Chapter 1

Introduction

Writing correct programs is hard; writing correct concurrent programs is harder. There are simply more things that can go wrong in a concurrent program than in a sequential one. So, why do we bother with concurrency? Threads are an inescapable feature of the Java language, and they can simplify the development of complex systems by turning complicated asynchronous code into simpler straight-line code. In addition, threads are the easiest way to tap the computing power of multiprocessor systems. And, as processor counts increase, exploiting concurrency effectively will only become more important.

1.1 A (very) brief history of concurrency

In the ancient past, computers didn't have operating systems; they executed a single program from beginning to end, and that program had direct access to all the resources of the machine. Not only was it difficult to write programs that ran on the bare metal, but running only a single program at a time was an inefficient use of expensive and scarce computer resources.

Operating systems evolved to allow more than one program to run at once, running individual programs in *processes*: isolated, independently executing programs to which the operating system allocates resources such as memory, file handles, and security credentials. If they needed to, processes could communicate with one another through a variety of coarse-grained communication mechanisms: sockets, signal handlers, shared memory, semaphores, and files.

Several motivating factors led to the development of operating systems that allowed multiple programs to execute simultaneously:

Resource utilization. Programs sometimes have to wait for external operations such as input or output, and while waiting can do no useful work. It is more efficient to use that wait time to let another program run.

Fairness. Multiple users and programs may have equal claims on the machine's resources. It is preferable to let them share the computer via finer-grained time slicing than to let one program run to completion and then start another.

Convenience. It is often easier or more desirable to write several programs that each perform a single task and have them coordinate with each other as necessary than to write a single program that performs all the tasks.

In early timesharing systems, each process was a virtual von Neumann computer; it had a memory space storing both instructions and data, executing instructions sequentially according to the semantics of the machine language, and interacting with the outside world via the operating system through a set of I/O primitives. For each instruction executed there was a clearly defined "next instruction", and control flowed through the program according to the rules of the instruction set. Nearly all widely used programming languages today follow this sequential programming model, where the language specification clearly defines "what comes next" after a given action is executed.

The sequential programming model is intuitive and natural, as it models the way humans work: do one thing at a time, in sequence—mostly. Get out of bed, put on your bathrobe, go downstairs and start the tea. As in programming languages, each of these real-world actions is an abstraction for a sequence of finer-grained actions—open the cupboard, select a flavor of tea, measure some tea into the pot, see if there's enough water in the teakettle, if not put some more water in, set it on the stove, turn the stove on, wait for the water to boil, and so on. This last step—waiting for the water to boil—also involves a degree of *asynchrony*. While the water is heating, you have a choice of what to do—just wait, or do other tasks in that time such as starting the toast (another asynchronous task) or fetching the newspaper, while remaining aware that your attention will soon be needed by the teakettle. The manufacturers of teakettles and toasters know their products are often used in an asynchronous manner, so they raise an audible signal when they complete their task. Finding the right balance of sequentiality and asynchrony is often a characteristic of efficient people—and the same is true of programs.

The same concerns (resource utilization, fairness, and convenience) that motivated the development of processes also motivated the development of *threads*. Threads allow multiple streams of program control flow to coexist within a process. They share process-wide resources such as memory and file handles, but each thread has its own program counter, stack, and local variables. Threads also provide a natural decomposition for exploiting hardware parallelism on multiprocessor systems; multiple threads within the same program can be scheduled simultaneously on multiple CPUs.

Threads are sometimes called *lightweight processes*, and most modern operating systems treat threads, not processes, as the basic units of scheduling. In the absence of explicit coordination, threads execute simultaneously and asynchronously with respect to one another. Since threads share the memory address space of their owning process, all threads within a process have access to the same variables and allocate objects from the same heap, which allows finer-grained data sharing than inter-process mechanisms. But without explicit synchronization to coordinate access to shared data, a thread may modify variables that another thread is in the middle of using, with unpredictable results.

1.2 Benefits of threads

When used properly, threads can reduce development and maintenance costs and improve the performance of complex applications. Threads make it easier to model how humans work and interact, by turning asynchronous workflows into mostly sequential ones. They can also turn otherwise convoluted code into straight-line code that is easier to write, read, and maintain.

Threads are useful in GUI applications for improving the responsiveness of the user interface, and in server applications for improving resource utilization and throughput. They also simplify the implementation of the JVM—the garbage collector usually runs in one or more dedicated threads. Most nontrivial Java applications rely to some degree on threads for their organization.

1.2.1 Exploiting multiple processors

Multiprocessor systems used to be expensive and rare, found only in large data centers and scientific computing facilities. Today they are cheap and plentiful; even low-end server and midrange desktop systems often have multiple processors. This trend will only accelerate; as it gets harder to scale up clock rates, processor manufacturers will instead put more processor cores on a single chip. All the major chip manufacturers have begun this transition, and we are already seeing machines with dramatically higher processor counts.

Since the basic unit of scheduling is the thread, a program with only one thread can run on at most one processor at a time. On a two-processor system, a single-threaded program is giving up access to half the available CPU resources; on a 100-processor system, it is giving up access to 99%. On the other hand, programs with multiple active threads can execute simultaneously on multiple processors. When properly designed, multithreaded programs can improve throughput by utilizing available processor resources more effectively.

Using multiple threads can also help achieve better throughput on single-processor systems. If a program is single-threaded, the processor remains idle while it waits for a synchronous I/O operation to complete. In a multithreaded program, another thread can still run while the first thread is waiting for the I/O to complete, allowing the application to still make progress during the blocking I/O. (This is like reading the newspaper while waiting for the water to boil, rather than waiting for the water to boil before starting to read.)

1.2.2 Simplicity of modeling

It is often easier to manage your time when you have only one type of task to perform (fix these twelve bugs) than when you have several (fix the bugs, interview replacement candidates for the system administrator, complete your team's performance evaluations, and create the slides for your presentation next week). When you have only one type of task to do, you can start at the top of the pile and keep working until the pile is exhausted (or you are); you don't have to spend any mental energy figuring out what to work on next. On the other hand, managing multiple priorities and deadlines and switching from task to task usually carries some overhead.

The same is true for software: a program that processes one type of task sequentially is simpler to write, less error-prone, and easier to test than one managing multiple different types of tasks at once. Assigning a thread to each type of task or to each element in a simulation affords the illusion of sequentiality and insulates domain logic from the details of scheduling, interleaved operations, asynchronous I/O, and resource waits. A complicated, asynchronous workflow can be decomposed into a number of simpler, synchronous workflows each running in a separate thread, interacting only with each other at specific synchronization points.

This benefit is often exploited by frameworks such as servlets or RMI (Remote Method Invocation). The framework handles the details of request management, thread creation, and load balancing, dispatching portions of the request handling to the appropriate application component at the appropriate point in the workflow. Servlet writers do not need to worry about how many other requests are being processed at the same time or whether the socket input and output streams block; when a servlet's `service` method is called in response to a web request, it can process the request synchronously as if it were a single-threaded program. This can simplify component development and reduce the learning curve for using such frameworks.

1.2.3 Simplified handling of asynchronous events

A server application that accepts socket connections from multiple remote clients may be easier to develop when each connection is allocated its own thread and allowed to use synchronous I/O.

If an application goes to read from a socket when no data is available, `read` blocks until some data is available. In a single-threaded application, this means that not only does processing the corresponding request stall, but processing of *all* requests stalls while the single thread is blocked. To avoid this problem, single-threaded server applications are forced to use nonblocking I/O, which is far more complicated and error-prone than synchronous I/O. However, if each request has its own thread, then blocking does not affect the processing of other requests.

Historically, operating systems placed relatively low limits on the number of threads that a process could create, as few as several hundred (or even less). As a result, operating systems developed efficient facilities for multiplexed I/O, such as the Unix `select` and `poll` system calls, and to access these facilities, the Java class libraries acquired a set of packages (`java.nio`) for nonblocking I/O. However, operating system support for larger numbers of threads has improved significantly, making the thread-per-client model practical even for large numbers of clients on some platforms.[1]

1. The NPTL threads package, now part of most Linux distributions, was designed to support hundreds of thousands of threads. Nonblocking I/O has its own benefits, but better OS support for threads means that there are fewer situations for which it is *essential*.

1.2.4 More responsive user interfaces

GUI applications used to be single-threaded, which meant that you had to either frequently poll throughout the code for input events (which is messy and intrusive) or execute all application code indirectly through a "main event loop". If code called from the main event loop takes too long to execute, the user interface appears to "freeze" until that code finishes, because subsequent user interface events cannot be processed until control is returned to the main event loop.

Modern GUI frameworks, such as the AWT and Swing toolkits, replace the main event loop with an *event dispatch thread* (EDT). When a user interface event such as a button press occurs, application-defined event handlers are called in the event thread. Most GUI frameworks are single-threaded subsystems, so the main event loop is effectively still present, but it runs in its own thread under the control of the GUI toolkit rather than the application.

If only short-lived tasks execute in the event thread, the interface remains responsive since the event thread is always able to process user actions reasonably quickly. However, processing a long-running task in the event thread, such as spell-checking a large document or fetching a resource over the network, impairs responsiveness. If the user performs an action while this task is running, there is a long delay before the event thread can process or even acknowledge it. To add insult to injury, not only does the UI become unresponsive, but it is impossible to cancel the offending task even if the UI provides a cancel button because the event thread is busy and cannot handle the cancel button-press event until the lengthy task completes! If, however, the long-running task is instead executed in a separate thread, the event thread remains free to process UI events, making the UI more responsive.

1.3 Risks of threads

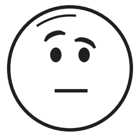
Java's built-in support for threads is a double-edged sword. While it simplifies the development of concurrent applications by providing language and library support and a formal cross-platform memory model (it is this formal cross-platform memory model that makes possible the development of write-once, run-anywhere *concurrent* applications in Java), it also raises the bar for developers because more programs will use threads. When threads were more esoteric, concurrency was an "advanced" topic; now, mainstream developers must be aware of thread-safety issues.

1.3.1 Safety hazards

Thread safety can be unexpectedly subtle because, in the absence of sufficient synchronization, the ordering of operations in multiple threads is unpredictable and sometimes surprising. `UnsafeSequence` in Listing 1.1, which is supposed to generate a sequence of unique integer values, offers a simple illustration of how the interleaving of actions in multiple threads can lead to undesirable results. It behaves correctly in a single-threaded environment, but in a multithreaded environment does not.

```
@NotThreadSafe
public class UnsafeSequence {
    private int value;

    /** Returns a unique value. */
    public int getNext() {
        return value++;
    }
}
```



Listing 1.1. Non-thread-safe sequence generator.

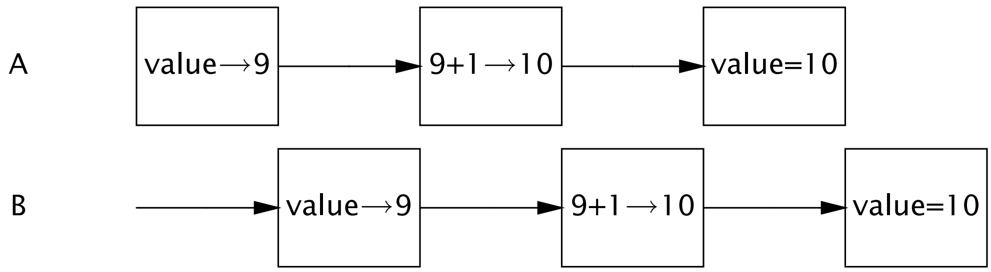


Figure 1.1. Unlucky execution of `UnsafeSequence.getNext`.

The problem with `UnsafeSequence` is that with some unlucky timing, two threads could call `getNext` and receive *the same value*. Figure 1.1 shows how this can happen. The increment notation, `someVariable++`, may *appear* to be a single operation, but is in fact three separate operations: read the value, add one to it, and write out the new value. Since operations in multiple threads may be arbitrarily interleaved by the runtime, it is possible for two threads to read the value at the same time, both see the same value, and then both add one to it. The result is that the same sequence number is returned from multiple calls in different threads.

Diagrams like Figure 1.1 depict possible interleavings of operations in different threads. In these diagrams, time runs from left to right, and each line represents the activities of a different thread. These interleaving diagrams usually depict the worst case[2] and are intended to show the danger of incorrectly assuming things will happen in a particular order.

`UnsafeSequence` uses a nonstandard annotation: `@NotThreadSafe`. This is one of several custom annotations used throughout this book to document concurrency properties of classes and class members. (Other class-level annotations used

2. Actually, as we'll see in Chapter 3, the worst case can be even worse than these diagrams usually show because of the possibility of reordering.

in this way are `@ThreadSafe` and `@Immutable`; see Appendix A for details.) Annotations documenting thread safety are useful to multiple audiences. If a class is annotated with `@ThreadSafe`, users can use it with confidence in a multithreaded environment, maintainers are put on notice that it makes thread safety guarantees that must be preserved, and software analysis tools can identify possible coding errors.

`UnsafeSequence` illustrates a common concurrency hazard called a *race condition*. Whether or not `getNext` returns a unique value when called from multiple threads, as required by its specification, depends on how the runtime interleaves the operations—which is not a desirable state of affairs.

Because threads share the same memory address space and run concurrently, they can access or modify variables that other threads might be using. This is a tremendous convenience, because it makes data sharing much easier than would other inter-thread communications mechanisms. But it is also a significant risk: threads can be confused by having data change unexpectedly. Allowing multiple threads to access and modify the same variables introduces an element of nonsequentiality into an otherwise sequential programming model, which can be confusing and difficult to reason about. For a multithreaded program's behavior to be predictable, access to shared variables must be properly coordinated so that threads do not interfere with one another. Fortunately, Java provides synchronization mechanisms to coordinate such access.

`UnsafeSequence` can be fixed by making `getNext` a `synchronized` method, as shown in `Sequence` in Listing 1.2,[3] thus preventing the unfortunate interaction in Figure 1.1. (Exactly why this works is the subject of Chapters 2 and 3.)

```
@ThreadSafe
public class Sequence {
    @GuardedBy("this") private int value;

    public synchronized int getNext() {
        return value++;
    }
}
```

Listing 1.2. Thread-safe sequence generator.

In the absence of synchronization, the compiler, hardware, and runtime are allowed to take substantial liberties with the timing and ordering of actions, such as caching variables in registers or processor-local caches where they are temporarily (or even permanently) invisible to other threads. These tricks are in aid of better performance and are generally desirable, but they place a burden on the developer to clearly identify where data is being shared across threads so that these optimizations do not undermine safety. (Chapter 16 gives the gory details on exactly what ordering guarantees the JVM makes and how synchronization

3. `@GuardedBy` is described in Section 2.4; it documents the *synchronization policy* for `Sequence`.

affects those guarantees, but if you follow the rules in Chapters 2 and 3, you can safely avoid these low-level details.)

1.3.2 Liveness hazards

It is critically important to pay attention to thread safety issues when developing concurrent code: safety cannot be compromised. The importance of safety is not unique to multithreaded programs—single-threaded programs also must take care to preserve safety and correctness—but the use of threads introduces additional safety hazards not present in single-threaded programs. Similarly, the use of threads introduces additional forms of *liveness failure* that do not occur in single-threaded programs.

While *safety* means "nothing bad ever happens", liveness concerns the complementary goal that "something good eventually happens". A liveness failure occurs when an activity gets into a state such that it is permanently unable to make forward progress. One form of liveness failure that can occur in sequential programs is an inadvertent infinite loop, where the code that follows the loop never gets executed. The use of threads introduces additional liveness risks. For example, if thread *A* is waiting for a resource that thread *B* holds exclusively, and *B* never releases it, *A* will wait forever. Chapter 10 describes various forms of liveness failures and how to avoid them, including deadlock (Section 10.1), starvation (Section 10.3.1), and livelock (Section 10.3.3). Like most concurrency bugs, bugs that cause liveness failures can be elusive because they depend on the relative timing of events in different threads, and therefore do not always manifest themselves in development or testing.

1.3.3 Performance hazards

Related to liveness is *performance*. While liveness means that something good *eventually* happens, eventually may not be good enough—we often want good things to happen quickly. Performance issues subsume a broad range of problems, including poor service time, responsiveness, throughput, resource consumption, or scalability. Just as with safety and liveness, multithreaded programs are subject to all the performance hazards of single-threaded programs, and to others as well that are introduced by the use of threads.

In well designed concurrent applications the use of threads is a net performance gain, but threads nevertheless carry some degree of runtime overhead. *Context switches*—when the scheduler suspends the active thread temporarily so another thread can run—are more frequent in applications with many threads, and have significant costs: saving and restoring execution context, loss of locality, and CPU time spent scheduling threads instead of running them. When threads share data, they must use synchronization mechanisms that can inhibit compiler optimizations, flush or invalidate memory caches, and create synchronization traffic on the shared memory bus. All these factors introduce additional performance costs; Chapter 11 covers techniques for analyzing and reducing these costs.

1.4 Threads are everywhere

Even if your program never explicitly creates a thread, frameworks may create threads on your behalf, and code called from these threads must be thread-safe. This can place a significant design and implementation burden on developers, since developing thread-safe classes requires more care and analysis than developing non-thread-safe classes.

Every Java application uses threads. When the JVM starts, it creates threads for JVM housekeeping tasks (garbage collection, finalization) and a main thread for running the `main` method. The AWT (Abstract Window Toolkit) and Swing user interface frameworks create threads for managing user interface events. `Timer` creates threads for executing deferred tasks. Component frameworks, such as servlets and RMI create pools of threads and invoke component methods in these threads.

If you use these facilities—as many developers do—you have to be familiar with concurrency and thread safety, because these frameworks create threads and call your components from them. It would be nice to believe that concurrency is an "optional" or "advanced" language feature, but the reality is that nearly all Java applications are multithreaded and these frameworks do not insulate you from the need to properly coordinate access to application state.

When concurrency is introduced into an application by a framework, it is usually impossible to restrict the concurrency-awareness to the framework code, because frameworks by their nature make callbacks to application components that in turn access application state. Similarly, the need for thread safety does not end with the components called by the framework—it extends to all code paths that access the program state accessed by those components. Thus, the need for thread safety is contagious.

> Frameworks introduce concurrency into applications by calling application components from framework threads. Components invariably access application state, thus requiring that *all* code paths accessing that state be thread-safe.

The facilities described below all cause application code to be called from threads not managed by the application. While the need for thread safety may start with these facilities, it rarely ends there; instead, it ripples through the application.

Timer. `Timer` is a convenience mechanism for scheduling tasks to run at a later time, either once or periodically. The introduction of a `Timer` can complicate an otherwise sequential program, because `TimerTask`s are executed in a thread managed by the `Timer`, not the application. If a `TimerTask` accesses data that is also accessed by other application threads, then not only must the `TimerTask` do so in a thread-safe manner, but *so must any other classes that access that data*. Often the easiest way to achieve this is to ensure that objects accessed by the `TimerTask` are themselves thread-safe, thus encapsulating the thread safety within the shared objects.

Servlets and JavaServer Pages (JSPs). The servlets framework is designed to handle all the infrastructure of deploying a web application and dispatching requests from remote HTTP clients. A request arriving at the server is dispatched, perhaps through a chain of filters, to the appropriate servlet or JSP. Each servlet represents a component of application logic, and in high-volume web sites, multiple clients may require the services of the same servlet at once. The servlets specification requires that a servlet be prepared to be called simultaneously from multiple threads. In other words, servlets need to be thread-safe.

Even if you could guarantee that a servlet was only called from one thread at a time, you would still have to pay attention to thread safety when building a web application. Servlets often access state information shared with other servlets, such as application-scoped objects (those stored in the `ServletContext`) or session-scoped objects (those stored in the per-client `HttpSession`). When a servlet accesses objects shared across servlets or requests, it must coordinate access to these objects properly, since multiple requests could be accessing them simultaneously from separate threads. Servlets and JSPs, as well as servlet filters and objects stored in scoped containers like `ServletContext` and `HttpSession`, simply have to be thread-safe.

Remote Method Invocation. RMI lets you invoke methods on objects running in another JVM. When you call a remote method with RMI, the method arguments are packaged (marshaled) into a byte stream and shipped over the network to the remote JVM, where they are unpacked (unmarshaled) and passed to the remote method.

When the RMI code calls your remote object, in what thread does that call happen? You don't know, but it's definitely not in a thread you created—your object gets called in a thread managed by RMI. How many threads does RMI create? Could the same remote method on the same remote object be called simultaneously in multiple RMI threads?[4]

A remote object must guard against two thread safety hazards: properly coordinating access to state that may be shared with other objects, and properly coordinating access to the state of the remote object itself (since the same object may be called in multiple threads simultaneously). Like servlets, RMI objects should be prepared for multiple simultaneous calls and must provide their own thread safety.

Swing and AWT. GUI applications are inherently asynchronous. Users may select a menu item or press a button at any time, and they expect that the application will respond promptly even if it is in the middle of doing something else. Swing and AWT address this problem by creating a separate thread for handling user-initiated events and updating the graphical view presented to the user.

4. Answer: yes, but it's not all that clear from the Javadoc—you have to read the RMI spec.

Swing components, such as `JTable`, are not thread-safe. Instead, Swing programs achieve their thread safety by confining all access to GUI components to the event thread. If an application wants to manipulate the GUI from outside the event thread, it must cause the code that will manipulate the GUI to run in the event thread instead.

When the user performs a UI action, an event handler is called in the event thread to perform whatever operation the user requested. If the handler needs to access application state that is also accessed from other threads (such as a document being edited), then the event handler, along with any other code that accesses that state, must do so in a thread-safe manner.