is empty, it blocks until a producer adds a new item.

Assume that producers perform the following operations over and over:

Listing 4.1: Basic producer code

```
event = waitForEvent()
buffer.add(event)
```

Also, assume that consumers perform the following operations:

Listing 4.2: Basic consumer code

```
event = buffer.get()
event.process()
```

As specified above, access to the buffer has to be exclusive, but `waitForEvent` and `event.process` can run concurrently.

Puzzle: Add synchronization statements to the producer and consumer code to enforce the synchronization constraints.

4.1.1 Producer-consumer hint

Here are the variables you might want to use:

Listing 4.3: Producer-consumer initialization

```
mutex = Semaphore(1)
items = Semaphore(0)
local event
```

Not surprisingly, `mutex` provides exclusive access to the buffer. When `items` is positive, it indicates the number of items in the buffer. When it is negative, it indicates the number of consumer threads in queue.

`event` is a **local variable**, which in this context means that each thread has its own version. So far we have been assuming that all threads have access to all variables, but we will sometimes find it useful to attach a variable to each thread.

There are a number of ways this can be implemented in different environments:

- If each thread has its own run-time stack, then any variables allocated on the stack are thread-specific.
- If threads are represented as objects, we can add an attribute to each thread object.
- If threads have unique IDs, we can use the IDs as an index into an array or hash table, and store per-thread data there.

In most programs, most variables are local unless declared otherwise, but in this book most variables are shared, so we will assume that that variables are shared unless they are explicitly declared `local`.

4.1.2 Producer-consumer solution

Here is the producer code from my solution.

Listing 4.4: Producer solution

```
event = waitForEvent()
mutex.wait()
    buffer.add(event)
    items.signal()
mutex.signal()
```

The producer doesn't have to get exclusive access to the buffer until it gets an event. Several threads can run `waitForEvent` concurrently.

The `items` semaphore keeps track of the number of items in the buffer. Each time the producer adds an item, it signals `items`, incrementing it by one.

The consumer code is similar.

Listing 4.5: Consumer solution

```
items.wait()
mutex.wait()
    event = buffer.get()
mutex.signal()
event.process()
```

Again, the buffer operation is protected by a mutex, but before the consumer gets to it, it has to decrement `items`. If `items` is zero or negative, the consumer blocks until a producer signals.

Although this solution is correct, there is an opportunity to make one small improvement to its performance. Imagine that there is at least one consumer in queue when a producer signals `items`. If the scheduler allows the consumer to run, what happens next? It immediately blocks on the mutex that is (still) held by the producer.

Blocking and waking up are moderately expensive operations; performing them unnecessarily can impair the performance of a program. So it would probably be better to rearrange the producer like this:

Listing 4.6: Improved producer solution

```
event = waitForEvent()
mutex.wait()
    buffer.add(event)
mutex.signal()
items.signal()
```

Now we don't bother unblocking a consumer until we know it can proceed (except in the rare case that another producer beats it to the mutex).

There's one other thing about this solution that might bother a stickler. In the hint section I claimed that the `items` semaphore keeps track of the number

of items in queue. But looking at the consumer code, we see the possibility that several consumers could decrement `items` before any of them gets the mutex and removes an item from the buffer. At least for a little while, `items` would be inaccurate.

We might try to address that by checking the buffer inside the mutex:

Listing 4.7: Broken consumer solution

```
mutex.wait()
    items.wait()
    event = buffer.get()
mutex.signal()
event.process()
```

This is a bad idea.

Puzzle: why?

4.1.3 Deadlock #4

If the consumer is running this code

Listing 4.8: Broken consumer solution

```
mutex.wait()
    items.wait()
    event = buffer.get()
mutex.signal()

event.process()
```

it can cause a deadlock. Imagine that the buffer is empty. A consumer arrives, gets the mutex, and then blocks on `items`. When the producer arrives, it blocks on `mutex` and the system comes to a grinding halt.

This is a common error in synchronization code: any time you wait for a semaphore while holding a mutex, there is a danger of deadlock. When you are checking a solution to a synchronization problem, you should check for this kind of deadlock.

4.1.4 Producer-consumer with a finite buffer

In the example I described above, event-handling threads, the shared buffer is usually infinite (more accurately, it is bounded by system resources like physical memory and swap space).

In the kernel of the operating system, though, there are limits on available space. Buffers for things like disk requests and network packets are usually fixed size. In situations like these, we have an additional synchronization constraint:

- If a producer arrives when the buffer is full, it blocks until a consumer removes an item.

Assume that we know the size of the buffer. Call it `bufferSize`. Since we have a semaphore that is keeping track of the number of items, it is tempting to write something like

Listing 4.9: Broken finite buffer solution

```
if items >= bufferSize:
    block()
```

But we can't. Remember that we can't check the current value of a semaphore; the only operations are `wait` and `signal`.

Puzzle: write producer-consumer code that handles the finite-buffer constraint.

4.1.5 Finite buffer producer-consumer hint

Add a second semaphore to keep track of the number of available spaces in the buffer.

Listing 4.10: Finite-buffer producer-consumer initialization

```
mutex = Semaphore(1)
items = Semaphore(0)
spaces = Semaphore(buffer.size())
```

When a consumer removes an item it should signal `spaces`. When a producer arrives it should decrement `spaces`, at which point it might block until the next consumer signals.

4.1.6 Finite buffer producer-consumer solution

Here is a solution.

Listing 4.11: Finite buffer consumer solution

```
items.wait()
mutex.wait()
    event = buffer.get()
mutex.signal()
spaces.signal()

event.process()
```

The producer code is symmetric, in a way:

Listing 4.12: Finite buffer producer solution

```
event = waitForEvent()

spaces.wait()
mutex.wait()
    buffer.add(event)
mutex.signal()
items.signal()
```

In order to avoid deadlock, producers and consumers check availability before getting the mutex. For best performance, they release the mutex before signaling.

4.2 Readers-writers problem

The next classical problem, called the Reader-Writer Problem, pertains to any situation where a data structure, database, or file system is read and modified by concurrent threads. While the data structure is being written or modified it is often necessary to bar other threads from reading, in order to prevent a reader from interrupting a modification in progress and reading inconsistent or invalid data.

As in the producer-consumer problem, the solution is asymmetric. Readers and writers execute different code before entering the critical section. The synchronization constraints are:

1. Any number of readers can be in the critical section simultaneously.
2. Writers must have exclusive access to the critical section.

In other words, a writer cannot enter the critical section while any other thread (reader or writer) is there, and while the writer is there, no other thread may enter.

The exclusion pattern here might be called **categorical mutual exclusion**. A thread in the critical section does not necessarily exclude other threads, but the presence of one category in the critical section excludes other categories.

Puzzle: Use semaphores to enforce these constraints, while allowing readers and writers to access the data structure, and avoiding the possibility of deadlock.

4.2.1 Readers-writers hint

Here is a set of variables that is sufficient to solve the problem.

Listing 4.13: Readers-writers initialization

```
int readers = 0
mutex = Semaphore(1)
roomEmpty = Semaphore(1)
```

The counter `readers` keeps track of how many readers are in the room. `mutex` protects the shared counter.

`roomEmpty` is 1 if there are no threads (readers or writers) in the critical section, and 0 otherwise. This demonstrates the naming convention I use for semaphores that indicate a condition. In this convention, "wait" usually means "wait for the condition to be true" and "signal" means "signal that the condition is true".

4.2.2 Readers-writers solution

The code for writers is simple. If the critical section is empty, a writer may enter, but entering has the effect of excluding all other threads:

Listing 4.14: Writers solution

```
roomEmpty.wait()
    critical section for writers
roomEmpty.signal()
```

When the writer exits, can it be sure that the room is now empty? Yes, because it knows that no other thread can have entered while it was there.

The code for readers is similar to the barrier code we saw in the previous section. We keep track of the number of readers in the room so that we can give a special assignment to the first to arrive and the last to leave.

The first reader that arrives has to wait for `roomEmpty`. If the room is empty, then the reader proceeds and, at the same time, bars writers. Subsequent readers can still enter because none of them will try to wait on `roomEmpty`.

If a reader arrives while there is a writer in the room, it waits on `roomEmpty`. Since it holds the mutex, any subsequent readers queue on `mutex`.

Listing 4.15: Readers solution

```
mutex.wait()
    readers += 1
    if readers == 1:
        roomEmpty.wait()   # first in locks
mutex.signal()

# critical section for readers

mutex.wait()
    readers -= 1
    if readers == 0:
        roomEmpty.signal() # last out unlocks
mutex.signal()
```

The code after the critical section is similar. The last reader to leave the room turns out the lights—that is, it signals `roomEmpty`, possibly allowing a waiting writer to enter.

Again, to demonstrate that this code is correct, it is useful to assert and demonstrate a number of claims about how the program must behave. Can you convince yourself that the following are true?

- Only one reader can queue waiting for `roomEmpty`, but several writers might be queued.
- When a reader signals `roomEmpty` the room must be empty.

Patterns similar to this reader code are common: the first thread into a section locks a semaphore (or queues) and the last one out unlocks it. In fact, it is so common we should give it a name and wrap it up in an object.

The name of the pattern is **Lightswitch**, by analogy with the pattern where the first person into a room turns on the light (locks the mutex) and the last one out turns it off (unlocks the mutex). Here is a class definition for a Lightswitch:

Listing 4.16: Lightswitch definition

```
class Lightswitch:
    def __init__(self):
        self.counter = 0
        self.mutex = Semaphore(1)

    def lock(self, semaphore):
        self.mutex.wait()
            self.counter += 1
            if self.counter == 1:
                semaphore.wait()
        self.mutex.signal()

    def unlock(self, semaphore):
        self.mutex.wait()
            self.counter -= 1
            if self.counter == 0:
                semaphore.signal()
        self.mutex.signal()
```

`lock` takes one parameter, a semaphore that it will check and possibly hold. If the semaphore is locked, the calling thread blocks on `semaphore` and all subsequent threads block on `self.mutex`. When the semaphore is unlocked, the first waiting thread locks it again and all waiting threads proceed.

If the semaphore is initially unlocked, the first thread locks it and all subsequent threads proceed.

`unlock` has no effect until every thread that called `lock` also calls `unlock`. When the last thread calls `unlock`, it unlocks the semaphore.

Using these functions, we can rewrite the reader code more simply:

Listing 4.17: Readers-writers initialization

```
readLightswitch = Lightswitch()
roomEmpty = Semaphore(1)
```

`readLightswitch` is a shared `Lightswitch` object whose counter is initially zero.

Listing 4.18: Readers-writers solution (reader)

```
readLightswitch.lock(roomEmpty)
# critical section
readLightswitch.unlock(roomEmpty)
```

The code for writers is unchanged.

It would also be possible to store a reference to `roomEmpty` as an attribute of the Lightswitch, rather than pass it as a parameter to `lock` and `unlock`. This alternative would be less error-prone, but I think it improves readability if each invocation of `lock` and `unlocks` specifies the semaphore it operates on.

4.2.3 Starvation

In the previous solution, is there any danger of deadlock? In order for a deadlock to occur, it must be possible for a thread to wait on a semaphore while holding another, and thereby prevent itself from being signaled.

In this example, deadlock is not possible, but there is a related problem that is almost as bad: it is possible for a writer to starve.

If a writer arrives while there are readers in the critical section, it might wait in queue forever while readers come and go. As long as a new reader arrives before the last of the current readers departs, there will always be at least one reader in the room.

This situation is not a deadlock, because some threads are making progress, but it is not exactly desirable. A program like this might work as long as the load on the system is low, because then there are plenty of opportunities for the writers. But as the load increases the behavior of the system would deteriorate quickly (at least from the point of view of writers).

Puzzle: Extend this solution so that when a writer arrives, the existing readers can finish, but no additional readers may enter.

4.2.4 No-starve readers-writers hint

Here's a hint. You can add a turnstile for the readers and allow writers to lock it. The writers have to pass through the same turnstile, but they should check the `roomEmpty` semaphore while they are inside the turnstile. If a writer gets stuck in the turnstile it has the effect of forcing the readers to queue at the turnstile. Then when the last reader leaves the critical section, we are guaranteed that at least one writer enters next (before any of the queued readers can proceed).

Listing 4.19: No-starve readers-writers initialization

```
readSwitch = Lightswitch()
roomEmpty = Semaphore(1)
turnstile = Semaphore(1)
```

`readSwitch` keeps track of how many readers are in the room; it locks `roomEmpty` when the first reader enters and unlocks it when the last reader exits.

`turnstile` is a turnstile for readers and a mutex for writers.

4.2.5 No-starve readers-writers solution

Here is the writer code:

Listing 4.20: No-starve writer solution

```
1 turnstile.wait()
2     roomEmpty.wait()
3     # critical section for writers
4 turnstile.signal()
5
6 roomEmpty.signal()
```

If a writer arrives while there are readers in the room, it will block at Line 2, which means that the turnstile will be locked. This will bar readers from entering while a writer is queued. Here is the reader code:

Listing 4.21: No-starve reader solution

```
1 turnstile.wait()
2 turnstile.signal()
3
4 readSwitch.lock(roomEmpty)
5     # critical section for readers
6 readSwitch.unlock(roomEmpty)
```

When the last reader leaves, it signals `roomEmpty`, unblocking the waiting writer. The writer immediately enters its critical section, since none of the waiting readers can pass the turnstile.

When the writer exits it signals `turnstile`, which unblocks a waiting thread, which could be a reader or a writer. Thus, this solution guarantees that at least one writer gets to proceed, but it is still possible for a reader to enter while there are writers queued.

Depending on the application, it might be a good idea to give more priority to writers. For example, if writers are making time-critical updates to a data structure, it is best to minimize the number of readers that see the old data before the writer has a chance to proceed.

In general, though, it is up to the scheduler, not the programmer, to choose which waiting thread to unblock. Some schedulers use a first-in-first-out queue, which means that threads are unblocked in the same order they queued. Other schedulers choose at random, or according to a priority scheme based on the properties of the waiting threads.

If your programming environment makes it possible to give some threads priority over others, then that is a simple way to address this issue. If not, you will have to find another way.

Puzzle: Write a solution to the readers-writers problem that gives priority to writers. That is, once a writer arrives, no readers should be allowed to enter until all writers have left the system.

4.2.6 Writer-priority readers-writers hint

As usual, the hint is in the form of variables used in the solution.

Listing 4.22: Writer-priority readers-writers initialization

```
readSwitch = Lightswitch()
writeSwitch = Lightswitch()
mutex = Semaphore(1)
noReaders = Semaphore(1)
noWriters = Semaphore(1)
```

4.2.7 Writer-priority readers-writers solution

Here is the reader code:

Listing 4.23: Writer-priority reader solution

```
noReaders.wait()
    readSwitch.lock(noWriters)
noReaders.signal()

    # critical section for readers

readSwitch.unlock(noWriters)
```

If a reader is in the critical section, it holds `noWriters`, but it doesn't hold `noReaders`. Thus if a writer arrives it can lock `noReaders`, which will cause subsequent readers to queue.

When the last reader exits, it signals `noWriters`, allowing any queued writers to proceed.

The writer code:

Listing 4.24: Writer-priority writer solution

```
writeSwitch.lock(noReaders)
    noWriters.wait()
        # critical section for writers
    noWriters.signal()
writeSwitch.unlock(noReaders)
```

When a writer is in the critical section it holds both `noReaders` and `noWriters`. This has the (relatively obvious) effect of insuring that there are no readers and no other writers in the critical section. In addition, `writeSwitch` has the (less obvious) effect of allowing multiple writers to queue on `noWriters`, but keeping `noReaders` locked while they are there. Thus, many writers can pass through the critical section without ever signaling `noReaders`. Only when the last writer exits can the readers enter.

Of course, a drawback of this solution is that now it is possible for *readers* to starve (or at least face long delays). For some applications it might be better to get obsolete data with predictable turnaround times.

4.3 No-starve mutex

In the previous section, we addressed what I'll call **categorical starvation**, in which one category of threads (readers) allows another category (writers) to starve. At a more basic level, we have to address the issue of **thread starvation**, which is the possibility that one thread might wait indefinitely while others proceed.

For most concurrent applications, starvation is unacceptable, so we enforce the requirement of **bounded waiting**, which means that the time a thread waits on a semaphore (or anywhere else, for that matter) has to be provably finite.

In part, starvation is the responsibility of the scheduler. Whenever multiple threads are ready to run, the scheduler decides which one or, on a parallel processor, which set of threads gets to run. If a thread is never scheduled, then it will starve, no matter what we do with semaphores.

So in order to say anything about starvation, we have to start with some assumptions about the scheduler. If we are willing to make a strong assumption, we can assume that the scheduler uses one of the many algorithms that can be proven to enforce bounded waiting. If we don't know what algorithm the scheduler uses, then we can get by with a weaker assumption:

> Property 1: if there is only one thread that is ready to run, the scheduler has to let it run.

If we can assume Property 1, then we can build a system that is provably free of starvation. For example, if there are a finite number of threads, then any program that contains a barrier cannot starve, since eventually all threads but one will be waiting at the barrier, at which point the last thread has to run.

In general, though, it is non-trivial to write programs that are free from starvation unless we make the stronger assumption:

> Property 2: if a thread is ready to run, then the time it waits until it runs is bounded.

In our discussion so far, we have been assuming Property 2 implicitly, and we will continue to. On the other hand, you should know that many existing systems use schedulers that do not guarantee this property strictly.

Even with Property 2, starvation rears its ugly head again when we introduce semaphores. In the definition of a semaphore, we said that when one thread executes `signal`, one of the waiting threads gets woken up. But we never said which one. In order to say anything about starvation, we have to make assumptions about the behavior of semaphores.

The weakest assumption that makes it possible to avoid starvation is:

> Property 3: if there are threads waiting on a semaphore when a thread executes `signal`, then one of the waiting threads has to be woken.

This requirement may seem obvious, but it is not trivial. It has the effect of barring one form of problematic behavior, which is a thread that signals a semaphore while other threads are waiting, and then keeps running, waits on the same semaphore, and gets its own signal! If that were possible, there would be nothing we could do to prevent starvation.

With Property 3, it becomes possible to avoid starvation, but even for something as simple as a mutex, it is not easy. For example, imagine three threads running the following code:

Listing 4.25: Mutex loop

```
while True:
    mutex.wait()
    # critical section
    mutex.signal()
```

The `while` statement is an infinite loop; in other words, as soon as a thread leaves the critical section, it loops to the top and tries to get the mutex again.

Imagine that Thread A gets the mutex and Thread B and C wait. When A leaves, B enters, but before B leaves, A loops around and joins C in the queue. When B leaves, there is no guarantee that C goes next. In fact, if A goes next, and B joins the queue, then we are back to the starting position, and we can repeat the cycle forever. C starves.

The existence of this pattern proves that the mutex is vulnerable to starvation. One solution to this problem is to change the implementation of the semaphore so that it guarantees a stronger property:

> Property 4: if a thread is waiting at a semaphore, then the number of threads that will be woken before it is bounded.

For example, if the semaphore maintains a first-in-first-out queue, then Property 4 holds because when a thread joins the queue, the number of threads ahead of it is finite, and no threads that arrive later can go ahead of it.

A semaphore that has Property 4 is sometimes called a **strong semaphore**; one that has only Property 3 is called a **weak semaphore**. We have shown that with weak semaphores, the simple mutex solution is vulnerable to starvation. In fact, Dijkstra conjectured that it is not possible to solve the mutex problem without starvation using only weak semaphores.

In 1979, J.M. Morris refuted the conjecture by solving the problem, assuming that the number of threads is finite [6]. If you are interested in this problem, the next section presents his solution. If this is not your idea of fun, you can just assume that semaphores have Property 4 and go on to Section 4.4.

Puzzle: write a solution to the mutual exclusion problem using weak semaphores. Your solution should provide the following guarantee: once a thread arrives and attempts to enter the mutex, there is a bound on the number of threads that can proceed ahead of it. You can assume that the total number of threads is finite.

4.3.1 No-starve mutex hint

Morris's solution is similar to the reusable barrier in Section 3.6. It uses two turnstiles to create two waiting rooms before the critical section. The mechanism works in two phases. During the first phase, the first turnstile is open and the second is closed, so threads accumulate in the second room. During the second phase, the first turnstile is closed, so no new threads can enter, and the second is open, so the existing threads can get to the critical section.

Although there may be an arbitrary number of threads in the waiting room, each one is guaranteed to enter the critical section before any future arrivals.

Here are the variables I used in the solution (I changed the names Morris used, trying to make the structure clearer).

Listing 4.26: No-starve mutex hint

```
room1 = room2 = 0
mutex = Semaphore(1)
t1 = Semaphore(1)
t2 = Semaphore(0)
```

`room1` and `room2` keep track of how many threads are in the waiting rooms. `mutex` helps protect the counters. `t1` and `t2` are the turnstiles.

4.3.2 No-starve mutex solution

Here is Morris's solution.

Listing 4.27: Morris's algorithm

```
1  mutex.wait()
2      room1 += 1
3  mutex.signal()
4
5  t1.wait()
6      room2 += 1
7      mutex.wait()
8      room1 -= 1
9
10     if room1 == 0:
11         mutex.signal()
12         t2.signal()
13     else:
14         mutex.signal()
15         t1.signal()
16
17 t2.wait()
18     room2 -= 1
19
20     # critical section
21
22     if room2 == 0:
23         t1.signal()
24     else:
25         t2.signal()
```

Before entering the critical section, a thread has to pass two turnstiles. These turnstiles divide the code into three "rooms". Room 1 is Lines 2– 8. Room 2 is Lines 6– 18. Room 3 is the rest. Speaking loosely, the counters `room1` and `room2` keep track of the number of threads in each room.

The counter `room1` is protected by `mutex` in the usual way, but guard duty for `room2` is split between `t1` and `t2`. Similarly, responsibility for exclusive access to the critical section involves both `t1` and `t2`. In order to enter the critical section, a thread has to hold one or the other, but not both. Then, before exiting, it gives up whichever one it has.

To understand how this solution works, start by following a single thread all the way through. When it gets to Line 8, it holds `mutex` and `t1`. Once it checks `room1`, which is 0, it can release `mutex` and then open the second turnstile, `t2`. As a result, it doesn't wait at Line 17 and it can safely decrement `room2` and enter the critical section, because any following threads have to be queued on `t1`. Leaving the critical section, it finds `room2 = 0` and releases `t1`, which brings us back to the starting state.

Of course, the situation is more interesting if there is more than one thread. In that case, it is possible that when the lead thread gets to Line 8, other threads have entered the waiting room and queued on `t1`. Since `room1 > 0`, the lead thread leaves `t2` locked and instead signals `t1` to allow a following thread to enter Room 2. Since `t2` is still locked, neither thread can enter Room 3.

Eventually (because there are a finite number of threads), a thread will get to Line 8 before another thread enters Room 1, in which case it will open `t2`, allowing any threads there to move into Room 3. The thread that opens `t2` continues to hold `t1`, so if any of the lead threads loop around, they will block at Line 5.

As each thread leaves Room 3, it signals `t2`, allowing another thread to leave Room 2. When the last thread leaves Room 2, it leaves `t2` locked and opens `t1`, which brings us back to the starting state.

To see how this solution avoids starvation, it helps to think of its operation in two phases. In the first phase, threads check into Room 1, increment `room1`, and then cascade into Room 2 one at a time. The only way to keep a `t2` locked is to maintain a procession of threads through Room 1. Because there are a finite number of threads, the procession has to end eventually, at which point `t1` stays locked and `t2` opens.

In the second phase, threads cascade into Room 3. Because there are a finite number of threads in Room 2, and no new threads can enter, eventually the last thread leaves, at which point `t2` locks and `t1` opens.

At the end of the first phase, we know that there are no threads waiting at `t1`, because `room1 = 0`. And at the end of the second phase, we know that there are no threads waiting at `t2` because `room2 = 0`.

With a finite number of threads, starvation is only possible if one thread can loop around and overtake another. But the two-turnstile mechanism makes that impossible, so starvation is impossible.

The moral of this story is that with weak semaphores, it is very difficult to prevent starvation, even for the simplest synchronization problems. In the rest of this book, when we discuss starvation, we will assume strong semaphores.

4.4 Dining philosophers

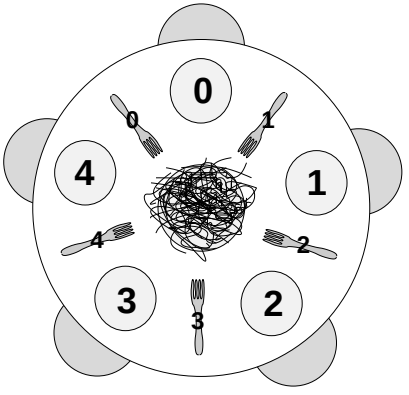
The Dining Philosophers Problem was proposed by Dijkstra in 1965, when dinosaurs ruled the earth [3]. It appears in a number of variations, but the standard features are a table with five plates, five forks (or chopsticks) and a big bowl of spaghetti. Five philosophers, who represent interacting threads, come to the table and execute the following loop:

Listing 4.28: Basic philosopher loop

```
while True:
   think()
   get_forks()
   eat()
   put_forks()
```

The forks represent resources that the threads have to hold exclusively in order to make progress. The thing that makes the problem interesting, unrealistic, and unsanitary, is that the philosophers need *two* forks to eat, so a hungry philosopher might have to wait for a neighbor to put down a fork.

Assume that the philosophers have a local variable `i` that identifies each philosopher with a value in (0..4). Similarly, the forks are numbered from 0 to 4, so that Philosopher i has fork i on the right and fork $i + 1$ on the left. Here is a diagram of the situation:



Assuming that the philosophers know how to `think` and `eat`, our job is to write a version of `get_forks` and `put_forks` that satisfies the following constraints:

- Only one philosopher can hold a fork at a time.
- It must be impossible for a deadlock to occur.
- It must be impossible for a philosopher to starve waiting for a fork.
- It must be possible for more than one philosopher to eat at the same time.

The last requirement is one way of saying that the solution should be efficient; that is, it should allow the maximum amount of concurrency.

We make no assumption about how long `eat` and `think` take, except that `eat` has to terminate eventually. Otherwise, the third constraint is impossible—if a philosopher keeps one of the forks forever, nothing can prevent the neighbors from starving.

To make it easy for philosophers to refer to their forks, we can use the functions `left` and `right`:

Listing 4.29: Which fork?

```
def left(i): return i
def right(i): return (i + 1) % 5
```

The `%` operator wraps around when it gets to 5, so `(4 + 1) % 5 = 0`.

Since we have to enforce exclusive access to the forks, it is natural to use a list of Semaphores, one for each fork. Initially, all the forks are available.

Listing 4.30: Variables for dining philosophers

```
forks = [Semaphore(1) for i in range(5)]
```

This notation for initializing a list might be unfamiliar to readers who don't use Python. The `range` function returns a list with 5 elements; for each element of this list, Python creates a Semaphore with initial value 1 and assembles the result in a list named `forks`.

Here is an initial attempt at `get_fork` and `put_fork`:

Listing 4.31: Dining philosophers non-solution

```
def get_forks(i):
    fork[right(i)].wait()
    fork[left(i)].wait()

def put_forks(i):
    fork[right(i)].signal()
    fork[left(i)].signal()
```

It's clear that this solution satisfies the first constraint, but we can be pretty sure it doesn't satisfy the other two, because if it did, this wouldn't be an interesting problem and you would be reading Chapter 5.

Puzzle: what's wrong?

4.4.1 Deadlock #5

The problem is that the table is round. As a result, each philosopher can pick up a fork and then wait forever for the other fork. Deadlock!

Puzzle: write a solution to this problem that prevents deadlock.

Hint: one way to avoid deadlock is to think about the conditions that make deadlock possible and then change one of those conditions. In this case, the deadlock is fairly fragile—a very small change breaks it.

4.4.2 Dining philosophers hint #1

If only four philosophers are allowed at the table at a time, deadlock is impossible.

First, convince yourself that this claim is true, then write code that limits the number of philosophers at the table.

4.4.3 Dining philosophers solution #1

If there are only four philosophers at the table, then in the worst case each one picks up a fork. Even then, there is a fork left on the table, and that fork has two neighbors, each of which is holding another fork. Therefore, either of these neighbors can pick up the remaining fork and eat.

We can control the number of philosophers at the table with a Multiplex named `footman` that is initialized to 4. Then the solution looks like this:

Listing 4.32: Dining philosophers solution #1

```
def get_forks(i):
    footman.wait()
    fork[right(i)].wait()
    fork[left(i)].wait()

def put_forks(i):
    fork[right(i)].signal()
    fork[left(i)].signal()
    footman.signal()
```

In addition to avoiding deadlock, this solution also guarantees that no philosopher starves. Imagine that you are sitting at the table and both of your neighbors are eating. You are blocked waiting for your right fork. Eventually your right neighbor will put it down, because `eat` can't run forever. Since you are the only thread waiting for that fork, you will necessarily get it next. By a similar argument, you cannot starve waiting for your left fork.

Therefore, the time a philosopher can spend at the table is bounded. That implies that the wait time to get into the room is also bounded, as long as `footman` has Property 4 (see Section 4.3).

This solution shows that by controlling the number of philosophers, we can avoid deadlock. Another way to avoid deadlock is to change the order in which the philosophers pick up forks. In the original non-solution, the philosophers are "righties"; that is, they pick up the right fork first. But what happens if Philosopher 0 is a leftie?

Puzzle: prove that if there is at least one leftie and at least one rightie, then deadlock is not possible.

Hint: deadlock can only occur when all 5 philosophers are holding one fork and waiting, forever, for the other. Otherwise, one of them could get both forks, eat, and leave.

The proof works by contradiction. First, assume that deadlock is possible. Then choose one of the supposedly deadlocked philosophers. If she's a leftie, you can prove that the philosophers are all lefties, which is a contradiction. Similarly, if she's a rightie, you can prove that they are all righties. Either way you get a contradiction; therefore, deadlock is not possible.

4.4.4 Dining philosopher's solution #2

In the asymmetric solution to the Dining philosophers problem, there has to be at least one leftie and at least one rightie at the table. In that case, deadlock is impossible. The previous hint outlines the proof. Here are the details.

Again, if deadlock is possible, it occurs when all 5 philosophers are holding one fork and waiting for the other. If we assume that Philosopher j is a leftie, then she must be holding her left fork and waiting for her right. Therefore her neighbor to the right, Philosopher k, must be holding his left fork and waiting for his right neighbor; in other words, Philosopher k must be a leftie. Repeating the same argument, we can prove that the philosophers are all lefties, which contradicts the original claim that there is at least one rightie. Therefore deadlock is not possible.

The same argument we used for the previous solution also proves that starvation is impossible for this solution.

4.4.5 Tanenbaum's solution

There is nothing wrong with the previous solutions, but just for completeness, let's look at some alternatives. One of the best known is the one that appears in Tanenbaum's popular operating systems textbook [12]. For each philosopher there is a state variable that indicates whether the philosopher is thinking, eating, or waiting to eat ("hungry") and a semaphore that indicates whether the philosopher can start eating. Here are the variables:

Listing 4.33: Variables for Tanenbaum's solution

```
state = ['thinking'] * 5
sem = [Semaphore(0) for i in range(5)]
mutex = Semaphore(1)
```

The initial value of `state` is a list of 5 copies of `'thinking'`. `sem` is a list of 5 semaphores with the initial value 0. Here is the code:

Listing 4.34: Tanenbaum's solution

```
def get_fork(i):
    mutex.wait()
    state[i] = 'hungry'
    test(i)
    mutex.signal()
    sem[i].wait()

def put_fork(i):
    mutex.wait()
    state[i] = 'thinking'
    test(right(i))
    test(left(i))
    mutex.signal()

def test(i):
    if state[i] == 'hungry' and
    state (left (i)) != 'eating' and
    state (right (i)) != 'eating':
        state[i] = 'eating'
        sem[i].signal()
```

The `test` function checks whether the ith philosopher can start eating, which he can if he is hungry and neither of his neighbors are eating. If so, the `test` signals semaphore i.

There are two ways a philosopher gets to eat. In the first case, the philosopher executes `get_forks`, finds the forks available, and proceeds immediately. In the second case, one of the neighbors is eating and the philosopher blocks on its own semaphore. Eventually, one of the neighbors will finish, at which point it executes `test` on both of its neighbors. It is possible that both tests

will succeed, in which case the neighbors can run concurrently. The order of the two tests doesn't matter.

In order to access `state` or invoke `test`, a thread has to hold `mutex`. Thus, the operation of checking and updating the array is atomic. Since a philosopher can only proceed when we know both forks are available, exclusive access to the forks is guaranteed.

No deadlock is possible, because the only semaphore that is accessed by more than one philosopher is `mutex`, and no thread executes `wait` while holding `mutex`.

But again, starvation is tricky.

Puzzle: Either convince yourself that Tanenbaum's solution prevents starvation or find a repeating pattern that allows a thread to starve while other threads make progress.

4.4.6 Starving Tanenbaums

Unfortunately, this solution is not starvation-free. Gingras demonstrated that there are repeating patterns that allow a thread to wait forever while other threads come and go [4].

Imagine that we are trying to starve Philosopher 0. Initially, 2 and 4 are at the table and 1 and 3 are hungry. Imagine that 2 gets up and 1 sit downs; then 4 gets up and 3 sits down. Now we are in the mirror image of the starting position.

If 3 gets up and 4 sits down, and then 1 gets up and 2 sits down, we are back where we started. We could repeat the cycle indefinitely and Philosopher 0 would starve.

So, Tanenbaum's solution doesn't satisfy all the requirements.

4.5 Cigarette smokers problem

The cigarette smokers problem problem was originally presented by Suhas Patil [8], who claimed that it cannot be solved with semaphores. That claim comes with some qualifications, but in any case the problem is interesting and challenging.

Four threads are involved: an agent and three smokers. The smokers loop forever, first waiting for ingredients, then making and smoking cigarettes. The ingredients are tobacco, paper, and matches.

We assume that the agent has an infinite supply of all three ingredients, and each smoker has an infinite supply of one of the ingredients; that is, one smoker has matches, another has paper, and the third has tobacco.

The agent repeatedly chooses two different ingredients at random and makes them available to the smokers. Depending on which ingredients are chosen, the smoker with the complementary ingredient should pick up both resources and proceed.

For example, if the agent puts out tobacco and paper, the smoker with the matches should pick up both ingredients, make a cigarette, and then signal the agent.

To explain the premise, the agent represents an operating system that allocates resources, and the smokers represent applications that need resources. The problem is to make sure that if resources are available that would allow one more applications to proceed, those applications should be woken up. Conversely, we want to avoid waking an application if it cannot proceed.

Based on this premise, there are three versions of this problem that often appear in textbooks:

The impossible version: Patil's version imposes restrictions on the solution. First, you are not allowed to modify the agent code. If the agent represents an operating system, it makes sense to assume that you don't want to modify it every time a new application comes along. The second restriction is that you can't use conditional statements or an array of semaphores. With these constraints, the problem cannot be solved, but as Parnas points out, the second restriction is pretty artificial [7]. With constraints like these, a lot of problems become unsolvable.

The interesting version: This version keeps the first restriction—you can't change the agent code—but it drops the others.

The trivial version: In some textbooks, the problem specifies that the agent should signal the smoker that should go next, according to the ingredients that are available. This version of the problem is uninteresting because it makes the whole premise, the ingredients and the cigarettes, irrelevant. Also, as a practical matter, it is probably not a good idea to require the agent to know about the other threads and what they are waiting for. Finally, this version of the problem is just too easy.

Naturally, we will focus on the interesting version. To complete the statement of the problem, we need to specify the agent code. The agent uses the following semaphores:

Listing 4.35: Agent semaphores

```
agentSem = Semaphore(1)
tobacco = Semaphore(0)
paper = Semaphore(0)
match = Semaphore(0)
```

The agent is actually made up of three concurrent threads, Agent A, Agent B and Agent C. Each waits on `agentSem`; each time `agentSem` is signaled, one of the Agents wakes up and provides ingredients by signaling two semaphores.

Listing 4.36: Agent A code

```
agentSem.wait()
tobacco.signal()
paper.signal()
```

Listing 4.37: Agent B code

```
agentSem.wait()
paper.signal()
match.signal()
```

Listing 4.38: Agent C code

```
agentSem.wait()
tobacco.signal()
match.signal()
```

This problem is hard because the natural solution does not work. It is tempting to write something like:

Listing 4.39: Smoker with matches

```
tobacco.wait()
paper.wait()
agentSem.signal()
```

Listing 4.40: Smoker with tobacco

```
paper.wait()
match.wait()
agentSem.signal()
```

Listing 4.41: Smoker with paper

```
tobacco.wait()
match.wait()
agentSem.signal()
```

What's wrong with this solution?

4.5.1 Deadlock #6

The problem with the previous solution is the possibility of deadlock. Imagine that the agent puts out tobacco and paper. Since the smoker with matches is waiting on `tobacco`, it might be unblocked. But the smoker with tobacco is waiting on `paper`, so it is possible (even likely) that it will also be unblocked. Then the first thread will block on `paper` and the second will block on `match`. Deadlock!

4.5.2 Smokers problem hint

The solution proposed by Parnas uses three helper threads called "pushers" that respond to the signals from the agent, keep track of the available ingredients, and signal the appropriate smoker.

The additional variables and semaphores are

Listing 4.42: Smokers problem hint

```
isTobacco = isPaper = isMatch = False
tobaccoSem = Semaphore(0)
paperSem = Semaphore(0)
matchSem = Semaphore(0)
```

The boolean variables indicate whether or not an ingredient is on the table. The pushers use `tobaccoSem` to signal the smoker with tobacco, and the other semaphores likewise.

4.5.3 Smoker problem solution

Here is the code for one of the pushers:

Listing 4.43: Pusher A

```
tobacco.wait()
mutex.wait()
    if isPaper:
        isPaper = False
        matchSem.signal()
    elif isMatch:
        isMatch = False
        paperSem.signal()
    else:
        isTobacco = True
mutex.signal()
```

This pusher wakes up any time there is tobacco on the table. If it finds `isPaper` true, it knows that Pusher B has already run, so it can signal the smoker with matches. Similarly, if it finds a match on the table, it can signal the smoker with paper.

But if Pusher A runs first, then it will find both `isPaper` and `isMatch` false. It cannot signal any of the smokers, so it sets `isTobacco`.

The other pushers are similar. Since the pushers do all the real work, the smoker code is trivial:

Listing 4.44: Smoker with tobacco

```
tobaccoSem.wait()
makeCigarette()
agentSem.signal()
smoke()
```

Parnas presents a similar solution that assembles the boolean variables, bitwise, into an integer, and then uses the integer as an index into an array of semaphores. That way he can avoid using conditionals (one of the artificial constraints). The resulting code is a bit more concise, but its function is not as obvious.

4.5.4 Generalized Smokers Problem

Parnas suggested that the smokers problem becomes more difficult if we modify the agent, eliminating the requirement that the agent wait after putting out ingredients. In this case, there might be multiple instances of an ingredient on the table.

Puzzle: modify the previous solution to deal with this variation.

4.5.5 Generalized Smokers Problem Hint

If the agents don't wait for the smokers, ingredients might accumulate on the table. Instead of using boolean values to keep track of ingredients, we need integers to count them.

Listing 4.45: Generalized Smokers problem hint

```
numTobacco = numPaper = numMatch = 0
```

4.5.6 Generalized Smokers Problem Solution

Here is the modified code for Pusher A:

Listing 4.46: Pusher A

```
tobacco.wait()
mutex.wait()
    if numPaper:
        numPaper -= 1
        matchSem.signal()
    elif numMatch:
        numMatch -= 1
        paperSem.signal()
    else:
        numTobacco += 1
mutex.signal()
```

One way to visualize this problem is to imagine that when an Agent runs, it creates two pushers, gives each of them one ingredient, and puts them in a room with all the other pushers. Because of the mutex, the pushers file into a room where there are three sleeping smokers and a table. One at a time, each pusher enters the room and checks the ingredients on the table. If he can assemble a complete set of ingredients, he takes them off the table and wakes the corresponding smoker. If not, he leaves his ingredient on the table and leaves without waking anyone.

This is an example of a pattern we will see several times, which I call a **scoreboard**. The variables `numPaper`, `numTobacco` and `numMatch` keep track of the state of the system. As each thread files through the mutex, it checks the state as if looking at the scoreboard, and reacts accordingly.

Chapter 5

Less classical synchronization problems

5.1 The dining savages problem

This problem is from Andrews's *Concurrent Programming* [1].

> A tribe of savages eats communal dinners from a large pot that can hold M servings of stewed missionary[1]. When a savage wants to eat, he helps himself from the pot, unless it is empty. If the pot is empty, the savage wakes up the cook and then waits until the cook has refilled the pot.

Any number of savage threads run the following code:

Listing 5.1: Unsynchronized savage code

```
while True:
    getServingFromPot()
    eat()
```

And one cook thread runs this code:

Listing 5.2: Unsynchronized cook code

```
while True:
    putServingsInPot(M)
```

[1] This problem is based on a cartoonish representation of the history of Western missionaries among hunter-gatherer societies. Some humor is intended by the allusion to the Dining Philosophers problem, but the representation of "savages" here isn't intended to be any more realistic than the previous representation of philosophers. If you are interested in hunter-gatherer societies, I recommend Jared Diamond's *Guns, Germs and Steel*, Napoleon Chagnon's *The Yanomamo*, and Redmond O'Hanlon's *In Trouble Again*, but not Tierney's *Darkness in El Dorado*, which I believe is unreliable.

The synchronization constraints are:

- Savages cannot invoke `getServingFromPot` if the pot is empty.
- The cook can invoke `putServingsInPot` only if the pot is empty.

Puzzle: Add code for the savages and the cook that satisfies the synchronization constraints.

5.1.1 Dining Savages hint

It is tempting to use a semaphore to keep track of the number of servings, as in the producer-consumer problem. But in order to signal the cook when the pot is empty, a thread would have to know before decrementing the semaphore whether it would have to wait, and we just can't do that.

An alternative is to use a scoreboard to keep track of the number of servings. If a savage finds the counter at zero, he wakes the cook and waits for a signal that the pot is full. Here are the variables I used:

Listing 5.3: Dining Savages hint

```
servings = 0
mutex = Semaphore(1)
emptyPot = Semaphore(0)
fullPot = Semaphore(0)
```

Not surprisingly, `emptyPot` indicates that the pot is empty and `fullPot` indicates that the pot is full.

5.1.2 Dining Savages solution

My solution is a combination of the scoreboard pattern with a rendezvous. Here is the code for the cook:

Listing 5.4: Dining Savages solution (cook)

```
while True:
    emptyPot.wait()
    putServingsInPot(M)
    fullPot.signal()
```

The code for the savages is only a little more complicated. As each savage passes through the mutex, he checks the pot. If it is empty, he signals the cook and waits. Otherwise, he decrements `servings` and gets a serving from the pot.

Listing 5.5: Dining Savages solution (savage)

```
while True:
    mutex.wait()
        if servings == 0:
            emptyPot.signal()
            fullPot.wait()
            servings = M
        servings -= 1
        getServingFromPot()
    mutex.signal()

    eat()
```

It might seem odd that the savage, rather than the cook, sets `servings = M`. That's not really necessary; when the cook runs `putServingsInPot`, we know that the savage that holds the mutex is waiting on `fullPot`. So the cook could access `servings` safely. But in this case, I decided to let the savage do it so that it is clear from looking at the code that all accesses to `servings` are inside the mutex.

This solution is deadlock-free. The only opportunity for deadlock comes when the savage that holds `mutex` waits for `fullPot`. While he is waiting, other savages are queued on `mutex`. But eventually the cook will run and signal `fullPot`, which allows the waiting savage to resume and release the mutex.

Does this solution assume that the pot is thread-safe, or does it guarantee that `putServingsInPot` and `getServingFromPot` are executed exclusively?

5.2 The barbershop problem

The original barbershop problem was proposed by Dijkstra. A variation of it appears in Silberschatz and Galvin's *Operating Systems Concepts* [10].

> A barbershop consists of a waiting room with n chairs, and the barber room containing the barber chair. If there are no customers to be served, the barber goes to sleep. If a customer enters the barbershop and all chairs are occupied, then the customer leaves the shop. If the barber is busy, but chairs are available, then the customer sits in one of the free chairs. If the barber is asleep, the customer wakes up the barber. Write a program to coordinate the barber and the customers.

To make the problem a little more concrete, I added the following information:

- Customer threads should invoke a function named `getHairCut`.
- If a customer thread arrives when the shop is full, it can invoke `balk`, which does not return.
- Barber threads should invoke `cutHair`.
- When the barber invokes `cutHair` there should be exactly one thread invoking `getHairCut` concurrently.

5.2.1 Barbershop hint

Listing 5.6: Barbershop hint

```
customers = 0
mutex = Semaphore(1)
customer = Semaphore(0)
barber = Semaphore(0)
```

`customers` counts the number of customers in the shop; it is protected by `mutex`.

The barber waits on `customer` until a customer enters the shop, then the customer waits on `barber` until the barber signals him to take a seat.

5.2.2 Barbershop solution

Again, my solution combines a scoreboard and a rendezvous. Here is the code for customers:

Listing 5.7: Barbershop solution (customer)

```
mutex.wait()
    if customers == n+1:
        mutex.signal()
        balk()
    customers += 1
mutex.signal()

customer.signal()
barber.wait()
getHairCut()

mutex.wait()
    customers -= 1
mutex.signal()
```

If there are n customers in the waiting room and one in the barber chair, then the shop is full and any customers that arrive immediately invoke `balk`. Otherwise each customer signals `customer` and waits on `barber`.

Here is the code for barbers:

Listing 5.8: Barbershop solution (barber)

```
customer.wait()
barber.signal()
cutHair()
```

Each time a customer signals, the barber wakes, signals `barber`, and gives one hair cut. If another customer arrives while the barber is busy, then on the next iteration the barber will pass the `customer` semaphore without sleeping.

The names for `customer` and `barber` are based on the naming convention for a rendezvous, so `customer.wait()` means "wait for a customer," not "customers wait here."

5.3 Hilzer's Barbershop problem

William Stallings [11] presents a more complicated version of the barbershop problem, which he attributes to Ralph Hilzer at the California State University at Chico.

> Our barbershop has three chairs, three barbers, and a waiting area that can accommodate four customers on a sofa and that has standing room for additional customers. Fire codes limit the total number of customers in the shop to 20.
>
> A customer will not enter the shop if it is filled to capacity with other customers. Once inside, the customer takes a seat on the sofa or stands if the sofa is filled. When a barber is free, the customer that has been on the sofa the longest is served and, if there are any standing customers, the one that has been in the shop the longest takes a seat on the sofa. When a customer's haircut is finished, any barber can accept payment, but because there is only one cash register, payment is accepted for one customer at a time. The barbers divide their time among cutting hair, accepting payment, and sleeping in their chair waiting for a customer.

In other words, the following synchronization constraints apply:

- Customers invoke the following functions in order: `enterShop`, `sitOnSofa`, `sitInBarberChair`, `pay`, `exitShop`.
- Barbers invoke `cutHair` and `acceptPayment`.
- Customers cannot invoke `enterShop` if the shop is at capacity.
- If the sofa is full, an arriving customer cannot invoke `sitOnSofa` until one of the customers on the sofa invokes `sitInBarberChair`.
- If all three barber chairs are busy, an arriving customer cannot invoke `sitInBarberChair` until one of the customers in a chair invokes `pay`.
- The customer has to `pay` before the barber can `acceptPayment`.
- The barber must `acceptPayment` before the customer can `exitShop`.

One difficulty with this problem is that in each waiting area (the sofa and the standing room), customers have to be served in first-in-first-out (FIFO) order. If our implementation of semaphores happens to enforce FIFO queueing, then we can use nested multiplexes to create the waiting areas. Otherwise we can use Fifo objects as defined in Section 3.8.

Puzzle: Write code that enforces the synchronization constraints for Hilzer's barbershop.

5.3.1 Hilzer's barbershop hint

Here are the variables I used in my solution:

Listing 5.9: Hilzer's barbershop hint

```
customers = 0
mutex = Semaphore(1)
standingRoom = Fifo(16)
sofa = Fifo(4)
chair = Semaphore(3)
barber = Semaphore(0)
customer = Semaphore(0)
cash = Semaphore(0)
receipt = Semaphore(0)
```

`mutex` protects `customers`, which keeps track of the number of customers in the shop so that if a thread arrives when the shop is full, it can exit. `standingRoom` and `sofa` are Fifos that represent the waiting areas. `chair` is a multiplex that limits the number of customers in the seating area.

The other semaphores are used for the rendezvous between the barber and the customers. The customer signals `barber` and then wait on `customer`. Then the customer signals `cash` and waits on `receipt`.

5.3.2 Hilzer's barbershop solution

There is nothing here that is new; it's just a combination of patterns we have seen before.

Listing 5.10: Hilzer's barbershop solution (customer)

```
mutex.wait()
    if customers == 20:
        mutex.signal()
        exitShop()
    customers += 1
mutex.signal()

standingRoom.wait()
enterShop()

sofa.wait()
sitOnSofa()
standingRoom.signal()

chair.wait()
sitInBarberChair()
sofa.signal()

customer.signal()
barber.wait()
getHairCut()

pay()
cash.signal()
receipt.wait()

mutex.wait()
    customers -= 1
mutex.signal()

exitShop()
```

The mechanism that counts the number of customers and allows threads to exit is the same as in the previous problem.

In order to maintain FIFO order for the whole system, threads cascade from `standingRoom` to `sofa` to `chair`; as each thread moves to the next stage, it signals the previous stage.

The exchange with the barber is basically two consecutive rendezvouses[2]

[2]The plural of rendezvous is rare, and not all dictionaries agree about what it is. Another possibility is that the plural is also spelled "rendezvous," but the final "s" is pronounced.

The code for the barber is self-explanatory:

Listing 5.11: Hilzer's barbershop solution (barber)

```
customer.wait()
barber.signal()
cutHair()

cash.wait()
acceptPayment()
receipt.signal()
```

If two customers signal `cash` concurrently, there is no way to know which waiting barber will get which signal, but the problem specification says that's ok. Any barber can take money from any customer.

5.4 The Santa Claus problem

This problem is from William Stallings's *Operating Systems* [11], but he attributes it to John Trono of St. Michael's College in Vermont.

> Stand Claus sleeps in his shop at the North Pole and can only be awakened by either (1) all nine reindeer being back from their vacation in the South Pacific, or (2) some of the elves having difficulty making toys; to allow Santa to get some sleep, the elves can only wake him when three of them have problems. When three elves are having their problems solved, any other elves wishing to visit Santa must wait for those elves to return. If Santa wakes up to find three elves waiting at his shop's door, along with the last reindeer having come back from the tropics, Santa has decided that the elves can wait until after Christmas, because it is more important to get his sleigh ready. (It is assumed that the reindeer do not want to leave the tropics, and therefore they stay there until the last possible moment.) The last reindeer to arrive must get Santa while the others wait in a warming hut before being harnessed to the sleigh.

Here are some addition specifications:

- After the ninth reindeer arrives, Santa must invoke `prepareSleigh`, and then all nine reindeer must invoke `getHitched`.
- After the third elf arrives, Santa must invoke `helpElves`. Concurrently, all three elves should invoke `getHelp`.
- All three elves must invoke `getHelp` before any additional elves enter (increment the elf counter).

Santa should run in a loop so he can help many sets of elves. We can assume that there are exactly 9 reindeer, but there may be any number of elves.

5.4.1 Santa problem hint

Listing 5.12: Santa problem hint

```
elves = 0
reindeer = 0
santaSem = Semaphore(0)
reindeerSem = Semaphore(0)
elfTex = Semaphore(1)
mutex = Semaphore(1)
```

`elves` and `reindeer` are counters, both protected by `mutex`. Elves and reindeer get `mutex` to modify the counters; Santa gets it to check them.

Santa waits on `santaSem` until either an elf or a reindeer signals him.

The reindeer wait on `reindeerSem` until Santa signals them to enter the paddock and get hitched.

The elves use `elfTex` to prevent additional elves from entering while three elves are being helped.

5.4.2 Santa problem solution

Santa's code is pretty straightforward. Remember that it runs in a loop.

Listing 5.13: Santa problem solution (Santa)

```
santaSem.wait()
mutex.wait()
    if reindeer == 9:
        prepareSleigh()
        reindeerSem.signal(9)
    else if elves == 3:
        helpElves()
mutex.signal()
```

When Santa wakes up, he checks which of the two conditions holds and either deals with the reindeer or the waiting elves. If there are nine reindeer waiting, Santa invokes `prepareSleigh`, then signals `reindeerSem` nine times, allowing the reindeer to invoke `getHitched`. If there are elves waiting, Santa just invokes `helpElves`. There is no need for the elves to wait for Santa; once they signal `santaSem`, they can invoke `getHelp` immediately.

Here is the code for reindeer:

Listing 5.14: Santa problem solution (reindeer)

```
mutex.wait()
    reindeer += 1
    if reindeer == 9:
        santaSem.signal()
mutex.signal()

reindeerSem.wait()
getHitched()
```

The ninth reindeer signals Santa and then joins the other reindeer waiting on `reindeerSem`. When Santa signals, the reindeer all execute `getHitched`.

The elf code is similar, except that when the third elf arrives it has to bar subsequent arrivals until the first three have executed `getHelp`.

Listing 5.15: Santa problem solution (elves)

```
elfTex.wait()
mutex.wait()
    elves += 1
    if elves == 3:
        santaSem.signal()
    else
        elfTex.signal()
mutex.signal()

getHelp()

mutex.wait()
    elves -= 1
    if elves == 0:
       elfTex.signal()
mutex.signal()
```

The first two elves release `elfTex` at the same time they release the `mutex`, but the last elf holds `elfTex`, barring other elves from entering until all three elves have invoked `getHelp`.

The last elf to leave releases `elfTex`, allowing the next batch of elves to enter.

5.5 Building H_2O

This problem has been a staple of the Operating Systems class at U.C. Berkeley for at least a decade. It seems to be based on an exercise in Andrews's *Concurrent Programming* [1].

There are two kinds of threads, oxygen and hydrogen. In order to assemble these threads into water molecules, we have to create a barrier that makes each thread wait until a complete molecule is ready to proceed.

As each thread passes the barrier, it should invoke `bond`. You must guarantee that all the threads from one molecule invoke `bond` before any of the threads from the next molecule do.

In other words:

- If an oxygen thread arrives at the barrier when no hydrogen threads are present, it has to wait for two hydrogen threads.
- If a hydrogen thread arrives at the barrier when no other threads are present, it has to wait for an oxygen thread and another hydrogen thread.

We don't have to worry about matching the threads up explicitly; that is, the threads do not necessarily know which other threads they are paired up with. The key is just that threads pass the barrier in complete sets; thus, if we examine the sequence of threads that invoke `bond` and divide them into groups of three, each group should contain one oxygen and two hydrogen threads.

Puzzle: Write synchronization code for oxygen and hydrogen molecules that enforces these constraints.

5.5.1 H_2O hint

Here are the variables I used in my solution:

Listing 5.16: Water building hint

```
mutex = Semaphore(1)
oxygen = 0
hydrogen = 0
barrier = Barrier(3)
oxyQueue = Semaphore(0)
hydroQueue = Semaphore(0)
```

`oxygen` and `hydrogen` are counters, protected by `mutex`. `barrier` is where each set of three threads meets after invoking `bond` and before allowing the next set of threads to proceed.

`oxyQueue` is the semaphore oxygen threads wait on; `hydroQueue` is the semaphore hydrogen threads wait on. I am using the naming convention for queues, so `oxyQueue.wait()` means "join the oxygen queue" and `oxyQueue.signal()` means "release an oxygen thread from the queue."

5.5.2 H_2O solution

Initially `hydroQueue` and `oxyQueue` are locked. When an oxygen thread arrives it signals `hydroQueue` twice, allowing two hydrogens to proceed. Then the oxygen thread waits for the hydrogen threads to arrive.

Listing 5.17: Oxygen code

```
mutex.wait()
oxygen += 1
if hydrogen >= 2:
    hydroQueue.signal(2)
    hydrogen -= 2
    oxyQueue.signal()
    oxygen -= 1
else:
    mutex.signal()

oxyQueue.wait()
bond()

barrier.wait()
mutex.signal()
```

As each oxygen thread enters, it gets the mutex and checks the scoreboard. If there are at least two hydrogen threads waiting, it signals two of them and itself and then bonds. If not, it releases the mutex and waits.

After bonding, threads wait at the barrier until all three threads have bonded, and then the oxygen thread releases the mutex. Since there is only one oxygen thread in each set of three, we are guaranteed to signal `mutex` once.

The code for hydrogen is similar:

Listing 5.18: Hydrogen code

```
mutex.wait()
hydrogen += 1
if hydrogen >= 2 and oxygen >= 1:
    hydroQueue.signal(2)
    hydrogen -= 2
    oxyQueue.signal()
    oxygen -= 1
else:
    mutex.signal()

hydroQueue.wait()
bond()

barrier.wait()
```

An unusual feature of this solution is that the exit point of the mutex is ambiguous. In some cases, threads enter the mutex, update the counter, and exit the mutex. But when a thread arrives that forms a complete set, it has to keep the mutex in order to bar subsequent threads until the current set have invoked `bond`.

After invoking `bond`, the three threads wait at a barrier. When the barrier opens, we know that all three threads have invoked `bond` and that one of them holds the mutex. We don't know *which* thread holds the mutex, but it doesn't matter as long as only one of them releases it. Since we know there is only one oxygen thread, we make it do the work.

This might seem wrong, because until now it has generally been true that a thread has to hold a lock in order to release it. But there is no rule that says that has to be true. This is one of those cases where it can be misleading to think of a mutex as a token that threads acquire and release.

5.6 River crossing problem

This is from a problem set written by Anthony Joseph at U.C. Berkeley, but I don't know if he is the original author. It is similar to the H_2O problem in the sense that it is a peculiar sort of barrier that only allows threads to pass in certain combinations.

Somewhere near Redmond, Washington there is a rowboat that is used by both Linux hackers and Microsoft employees (serfs) to cross a river. The ferry can hold exactly four people; it won't leave the shore with more or fewer. To guarantee the safety of the passengers, it is not permissible to put one hacker in the boat with three serfs, or to put one serf with three hackers. Any other combination is safe.

As each thread boards the boat it should invoke a function called `board`. You must guarantee that all four threads from each boatload invoke `board` before any of the threads from the next boatload do.

After all four threads have invoked `board`, exactly one of them should call a function named `rowBoat`, indicating that that thread will take the oars. It doesn't matter which thread calls the function, as long as one does.

Don't worry about the direction of travel. Assume we are only interested in traffic going in one of the directions.

5.6.1 River crossing hint

Here are the variables I used in my solution:

Listing 5.19: River crossing hint

```
barrier = Barrier(4)
mutex = Semaphore(1)
hackers = 0
serfs = 0
hackerQueue = Semaphore(0)
serfQueue = Semaphore(0)
local isCaptain = False
```

`hackers` and `serfs` count the number of hackers and serfs waiting to board. Since they are both protected by `mutex`, we can check the condition of both variables without worrying about an untimely update. This is another example of a scoreboard.

`hackerQueue` and `serfQueue` allow us to control the number of hackers and serfs that pass. The barrier makes sure that all four threads have invoked `board` before the captain invokes `rowBoat`.

`isCaptain` is a local variable that indicates which thread should invoke `row`.

5.6.2 River crossing solution

The basic idea of this solution is that each arrival updates one of the counters and then checks whether it makes a full complement, either by being the fourth of its kind or by completing a mixed pair of pairs.

I'll present the code for hackers; the serf code is symmetric (except, of course, that it is 1000 times bigger, full of bugs, and it contains an embedded web browser):

Listing 5.20: River crossing solution

```
mutex.wait()
    hackers += 1
    if hackers == 4:
        hackerQueue.signal(4)
        hackers = 0
        isCaptain = True
    elif hackers == 2 and serfs >= 2:
        hackerQueue.signal(2)
        serfQueue.signal(2)
        serfs -= 2
        hackers = 0
        isCaptain = True
    else:
        mutex.signal()    # captain keeps the mutex

hackerQueue.wait()

board()
barrier.wait()

if isCaptain:
    rowBoat()
    mutex.signal()        # captain releases the mutex
```

As each thread files through the mutual exclusion section, it checks whether a complete crew is ready to board. If so, it signals the appropriate threads, declares itself captain, and holds the mutex in order to bar additional threads until the boat has sailed.

The barrier keeps track of how many threads have boarded. When the last thread arrives, all threads proceed. The captain invoked `row` and then (finally) releases the mutex.

5.7 The roller coaster problem

This problem is from Andrews's *Concurrent Programming* [1], but he attributes it to J. S. Herman's Master's thesis.

> Suppose there are n passenger threads and a car thread. The passengers repeatedly wait to take rides in the car, which can hold C passengers, where $C < n$. The car can go around the tracks only when it is full.

Here are some additional details:

- Passengers should invoke `board` and `unboard`.
- The car should invoke `load`, `run` and `unload`.
- Passengers cannot board until the car has invoked `load`
- The car cannot depart until C passengers have boarded.
- Passengers cannot unboard until the car has invoked `unload`.

Puzzle: Write code for the passengers and car that enforces these constraints.

5.7.1 Roller Coaster hint

Listing 5.21: Roller Coaster hint

```
mutex = Semaphore(1)
mutex2 = Semaphore(1)
boarders = 0
unboarders = 0
boardQueue = Semaphore(0)
unboardQueue = Semaphore(0)
allAboard = Semaphore(0)
allAshore = Semaphore(0)
```

`mutex` protects `passengers`, which counts the number of passengers that have invoked `boardCar`.

Passengers wait on `boardQueue` before boarding and `unboardQueue` before unboarding. `allAboard` indicates that the car is full.

5.7.2 Roller Coaster solution

Here is my code for the car thread:

Listing 5.22: Roller Coaster solution (car)

```
load()
boardQueue.signal(C)
allAboard.wait()

run()

unload()
unboardQueue.signal(C)
allAshore.wait()
```

When the car arrives, it signals C passengers, then waits for the last one to signal `allAboard`. After it departs, it allows C passengers to disembark, then waits for `allAshore`.

Listing 5.23: Roller Coaster solution (passenger)

```
boardQueue.wait()
board()

mutex.wait()
   boarders += 1
   if boarders == C:
       allAboard.signal()
       boarders = 0
mutex.signal()

unboardQueue.wait()
unboard()

mutex2.wait()
   unboarders += 1
   if unboarders == C:
       allAshore.signal()
       unboarders = 0
mutex2.signal()
```

Passengers wait for the car before boarding, naturally, and wait for the car to stop before leaving. The last passenger to board signals the car and resets the passenger counter.

5.7.3 Multi-car Roller Coaster problem

This solution does not generalize to the case where there is more than one car. In order to do that, we have to satisfy some additional constraints:

- Only one car can be boarding at a time.
- Multiple cars can be on the track concurrently.
- Since cars can't pass each other, they have to unload in the same order they boarded.
- All the threads from one carload must disembark before any of the threads from subsequent carloads.

Puzzle: modify the previous solution to handle the additional constraints. You can assume that there are m cars, and that each car has a local variable named `i` that contains an identifier between 0 and $m - 1$.

5.7.4 Multi-car Roller Coaster hint

I used two lists of semaphores to keep the cars in order. One represents the loading area and one represents the unloading area. Each list contains one semaphore for each car. At any time, only one semaphore in each list is unlocked, so that enforces the order threads can load and unload. Initially, only the semaphores for Car 0 are unlocked. As each car enters the loading (or unloading) it waits on its own semaphore; as it leaves it signals the next car in line.

Listing 5.24: Multi-car Roller Coaster hint

```
loadingArea = [Semaphore(0) for i in range(m)]
loadingArea[1].signal()
unloadingArea = [Semaphore(0) for i in range(m)]
unloadingArea[1].signal()
```

The function `next` computes the identifier of the next car in the sequence (wrapping around from $m - 1$ to 0):

Listing 5.25: Implementation of `next`

```
def next(i):
    return (i + 1) % m
```

5.7.5 Multi-car Roller Coaster solution

Here is the modified code for the cars:

Listing 5.26: Multi-car Roller Coaster solution (car)

```
loadingArea[i].wait()
load()
boardQueue.signal(C)
allAboard.wait()
loadingArea[next(i)].signal()

run()

unloadingArea[i].wait()
unload()
unboardQueue.signal(C)
allAshore.wait()
unloadingArea[next(i)].signal()
```

The code for the passengers is unchanged.

Chapter 6

Not-so-classical problems

6.1 The search-insert-delete problem

This one is from Andrews's *Concurrent Programming* [1].

> Three kinds of threads share access to a singly-linked list: searchers, inserters and deleters. Searchers merely examine the list; hence they can execute concurrently with each other. Inserters add new items to the end of the list; insertions must be mutually exclusive to preclude two inserters from inserting new items at about the same time. However, one insert can proceed in parallel with any number of searches. Finally, deleters remove items from anywhere in the list. At most one deleter process can access the list at a time, and deletion must also be mutually exclusive with searches and insertions.

Puzzle: write code for searchers, inserters and deleters that enforces this kind of three-way categorical mutual exclusion.

6.1.1 Search-Insert-Delete hint

Listing 6.1: Search-Insert-Delete hint

```
insertMutex = Semaphore(1)
noSearcher = Semaphore(1)
noInserter = Semaphore(1)
searchSwitch = Lightswitch()
insertSwitch = Lightswitch()
```

`insertMutex` ensures that only one inserter is in its critical section at a time. `noSearcher` and `noInserter` indicate (surprise) that there are no searchers and no inserters in their critical sections; a deleter needs to hold both of these to enter.

`searchSwitch` and `insertSwitch` are used by searchers and inserters to exclude deleters.

6.1.2 Search-Insert-Delete solution

Here is my solution:

Listing 6.2: Search-Insert-Delete solution (searcher)

```
searchSwitch.wait(noSearcher)
# critical section
searchSwitch.signal(noSearcher)
```

The only thing a searcher needs to worry about is a deleter. The first searcher in takes `noSearcher`; the last one out releases it.

Listing 6.3: Search-Insert-Delete solution (inserter)

```
insertSwitch.wait(noInserter)
insertMutex.wait()
# critical section
insertMutex.signal()
insertSwitch.signal(noInserter)
```

Similarly, the first inserter takes `noInserter` and the last one out releases it. Since searchers and inserters compete for different semaphores, they can be in their critical section concurrently. But `insertMutex` ensures that only one inserter is in the room at a time.

Listing 6.4: Search-Insert-Delete solution (deleter)

```
noSearcher.wait()
noInserter.wait()
# critical section
noInserter.signal()
noSearcher.signal()
```

Since the deleter holds both `noSearcher` and `noInserter`, it is guaranteed exclusive access. Of course, any time we see a thread holding more than one semaphore, we need to check for deadlocks. By trying out a few scenarios, you should be able to convince yourself that this solution is deadlock free.

On the other hand, like many categorical exclusion problems, this one is prone to starvation. As we saw in the Readers-Writers problem, we can sometimes mitigate this problem by giving priority to one category of threads according to application-specific criteria. But in general it is difficult to write an efficient solution (one that allows the maximum degree of concurrency) that avoids starvation.

6.2 The unisex bathroom problem

I wrote this problem[1] when a friend of mine left her position teaching physics at Colby College and took a job at Xerox.

She was working in a cubicle in the basement of a concrete monolith, and the nearest women's bathroom was two floors up. She proposed to the Uberboss that they convert the men's bathroom on her floor to a unisex bathroom, sort of like on Ally McBeal.

The Uberboss agreed, provided that the following synchronization constraints can be maintained:

- There cannot be men and women in the bathroom at the same time.
- There should never be more than three employees squandering company time in the bathroom.

Of course the solution should avoid deadlock. For now, though, don't worry about starvation. You may assume that the bathroom is equipped with all the semaphores you need.

[1] Later I learned that a nearly identical problem appears in Andrews's *Concurrent Programming*[1]

6.2.1 Unisex bathroom hint

Here are the variables I used in my solution:

Listing 6.5: Unisex bathroom hint

```
empty = Semaphore(1)
maleSwitch = Lightswitch()
femaleSwitch = Lightswitch()
maleMultiplex = Semaphore(3)
femaleMultiplex = Semaphore(3)
```

`empty` is 1 if the room is empty and 0 otherwise.

`maleSwitch` allows men to bar women from the room. When the first male enters, the lightswitch locks `empty`, barring women; When the last male exits, it unlocks `empty`, allowing women to enter. Women do likewise using `femaleSwitch`.

`maleMultiplex` and `femaleMultiplex` ensure that there are no more than three men and three women in the system at a time.

6.2.2 Unisex bathroom solution

Here is the female code:

Listing 6.6: Unisex bathroom solution (female)

```
femaleSwitch.lock(empty)
    femaleMultiplex.wait()
        # bathroom code here
    femaleMultiplex.signal()
female Switch.unlock(empty)
```

The male code is similar.
Are there any problems with this solution?

6.2.3 No-starve unisex bathroom problem

The problem with the previous solution is that it allows starvation. A long line of women can arrive and enter while there is a man waiting, and vice versa.

Puzzle: fix the problem.

6.2.4 No-starve unisex bathroom solution

As we have seen before, we can use a turnstile to allow one kind of thread to stop the flow of the other kind of thread. This time we'll look at the male code:

Listing 6.7: No-starve unisex bathroom solution (male)

```
turnstile.wait()
    maleSwitch.lock(empty)
turnstile.signal()

    maleMultiplex.wait()
        # bathroom code here
    maleMultiplex.signal()

maleSwitch.unlock (empty)
```

As long as there are men in the room, new arrivals will pass through the turnstile and enter. If there are women in the room when a male arrives, the male will block inside the turnstile, which will bar all later arrivals (male and female) from entering until the current occupants leave. At that point the male in the turnstile enters, possibly allowing additional males to enter.

The female code is similar, so if there are men in the room an arriving female will get stuck in the turnstile, barring additional men.

This solution may not be efficient. If the system is busy, then there will often be several threads, male and female, queued on the turnstile. Each time `empty` is signaled, one thread will leave the turnstile and another will enter. If the new thread is the opposite gender, it will promptly block, barring additional threads. Thus, there will usually be only 1-2 threads in the bathroom at a time, and the system will not take full advantage of the available concurrency.

6.3 Baboon crossing problem

This problem is adapted from Tanenbaum's *Operating Systems: Design and Implementation* [12]. There is a deep canyon somewhere in Kruger National Park, South Africa, and a single rope that spans the canyon. Baboons can cross the canyon by swinging hand-over-hand on the rope, but if two baboons going in opposite directions meet in the middle, they will fight and drop to their deaths. Furthermore, the rope is only strong enough to hold 5 baboons. If there are more baboons on the rope at the same time, it will break.

Assuming that we can teach the baboons to use semaphores, we would like to design a synchronization scheme with the following properties:

- Once a baboon has begun to cross, it is guaranteed to get to the other side without running into a baboon going the other way.
- There are never more than 5 baboons on the rope.

- A continuing stream of baboons crossing in one direction should not bar baboons going the other way indefinitely (no starvation).

I will not include a solution to this problem for reasons that should be clear.

6.4 The Modus Hall Problem

This problem was written by Nathan Karst, one of the Olin students living in Modus Hall[2] during the winter of 2005.

> After a particularly heavy snowfall this winter, the denizens of Modus Hall created a trench-like path between their cardboard shantytown and the rest of campus. Every day some of the residents walk to and from class, food and civilization via the path; we will ignore the indolent students who chose daily to drive to Tier 3. We will also ignore the direction in which pedestrians are traveling. For some unknown reason, students living in West Hall would occasionally find it necessary to venture to the Mods.
>
> Unfortunately, the path is not wide enough to allow two people to walk side-by-side. If two Mods persons meet at some point on the path, one will gladly step aside into the neck high drift to accommodate the other. A similar situation will occur if two ResHall inhabitants cross paths. If a Mods heathen and a ResHall prude meet, however, a violent skirmish will ensue with the victors determined solely by strength of numbers; that is, the faction with the larger population will force the other to wait.

This is similar to the Baboon Crossing problem (in more ways than one), with the added twist that control of the critical section is determined by majority rule. This has the potential to be an efficient and starvation-fee solution to the categorical exclusion problem.

Starvation is avoided because while one faction controls the critical section, members of the other faction accumulate in queue until they achieve a majority. Then they can bar new opponents from entering while they wait for the critical section to clear. I expect this solution to be efficient because it will tend to move threads through in batches, allowing maximum concurrency in the critical section.

Puzzle: write code that implements categorical exclusion with majority rule.

[2] Modus Hall is one of several nicknames for the modular buildings, aka Mods, that some students lived in while the second residence hall was being built.

6.4.1 Modus Hall problem hint

Here are the variables I used in my solution.

Listing 6.8: Modus problem hint

```
heathens = 0
prudes = 0
status = 'neutral'
mutex = Semaphore(1)
heathenTurn = Semaphore(1)
prudeTurn = Semaphore(1)
heathenQueue = Semaphore(0)
prudeQueue = Semaphore(0)
```

`heathens` and `prudes` are counters, and `status` records the status of the field, which can be 'neutral', 'heathens rule', 'prudes rule', 'transition to heathens' or 'transition to prudes'. All three are protected by `mutex` in the usual scoreboard pattern.

`heathenTurn` and `prudeTurn` control access to the field so that we can bar one side or the other during a transition.

`heathenQueue` and `prudeQueue` are where threads wait after checking in and before taking the field.

6.4.2 Modus Hall problem solution

Here is the code for heathens:

Listing 6.9: Modus problem solution

```
heathenTurn.wait()
heathenTurn.signal()

mutex.wait()
heathens++

if status == 'neutral':
    status = 'heathens rule'
    mutex.signal()
elif status == 'prudes rule':
    if heathens > prudes:
        status = 'transition to heathens'
        prudeTurn.wait()
    mutex.signal()
    heathenQueue.wait()
elif status == 'transition to heathens':
    mutex.signal()
    heathenQueue.wait()
else
    mutex.signal()

# cross the field

mutex.wait()
heathens--

if heathens == 0:
    if status == 'transition to prudes':
        prudeTurn.signal()
    if prudes:
        prudeQueue.signal(prudes)
        status = 'prudes rule'
    else:
        status = 'neutral'

if status == 'heathens rule':
    if prudes > heathens:
        status = 'transition to prudes'
        heathenTurn.wait()

mutex.signal()
```

As each student checks in, he has to consider the following cases:

- If the field is empty, the student lays claim for the heathens.
- If the heathens currently in charge, but the new arrival has tipped the balance, he locks the prude turnstile and the system switches to transition mode.
- If the prudes in charge, but the new arrival doesn't tip the balance, he joins the queue.
- If the system is transitioning to heathen control, the new arrival joins the queue.
- Otherwise we conclude that either the heathens are in charge, or the system is transitioning to prude control. In either case, this thread can proceed.

Similarly, as each student checks out, she has to consider several cases.

- If she is the last heathen to check out, she has to consider the following:
  - If the system is in transition, that means that the prude turnstile is locked, so she has to open it.
  - If there are prudes waiting, she signals them and updates `status` so the prudes are in charge. If not, the new status is 'neutral'.
- If she is not the last heathen to check out, she still has to check the possibility that her departure will tip the balance. In that case, she closes the heathen turnstile and starts the transition.

One potential difficulty of this solution is that any number of threads could be interrupted at Line 3, where they would have passed the turnstile but not yet checked in. Until they check in, they are not counted, so the balance of power may not reflect the number of threads that have passed the turnstile. Also, a transition ends when all the threads that have checked in have also checked out. At that point, there may be threads (of both types) that have passed the turnstile.

These behaviors may affect efficiency—this solution does not guarantee maximum concurrency—but they don't affect correctness, if you accept that "majority rule" only applies to threads that have registered to vote.

Chapter 7

Not remotely classical problems

7.1 The sushi bar problem

This problem was inspired by a problem proposed by Kenneth Reek [9]. Imagine a sushi bar with 5 seats. If you arrive while there is an empty seat, you can take a seat immediately. But if you arrive when all 5 seats are full, that means that all of them are dining together, and you will have to wait for the entire party to leave before you sit down.

Puzzle: write code for customers entering and leaving the sushi bar that enforces these requirements.

7.1.1 Sushi bar hint

Here are the variables I used:

Listing 7.1: Sushi bar hint

```
eating = waiting = 0
mutex = Semaphore(1)
block = Semaphore(0)
must_wait = False
```

`eating` and `waiting` keep track of the number of threads sitting at the bar and waiting. `mutex` protects both counters. `must_wait` indicates that the bar is (or has been) full, som incoming customers have to block on `block`.

7.1.2 Sushi bar non-solution

Here is an incorrect solution Reek uses to illustrate one of the difficulties of this problem.

Listing 7.2: Sushi bar non-solution

```
mutex.wait()
if must_wait:
    waiting += 1
    mutex.signal()
    block.wait()

    mutex.wait()    # reacquire mutex
    waiting -= 1

eating += 1
must_wait = (eating == 5)
mutex.signal()

# eat sushi

mutex.wait()
eating -= 1
if eating == 0:
    n = min(5, waiting)
    block.signal(n)
    must_wait = False
mutex.signal()
```

Puzzle: what's wrong with this solution?

7.1.3 Sushi bar non-solution

The problem is at Line 7. If a customer arrives while the bar is full, he has to give up the mutex while he waits so that other customers can leave. When the last customer leaves, she signals `block`, which wakes up at least some of the waiting customers, and clears `must_wait`.

But when the customers wake up, they have to get the mutex back, and that means they have to compete with incoming new threads. If new threads arrive and get the mutex first, they could take all the seats before the waiting threads. This is not just a question of injustice; it is possible for more than 5 threads to be in the critical section concurrently, which violates the synchronization constraints.

Reek provides two solutions to this problem, which appear in the next two sections.

Puzzle: see if you can come up with two different correct solutions!

Hint: neither solution uses any additional variables.

7.1.4 Sushi bar solution #1

The only reason a waiting customer has to reacquire the mutex is to update the state of `eating` and `waiting`, so one way to solve the problem is to make the departing customer, who already has the mutex, do the updating.

Listing 7.3: Sushi bar solution #1

```
mutex.wait()
if must_wait:
    waiting += 1
    mutex.signal()
    block.wait()
else:
    eating += 1
    must_wait = (eating == 5)
    mutex.signal()

# eat sushi

mutex.wait()
eating -= 1
if eating == 0:
    n = min(5, waiting)
    waiting -= n
    eating += n
    must_wait = (eating == 5)
    block.signal(n)
mutex.signal()
```

When the last departing customer releases the mutex, `eating` has already been updated, so newly arriving customers see the right state and block if necessary. Reek calls this pattern "I'll do it for you," because the departing thread is doing work that seems, logically, to belong to the waiting threads.

A drawback of this approach is that is it a little more difficult to confirm that the state is being updated correctly.

7.1.5 Sushi bar solution #2

Reek's alternative solution is based on the counterintuitive notion that we can transfer a mutex from one thread to another! In other words, one thread can acquire a lock and then another thread can release it. As long as both threads understand that the lock has been transferred, there is nothing wrong with this.

Listing 7.4: Sushi bar solution #2

```
mutex.wait()
if must_wait:
    waiting += 1
    mutex.signal()
    block.wait()   # when we resume, we have the mutex
    waiting -= 1

eating += 1
must_wait = (eating == 5)
if waiting and not must_wait:
    block.signal()         # and pass the mutex
else:
    mutex.signal()

# eat sushi

mutex.wait()
eating -= 1
if eating == 0: must_wait = False

if waiting and not must_wait:
    block.signal()         # and pass the mutex
else:
    mutex.signal()
```

If there are fewer than 5 customers at the bar and no one waiting, an entering customer just increments `eating` and releases the mutex. The fifth customer sets `must_wait`.

If `must_wait` is set, entering customers block until the last customer at the bar clears `must_wait` and signals `block`. It is understood that the signaling thread gives up the mutex and the waiting thread receives it. Keep in mind, though, that this is an invariant understood by the programmer, and documented in the comments, but not enforced by the semantics of semaphores. It is up to us to get it right.

When the waiting thread resumes, we understand that it has the mutex. If there are other threads waiting, it signals `block` which, again, passes the mutex to a waiting thread. This process continues, with each thread passing the mutex to the next until there are no more chairs or no more waiting threads. In either case, the last thread releases the mutex and goes to sit down.

Reek calls this pattern "Pass the baton," since the mutex is being passed from one thread to the next like a baton in a relay race. One nice thing about this solution is that it is easy to confirm that updates to `eating` and `waiting` are consistent. A drawback is that it is harder to confirm that the mutex is being used correctly.

7.2 The child care problem

Max Hailperin wrote this problem for his textbook *Operating Systems and Middleware* [5]. At a child care center, state regulations require that there is always one adult present for every three children.

Puzzle: Write code for child threads and adult threads that enforces this constraint in a critical section.

7.2.1 Child care hint

Hailperin suggests that you can *almost* solve this problem with one semaphore.

Listing 7.5: Child care hint

```
multiplex = Semaphore(0)
```

`multiplex` counts the number of tokens available, where each token allows a child thread to enter. As adults enter, they signal `multiplex` three times; as they leave, they `wait` three times. But there is a problem with this solution.

Puzzle: what is the problem?

7.2.2 Child care non-solution

Here is what the adult code looks like in Hailperin's non-solution:

Listing 7.6: Child care non-solution (adult)

```
multiplex.signal(3)

# critical section

multiplex.wait()
multiplex.wait()
multiplex.wait()
```

The problem is a potential deadlock. Imagine that there are three children and two adults in the child care center. The value of `multiplex` is 3, so either adult should be able to leave. But if both adults start to leave at the same time, they might divide the available tokens between them, and both block.

Puzzle: solve this problem with a minimal change.

7.2.3 Child care solution

Adding a mutex solves the problem:

Listing 7.7: Child care solution (adult)

```
multiplex.signal(3)

# critical section

mutex.wait()
    multiplex.wait()
    multiplex.wait()
    multiplex.wait()
mutex.signal()
```

Now the three `wait` operations are atomic. If there are three tokens available, the thread that gets the mutex will get all three tokens and exit. If there are fewer tokens available, the first thread will block in the mutex and subsequent threads will queue on the mutex.

7.2.4 Extended child care problem

One feature of this solution is that an adult thread waiting to leave can prevent child threads from entering.

Imagine that there are 4 children and two adults, so the value of the multiplex is 2. If one of the adults tries to leave, she will take two tokens and then block waiting for the third. If a child thread arrives, it will wait even though it would be legal to enter. From the point of view of the adult trying to leave, that might be just fine, but if you are trying to maximize the utilization of the child care center, it's not.

Puzzle: write a solution to this problem that avoids unnecessary waiting.

Hint: think about the dancers in Section 3.7.

7.2.5 Extended child care hint

Here are the variables I used in my solution:

Listing 7.8: Extended child care hint

```
children = adults = waiting = leaving = 0
mutex = Semaphore(1)
childQueue = Semaphore(0)
adultQueue = Semaphore(0)
```

`children`, `adults`, `waiting` and `leaving` keep track of the number of children, adults, children waiting to enter, and adults waiting to leave; they are protected by `mutex`.

Children wait on `childQueue` to enter, if necessary. Adupts wait on `adultQueue` to leave.

7.2.6 Extended child care solution

This solution is more complicated than Hailperin's elegant solution, but it is mostly a combination of patterns we have seen before: a scoreboard, two queues, and "I'll do it for you".

Here is the child code:

Listing 7.9: Extended child care solution (child)

```
mutex.wait()
    if children < 3 * adults:
        children++
        mutex.signal()
    else:
        waiting++
        mutex.signal()
        childQueue.wait()

# critical section

mutex.wait()
    children--
    if leaving and children <= 3 * (adults-1):
        leaving--
        adults--
        adultQueue.signal()
mutex.signal()
```

As children enter, they check whether there are enough adults and either (1) increment `children` and enter or (2) increment `waiting` and block. When they exit, they check for an adult thread waiting to leave and signal it if possible.

Here is the code for adults:

Listing 7.10: Extended child care solution (adult)

```
mutex.wait()
    adults++
    if waiting:
        n = min(3, waiting)
        childQueue.signal(n)
        waiting -= n
        children += n
mutex.signal()

# critical section

mutex.wait()
    if children <= 3 * (adults-1):
        adults--
        mutex.signal()
    else:
        leaving++
        mutex.signal()
        adultQueue.wait()
```

As adults enter, they signal waiting children, if any. Before they leave, they check whether there are enough adults left. If so, they decrement `adults` and exit. Otherwise they increment `leaving` and block. While an adult thread is waiting to leave, it counts as one of the adults in the critical section, so additional children can enter.

7.3 The room party problem

I wrote this problem while I was at Colby College. One semester there was a controversy over an allegation by a student that someone from the Dean of Students Office had searched his room in his absence. Although the allegation was public, the Dean of Students wasn't able to comment on the case, so we never found out what really happened. I wrote this problem to tease a friend of mine, who was the Dean of Student Housing.

The following synchronization constraints apply to students and the Dean of Students:

1. Any number of students can be in a room at the same time.
2. The Dean of Students can only enter a room if there are no students in the room (to conduct a search) or if there are more than 50 students in the room (to break up the party).
3. While the Dean of Students is in the room, no additional students may enter, but students may leave.
4. The Dean of Students may not leave the room until all students have left.
5. There is only one Dean of Students, so you do not have to enforce exclusion among multiple deans.

Puzzle: write synchronization code for students and for the Dean of Students that enforces all of these constraints.

7.3.1 Room party hint

Listing 7.11: Room party hint

```
students = 0
dean = 'not here'
mutex = Semaphore(1)
turn = Semaphore(1)
clear = Semaphore(0)
lieIn = Semaphore(0)
```

`students` counts the number of students in the room, and `dean` is the state of the Dean, which can also be "waiting" or "in the room". `mutex` protects `students` and `dean`, so this is yet another example of a scoreboard.

`turn` is a turnstile that keeps students from entering while the Dean is in the room.

`clear` and `lieIn` are used as rendezvouses between a student and the Dean (which is a whole other kind of scandal!).

7.3.2 Room party solution

This problem is hard. I worked through a lot of versions before I got to this one. The version that appeared in the first edition was mostly correct, but occasionally the Dean would enter the room and then find that he could neither search nor break up the party, so he would have to skulk off in embarrassed silence.

Matt Tesch wrote a solution that spared this humiliation, but the result was complicated enough that we had a hard time convincing ourselves that it was correct. But that solution led me to this one, which is a bit more readable.

Listing 7.12: Room party solution (dean)

```
mutex.wait()
    if students > 0 and students < 50:
        dean = 'waiting'
        mutex.signal()
        lieIn.wait()   # and get mutex from the student.

    # students must be 0 or >= 50

    if students >= 50:
        dean = 'in the room'
        breakup()
        turn.wait()    # lock the turnstile
        mutex.signal()
        clear.wait()   # and get mutex from the student.
        turn.signal()  # unlock the turnstile

    else:              # students must be 0
        search()

dean = 'not here'
mutex.signal()
```

When the Dean arrives, there are three cases: if there are students in the room, but not 50 or more, the Dean has to wait. If there are 50 or more, the Dean breaks up the party and waits for the students to leave. If there are no students, the Dean searches and leaves.

In the first two cases, the Dean has to wait for a rendezvous with a student, so he has to give up `mutex` to avoid a deadlock. When the Dean wakes up, he has to modify the scoreboard, so he needs to get the mutex back. This is similar to the situation we saw in the Sushi Bar problem. The solution I chose is the "Pass the baton" pattern.

Listing 7.13: Room party solution (student)

```
1  mutex.wait()
2      if dean == 'in the room':
3          mutex.signal()
4          turn.wait()
5          turn.signal()
6          mutex.wait()
7
8      students += 1
9
10     if students == 50 and dean == 'waiting':
11         lieIn.signal()          # and pass mutex to the dean
12     else:
13         mutex.signal()
14
15 party()
16
17 mutex.wait()
18     students -= 1
19
20     if students == 0 and dean == 'waiting':
21         lieIn.signal()       # and pass mutex to the dean
22     elif students == 0 and dean == 'in the room':
23         clear.signal()       # and pass mutex to the dean
24     else:
25         mutex.signal()
```

There are three cases where a student might have to signal the Dean. If the Dean is waiting, then the 50th student in or the last one out has to signal `lieIn`. If the Dean is in the room (waiting for all the students to leave), the last student out signals `clear`. In all three cases, it is understood that the mutex passes from the student to the Dean.

One part of this solution that may not be obvious is how we know at Line 7 of the Dean's code that `students` must be 0 or not less than 50. The key is to realize that there are only two ways to get to this point: either the first conditional was false, which means that `students` is either 0 or not less than 50; or the Dean was waiting on `lieIn` when a student signaled, which means, again, that `students` is either 0 or not less than 50.

7.4 The Senate Bus problem

This problem was originally based on the Senate bus at Wellesley College. Riders come to a bus stop and wait for a bus. When the bus arrives, all the waiting riders invoke `boardBus`, but anyone who arrives while the bus is boarding has to wait for the next bus. The capacity of the bus is 50 people; if there are more than 50 people waiting, some will have to wait for the next bus.

When all the waiting riders have boarded, the bus can invoke `depart`. If the bus arrives when there are no riders, it should depart immediately.

Puzzle: Write synchronization code that enforces all of these constraints.

7.4.1 Bus problem hint

Here are the variables I used in my solution:

Listing 7.14: Bus problem hint

```
riders = 0
mutex = Semaphore(1)
multiplex = Semaphore(50)
bus = Semaphore(0)
allAboard = Semaphore(0)
```

`mutex` protects `riders`, which keeps track of how many riders are waiting; `multiplex` makes sure there are no more than 50 riders in the boarding area.

Riders wait on `bus`, which gets signaled when the bus arrives. The bus waits on `allAboard`, which gets signaled by the last student to board.

7.4.2 Bus problem solution #1

Here is the code for the bus. Again, we are using the "Pass the baton" pattern.

Listing 7.15: Bus problem solution (bus)

```
mutex.wait()
if riders > 0:
    bus.signal()      # and pass the mutex
    allAboard.wait()  # and get the mutex back
mutex.signal()

depart()
```

When the bus arrives, it gets `mutex`, which prevents late arrivals from entering the boarding area. If there are no riders, it departs immediately. Otherwise, it signals `bus` and waits for the riders to board.

Here is the code for the riders:

Listing 7.16: Bus problem solution (riders)

```
multiplex.wait()
    mutex.wait()
        riders += 1
    mutex.signal()

    bus.wait()            # and get the mutex
multiplex.signal()

boardBus()

riders -= 1
if riders == 0:
    allAboard.signal()
else:
    bus.signal()          # and pass the mutex
```

The multiplex controls the number of riders in the waiting area, although strictly speaking, a rider doesn't enter the waiting area until she increments `riders`.

Riders wait on `bus` until the bus arrives. When a rider wakes up, it is understood that she has the mutex. After boarding, each rider decrements `riders`. If there are more riders waiting, the boarding rider signals `bus` and pass the mutex to the next rider. The last rider signals `allAboard` and passes the mutex back to the bus.

Finally, the bus releases the mutex and departs.

Puzzle: can you find a solution to this problem using the "I'll do it for you" pattern?

7.4.3 Bus problem solution #2

Grant Hutchins came up with this solution, which uses fewer variables than the previous one, and doesn't involve passing around any mutexes. Here are the variables:

Listing 7.17: Bus problem solution #2 (initialization)

```
waiting = 0
mutex = new Semaphore(1)
bus = new Semaphore(0)
boarded = new Semaphore(0)
```

`waiting` is the number of riders in the boarding area, which is protected by `mutex`. `bus` signals when the bus has arrived; `boarded` signals that a rider has boarded.

Here is the code for the bus.

Listing 7.18: Bus problem solution (bus)

```
mutex.wait()
n = min(waiting, 50)
for i in range(n):
    bus.signal()
    boarded.wait()

waiting = max(waiting-50, 0)
mutex.signal()

depart()
```

The bus gets the `mutex` and holds it throughout the boarding process. The loop signals each rider in turn and waits for her to board. By controlling the number of signals, the bus prevents more than 50 riders from boarding.

When all the riders have boarded, the bus updates `waiting`, which is an example of the "I'll do it for you" pattern.

The code for the riders uses two simple patterns: a mutex and a rendezvous.

Listing 7.19: Bus problem solution (riders)

```
mutex.wait()
     waiting += 1
mutex.signal()

bus.wait()
board()
boarded.signal()
```

Challenge: if riders arrive while the bus is boarding, they might be annoyed if you make them wait for the next one. Can you find a solution that allows late arrivals to board without violating the other constraints?

7.5 The Faneuil Hall problem

This problem was written by Grant Hutchins, who was inspired by a friend who took her Oath of Citizenship at Faneuil Hall in Boston.

"There are three kinds of threads: immigrants, spectators, and a one judge. Immigrants must wait in line, check in, and then sit down. At some point, the judge enters the building. When the judge is in the building, no one may enter, and the immigrants may not leave. Spectators may leave. Once all immigrants check in, the judge can confirm the naturalization. After the confirmation, the immigrants pick up their certificates of U.S. Citizenship. The judge leaves at some point after the confirmation. Spectators may now enter as before. After immigrants get their certificates, they may leave."

To make these requirements more specific, let's give the threads some functions to execute, and put constraints on those functions.

- Immigrants must invoke `enter`, `checkIn`, `sitDown`, `swear`, `getCertificate` and `leave`.
- The judge invokes `enter`, `confirm` and `leave`.
- Spectators invoke `enter`, `spectate` and `leave`.
- While the judge is in the building, no one may `enter` and immigrants may not `leave`.
- The judge can not `confirm` until all immigrants who have invoked `enter` have also invoked `checkIn`.
- Immigrants can not `getCertificate` until the judge has executed `confirm`.

7.5.1 Faneuil Hall Problem Hint

Listing 7.20: Faneuil Hall problem hint

```
noJudge = Semaphore(1)
entered = 0
checked = 0
mutex = Semaphore(1)
confirmed = Semaphore(0)
```

`noJudge` acts as a turnstile for incoming immigrants and spectators; it also protects `entered`, which counts the number of immigrants in the room. `checked` counts the number of immigrants who have checked in; it is protected by `mutex`.

`confirmed` signals that the judge has executed `confirm`.

7.5.2 Faneuil Hall problem solution

Here is the code for immigrants:

Listing 7.21: Faneuil Hall problem solution (immigrant)

```
noJudge.wait()
enter()
entered++
noJudge.signal()

mutex.wait()
checkIn()
checked++

if judge = 1 and entered == checked:
    allSignedIn.signal()          # and pass the mutex
else:
    mutex.signal()

sitDown()
confirmed.wait()

swear()
getCertificate()

noJudge.wait()
leave()
noJudge.signal()
```

Immigrants pass through a turnstile when they enter; while the judge is in the room, the turnstile is locked.

After entering, immigrants have to get `mutex` to check in and update `checked`. If there is a judge waiting, the last immigrant to check in signals `allSignedIn` and passes the mutex to the judge.

Here is the code for the judge:

Listing 7.22: Faneuil Hall problem solution (judge)

```
noJudge.wait()
mutex.wait()

enter()
judge = 1

if entered > checked:
    mutex.signal()
    allSignedIn.wait()            # and get the mutex back.
```

```

confirm()
confirmed.signal(checked)
entered = checked = 0

leave()
judge = 0

mutex.signal()
noJudge.signal()
```

The judge holds `noJudge` to bar immigrants and spectators from entering, and `mutex` so he can access `entered` and `checked`.

If the judge arrives at an instant when everyone who has entered has also checked in, she can proceed immediately. Otherwise, she has to give up the mutex and wait. When the last immigrant checks in and signals `allSignedIn`, it is understood that the judge will get the mutex back.

After invoking `confirm`, the judge signals `confirmed` once for every immigrant who has checked in, and then resets the counters (an example of "I'll do it for you"). Then the judge leaves and releases `mutex` and `noJudge`.

After the judge signals `confirmed`, immigrants invoke `swear` and `getCertificate` concurrently, and then wait for the `noJudge` turnstile to open before leaving.

The code for spectators is easy; the only constraint they have to obey is the `noJudge` turnstile.

Listing 7.23: Faneuil Hall problem solution (spectator)

```
noJudge.wait()
enter()
noJudge.signal()

spectate()

leave()
```

Note: in this solution it is possible for immigrants to get stuck, after they get their certificate, by another judge coming to swear in the next batch of immigrants. If that happens, they might have to wait through another swearing in-ceremony.

Puzzle: modify this solution to handle the additional constraint that after the judge leaves, all immigrants who have been sworn in must leave before the judge can enter again.

7.5.3 Extended Faneuil Hall Problem Hint

My solution uses the following additional variables:

Listing 7.24: Faneuil Hall problem hint

```
exit = Semaphore(0)
allGone = Semaphore(0)
```

Since the extended problem involves an additional rendezvous, we can solve it with two semaphores.

One other hint: I found it useful to use the "pass the baton" pattern again.

7.5.4 Extended Faneuil Hall problem solution

The top half of this solution is the same as before. The difference starts at Line 21. Immigrants wait here for the judge to leave.

Listing 7.25: Faneuil Hall problem solution (immigrant)

```
1  noJudge.wait()
2  enter()
3  entered++
4  noJudge.signal()
5
6  mutex.wait()
7  checkIn()
8  checked++
9
10 if judge = 1 and entered == checked:
11     allSignedIn.signal()           # and pass the mutex
12 else:
13     mutex.signal()
14
15 sitDown()
16 confirmed.wait()
17
18 swear()
19 getCertificate()
20
21 exit.wait()                      # and get the mutex
22 leave()
23 checked--
24 if checked == 0:
25     allGone.signal()             # and pass the mutex
26 else:
27     exit.signal()                # and pass the mutex
```

For the judge, the difference starts at Line 18. When the judge is ready to leave, she can't release `noJudge`, because that would allow more immigrants, and possibly another judge, to enter. Instead, she signals `exit`, which allows one immigrant to leave, and passes `mutex`.

The immigrant that gets the signal decrements `checked` and then passes the baton to the next immigrant. The last immigrant to leave signals `allGone` and passes the mutex back to the judge. This pass-back is not strictly necessary, but it has the nice feature that the judge releases both `mutex` and `noJudge` to end the phase cleanly.

Listing 7.26: Faneuil Hall problem solution (judge)

```
noJudge.wait()
mutex.wait()

enter()
judge = 1

if entered > checked:
    mutex.signal()
    allSignedIn.wait()            # and get the mutex back.

confirm()
confirmed.signal(checked)
entered = 0

leave()
judge = 0

exit.signal()                    # and pass the mutex
allGone.wait()                   # and get it back
mutex.signal()
noJudge.signal()
```

The spectator code for the extended problem is unchanged.

7.6 Dining Hall problem

This problem was written by Jon Pollack during my Synchronization class at Olin College.

Students in the dining hall invoke `dine` and then `leave`. After invoking `dine` and before invoking `leave` a student is considered "ready to leave".

The synchronization constraint that applies to students is that, in order to maintain the illusion of social suave, a student may never sit at a table alone. A student is considered to be sitting alone if everyone else who has invoked `dine` invokes `leave` before she has finished `dine`.

Puzzle: write code that enforces this constraint.

7.6.1 Dining Hall problem hint

Listing 7.27: Dining Hall problem hint

```
eating = 0
readyToLeave = 0
mutex = Semaphore(1)
okToLeave = Semaphore(0)
```

`eating` and `readyToLeave` are counters protected by `mutex`, so this is the usual scoreboard pattern.

If a student is ready to leave, but another student would be left alone at the table, she waits on `okToLeave` until another student changes the situation and signals.

7.6.2 Dining Hall problem solution

If you analyze the constraints, you will realize that there is only one situation where a student has to wait, if there is one student eating and one student who wants to leave. But there are two ways to get out of this situation: another student might arrive to eat, or the dining student might finish.

In either case, the student who signals the waiting student updates the counters, so the waiting student doesn't have to get the mutex back. This is another example of the the "I'll do it for you" pattern.

Listing 7.28: Dining Hall problem solution

```
getFood()

mutex.wait()
eating++
if eating == 2 and readyToLeave == 1:
    okToLeave.signal()
    readyToLeave--
mutex.signal()

dine()

mutex.wait()
eating--
readyToLeave++

if eating == 1 and readyToLeave == 1:
    mutex.signal()
    okToLeave.wait()
elif eating == 0 and readyToLeave == 2:
    okToLeave.signal()
    readyToLeave -= 2
    mutex.signal()
else:
    readyToLeave--
    mutex.signal()

leave()
```

When is student is checking in, if she sees one student eating and one waiting to leave, she lets the waiter off the hook and decrements `readyToLeave` for him.

After dining, the student checks three cases:

- If there is only one student left eating, the departing student has to give up the mutex and wait.
- If the departing student finds that someone is waiting for her, she signals him and updates the counter for both of them.
- Otherwise, she just decrements `readyToLeave` and leaves.

7.6.3 Extended Dining Hall problem

The Dining Hall problem gets a little more challenging if we add another step. As students come to lunch they invoke `getFood`, `dine` and then `leave`. After invoking `getFood` and before invoking `dine`, a student is considered "ready to eat". Similarly, after invoking `dine` a student is considered "ready to leave".

The same synchronization constraint applies: a student may never sit at a table alone. A student is considered to be sitting alone if either

- She invokes `dine` while there is no one else at the table and no one ready to eat, or
- everyone else who has invoked `dine` invokes `leave` before she has finished `dine`.

Puzzle: write code that enforces these constraints.

7.6.4 Extended Dining Hall problem hint

Here are the variables I used in my solution:

Listing 7.29: Extended Dining Hall problem hint

```
readyToEat = 0
eating = 0
readyToLeave = 0
mutex = Semaphore(1)
okToSit = Semaphore(0)
okToLeave = Semaphore(0)
```

`readyToEat`, `eating` and `readyToLeave` are counters, all protected by `mutex`.

If a student is in a situation where she cannot proceed, she waits on `okToSit` or `okToLeave` until another student changes the situation and signals.

I also used a per-thread variable named `hasMutex` to help keep track of whether or not a thread holds the mutex.

7.6.5 Extended Dining Hall problem solution

Again, if we analyze the constraints, we realize that there is only one situation where a student who is ready to eat has to wait, if there is no one eating and no one else ready to eat. And the only way out is if someone else arrives who is ready to eat.

Listing 7.30: Extended Dining Hall problem solution

```
getFood()

mutex.wait()
readyToEat++
if eating == 0 and readyToEat == 1:
    mutex.signal()
    okToSit.wait()
elif eating == 0 and readyToEat == 2:
    okToSit.signal()
    readyToEat -= 2
    eating += 2
    mutex.signal()
else:
    readyToEat--
    eating++
    if eating == 2 and readyToLeave == 1:
        okToLeave.signal()
        readyToLeave--
    mutex.signal()

dine()

mutex.wait()
eating--
readyToLeave++
if eating == 1 and readyToLeave == 1:
    mutex.signal()
    okToLeave.wait()
elif eating == 0 and readyToLeave == 2:
    okToLeave.signal()
    readyToLeave -= 2
    mutex.signal()
else:
    readyToLeave--
    mutex.signal()

leave()
```

As in the previous solution, I used the "I'll do it for you" pattern so that a waiting student doesn't have to get the mutex back.

The primary difference between this solution and the previous one is that the first student who arrives at an empty table has to wait, and the second student allows both students to proceed. It either case, we don't have to check for students waiting to leave, since no one can leave an empty table!

Chapter 8

Synchronization in Python

By using pseudocode, we have avoided some of the ugly details of synchronization in the real world. In this chapter we'll look at real synchronization code in Python; in the next chapter we'll look at C.

Python provides a reasonably pleasant multithreading environment, complete with Semaphore objects. It has a few foibles, but there is some cleanup code in Appendix A that makes things a little better.

Here is a simple example:

```
from threading_cleanup import *

class Shared:
    def __init__(self):
        self.counter = 0

def child_code(shared):
    while True:
        shared.counter += 1
        print shared.counter
        time.sleep(0.5)

shared = Shared()
children = [Thread(child_code, shared) for i in range(2)]
for child in children: child.join()
```

The first line runs the cleanup code from Appendix A; I will leave this line out of the other examples.

`Shared` defines an object type that will contain shared variables. Global variables are also shared between threads, but we won't use any in these examples. Threads that are local in the sense that they are declared inside a function are also local in the sense that they are thread-specific.

The child code is an infinite loop that increments `counter`, prints the new value, and then sleeps for 0.5 seconds.

The parent thread creates `shared` and two children, then waits for the children to exit (which in this case, they won't).

8.1 Mutex checker problem

Diligent students of synchronization will notice that the children make unsynchronized updates to `counter`, which is not safe! If you run this program, you might see some errors, but you probably won't. The nasty thing about synchronization errors is that they are unpredictable, which means that even extensive testing may not reveal them.

To detect errors, it is often necessary to automate the search. In this case, we can detect errors by keeping track of the values of `counter`.

```
class Shared:
    def __init__(self, end=10):
        self.counter = 0
        self.end = end
        self.array = [0]* self.end

def child_code(shared):
    while True:
        if shared.counter >= shared.end: break
        shared.array[shared.counter] += 1
        shared.counter += 1

shared = Shared(10)
children = [Thread(child_code, shared) for i in range(2)]
for child in children: child.join()
print shared.array
```

In this example, `shared` contains a list (misleadingly named `array`) that keeps track of the number of times each value of counter is used. Each time through the loop, the children check `counter` and quit if it exceeds `end`. If not, they use `counter` as an index into `array` and increment the corresponding entry. Then they increment `counter`.

If everything works correctly, each entry in the array should be incremented exactly once. When the children exit, the parent returns from `join` and prints the value of `array`. When I ran the program, I got

```
[1, 1, 1, 1, 1, 1, 1, 1, 1, 1]
```

which is disappointingly correct. If we increase the size of the array, we might expect more errors, but it also gets harder to check the result.

We can automate the checker by making a histogram of the results in the array:

```
class Histogram(dict):
    def __init__(self, seq=[]):
        for item in seq:
            self[item] = self.get(item, 0) + 1

print Histogram(shared.array)
```

Now when I run the program, I get

```
{1: 10}
```

which means that the value 1 appeared 10 times, as expected. No errors so far, but if we make `end` bigger, things get more interesting:

```
end = 100, {1: 100}
end = 1000, {1: 1000}
end = 10000, {1: 10000}
end = 100000, {1: 27561, 2: 72439}
```

Oops! When `end` is big enough that there are a lot of context switches between the children, we start to get synchronization errors. In this case, we get a *lot* of errors, which suggests that the program falls into a recurring pattern where threads are consistently interrupted in the critical section.

This example demonstrates one of the dangers of synchronization errors, which is that they may be rare, but they are not random. If an error occurs one time in a million, that doesn't mean it won't happen a million times in a row.

Puzzle: add synchronization code to this program to enforce exclusive access to the shared variables. You can download the code in this section from greenteapress.com/semaphores/counter.py

8.1.1 Mutex checker hint

Here is the version of `Shared` I used:

```
class Shared:
    def __init__(self, end=10):
        self.counter = 0
        self.end = end
        self.array = [0]* self.end
        self.mutex = Semaphore(1)
```

The only change is the Semaphore named `mutex`, which should come as no surprise.

8.1.2 Mutex checker solution

Here is my solution:

```
def child_code(shared):
    while True:
        shared.mutex.wait()
        if shared.counter < shared.end:
            shared.array[shared.counter] += 1
            shared.counter += 1
            shared.mutex.signal()
        else:
            shared.mutex.signal()
            break
```

Although this is not the most difficult synchronization problem in this book, you might have found it tricky to get the details right. In particular, it is easy to forget to signal the mutex before breaking out of the loop, which would cause a deadlock.

I ran this solution with `end = 1000000`, and got the following result:

```
{1: 1000000}
```

Of course, that doesn't mean my solution is correct, but it is off to a good start.

8.2 The coke machine problem

The following program simulates producers and consumers adding and removing cokes from a coke machine:

```
import random

class Shared:
    def __init__(self, start=5):
        self.cokes = start

def consume(shared):
    shared.cokes -= 1
    print shared.cokes

def produce(shared):
    shared.cokes += 1
    print shared.cokes

def loop(shared, f, mu=1):
    while True:
        t = random.expovariate(1.0/mu)
        time.sleep(t)
        f(shared)

shared = Shared()
fs = [consume]*2 + [produce]*2
threads = [Thread(loop, shared, f) for f in fs]
for thread in threads: thread.join()
```

The capacity is 10 cokes, and that the machine is initially half full. So the shared variable `cokes` is 5.

The program creates 4 threads, two producers and two consumers. They both run `loop`, but producers invoke `produce` and consumers invoke `consume`. These functions make unsynchronized access to a shared variable, which is a no-no.

Each time through the loop, producers and consumers sleep for a duration chosen from an exponential distribution with mean `mu`. Since there are two producers and two consumers, two cokes get added to the machine per second, on average, and two get removed.

So on average the number of cokes is constant, but in the short run in can vary quite widely. If you run the program for a while, you will probably see the value of `cokes` dip below zero, or climb above 10. Of course, neither of these should happen.

Puzzle: add code to this program to enforce the following synchronization constraints:

- Access to `cokes` should be mutually exclusive.
- If the number of cokes is zero, consumers should block until a coke is added.
- If the number of cokes is 10, producers should block until a coke is removed.

You can download the program from `greenteapress.com/semaphores/coke.py`

8.2.1 Coke machine hint

Here are the shared variables I used in my solution:

```
class Shared:
    def __init__(self, start=5, capacity=10):
        self.cokes = Semaphore(start)
        self.slots = Semaphore(capacity-start)
        self.mutex = Semaphore(1)
```

`cokes` is a Semaphore now (rather than a simple integer), which makes it tricky to print its value. Of course, you should never access the value of a Semaphore, and Python in its usual do-gooder way doesn't provide any of the cheater methods you see in some implementations.

But you might find it interesting to know that the value of a Semaphore is stored in a private attribute named `_Semaphore__value`. Also, in case you don't know, Python doesn't actually enforce any restriction on access to private attributes. You should never access it, of course, but I thought you might be interested.

Ahem.

8.2.2 Coke machine solution

If you've read the rest of this book, you should have had no trouble coming up with something at least as good as this:

```
def consume(shared):
    shared.cokes.wait()
    shared.mutex.wait()
    print shared.cokes.value()
    shared.mutex.signal()
    shared.slots.signal()

def produce(shared):
    shared.slots.wait()
    shared.mutex.wait()
    print shared.cokes._Semaphore__value
    shared.mutex.signal()
    shared.cokes.signal()
```

If you run this program for a while, you should be able to confirm that the number of cokes in the machine is never negative or greater than 10. So this solution seems to be correct.

So far.

Chapter 9

Synchronization in C

In this section we will write a multithreaded, synchronized program in C. Appendix B provides some of the utility code I use to make the C code a little more palatable. The examples in this section depend on that code.

9.1 Mutual exclusion

We'll start by defining a structure that contains shared variables:

```
typedef struct {
  int counter;
  int end;
  int *array;
} Shared;

Shared *make_shared (int end)
{
  int i;
  Shared *shared = check_malloc (sizeof (Shared));

  shared->counter = 0;
  shared->end = end;

  shared->array = check_malloc (shared->end * sizeof(int));
  for (i=0; i<shared->end; i++) {
    shared->array[i] = 0;
  }
  return shared;
}
```

`counter` is a shared variable that will be incremented by concurrent threads until it reaches `end`. We will use `array` to check for synchronization errors by

keeping track of the value of `counter` after each increment.

9.1.1 Parent code

Here is the code the parent thread uses to create threads and wait for them to complete:

```
int main ()
{
  int i;
  pthread_t child[NUM_CHILDREN];

  Shared *shared = make_shared (100000);

  for (i=0; i<NUM_CHILDREN; i++) {
    child[i] = make_thread (entry, shared);
  }

  for (i=0; i<NUM_CHILDREN; i++) {
    join_thread (child[i]);
  }

  check_array (shared);
  return 0;
}
```

The first loop creates the child threads; the second loop waits for them to complete. When the last child has finished, the parent invokes `check_array` to check for errors. `make_thread` and `join_thread` are defined in Appendix B.

9.1.2 Child code

Here is the code that is executed by each of the children:

```
void child_code (Shared *shared)
{
  while (1) {
    if (shared->counter >= shared->end) {
      return;
    }
    shared->array[shared->counter]++;
    shared->counter++;
  }
}
```

Each time through the loop, the child threads use `counter` as an index into `array` and increment the corresponding element. Then they increment `counter` and check to see if they're done.

9.1.3 Synchronization errors

If everything works correctly, each element of the array should be incremented once. So to check for errors, we can just count the number of elements that are not 1:

```
void check_array (Shared *shared)
{
  int i, errors=0;

  for (i=0; i<shared->end; i++) {
    if (shared->array[i] != 1) errors++;
  }
  printf ("%d errors.\n", errors);
}
```

You can download this program (including the cleanup code) from greenteapress.com/semaphores/counter.c

If you compile and run the program, you should see output like this:

```
Starting child at counter 0
10000
20000
30000
40000
50000
60000
70000
80000
90000
Child done.
Starting child at counter 100000
Child done.
Checking...
0 errors.
```

Of course, the interaction of the children depends on details of your operating system and also other programs running on your computer. In the example shown here, one thread ran all the way from 0 to `end` before the other thread got started, so it is not surprising that there were no synchronization errors.

But as `end` gets bigger, there are more context switches between the children. On my system I start to see errors when `end` is 100,000,000.

Puzzle: use semaphores to enforce exclusive access to the shared variables and run the program again to confirm that there are no errors.

9.1.4 Mutual exclusion hint

Here is the version of `Shared` I used in my solution:

```
1  typedef struct {
2    int counter;
3    int end;
4    int *array;
5    Semaphore *mutex;
6  } Shared;
7
8  Shared *make_shared (int end)
9  {
10   int i;
11   Shared *shared = check_malloc (sizeof (Shared));
12
13   shared->counter = 0;
14   shared->end = end;
15
16   shared->array = check_malloc (shared->end * sizeof(int));
17   for (i=0; i<shared->end; i++) {
18     shared->array[i] = 0;
19   }
20   shared->mutex = make_semaphore(1);
21   return shared;
22 }
```

Line 5 declares `mutex` as a Semaphore; Line 20 initializes the mutex with the value 1.

9.1.5 Mutual exclusion solution

Here is the synchronized version of the child code:

```
void child_code (Shared *shared)
{
  while (1) {
    sem_wait(shared->mutex);
    if (shared->counter >= shared->end) {
      sem_signal(shared->mutex);
      return;
    }

    shared->array[shared->counter]++;
    shared->counter++;
    sem_signal(shared->mutex);
  }
}
```

There is nothing too surprising here; the only tricky thing is to remember to release the mutex before the `return` statement.

You can download this solution from greenteapress.com/semaphores/counter_mutex.c

9.2 Make your own semaphores

The most commonly used synchronization tools for programs that use Pthreads are mutexes and condition variables, not semaphores. For an explanation of these tools, I recommend Butenhof's *Programming with POSIX Threads* [2].

Puzzle: read about mutexes and condition variables, and then use them to write an implementation of semaphores.

You might want to use the following utility code in your solutions. Here is my wrapper for Pthreads mutexes:

```
typedef pthread_mutex_t Mutex;

Mutex *make_mutex ()
{
  Mutex *mutex = check_malloc (sizeof(Mutex));
  int n = pthread_mutex_init (mutex, NULL);
  if (n != 0) perror_exit ("make_lock failed");
  return mutex;
}

void mutex_lock (Mutex *mutex)
{
  int n = pthread_mutex_lock (mutex);
  if (n != 0) perror_exit ("lock failed");
}

void mutex_unlock (Mutex *mutex)
{
  int n = pthread_mutex_unlock (mutex);
  if (n != 0) perror_exit ("unlock failed");
}
```

And my wrapper for Pthread condition variables:

```
typedef pthread_cond_t Cond;

Cond *make_cond ()
{
  Cond *cond = check_malloc (sizeof(Cond));
  int n = pthread_cond_init (cond, NULL);
  if (n != 0) perror_exit ("make_cond failed");
  return cond;
}

void cond_wait (Cond *cond, Mutex *mutex)
{
  int n = pthread_cond_wait (cond, mutex);
  if (n != 0) perror_exit ("cond_wait failed");
}

void cond_signal (Cond *cond)
{
  int n = pthread_cond_signal (cond);
  if (n != 0) perror_exit ("cond_signal failed");
}
```

9.2.1 Semaphore implementation hint

Here is the structure definition I used for my semaphores:

```
typedef struct {
  int value, wakeups;
  Mutex *mutex;
  Cond *cond;
} Semaphore;
```

`value` is the value of the semaphore. `wakeups` counts the number of pending signals; that is, the number of threads that have been woken but have not yet resumed execution. The reason for wakeups is to make sure that our semaphores have Property 3, described in Section 4.3.

`mutex` provides exclusive access to `value` and `wakeups`; `cond` is the condition variable threads wait on if they wait on the semaphore.

Here is the initialization code for this structure:

```
Semaphore *make_semaphore (int value)
{
  Semaphore *semaphore = check_malloc (sizeof(Semaphore));
  semaphore->value = value;
  semaphore->wakeups = 0;
  semaphore->mutex = make_mutex ();
  semaphore->cond = make_cond ();
  return semaphore;
}
```

9.2.2 Semaphore implementation

Here is my implementation of semaphores using Pthread's mutexes and condition variables:

```
1  void sem_wait (Semaphore *semaphore)
2  {
3    mutex_lock (semaphore->mutex);
4    semaphore->value--;
5
6    if (semaphore->value < 0) {
7      do {
8        cond_wait (semaphore->cond, semaphore->mutex);
9      } while (semaphore->wakeups < 1);
10     semaphore->wakeups--;
11   }
12   mutex_unlock (semaphore->mutex);
13 }
14
15 void sem_signal (Semaphore *semaphore)
16 {
17   mutex_lock (semaphore->mutex);
18   semaphore->value++;
19
20   if (semaphore->value <= 0) {
21     semaphore->wakeups++;
22     cond_signal (semaphore->cond);
23   }
24   mutex_unlock (semaphore->mutex);
25 }
```

Most of this is straightforward; the only thing that might be tricky is the `do...while` loop at Line 7. This is an unusual way to use a condition variable, but in this case it is necessary.

Puzzle: why can't we replace this `do...while` loop with a `while` loop?

9.2.3 Semaphore implementation detail

With a `while` loop, this implementation would not have Property 3. It would be possible for a thread to signal and then run around and catch its own signal.

With the `do...while` loop, it is guaranteed[1] that when a thread signals, one of the waiting threads will get the signal, even if another thread gets the mutex at Line 3 before one of the waiting threads resumes.

[1] Well, almost. It turns out that a well-timed spurious wakeup (see http://en.wikipedia.org/wiki/Spurious_wakeup) can violate this guarantee.

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Appendix A

Cleaning up Python threads

Compared to a lot of other threading environments, Python threads are pretty good, but there are a couple of features that annoy me. Fortunately, you can fix them with a little clean-up code.

A.1 Semaphore methods

First, the methods for Python semaphores are called `acquire` and `release`, which is a perfectly reasonable choice, but after working on this book for a couple of years, I am used to `signal` and `wait`. Fortunately, I can have it my way by subclassing the version of Semaphore in the `threading` module:

Listing A.1: Semaphore name change

```
import threading

class Semaphore(threading._Semaphore):
    wait = threading._Semaphore.acquire
    signal = threading._Semaphore.release
```

Once this class is defined, you can create and manipulate Semaphores using the syntax in this book.

Listing A.2: Semaphore example

```
mutex = Semaphore()
mutex.wait()
mutex.signal()
```

A.2 Creating threads

The other feature of the `threading` module that annoys me is the interface for creating and starting threads. The usual way requires keyword arguments and

two steps:

Listing A.3: Thread example (standard way)

```
import threading

def function(x, y, z):
    print x, y, z

thread = threading.Thread(target=function, args=[1, 2, 3])
thread.start()
```

In this example, creating the thread has no immediate effect. But when you invoke `start`, the new thread executes the target function with the given arguments. This is great if you need to do something with the thread before it starts, but I almost never do. Also, I think the keyword arguments `target` and `args` are awkward.

Fortunately, we can solve both of these problems with four lines of code.

Listing A.4: Cleaned-up Thread class

```
class Thread(threading.Thread):
    def __init__(self, t, *args):
        threading.Thread.__init__(self, target=t, args=args)
        self.start()
```

Now we can create threads with a nicer interface, and they start automatically:

Listing A.5: Thread example (my way)

```
thread = Thread(function, 1, 2, 3)
```

This also lends itself to an idiom I like, which is to create multiple Threads with a list comprehension:

Listing A.6: Multiple thread example

```
threads = [Thread(function, i, i, i) for i in range(10)]
```

A.3 Handling keyboard interrupts

One other problem with the `threading` class is that `Thread.join` can't be interrupted by Ctrl-C, which generates the signal `SIGINT`, which Python translates into a KeyboardInterrupt.

So, if you write the following program:

Listing A.7: Unstoppable program

```
import threading, time

class Thread(threading.Thread):
    def __init__(self, t, *args):
        threading.Thread.__init__(self, target=t, args=args)
        self.start()

def parent_code():
    child = Thread(child_code, 10)
    child.join()

def child_code(n=10):
    for i in range(n):
        print i
        time.sleep(1)

parent_code()
```

You will find that it cannot be interrupted with Ctrl-C or a `SIGINT`[1].

My workaround for this problem uses `os.fork` and `os.wait`, so it only works on UNIX and Macintosh. Here's how it works: before creating new threads, the program invokes `watcher`, which forks a new process. The new process returns and executes the rest of the program. The original process waits for the child process to complete, hence the name `watcher`:

Listing A.8: The watcher

```
import threading, time, os, signal, sys

class Thread(threading.Thread):
    def __init__(self, t, *args):
        threading.Thread.__init__(self, target=t, args=args)
        self.start()

def parent_code():
    child = Thread(child_code, 10)
    child.join()

def child_code(n=10):
    for i in range(n):
        print i
        time.sleep(1)
```

[1] At the time of this writing, this bug had been reported and assigned number 1167930, but it was open and unassigned (https://sourceforge.net/projects/python/).

```

def watcher():
    child = os.fork()
    if child == 0: return
    try:
        os.wait()
    except KeyboardInterrupt:
        print 'KeyboardInterrupt'
        os.kill(child, signal.SIGKILL)
    sys.exit()

watcher()
parent_code()
```

If you run this version of the program, you should be able to interrupt it with Ctrl-C. I am not sure, but I think it is guaranteed that the `SIGINT` is delivered to the watcher process, so that's one less thing the parent and child threads have to deal with.

I keep all this code in a file named `threading_cleanup.py`, which you can download from greenteapress.com/semaphores/threading_cleanup.py

The examples in Chapter 8 are presented with the understanding that this code executes prior to the example code.

Appendix B

Cleaning up POSIX threads

In this section, I present some utility code I use to make multithreading in C a little more pleasant. The examples in Section 9 are based on this code.

Probably the most popular threading standard used with C is POSIX Threads, or Pthreads for short. The POSIX standard defines a thread model and an interface for creating and controlling threads. Most versions of UNIX provide an implementation of Pthreads.

B.1 Compiling Pthread code

Using Pthreads is like using most C libraries:

- You include headers files at the beginning of your program.
- You write code that calls functions defined by Pthreads.
- When you compile the program, you link it with the Pthread library.

For my examples, I include the following headers:

Listing B.1: Headers

```
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>
#include <semaphore.h>
```

The first two are standard; the third is for Pthreads and the fourth is for semaphores. To compile with the Pthread library in `gcc`, you can use the `-l` option on the command line:

```
gcc -g -O2 -o array array.c -lpthread
```

This compiles `array.c` with debugging info and optimization, links with the Pthread library, and generates an executable named `array`.

If you are used to a language like Python that provides exception handling, you will probably be annoyed with languages like C that require you to check for error conditions explicitly. I often mitigate this hassle by wrapping library function calls together with their error-checking code inside my own functions. For example, here is a version of `malloc` that checks the return value.

```
void *check_malloc(int size)
{
  void *p = malloc (size);
  if (p == NULL) {
    perror ("malloc failed");
    exit (-1);
  }
  return p;
}
```

B.2 Creating threads

I've done the same thing with the Pthread functions I'm going to use; here's my wrapper for `pthread_create`.

```
pthread_t make_thread(void *entry)(void , Shared *shared)
{
  int n;
  pthread_t thread;

  n = pthread_create (&thread, NULL, entry, (void *)shared);
  if (n != 0) {
    perror ("pthread_create failed");
    exit (-1);
  }
  return thread;
}
```

The return type from `pthread_create` is `pthread_t`, which you can think of as a handle for the new thread. You shouldn't have to worry about the implementation of `pthread_t`, but you do have to know that it has the semantics of a primitive type[1]. That means that you can think of a thread handle as an immutable value, so you can copy it or pass it by value without causing problems. I point this out now because it is not true for semaphores, which I will get to in a minute.

[1] Like an integer, for example, which is what a `pthread_t` is in all the implementations I know.

If pthread_create succeeds, it returns 0 and my function returns the handle of the new thread. If an error occurs, pthread_create returns an error code and my function prints an error message and exits.

The parameters of pthread_create take some explaining. Starting with the second, Shared is a user-defined structure that contains shared variables. The following typedef statement creates the new type:

```
typedef struct {
  int counter;
} Shared;
```

In this case, the only shared variable is counter. make_shared allocates space for a Shared structure and initializes the contents:

```
Shared *make_shared ()
{
  int i;
  Shared *shared = check_malloc (sizeof (Shared));
  shared->counter = 0;
  return shared;
}
```

Now that we have a shared data structure, let's get back to pthread_create. The first parameter is a pointer to a function that takes a void pointer and returns a void pointer. If the syntax for declaring this type makes your eyes bleed, you are not alone. Anyway, the purpose of this parameter is to specify the function where the execution of the new thread will begin. By convention, this function is named entry:

```
void *entry (void *arg)
{
  Shared *shared = (Shared *) arg;
  child_code (shared);
  pthread_exit (NULL);
}
```

The parameter of entry has to be declared as a void pointer, but in this program we know that it is really a pointer to a Shared structure, so we can typecast it accordingly and then pass it along to child_code, which does the real work.

When child_code returns, we invoke pthread_exit which can be used to pass a value to any thread (usually the parent) that joins with this thread. In this case, the child has nothing to say, so we pass NULL.

B.3 Joining threads

When one thread want to wait for another thread to complete, it invokes pthread_join. Here is my wrapper for pthread_join:

```
void join_thread (pthread_t thread)
{
  int ret = pthread_join (thread, NULL);
  if (ret == -1) {
    perror ("pthread_join failed");
    exit (-1);
  }
}
```

The parameter is the handle of the thread you want to wait for. All my function does is call `pthread_join` and check the result.

B.4 Semaphores

The POSIX standard specifies an interface for semaphores. This interface is not part of Pthreads, but most UNIXes that implement Pthreads also provide semaphores. If you find yourself with Pthreads and without semaphores, you can make your own; see Section 9.2.

POSIX semaphores have type `sem_t`. You shouldn't have to know about the implementation of this type, but you do have to know that it has structure semantics, which means that if you assign it to a variable you are making a copy of the contents of a structure. Copying a semaphore is almost certainly a bad idea. In POSIX, the behavior of the copy is undefined.

In my programs, I use capital letters to denote types with structure semantics, and I always manipulate them with pointers. Fortunately, it is easy to put a wrapper around `sem_t` to make it behave like a proper object. Here is the `typedef` and the wrapper that creates and initializes semaphores:

```
typedef sem_t Semaphore;

Semaphore *make_semaphore (int n)
{
  Semaphore *sem = check_malloc (sizeof(Semaphore));
  int ret = sem_init(sem, 0, n);
  if (ret == -1) {
    perror ("sem_init failed");
    exit (-1);
  }
  return sem;
}
```

`make_semaphore` takes the initial value of the semaphore as a parameter. It allocates space for a Semaphore, initializes it, and returns a pointer to `Semaphore`.

`sem_init` uses old-style UNIX error reporting, which means that it returns -1 if something went wrong. Once nice thing about these wrapper functions is that we don't have to remember which functions use which reporting style.

With these definitions, we can write C code that almost looks like a real programming language:

```
Semaphore *mutex = make_semaphore(1);
sem_wait(mutex);
sem_post(mutex);
```

Annoyingly, POSIX semaphores use `post` instead of `signal`, but we can fix that:

```
int sem_signal(Semaphore *sem)
{
  return sem_post(sem);
}
```

That's enough cleanup for now.