CHAPTER 1

An Introduction to Concurrency

Concurrency is an interesting word because it means different things to different people in our field. In addition to "concurrency," you may have heard the words, "asynchronous," "parallel," or "threaded" bandied about. Some people take these words to mean the same thing, and other people very specifically delineate between each of those words. If we're to spend an entire book's worth of time discussing concurrency, it would be beneficial to first spend some time discussing what we mean when we say "concurrency."

We'll spend some time on the philosophy of concurrency in Chapter 2, but for now let's adopt a practical definition that will serve as the foundation of our understanding.

When most people use the word "concurrent," they're usually referring to a process that occurs simultaneously with one or more processes. It is also usually implied that all of these processes are making progress at about the same time. Under this definition, an easy way to think about this are people. You are currently reading this sentence while others in the world are simultaneously living their lives. They are existing *concurrently* to you.

Concurrency is a broad topic in computer science, and from this definition spring all kinds of topics: theory, approaches to modeling concurrency, correctness of logic, practical issues—even theoretical physics! We'll touch on some of the ancillary topics throughout the book, but we'll mostly stick to the practical issues that involve understanding concurrency within the context of Go, specifically: how Go chooses to model concurrency, what issues arise from this model, and how we can compose primitives within this model to solve problems.

In this chapter, we'll take a broad look at some of the reasons concurrency became such an important topic in computer science, why concurrency is difficult and warrants careful study, and—most importantly—the idea that despite these challenges, Go can make programs clearer and faster by using its concurrency primitives.

As with most paths toward understanding, we'll begin with a bit of history. Let's first take a look at how concurrency became such an important topic.

Moore's Law, Web Scale, and the Mess We're In

In 1965, Gordon Moore wrote a three-page paper that described both the consolidation of the electronics market toward integrated circuits, and the doubling of the number of components in an integrated circuit every year for at least a decade. In 1975, he revised this prediction to state that the number of components on an integrated circuit would double every two years. This prediction more or less held true until just recently—around 2012.

Several companies foresaw this slowdown in the rate Moore's law predicted and began to investigate alternative ways to increase computing power. As the saying goes, necessity is the mother of innovation, and so it was in this way that multicore processors were born.

This looked like a clever way to solve the bounding problems of Moore's law, but computer scientists soon found themselves facing down the limits of another law: Amdahl's law, named after computer architect Gene Amdahl.

Amdahl's law describes a way in which to model the potential performance gains from implementing the solution to a problem in a parallel manner. Simply put, it states that the gains are bounded by how much of the program must be written in a sequential manner.

For example, imagine you were writing a program that was largely GUI based: a user is presented with an interface, clicks on some buttons, and stuff happens. This type of program is bounded by one very large sequential portion of the pipeline: human interaction. No matter how many cores you make available to this program, it will always be bounded by how quickly the user can interact with the interface.

Now consider a different example, calculating digits of pi. Thanks to a class of algorithms called spigot algorithms, this problem is called *embarrassingly parallel*, which —despite sounding made up—is a technical term which means that it can easily be divided into parallel tasks. In this case, significant gains can be made by making more cores available to your program, and your new problem becomes how to combine and store the results.

Amdahl's law helps us understand the difference between these two problems, and can help us decide whether parallelization is the right way to address performance concerns in our system.

For problems that are embarrassingly parallel, it is recommended that you write your application so that it can *scale horizontally*. This means that you can take instances of your program, run it on more CPUs, or machines, and this will cause the runtime of the system to improve. Embarrassingly parallel problems fit this model so well because it's very easy to structure your program in such a way that you can send chunks of a problem to different instances of your application.

Scaling horizontally became much easier in the early 2000s when a new paradigm began to take hold: *cloud computing*. Although there are indications that the phrase had been used as early as the 1970s, the early 2000s are when the idea really took root in the zeitgeist. Cloud computing implied a new kind of scale and approach to application deployments and horizontal scaling. Instead of machines that you carefully curated, installed software on, and maintained, cloud computing implied access to vast pools of resources that were provisioned into machines for workloads on-demand. Machines became something that were almost ephemeral, and provisioned with characteristics specifically suited to the programs they would run. Usually (but not always) these resource pools were hosted in data centers owned by other companies.

This change encouraged a new kind of thinking. Suddenly, developers had relatively cheap access to vast amounts of computing power that they could use to solve large problems. Solutions could now trivially span many machines and even global regions. Cloud computing made possible a whole new set of solutions to problems that were previously only solvable by tech giants.

But cloud computing also presented many new challenges. Provisioning these resources, communicating between machine instances, and aggregating and storing the results all became problems to solve. But among the most difficult was figuring out how to model code concurrently. The fact that pieces of your solution could be running on disparate machines exacerbated some of the issues commonly faced when modeling a problem concurrently. Successfully solving these issues soon led to a new type of brand for software, *web scale*.

If software was web scale, among other things, you could expect that it would be embarrassingly parallel; that is, web scale software is usually expected to be able to handle hundreds of thousands (or more) of simultaneous workloads by adding more instances of the application. This enabled all kinds of properties like rolling upgrades, elastic horizontally scalable architecture, and geographic distribution. It also introduced new levels of complexity both in comprehension and fault tolerance.

And so it is in this world of multiple cores, cloud computing, web scale, and problems that may or may not be parallelizable that we find the modern developer, maybe a bit overwhelmed. The proverbial buck has been passed to us, and we are expected to rise to the challenge of solving problems within the confines of the hardware we've been handed. In 2005, Herb Sutter authored an article for *Dr. Dobb's*, titled, "The free lunch is over: A fundamental turn toward concurrency in software". The title is apt, and the article prescient. Toward the end, Sutter states, "We desperately need a higher-level programming model for concurrency than languages offer today."

To know why Sutter used such strong language, we have to look at why concurrency is so hard to get right.

Why Is Concurrency Hard?

Concurrent code is notoriously difficult to get right. It usually takes a few iterations to get it working as expected, and even then it's not uncommon for bugs to exist in code for years before some change in timing (heavier disk utilization, more users logged into the system, etc.) causes a previously undiscovered bug to rear its head. Indeed, for this very book, I've gotten as many eyes as possbile on the code to try and mitigate this.

Fortunately *everyone* runs into the same issues when working with concurrent code. Because of this, computer scientists have been able to label the common issues, which allows us to discuss how they arise, why, and how to solve them.

So let's get started. Following are some of the most common issues that make working with concurrent code both frustrating and interesting.

Race Conditions

A race condition occurs when two or more operations must execute in the correct order, but the program has not been written so that this order is guaranteed to be maintained.

Most of the time, this shows up in what's called a *data race*, where one concurrent operation attempts to read a variable while at some undetermined time another concurrent operation is attempting to write to the same variable.

Here's a basic example:

```go
var data int
go func() { ❶
    data++
}()
if data == 0 {
    fmt.Printf("the value is %v.\n", data)
}
```

❶ In Go, you can use the `go` keyword to run a function concurrently. Doing so creates what's called a *goroutine*. We'll discuss this in detail in the section, "Goroutines" on page 37.

Here, lines 3 and 5 are both trying to access the variable data, but there is no guarantee what order this might happen in. There are three possible outcomes to running this code:

- Nothing is printed. In this case, line 3 was executed before line 5.
- "the value is 0" is printed. In this case, lines 5 and 6 were executed before line 3.
- "the value is 1" is printed. In this case, line 5 was executed before line 3, but line 3 was executed before line 6.

As you can see, just a few lines of incorrect code can introduce tremendous variability into your program.

Most of the time, data races are introduced because the developers are thinking about the problem sequentially. They assume that because a line of code falls before another that it will run first. They assume the goroutine above will be scheduled and execute before the `data` variable is read in the `if` statement.

When writing concurrent code, you have to meticulously iterate through the possible scenarios. Unless you're utilizing some of the techniques we'll cover later in the book, you have no guarantees that your code will run in the order it's listed in the sourcecode. I sometimes find it helpful to imagine a large period of time passing between operations. Imagine an hour passes between the time when the goroutine is invoked, and when it is run. How would the rest of the program behave? What if it took an hour between the goroutine executing successfully and the program reaching the `if` statement? Thinking in this manner helps me because to a computer, the scale may be different, but the relative time differentials are more or less the same.

Indeed, some developers fall into the trap of sprinkling sleeps throughout their code exactly because it seems to solve their concurrency problems. Let's try that in the preceding program:

```
var data int
go func() { data++ }()
time.Sleep(1*time.Second) // This is bad!
if data == 0 {
    fmt.Printf("the value is %v.\n" data)
}
```

Have we solved our data race? No. In fact, it's still possible for all three outcomes to arise from this program, just increasingly *unlikely*. The longer we sleep in between invoking our goroutine and checking the value of data, the closer our program gets to achieving correctness—but this probability asymptotically approaches logical correctness; it will never be logically correct.

In addition to this, we've now introduced an inefficiency into our algorithm. We now have to sleep for one second to make it more likely we won't see our data race. If we utilized the correct tools, we might not have to wait at all, or the wait could be only a microsecond.

The takeaway here is that you should always target logical correctness. Introducing sleeps into your code can be a handy way to debug concurrent programs, but they are not a solution.

Race conditions are one of the most insidious types of concurrency bugs because they may not show up until years after the code has been placed into production. They are usually precipitated by a change in the environment the code is executing in, or an unprecedented occurrence. In these cases, the code seems to be behaving correctly, but in reality, there's just a very high chance that the operations will be executed in order. Sooner or later, the program will have an unintended consequence.

Atomicity

When something is considered atomic, or to have the property of atomicity, this means that within the context that it is operating, it is indivisible, or uninterruptible.

So what does that really mean, and why is this important to know when working with concurrent code?

The first thing that's very important is the word "context." Something may be atomic in one context, but not another. Operations that are atomic within the context of your process may not be atomic in the context of the operating system; operations that are atomic within the context of the operating system may not be atomic within the context of your machine; and operations that are atomic within the context of your machine may not be atomic within the context of your application. In other words, the atomicity of an operation can change depending on the currently defined scope. This fact can work both for and against you!

When thinking about atomicity, very often the first thing you need to do is to define the context, or scope, the operation will be considered to be atomic in. Everything follows from this.

Fun Fact

In 2006, the gaming company Blizzard successfully sued MDY Industries for $6,000,000 USD for making a program called "Glider," which would automatically play their game, World of Warcraft, without user intervention. These types of programs are commonly referred to as "bots" (short for robots).

At the time, World of Warcraft had an anti-cheating program called "Warden," which would run anytime you played the game. Among other things, Warden would scan the memory of the host machine and run a heuristic to look for programs that appeared to be used for cheating.

Glider successfully avoided this check by taking advantage of the concept of atomic context. Warden considered scanning the memory on the machine as an atomic operation, but Glider utilized hardware interrupts to hide itself before this scanning started! Warden's scan of memory was atomic within the context of the process, but not within the context of the operating system.

Now let's look at the terms "indivisible" and "uninterruptible." These terms mean that within the context you've defined, something that is atomic will happen in its entirety without anything happening in that context simultaneously. That's still a mouthful, so let's look at an example:

```
i++
```

This is about as simple an example as anyone can contrive, and yet it easily demonstrates the concept of atomicity. It may *look* atomic, but a brief analysis reveals several operations:

- Retrieve the value of `i`.
- Increment the value of `i`.
- Store the value of `i`.

While each of these operations alone is atomic, the combination of the three may not be, depending on your context. This reveals an interesting property of atomic operations: combining them does not necessarily produce a larger atomic operation. Making the operation atomic is dependent on which context you'd like it to be atomic within. If your context is a program with no concurrent processes, then this code is atomic within that context. If your context is a goroutine that doesn't expose `i` to other goroutines, then this code is atomic.

So why do we care? Atomicity is important because if something is atomic, implicitly it is safe within concurrent contexts. This allows us to compose logically correct programs, and—as we'll later see—can even serve as a way to optimize concurrent programs.

Most statements are not atomic, let alone functions, methods, and programs. If atomicity is the key to composing logically correct programs, and most statements aren't atomic, how do we reconcile these two statements? We'll go into more depth later, but in short we can force atomicity by employing various techniques. The art then becomes determining which areas of your code need to be atomic, and at what level of granularity. We discuss some of these challenges in the next section.

Memory Access Synchronization

Let's say we have a data race: two concurrent processes are attempting to access the same area of memory, and the way they are accessing the memory is not atomic. Our previous example of a simple data race will do nicely with a few modifications:

```
var data int
go func() { data++}()
if data == 0 {
    fmt.Println("the value is 0.")
} else {
    fmt.Printf("the value is %v.\n", data)
}
```

We've added an `else` clause here so that regardless of the value of `data` we'll always get some output. Remember that as it is written, there is a data race and the output of the program will be completely nondeterministic.

In fact, there's a name for a section of your program that needs exclusive access to a shared resource. This is called a *critical section*. In this example, we have three critical sections:

- Our goroutine, which is incrementing the `data` variables.
- Our `if` statement, which checks whether the value of `data` is 0.
- Our `fmt.Printf` statement, which retrieves the value of `data` for output.

There are various ways to guard your program's critical sections, and Go has some better ideas on how to deal with this, but one way to solve this problem is to synchronize access to the memory between your critical sections. Let's see what that looks like.

The following code is not idiomatic Go (and I don't suggest you attempt to solve your data race problems like this), but it very simply demonstrates memory access synchronization. If any of the types, functions, or methods in this example are foreign to you, that's OK. Focus on the concept of synchronizing access to the memory by following the callouts.

```
var memoryAccess sync.Mutex ❶
var value int
go func() {
    memoryAccess.Lock() ❷
    value++
    memoryAccess.Unlock() ❸
}()

memoryAccess.Lock() ❹
if value == 0 {
    fmt.Printf("the value is %v.\n", value)
```

```go
} else {
    fmt.Printf("the value is %v.\n", value)
}
memoryAccess.Unlock() ❺
```

❶ Here we add a variable that will allow our code to synchronize access to the `data` variable's memory. We'll go over the `sync.Mutex` type in detail in "The sync Package" on page 47.

❷ Here we declare that until we declare otherwise, our goroutine should have exclusive access to this memory.

❸ Here we declare that the goroutine is done with this memory.

❹ Here we once again declare that the following conditional statements should have exclusive access to the `data` variable's memory.

❺ Here we declare we're once again done with this memory.

In this example we've created a convention for developers to follow. Anytime developers want to access the `data` variable's memory, they must first call `Lock`, and when they're finished they must call `Unlock`. Code between those two statements can then assume it has exclusive access to `data`; we have successfully *synchronized* access to the memory. Also note that if developers don't follow this convention, we have no guarantee of exclusive access! We'll return to this idea in the section "Confinement" on page 85.

You may have noticed that while we have solved our data race, we haven't actually solved our race condition! The order of operations in this program is still nondeterministic; we've just narrowed the scope of the nondeterminism a bit. In this example, either the goroutine will execute first, or both our `if` and `else` blocks will. We still don't know which will occur first in any given execution of this program. Later, we'll explore the tools to solve this kind of issue properly.

On its face this seems pretty simple: if you find you have critical sections, add points to synchronize access to the memory! Easy, right? Well…sort of.

It is true that you can solve some problems by synchronizing access to the memory, but as we just saw, it doesn't automatically solve data races or logical correctness. Further, it can also create maintenance and performance problems.

Note that earlier we mentioned that we had created a *convention* for declaring we needed exclusive access to some memory. Conventions are great, but they're also easy to ignore—especially in software engineering where the demands of business sometimes outweigh prudence. By synchronizing access to the memory in this manner, you are counting on all other developers to follow the same convention now and into the future. That's a pretty tall order. Thankfully, later in this book we'll also look at some ways we can help our colleagues be more successful.

Synchronizing access to the memory in this manner also has performance ramifications. We'll save the details for later when we examine the `sync` package in the section "The sync Package" on page 47, but the calls to `Lock` you see can make our program *slow*. Every time we perform one of these operations, our program pauses for a period of time. This brings up two questions:

- Are my critical sections entered and exited repeatedly?
- What size should my critical sections be?

Answering these two questions in the context of your program is an art, and this adds to the difficulty in synchronizing access to the memory.

Synchronizing access to the memory also shares some problems with other techniques of modeling concurrent problems, and we'll discuss those in the next section.

Deadlocks, Livelocks, and Starvation

The previous sections have all been about discussing program correctness in that if these issues are managed correctly, your program will never give an incorrect answer. Unfortunately, even if you successfully handle these classes of issues, there is another class of issues to contend with: deadlocks, livelocks, and starvation. These issues all concern ensuring your program has something useful to do at all times. If not handled properly, your program could enter a state in which it will stop functioning altogether.

Deadlock

A deadlocked program is one in which all concurrent processes are waiting on one another. In this state, the program will never recover without outside intervention.

If that sounds grim, it's because it is! The Go runtime attempts to do its part and will detect some deadlocks (all goroutines must be blocked, or "asleep"[1]), but this doesn't do much to help you prevent deadlocks.

To help solidify what a deadlock is, let's first look at an example. Again, it's safe to ignore any types, functions, methods, or packages you don't know and just follow the code callouts.

```
type value struct {
    mu    sync.Mutex
```

1 There is an accepted proposal to allow the runtime to detect partial deadlocks, but it has not been implemented. For more information, see *https://github.com/golang/go/issues/13759*.

```
        value int
    }

    var wg sync.WaitGroup
    printSum := func(v1, v2 *value) {
        defer wg.Done()
        v1.mu.Lock() ❶
        defer v1.mu.Unlock() ❷

        time.Sleep(2*time.Second) ❸
        v2.mu.Lock()
        defer v2.mu.Unlock()

        fmt.Printf("sum=%v\n", v1.value + v2.value)
    }

    var a, b value
    wg.Add(2)
    go printSum(&a, &b)
    go printSum(&b, &a)
    wg.Wait()
```

❶ Here we attempt to enter the critical section for the incoming value.

❷ Here we use the `defer` statement to exit the critical section before `printSum` returns.

❸ Here we sleep for a period of time to simulate work (and trigger a deadlock).

If you were to try and run this code, you'd probably see:

```
fatal error: all goroutines are asleep - deadlock!
```

Why? If you look carefully, you'll see a timing issue in this code. Following is a graphical representation of what's going on. The boxes represent functions, the horizontal lines calls to these functions, and the vertical bars lifetimes of the function at the head of the graphic (Figure 1-1).

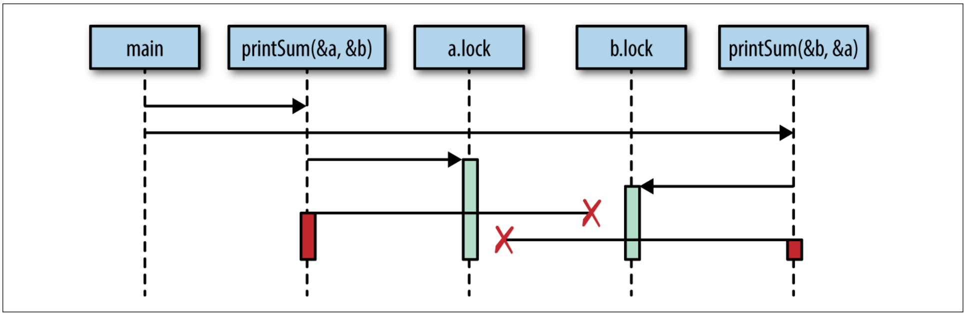


Figure 1-1. Demonstration of a timing issue giving rise to a deadlock

Essentially, we have created two gears that cannot turn together: our first call to `printSum` locks `a` and then attempts to lock `b`, but in the meantime our second call to `printSum` has locked `b` and has attempted to lock `a`. Both goroutines wait infinitely on each other.

> **Irony**
>
> To keep this example simple, I use a `time.Sleep` to trigger the deadlock. However, this introduces a race condition! Can you find it?
>
> A logically "perfect" deadlock would require correct synchronization.[2]

It seems pretty obvious why this deadlock is occurring when we lay it out graphically like that, but we would benefit from a more rigorous definition. It turns out there are a few conditions that must be present for deadlocks to arise, and in 1971, Edgar Coffman enumerated these conditions in a paper. The conditions are now known as the *Coffman Conditions* and are the basis for techniques that help detect, prevent, and correct deadlocks.

The Coffman Conditions are as follows:

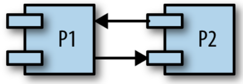
Mutual Exclusion
: A concurrent process holds exclusive rights to a resource at any one time.

Wait For Condition
: A concurrent process must simultaneously hold a resource and be waiting for an additional resource.

No Preemption
: A resource held by a concurrent process can only be released by that process, so it fulfills this condition.

Circular Wait
: A concurrent process (P1) must be waiting on a chain of other concurrent processes (P2), which are in turn waiting on it (P1), so it fulfills this final condition too.

2 We actually have no guarantee what order the goroutines will run in, or how long it will take them to start. It's plausible, although unlikely, that one goroutine could acquire and release both locks before the other begins, thus avoiding the deadlock!



Let's examine our contrived program and determine if it meets all four conditions:

1. The `printSum` function does require exclusive rights to both `a` and `b`, so it fulfills this condition.
2. Because `printSum` holds either `a` or `b` and is waiting on the other, it fulfills this condition.
3. We haven't given any way for our goroutines to be preempted.
4. Our first invocation of `printSum` is waiting on our second invocation, and vice versa.

Yep, we definitely have a deadlock on our hands.

These laws allow us to *prevent* deadlocks too. If we ensure that at least one of these conditions is not true, we can prevent deadlocks from occurring. Unfortunately, in practice these conditions can be hard to reason about, and therefore difficult to prevent. The web is strewn with questions from developers like you and me wondering why a snippet of code is deadlocking. Usually it's pretty obvious once someone points it out, but often it requires another set of eyes. We'll talk about why this is in the section "Determining Concurrency Safety" on page 18.

Livelock

Livelocks are programs that are actively performing concurrent operations, but these operations do nothing to move the state of the program forward.

Have you ever been in a hallway walking toward another person? She moves to one side to let you pass, but you've just done the same. So you move to the other side, but she's also done the same. Imagine this going on forever, and you understand livelocks.

Let's actually write some code that will help demonstrate this scenario. First, we'll set up a few helper functions that will simplify the example. In order to have a working example, the code here utilizes several topics we haven't yet covered. I don't advise attempting to understand it in any detail until you have a firm grasp on the `sync` package. Instead, I recommend following the code callouts to understand the highlights, and then turning your attention to the second code block, which contains the heart of the example.

```
cadence := sync.NewCond(&sync.Mutex{})
go func() {
    for range time.Tick(1*time.Millisecond) {
```

```
            cadence.Broadcast()
        }
    }()

    takeStep := func() {
        cadence.L.Lock()
        cadence.Wait()
        cadence.L.Unlock()
    }

    tryDir := func(dirName string, dir *int32, out *bytes.Buffer) bool { ❶
        fmt.Fprintf(out, " %v", dirName)
        atomic.AddInt32(dir, 1) ❷
        takeStep() ❸
        if atomic.LoadInt32(dir) == 1 {
            fmt.Fprint(out, ". Success!")
            return true
        }
        takeStep()
        atomic.AddInt32(dir, -1) ❹
        return false
    }

    var left, right int32
    tryLeft := func(out *bytes.Buffer) bool { return tryDir("left", &left, out) }
    tryRight := func(out *bytes.Buffer) bool { return tryDir("right", &right, out) }
```

❶ `tryDir` allows a person to attempt to move in a direction and returns whether or not they were successful. Each direction is represented as a count of the number of people trying to move in that direction, `dir`.

❷ First, we declare our intention to move in a direction by incrementing that direction by one. We'll discuss the `atomic` package in detail in Chapter 3. For now, all you need to know is that this package's operations are atomic.

❸ For the example to demonstrate a livelock, each person must move at the same rate of speed, or cadence. `takeStep` simulates a constant cadence between all parties.

❹ Here the person realizes they cannot go in this direction and gives up. We indicate this by decrementing that direction by one.

```
    walk := func(walking *sync.WaitGroup, name string) {
        var out bytes.Buffer
        defer func() { fmt.Println(out.String()) }()
        defer walking.Done()
        fmt.Fprintf(&out, "%v is trying to scoot:", name)
        for i := 0; i < 5; i++ { ❶
            if tryLeft(&out) || tryRight(&out) { ❷
```

```
                return
            }
        }
        fmt.Fprintf(&out, "\n%v tosses her hands up in exasperation!", name)
    }

    var peopleInHallway sync.WaitGroup ❸
    peopleInHallway.Add(2)
    go walk(&peopleInHallway, "Alice")
    go walk(&peopleInHallway, "Barbara")
    peopleInHallway.Wait()
```

❶ I placed an artificial limit on the number of attempts so that this program would end. In a program that has a livelock, there may be no such limit, which is why it's a problem!

❷ First, the person will attempt to step left, and if that fails, they will attempt to step right.

❸ This variable provides a way for the program to wait until both people are either able to pass one another, or give up.

This produces the following output:

```
Alice is trying to scoot: left right left right left right left right left right
Alice tosses her hands up in exasperation!
Barbara is trying to scoot: left right left right left right left right
left right
Barbara tosses her hands up in exasperation!
```

You can see that Alice and Barbara continue getting in each other's way before finally giving up.

This example demonstrates a very common reason livelocks are written: two or more concurrent processes attempting to prevent a deadlock without coordination. If the people in the hallway had agreed with one another that only one person would move, there would be no livelock: one person would stand still, the other would move to the other side, and they'd continue walking.

In my opinion, livelocks are more difficult to spot than deadlocks simply because it can appear as if the program is doing work. If a livelocked program were running on your machine and you took a look at the CPU utilization to determine if it was doing anything, you might think it was. Depending on the livelock, it might even be emitting other signals that would make you think it was doing work. And yet all the while, your program would be playing an eternal game of hallway-shuffle.

Livelocks are a subset of a larger set of problems called *starvation*. We'll look at that next.

Starvation

Starvation is any situation where a concurrent process cannot get all the resources it needs to perform work.

When we discussed livelocks, the resource each goroutine was starved of was a shared lock. Livelocks warrant discussion separate from starvation because in a livelock, all the concurrent processes are starved equally, and *no* work is accomplished. More broadly, starvation usually implies that there are one or more greedy concurrent process that are unfairly preventing one or more concurrent processes from accomplishing work as efficiently as possible, or maybe at all.

Here's an example of a program with a greedy goroutine and a polite goroutine:

```
var wg sync.WaitGroup
var sharedLock sync.Mutex
const runtime = 1*time.Second

greedyWorker := func() {
    defer wg.Done()

    var count int
    for begin := time.Now(); time.Since(begin) <= runtime; {
        sharedLock.Lock()
        time.Sleep(3*time.Nanosecond)
        sharedLock.Unlock()
        count++
    }

    fmt.Printf("Greedy worker was able to execute %v work loops\n", count)
}

politeWorker := func() {
    defer wg.Done()

    var count int
    for begin := time.Now(); time.Since(begin) <= runtime; {
        sharedLock.Lock()
        time.Sleep(1*time.Nanosecond)
        sharedLock.Unlock()

        sharedLock.Lock()
        time.Sleep(1*time.Nanosecond)
        sharedLock.Unlock()

        sharedLock.Lock()
        time.Sleep(1*time.Nanosecond)
        sharedLock.Unlock()

        count++
    }
```

```
        fmt.Printf("Polite worker was able to execute %v work loops.\n", count)
    }

    wg.Add(2)
    go greedyWorker()
    go politeWorker()

    wg.Wait()
```

This produces:

```
Polite worker was able to execute 289777 work loops.
Greedy worker was able to execute 471287 work loops
```

The greedy worker greedily holds onto the shared lock for the entirety of its work loop, whereas the polite worker attempts to only lock when it needs to. Both workers do the same amount of simulated work (sleeping for three nanoseconds), but as you can see in the same amount of time, the greedy worker got almost *twice* the amount of work done!

If we assume both workers have the same-sized critical section, rather than concluding that the greedy worker's algorithm is more efficient (or that the calls to `Lock` and `Unlock` are slow—they aren't), we instead conclude that the greedy worker has unnecessarily expanded its hold on the shared lock beyond its critical section and is preventing (via starvation) the polite worker's goroutine from performing work efficiently.

Note our technique here for identifying the starvation: a metric. Starvation makes for a good argument for recording and sampling metrics. One of the ways you can detect and solve starvation is by logging when work is accomplished, and then determining if your rate of work is as high as you expect it.

Finding a Balance

It is worth mentioning that the previous code example can also serve as an example of the performance ramifications of memory access synchronization. Because synchronizing access to the memory is expensive, it might be advantageous to broaden our lock beyond our critical sections. On the other hand, by doing so—as we saw—we run the risk of starving other concurrent processes.

If you utilize memory access synchronization, you'll have to find a balance between preferring coarse-grained synchronization for performance, and fine-grained synchronization for fairness. When it comes time to performance tune your application, to start with, I highly recommend you constrain memory access synchronization only to critical sections; if the synchronization becomes a performance problem, you can always broaden the scope. It's much harder to go the other way.

So starvation can cause your program to behave inefficiently or incorrectly. The prior example demonstrates an inefficiency, but if you have a concurrent process that is so greedy as to *completely* prevent another concurrent process from accomplishing work, you have a larger problem on your hands.

We should also consider the case where the starvation is coming from outside the Go process. Keep in mind that starvation can also apply to CPU, memory, file handles, database connections: any resource that must be shared is a candidate for starvation.

Determining Concurrency Safety

Finally, we come to the most difficult aspect of developing concurrent code, the thing that underlies all the other problems: people. Behind every line of code is at least one person.

As we've discovered, concurrent code is difficult for myriad reasons. If you're a developer and you're trying to wrangle all of these problems as you introduce new functionality, or fix bugs in your program, it can be really difficult to determine the right thing to do.

If you're starting with a blank slate and need to build up a sensible way to model your problem space and concurrency is involved, it can be difficult to find the right level of abstraction. How do you expose the concurrency to callers? What techniques do you use to create a solution that is both easy to use and modify? What is the right *level* of concurrency for this problem? Although there are ways to think about these problems in structured ways, it remains an art.

As a developer interfacing with *existing* code, it's not always obvious what code is utilizing concurrency, and how to utilize the code safely. Take this function signature:

```go
// CalculatePi calculates digits of Pi between the begin and end
// place.
func CalculatePi(begin, end int64, pi *Pi)
```

Calculating pi with a large precision is something that is best done concurrently, but this example raises a lot of questions:

- How do I do so with this function?
- Am I responsible for instantiating multiple concurrent invocations of this function?
- It looks like all instances of the function are going to be operating directly on the instance of `Pi` whose address I pass in; am I responsible for synchronizing access to that memory, or does the `Pi` type handle this for me?

One function raises all these questions. Imagine a program of any moderate size, and you can begin to understand the complexities concurrency can pose.

Comments can work wonders here. What if the `CalculatePi` function were instead written like this:

```
// CalculatePi calculates digits of Pi between the begin and end
// place.
//
// Internally, CalculatePi will create FLOOR((end-begin)/2) concurrent
// processes which recursively call CalculatePi. Synchronization of
// writes to pi are handled internally by the Pi struct.
func CalculatePi(begin, end int64, pi *Pi)
```

We now understand that we can call the function plainly and not worry about concurrency or synchronization. Importantly, the comment covers these aspects:

- Who is responsible for the concurrency?
- How is the problem space mapped onto concurrency primitives?
- Who is responsible for the synchronization?

When exposing functions, methods, and variables in problem spaces that involve concurrency, do your colleagues and future self a favor: err on the side of verbose comments, and try and cover these three aspects.

Also consider that perhaps the ambiguity in this function suggests that we've modeled it wrong. Maybe we should instead take a functional approach and ensure our function has no side effects:

```
func CalculatePi(begin, end int64) []uint
```

The signature of this function alone removes any questions of synchronization, but still leaves the question of whether concurrency is used. We can modify the signature again to throw out another signal as to what is happening:

```
func CalculatePi(begin, end int64) <-chan uint
```

Here we see the first usage of what's called a *channel*. For reasons we'll explore later in the section "Channels" on page 64, this suggests that `CalculatePi` will at least have one goroutine and that we shouldn't bother with creating our own.

These modifications then have performance ramifications that have to be taken into consideration, and we're back to the problem of balancing clarity with performance. Clarity is important because we want to make it as likely as possible that people working with this code in the future will do the right thing, and performance is important for obvious reasons. The two aren't mutually exclusive, but they are difficult to mix.

Now consider these difficulties in communication and try and scale them up to team-sized projects.

Wow, this is a problem.

The good news is that Go has made progress in making these types of problems easier to solve. The language itself favors readability and simplicity. The way it encourages modeling your concurrent code encourages correctness, composability, and scalability. In fact, the way Go handles concurrency can actually help express problem domains more clearly! Let's take a look at why this is the case.

Simplicity in the Face of Complexity

So far, I've painted a pretty grim picture. Concurrency is certainly a difficult area in computer science, but I want to leave you with hope: these problems aren't intractable, and with Go's concurrency primitives, you can more safely and clearly express your concurrent algorithms. The runtime and communication difficulties we've discussed are by no means solved by Go, but they have been made significantly easier. In the next chapter, we'll discover the root of how this progress has been accomplished. Here, let's spend a little time exploring the idea that Go's concurrency primitives can actually make it easier to model problem domains and express algorithms more clearly.

Go's runtime does most of the heavy lifting and provides the foundation for most of Go's concurrency niceties. We'll save the discussion of how it all works for Chapter 6, but here we'll discuss how these things make your life easier.

Let's first discuss Go's concurrent, low-latency, garbage collector. There is often debate among developers as to whether garbage collectors are a good thing to have in a language. Detractors suggest that garbage collectors prevent work in any problem domain that requires real-time performance or a deterministic performance profile—that pausing all activity in a program to clean up garbage simply isn't acceptable. While there is some merit to this, the excellent work that has been done on Go's garbage collector has dramatically reduced the audience that needs to concern themselves with the minutia of how Go's garbage collection works. As of Go 1.8, garbage collection pauses are generally between 10 and 100 microseconds!

How does this help you? Memory management can be another difficult problem domain in computer science, and when combined with concurrency, it can become extraordinarily difficult to write correct code. If you're in the majority of developers who don't need to worry about pauses as small as 10 microseconds, Go has made it much easier to use concurrency in your program by not forcing you to manage memory, let alone across concurrent processes.

Go's runtime also automatically handles multiplexing concurrent operations onto operating system threads. That's a mouthful, and we'll see exactly what that means in the section on "Goroutines" on page 37. For the purposes of understanding how this helps you, all you need to know is that it allows you to directly map concurrent problems into concurrent constructs instead of dealing with the minutia of starting and managing threads, and mapping logic evenly across available threads.

For example, say you write a web server, and you'd like every connection accepted to be handled concurrently with every other connection. In some languages, before your web server begins accepting connections, you'd likely have to create a collection of threads, commonly called a *thread pool*, and then map incoming connections onto threads. Then, within each thread you've created, you'd need to loop over all the connections on that thread to ensure they were all receiving some CPU time. In addition, you'd have to write your connection-handling logic to be pausable so that it shares fairly with the other connections.

Whew! In contrast, in Go you would write a function and then prepend its invocation with the `go` keyword. The runtime handles everything else we discussed automatically! When you're going through the process of designing your program, under which model do you think you're more likely to reach for concurrency? Which do you think is more likely to turn out correct?

Go's concurrency primitives also make composing larger problems easier. As we'll see in the section "Channels" on page 64, Go's *channel* primitive provides a composable, concurrent-safe way to communicate between concurrent processes.

I've glossed over most of the details of how these things work, but I wanted to give you some sense of how Go invites you to use concurrency in your program to help you solve your problems in a clear and performant way. In the next chapter we'll discuss the philosophy concurrency and why Go got so much right. If you're eager to jump into some code, you might want to flip over to Chapter 3.