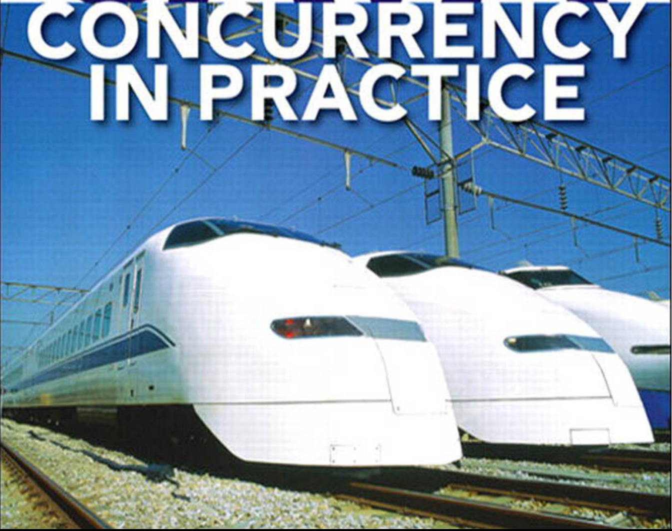
BRIAN GOETZ

WITH TIM PEIERLS, JOSHUA BLOCH,
JOSEPH BOWBEER, DAVID HOLMES,
AND DOUG LEA

JAVA CONCURRENCY IN PRACTICE



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Advance praise for *Java Concurrency in Practice*

I was fortunate indeed to have worked with a fantastic team on the design and implementation of the concurrency features added to the Java platform in Java 5.0 and Java 6. Now this same team provides the best explanation yet of these new features, and of concurrency in general. Concurrency is no longer a subject for advanced users only. Every Java developer should read this book.

—Martin Buchholz
JDK Concurrency Czar, Sun Microsystems

For the past 30 years, computer performance has been driven by Moore's Law; from now on, it will be driven by Amdahl's Law. Writing code that effectively exploits multiple processors can be very challenging. *Java Concurrency in Practice* provides you with the concepts and techniques needed to write safe and scalable Java programs for today's—and tomorrow's—systems.

—Doron Rajwan
Research Scientist, Intel Corp

This is the book you need if you're writing—or designing, or debugging, or maintaining, or contemplating—multithreaded Java programs. If you've ever had to synchronize a method and you weren't sure why, you owe it to yourself and your users to read this book, cover to cover.

—Ted Neward
Author of Effective Enterprise Java

Brian addresses the fundamental issues and complexities of concurrency with uncommon clarity. This book is a must-read for anyone who uses threads and cares about performance.

—Kirk Pepperdine
CTO, JavaPerformanceTuning.com

This book covers a very deep and subtle topic in a very clear and concise way, making it the perfect Java Concurrency reference manual. Each page is filled with the problems (and solutions!) that programmers struggle with every day. Effectively exploiting concurrency is becoming more and more important now that Moore's Law is delivering more cores but not faster cores, and this book will show you how to do it.

—Dr. Cliff Click
Senior Software Engineer, Azul Systems

I have a strong interest in concurrency, and have probably written more thread deadlocks and made more synchronization mistakes than most programmers. Brian's book is the most readable on the topic of threading and concurrency in Java, and deals with this difficult subject with a wonderful hands-on approach. This is a book I am recommending to all my readers of The Java Specialists' Newsletter, because it is interesting, useful, and relevant to the problems facing Java developers today.

—Dr. Heinz Kabutz
The Java Specialists' Newsletter

I've focused a career on simplifying simple problems, but this book ambitiously and effectively works to simplify a complex but critical subject: concurrency. *Java Concurrency in Practice* is revolutionary in its approach, smooth and easy in style, and timely in its delivery—it's destined to be a very important book.

—Bruce Tate
Author of Beyond Java

Java Concurrency in Practice is an invaluable compilation of threading know-how for Java developers. I found reading this book intellectually exciting, in part because it is an excellent introduction to Java's concurrency API, but mostly because it captures in a thorough and accessible way expert knowledge on threading not easily found elsewhere.

—Bill Venners
Author of Inside the Java Virtual Machine

Java Concurrency in Practice

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Java Concurrency in Practice

Brian Goetz
with
Tim Peierls
Joshua Bloch
Joseph Bowbeer
David Holmes
and Doug Lea

Addison-Wesley

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To Jessica

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Preface

At this writing, multicore processors are just now becoming inexpensive enough for midrange desktop systems. Not coincidentally, many development teams are noticing more and more threading-related bug reports in their projects. In a recent post on the NetBeans developer site, one of the core maintainers observed that a single class had been patched over 14 times to fix threading-related problems. Dion Almaer, former editor of TheServerSide, recently blogged (after a painful debugging session that ultimately revealed a threading bug) that most Java programs are so rife with concurrency bugs that they work only "by accident".

Indeed, developing, testing and debugging multithreaded programs can be extremely difficult because concurrency bugs do not manifest themselves predictably. And when they do surface, it is often at the worst possible time—in production, under heavy load.

One of the challenges of developing concurrent programs in Java is the mismatch between the concurrency features offered by the platform and how developers need to think about concurrency in their programs. The language provides low-level *mechanisms* such as synchronization and condition waits, but these mechanisms must be used consistently to implement application-level protocols or *policies*. Without such policies, it is all too easy to create programs that compile and appear to work but are nevertheless broken. Many otherwise excellent books on concurrency fall short of their goal by focusing excessively on low-level mechanisms and APIs rather than design-level policies and patterns.

Java 5.0 is a huge step forward for the development of concurrent applications in Java, providing new higher-level components and additional low-level mechanisms that make it easier for novices and experts alike to build concurrent applications. The authors are the primary members of the JCP Expert Group that created these facilities; in addition to describing their behavior and features, we present the underlying design patterns and anticipated usage scenarios that motivated their inclusion in the platform libraries.

Our goal is to give readers a set of design rules and mental models that make it easier—and more fun—to build correct, performant concurrent classes and applications in Java.

We hope you enjoy *Java Concurrency in Practice*.

Brian Goetz
Williston, VT
March 2006

How to use this book

To address the abstraction mismatch between Java's low-level mechanisms and the necessary design-level policies, we present a *simplified* set of rules for writing concurrent programs. Experts may look at these rules and say "Hmm, that's not entirely true: class *C* is thread-safe even though it violates rule *R*." While it is possible to write correct programs that break our rules, doing so requires a deep understanding of the low-level details of the Java Memory Model, and we want developers to be able to write correct concurrent programs *without* having to master these details. Consistently following our simplified rules will produce correct and maintainable concurrent programs.

We assume the reader already has some familiarity with the basic mechanisms for concurrency in Java. *Java Concurrency in Practice* is not an introduction to concurrency—for that, see the threading chapter of any decent introductory volume, such as *The Java Programming Language* (Arnold et al., 2005). Nor is it an encyclopedic reference for All Things Concurrency—for that, see *Concurrent Programming in Java* (Lea, 2000). Rather, it offers practical design rules to assist developers in the difficult process of creating safe and performant concurrent classes. Where appropriate, we cross-reference relevant sections of *The Java Programming Language*, *Concurrent Programming in Java*, *The Java Language Specification* (Gosling et al., 2005), and *Effective Java* (Bloch, 2001) using the conventions [JPL n.m], [CPJ n.m], [JLS n.m], and [EJ Item n].

After the introduction (Chapter 1), the book is divided into four parts:

Fundamentals. Part I (Chapters 2-5) focuses on the basic concepts of concurrency and thread safety, and how to compose thread-safe classes out of the concurrent building blocks provided by the class library. A "cheat sheet" summarizing the most important of the rules presented in Part I appears on page 110.

Chapters 2 (Thread Safety) and 3 (Sharing Objects) form the foundation for the book. Nearly all of the rules on avoiding concurrency hazards, constructing thread-safe classes, and verifying thread safety are here. Readers who prefer "practice" to "theory" may be tempted to skip ahead to Part II, but make sure to come back and read Chapters 2 and 3 before writing any concurrent code!

Chapter 4 (Composing Objects) covers techniques for composing thread-safe classes into larger thread-safe classes. Chapter 5 (Building Blocks) covers the concurrent building blocks—thread-safe collections and synchronizers—provided by the platform libraries.

Structuring Concurrent Applications. Part II (Chapters 6-9) describes how to exploit threads to improve the throughput or responsiveness of concurrent applications. Chapter 6 (Task Execution) covers identifying parallelizable tasks and executing them within the task-execution framework. Chapter 7 (Cancellation and Shutdown) deals with techniques for convincing tasks and threads to terminate before they would normally do so; how programs deal with cancellation and shutdown is often one of the factors that separates truly robust concurrent applications from those that merely work. Chapter 8 (Applying Thread Pools) addresses some of the more advanced features of the task-execution framework.

Chapter 9 (GUI Applications) focuses on techniques for improving responsiveness in single-threaded subsystems.

Liveness, Performance, and Testing. Part III (Chapters 10-12) concerns itself with ensuring that concurrent programs actually do what you want them to do and do so with acceptable performance. Chapter 10 (Avoiding Liveness Hazards) describes how to avoid liveness failures that can prevent programs from making forward progress. Chapter 11 (Performance and Scalability) covers techniques for improving the performance and scalability of concurrent code. Chapter 12 (Testing Concurrent Programs) covers techniques for testing concurrent code for both correctness and performance.

Advanced Topics. Part IV (Chapters 13-16) covers topics that are likely to be of interest only to experienced developers: explicit locks, atomic variables, nonblocking algorithms, and developing custom synchronizers.

Code examples

While many of the general concepts in this book are applicable to versions of Java prior to Java 5.0 and even to non-Java environments, most of the code examples (and all the statements about the Java Memory Model) assume Java 5.0 or later. Some of the code examples may use library features added in Java 6.

The code examples have been compressed to reduce their size and to highlight the relevant portions. The full versions of the code examples, as well as supplementary examples and errata, are available from the book's website, `http://www.javaconcurrencyinpractice.com`.

The code examples are of three sorts: "good" examples, "not so good" examples, and "bad" examples. Good examples illustrate techniques that should be emulated. Bad examples illustrate techniques that should definitely *not* be emulated, and are identified with a "Mr. Yuk" icon[1] to make it clear that this is "toxic" code (see Listing 1). Not-so-good examples illustrate techniques that are not *necessarily* wrong but are fragile, risky, or perform poorly, and are decorated with a "Mr. Could Be Happier" icon as in Listing 2.

```
public <T extends Comparable<? super T>> void sort(List<T> list) {
    // Never returns the wrong answer!
    System.exit(0);
}
```

Listing 1. Bad way to sort a list. *Don't do this.*

Some readers may question the role of the "bad" examples in this book; after all, a book should show how to do things right, not wrong. The bad examples have two purposes. They illustrate common pitfalls, but more importantly they demonstrate how to analyze a program for thread safety—and the best way to do that is to see the ways in which thread safety is compromised.

[1] Mr. Yuk is a registered trademark of the Children's Hospital of Pittsburgh and appears by permission.

```
public <T extends Comparable<? super T>> void sort(List<T> list) {
    for (int i=0; i<1000000; i++)
        doNothing();
    Collections.sort(list);
}
```

LISTING 2. Less than optimal way to sort a list.

Acknowledgments

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Chapter 6

Task Execution

Most concurrent applications are organized around the execution of *tasks*: abstract, discrete units of work. Dividing the work of an application into tasks simplifies program organization, facilitates error recovery by providing natural transaction boundaries, and promotes concurrency by providing a natural structure for parallelizing work.

6.1 Executing tasks in threads

The first step in organizing a program around task execution is identifying sensible *task boundaries*. Ideally, tasks are *independent* activities: work that doesn't depend on the state, result, or side effects of other tasks. Independence facilitates concurrency, as independent tasks can be executed in parallel if there are adequate processing resources. For greater flexibility in scheduling and load balancing tasks, each task should also represent a small fraction of your application's processing capacity.

Server applications should exhibit both *good throughput* and *good responsiveness* under normal load. Application providers want applications to support as many users as possible, so as to reduce provisioning costs per user; users want to get their response quickly. Further, applications should exhibit *graceful degradation* as they become overloaded, rather than simply falling over under heavy load. Choosing good task boundaries, coupled with a sensible *task execution policy* (see Section 6.2.2), can help achieve these goals.

Most server applications offer a natural choice of task boundary: individual client requests. Web servers, mail servers, file servers, EJB containers, and database servers all accept requests via network connections from remote clients. Using individual requests as task boundaries usually offers both independence and appropriate task sizing. For example, the result of submitting a message to a mail server is not affected by the other messages being processed at the same time, and handling a single message usually requires a very small percentage of the server's total capacity.

6.1.1 Executing tasks sequentially

There are a number of possible policies for scheduling tasks within an application, some of which exploit the potential for concurrency better than others. The simplest is to execute tasks sequentially in a single thread. `SingleThreadWebServer` in Listing 6.1 processes its tasks—HTTP requests arriving on port 80—sequentially. The details of the request processing aren't important; we're interested in characterizing the concurrency of various scheduling policies.

```
class SingleThreadWebServer {
    public static void main(String[] args) throws IOException {
        ServerSocket socket = new ServerSocket(80);
        while (true) {
            Socket connection = socket.accept();
            handleRequest(connection);
        }
    }
}
```

Listing 6.1. Sequential web server.

`SingleThreadedWebServer` is simple and theoretically correct, but would perform poorly in production because it can handle only one request at a time. The main thread alternates between accepting connections and processing the associated request. While the server is handling a request, new connections must wait until it finishes the current request and calls `accept` again. This might work if request processing were so fast that `handleRequest` effectively returned immediately, but this doesn't describe any web server in the real world.

Processing a web request involves a mix of computation and I/O. The server must perform socket I/O to read the request and write the response, which can block due to network congestion or connectivity problems. It may also perform file I/O or make database requests, which can also block. In a single-threaded server, blocking not only delays completing the current request, but prevents pending requests from being processed at all. If one request blocks for an unusually long time, users might think the server is unavailable because it appears unresponsive. At the same time, resource utilization is poor, since the CPU sits idle while the single thread waits for its I/O to complete.

In server applications, sequential processing rarely provides either good throughput or good responsiveness. There are exceptions—such as when tasks are few and long-lived, or when the server serves a single client that makes only a single request at a time—but most server applications do not work this way.[1]

[1] In some situations, sequential processing may offer a simplicity or safety advantage; most GUI frameworks process tasks sequentially using a single thread. We return to the sequential model in Chapter 9.

6.1.2 Explicitly creating threads for tasks

A more responsive approach is to create a new thread for servicing each request, as shown in ThreadPerTaskWebServer in Listing 6.2.

```
class ThreadPerTaskWebServer {
    public static void main(String[] args) throws IOException {
        ServerSocket socket = new ServerSocket(80);
        while (true) {
            final Socket connection = socket.accept();
            Runnable task = new Runnable() {
                    public void run() {
                        handleRequest(connection);
                    }
                };
            new Thread(task).start();
        }
    }
}
```

Listing 6.2. Web server that starts a new thread for each request.

ThreadPerTaskWebServer is similar in structure to the single-threaded version—the main thread still alternates between accepting an incoming connection and dispatching the request. The difference is that for each connection, the main loop creates a new thread to process the request instead of processing it within the main thread. This has three main consequences:

- Task processing is offloaded from the main thread, enabling the main loop to resume waiting for the next incoming connection more quickly. This enables new connections to be accepted before previous requests complete, improving responsiveness.
- Tasks can be processed in parallel, enabling multiple requests to be serviced simultaneously. This may improve throughput if there are multiple processors, or if tasks need to block for any reason such as I/O completion, lock acquisition, or resource availability.
- Task-handling code must be thread-safe, because it may be invoked concurrently for multiple tasks.

Under light to moderate load, the thread-per-task approach is an improvement over sequential execution. As long as the request arrival rate does not exceed the server's capacity to handle requests, this approach offers better responsiveness and throughput.

6.1.3 Disadvantages of unbounded thread creation

For production use, however, the thread-per-task approach has some practical drawbacks, especially when a large number of threads may be created:

Thread lifecycle overhead. Thread creation and teardown are not free. The actual overhead varies across platforms, but thread creation takes time, introducing latency into request processing, and requires some processing activity by the JVM and OS. If requests are frequent and lightweight, as in most server applications, creating a new thread for each request can consume significant computing resources.

Resource consumption. Active threads consume system resources, especially memory. When there are more runnable threads than available processors, threads sit idle. Having many idle threads can tie up a lot of memory, putting pressure on the garbage collector, and having many threads competing for the CPUs can impose other performance costs as well. If you have enough threads to keep all the CPUs busy, creating more threads won't help and may even hurt.

Stability. There is a limit on how many threads can be created. The limit varies by platform and is affected by factors including JVM invocation parameters, the requested stack size in the `Thread` constructor, and limits on threads placed by the underlying operating system.[2] When you hit this limit, the most likely result is an `OutOfMemoryError`. Trying to recover from such an error is very risky; it is far easier to structure your program to avoid hitting this limit.

Up to a certain point, more threads can improve throughput, but beyond that point creating more threads just slows down your application, and creating one thread too many can cause your entire application to crash horribly. The way to stay out of danger is to place some bound on how many threads your application creates, and to test your application thoroughly to ensure that, even when this bound is reached, it does not run out of resources.

The problem with the thread-per-task approach is that nothing places any limit on the number of threads created except the rate at which remote users can throw HTTP requests at it. Like other concurrency hazards, unbounded thread creation may *appear* to work just fine during prototyping and development, with problems surfacing only when the application is deployed and under heavy load. So a malicious user, or enough ordinary users, can make your web server crash if the traffic load ever reaches a certain threshold. For a server application that is supposed to provide high availability and graceful degradation under load, this is a serious failing.

[2] On 32-bit machines, a major limiting factor is address space for thread stacks. Each thread maintains two execution stacks, one for Java code and one for native code. Typical JVM defaults yield a combined stack size of around half a megabyte. (You can change this with the `-Xss` JVM flag or through the `Thread` constructor.) If you divide the per-thread stack size into 2^{32}, you get a limit of a few thousands or tens of thousands of threads. Other factors, such as OS limitations, may impose stricter limits.

6.2 The Executor framework

Tasks are logical units of work, and threads are a mechanism by which tasks can run asynchronously. We've examined two policies for executing tasks using threads—execute tasks sequentially in a single thread, and execute each task in its own thread. Both have serious limitations: the sequential approach suffers from poor responsiveness and throughput, and the thread-per-task approach suffers from poor resource management.

In Chapter 5, we saw how to use *bounded queues* to prevent an overloaded application from running out of memory. *Thread pools* offer the same benefit for thread management, and `java.util.concurrent` provides a flexible thread pool implementation as part of the `Executor` framework. The primary abstraction for task execution in the Java class libraries is *not* `Thread`, but `Executor`, shown in Listing 6.3.

```
public interface Executor {
    void execute(Runnable command);
}
```

Listing 6.3. `Executor` interface.

`Executor` may be a simple interface, but it forms the basis for a flexible and powerful framework for asynchronous task execution that supports a wide variety of task execution policies. It provides a standard means of decoupling *task submission* from *task execution*, describing tasks with `Runnable`. The `Executor` implementations also provide lifecycle support and hooks for adding statistics gathering, application management, and monitoring.

`Executor` is based on the producer-consumer pattern, where activities that submit tasks are the producers (producing units of work to be done) and the threads that execute tasks are the consumers (consuming those units of work). *Using an `Executor` is usually the easiest path to implementing a producer-consumer design in your application.*

6.2.1 Example: web server using Executor

Building a web server with an `Executor` is easy. `TaskExecutionWebServer` in Listing 6.4 replaces the hard-coded thread creation with an `Executor`. In this case, we use one of the standard `Executor` implementations, a fixed-size thread pool with 100 threads.

In `TaskExecutionWebServer`, submission of the request-handling task is decoupled from its execution using an `Executor`, and its behavior can be changed merely by substituting a different `Executor` implementation. Changing `Executor` implementations or configuration is far less invasive than changing the way tasks are submitted; `Executor` configuration is generally a one-time event and can easily be exposed for deployment-time configuration, whereas task submission code tends to be strewn throughout the program and harder to expose.

```
class TaskExecutionWebServer {
    private static final int NTHREADS = 100;
    private static final Executor exec
        = Executors.newFixedThreadPool(NTHREADS);

    public static void main(String[] args) throws IOException {
        ServerSocket socket = new ServerSocket(80);
        while (true) {
            final Socket connection = socket.accept();
            Runnable task = new Runnable() {
                public void run() {
                    handleRequest(connection);
                }
            };
            exec.execute(task);
        }
    }
}
```

Listing 6.4. Web server using a thread pool.

We can easily modify `TaskExecutionWebServer` to behave like `ThreadPerTaskWebServer` by substituting an `Executor` that creates a new thread for each request. Writing such an `Executor` is trivial, as shown in `ThreadPerTaskExecutor` in Listing 6.5.

```
public class ThreadPerTaskExecutor implements Executor {
    public void execute(Runnable r) {
        new Thread(r).start();
    };
}
```

Listing 6.5. `Executor` that starts a new thread for each task.

Similarly, it is also easy to write an `Executor` that would make `TaskExecutionWebServer` behave like the single-threaded version, executing each task synchronously before returning from `execute`, as shown in `WithinThreadExecutor` in Listing 6.6.

6.2.2 Execution policies

The value of decoupling submission from execution is that it lets you easily specify, and subsequently change without great difficulty, the *execution policy* for a given class of tasks. An execution policy specifies the "what, where, when, and how" of task execution, including:

```
public class WithinThreadExecutor implements Executor {
    public void execute(Runnable r) {
        r.run();
    };
}
```

Listing 6.6. `Executor` that executes tasks synchronously in the calling thread.

- In what thread will tasks be executed?
- In what order should tasks be executed (FIFO, LIFO, priority order)?
- How many tasks may execute concurrently?
- How many tasks may be queued pending execution?
- If a task has to be rejected because the system is overloaded, which task should be selected as the victim, and how should the application be notified?
- What actions should be taken before or after executing a task?

Execution policies are a resource management tool, and the optimal policy depends on the available computing resources and your quality-of-service requirements. By limiting the number of concurrent tasks, you can ensure that the application does not fail due to resource exhaustion or suffer performance problems due to contention for scarce resources.[3] Separating the specification of execution policy from task submission makes it practical to select an execution policy at deployment time that is matched to the available hardware.

Whenever you see code of the form:

```
    new Thread(runnable).start()
```

and you think you might at some point want a more flexible execution policy, seriously consider replacing it with the use of an `Executor`.

6.2.3 Thread pools

A thread pool, as its name suggests, manages a homogeneous pool of worker threads. A thread pool is tightly bound to a *work queue* holding tasks waiting to be executed. Worker threads have a simple life: request the next task from the work queue, execute it, and go back to waiting for another task.

[3] This is analogous to one of the roles of a transaction monitor in an enterprise application: it can throttle the rate at which transactions are allowed to proceed so as not to exhaust or overstress limited resources.

Executing tasks in pool threads has a number of advantages over the thread-per-task approach. Reusing an existing thread instead of creating a new one amortizes thread creation and teardown costs over multiple requests. As an added bonus, since the worker thread often already exists at the time the request arrives, the latency associated with thread creation does not delay task execution, thus improving responsiveness. By properly tuning the size of the thread pool, you can have enough threads to keep the processors busy while not having so many that your application runs out of memory or thrashes due to competition among threads for resources.

The class library provides a flexible thread pool implementation along with some useful predefined configurations. You can create a thread pool by calling one of the static factory methods in `Executors`:

`newFixedThreadPool`. A fixed-size thread pool creates threads as tasks are submitted, up to the maximum pool size, and then attempts to keep the pool size constant (adding new threads if a thread dies due to an unexpected `Exception`).

`newCachedThreadPool`. A cached thread pool has more flexibility to reap idle threads when the current size of the pool exceeds the demand for processing, and to add new threads when demand increases, but places no bounds on the size of the pool.

`newSingleThreadExecutor`. A single-threaded executor creates a single worker thread to process tasks, replacing it if it dies unexpectedly. Tasks are guaranteed to be processed sequentially according to the order imposed by the task queue (FIFO, LIFO, priority order).[4]

`newScheduledThreadPool`. A fixed-size thread pool that supports delayed and periodic task execution, similar to `Timer`. (See Section 6.2.5.)

The `newFixedThreadPool` and `newCachedThreadPool` factories return instances of the general-purpose `ThreadPoolExecutor`, which can also be used directly to construct more specialized executors. We discuss thread pool configuration options in depth in Chapter 8.

The web server in `TaskExecutionWebServer` uses an `Executor` with a bounded pool of worker threads. Submitting a task with `execute` adds the task to the work queue, and the worker threads repeatedly dequeue tasks from the work queue and execute them.

Switching from a thread-per-task policy to a pool-based policy has a big effect on application stability: the web server will no longer fail under heavy load.[5]

[4] Single-threaded executors also provide sufficient internal synchronization to guarantee that any memory writes made by tasks are visible to subsequent tasks; this means that objects can be safely confined to the "task thread" even though that thread may be replaced with another from time to time.

[5] While the server may not fail due to the creation of too many threads, if the task arrival rate exceeds the task service rate for long enough it is still possible (just harder) to run out of memory because of the growing queue of `Runnable`s awaiting execution. This can be addressed within the `Executor` framework by using a bounded work queue—see Section 8.3.2.

It also degrades more gracefully, since it does not create thousands of threads that compete for limited CPU and memory resources. And using an Executor opens the door to all sorts of additional opportunities for tuning, management, monitoring, logging, error reporting, and other possibilities that would have been far more difficult to add without a task execution framework.

6.2.4 Executor lifecycle

We've seen how to create an Executor but not how to shut one down. An Executor implementation is likely to create threads for processing tasks. But the JVM can't exit until all the (nondaemon) threads have terminated, so failing to shut down an Executor could prevent the JVM from exiting.

Because an Executor processes tasks asynchronously, at any given time the state of previously submitted tasks is not immediately obvious. Some may have completed, some may be currently running, and others may be queued awaiting execution. In shutting down an application, there is a spectrum from graceful shutdown (finish what you've started but don't accept any new work) to abrupt shutdown (turn off the power to the machine room), and various points in between. Since Executors provide a service to applications, they should be able to be shut down as well, both gracefully and abruptly, and feed back information to the application about the status of tasks that were affected by the shutdown.

To address the issue of execution service lifecycle, the ExecutorService interface extends Executor, adding a number of methods for lifecycle management (as well as some convenience methods for task submission). The lifecycle management methods of ExecutorService are shown in Listing 6.7.

```
public interface ExecutorService extends Executor {
    void shutdown();
    List<Runnable> shutdownNow();
    boolean isShutdown();
    boolean isTerminated();
    boolean awaitTermination(long timeout, TimeUnit unit)
        throws InterruptedException;
    // ... additional convenience methods for task submission
}
```

Listing 6.7. Lifecycle methods in ExecutorService.

The lifecycle implied by ExecutorService has three states—*running*, *shutting down*, and *terminated*. ExecutorServices are initially created in the *running* state. The shutdown method initiates a graceful shutdown: no new tasks are accepted but previously submitted tasks are allowed to complete—including those that have not yet begun execution. The shutdownNow method initiates an abrupt shutdown: it attempts to cancel outstanding tasks and does not start any tasks that are queued but not begun.

Tasks submitted to an ExecutorService after it has been shut down are handled by the *rejected execution handler* (see Section 8.3.3), which might silently discard the task or might cause execute to throw the unchecked RejectedExecutionException. Once all tasks have completed, the ExecutorService transitions to the *terminated* state. You can wait for an ExecutorService to reach the terminated state with awaitTermination, or poll for whether it has yet terminated with isTerminated. It is common to follow shutdown immediately by awaitTermination, creating the effect of synchronously shutting down the ExecutorService. (Executor shutdown and task cancellation are covered in more detail in Chapter 7.)

LifecycleWebServer in Listing 6.8 extends our web server with lifecycle support. It can be shut down in two ways: programmatically by calling stop, and through a client request by sending the web server a specially formatted HTTP request.

```
class LifecycleWebServer {
    private final ExecutorService exec = ...;

    public void start() throws IOException {
        ServerSocket socket = new ServerSocket(80);
        while (!exec.isShutdown()) {
            try {
                final Socket conn = socket.accept();
                exec.execute(new Runnable() {
                    public void run() { handleRequest(conn); }
                });
            } catch (RejectedExecutionException e) {
                if (!exec.isShutdown())
                    log("task submission rejected", e);
            }
        }
    }

    public void stop() { exec.shutdown(); }

    void handleRequest(Socket connection) {
        Request req = readRequest(connection);
        if (isShutdownRequest(req))
            stop();
        else
            dispatchRequest(req);
    }
}
```

Listing 6.8. Web server with shutdown support.

6.2.5 Delayed and periodic tasks

The Timer facility manages the execution of deferred ("run this task in 100 ms") and periodic ("run this task every 10 ms") tasks. However, Timer has some drawbacks, and ScheduledThreadPoolExecutor should be thought of as its replacement.[6] You can construct a ScheduledThreadPoolExecutor through its constructor or through the newScheduledThreadPool factory.

A Timer creates only a single thread for executing timer tasks. If a timer task takes too long to run, the timing accuracy of other TimerTasks can suffer. If a recurring TimerTask is scheduled to run every 10 ms and another TimerTask takes 40 ms to run, the recurring task either (depending on whether it was scheduled at fixed rate or fixed delay) gets called four times in rapid succession after the long-running task completes, or "misses" four invocations completely. Scheduled thread pools address this limitation by letting you provide multiple threads for executing deferred and periodic tasks.

Another problem with Timer is that it behaves poorly if a TimerTask throws an unchecked exception. The Timer thread doesn't catch the exception, so an unchecked exception thrown from a TimerTask terminates the timer thread. Timer also doesn't resurrect the thread in this situation; instead, it erroneously assumes the entire Timer was cancelled. In this case, TimerTasks that are already scheduled but not yet executed are never run, and new tasks cannot be scheduled. (This problem, called "thread leakage" is described in Section 7.3, along with techniques for avoiding it.)

OutOfTime in Listing 6.9 illustrates how a Timer can become confused in this manner and, as confusion loves company, how the Timer shares its confusion with the next hapless caller that tries to submit a TimerTask. You might expect the program to run for six seconds and exit, but what actually happens is that it terminates after one second with an IllegalStateException whose message text is "Timer already cancelled". ScheduledThreadPoolExecutor deals properly with ill-behaved tasks; there is little reason to use Timer in Java 5.0 or later.

If you need to build your own scheduling service, you may still be able to take advantage of the library by using a DelayQueue, a BlockingQueue implementation that provides the scheduling functionality of ScheduledThreadPoolExecutor. A DelayQueue manages a collection of Delayed objects. A Delayed has a delay time associated with it: DelayQueue lets you take an element only if its delay has expired. Objects are returned from a DelayQueue ordered by the time associated with their delay.

6.3 Finding exploitable parallelism

The Executor framework makes it easy to specify an execution policy, but in order to use an Executor, you have to be able to describe your task as a Runnable. In most server applications, there is an obvious task boundary: a single client request. But sometimes good task boundaries are not quite so obvious, as

[6] Timer does have support for scheduling based on absolute, not relative time, so that tasks can be sensitive to changes in the system clock; ScheduledThreadPoolExecutor supports only relative time.

```
public class OutOfTime {
    public static void main(String[] args) throws Exception {
        Timer timer = new Timer();
        timer.schedule(new ThrowTask(), 1);
        SECONDS.sleep(1);
        timer.schedule(new ThrowTask(), 1);
        SECONDS.sleep(5);
    }

    static class ThrowTask extends TimerTask {
        public void run() { throw new RuntimeException(); }
    }
}
```

Listing 6.9. Class illustrating confusing `Timer` behavior.

in many desktop applications. There may also be exploitable parallelism within a single client request in server applications, as is sometimes the case in database servers. (For a further discussion of the competing design forces in choosing task boundaries, see [CPJ 4.4.1.1].)

In this section we develop several versions of a component that admit varying degrees of concurrency. Our sample component is the page-rendering portion of a browser application, which takes a page of HTML and renders it into an image buffer. To keep it simple, we assume that the HTML consists only of marked up text interspersed with image elements with pre-specified dimensions and URLs.

6.3.1 Example: sequential page renderer

The simplest approach is to process the HTML document sequentially. As text markup is encountered, render it into the image buffer; as image references are encountered, fetch the image over the network and draw it into the image buffer as well. This is easy to implement and requires touching each element of the input only once (it doesn't even require buffering the document), but is likely to annoy the user, who may have to wait a long time before all the text is rendered.

A less annoying but still sequential approach involves rendering the text elements first, leaving rectangular placeholders for the images, and after completing the initial pass on the document, going back and downloading the images and drawing them into the associated placeholder. This approach is shown in `SingleThreadRenderer` in Listing 6.10.

Downloading an image mostly involves waiting for I/O to complete, and during this time the CPU does little work. So the sequential approach may underutilize the CPU, and also makes the user wait longer than necessary to see the finished page. We can achieve better utilization and responsiveness by breaking the problem into independent tasks that can execute concurrently.

```
public class SingleThreadRenderer {
    void renderPage(CharSequence source) {
        renderText(source);
        List<ImageData> imageData = new ArrayList<ImageData>();
        for (ImageInfo imageInfo : scanForImageInfo(source))
            imageData.add(imageInfo.downloadImage());
        for (ImageData data : imageData)
            renderImage(data);
    }
}
```

Listing 6.10. Rendering page elements sequentially.

6.3.2 Result-bearing tasks: `Callable` and `Future`

The `Executor` framework uses `Runnable` as its basic task representation. `Runnable` is a fairly limiting abstraction; `run` cannot return a value or throw checked exceptions, although it can have side effects such as writing to a log file or placing a result in a shared data structure.

Many tasks are effectively deferred computations—executing a database query, fetching a resource over the network, or computing a complicated function. For these types of tasks, `Callable` is a better abstraction: it expects that the main entry point, `call`, will return a value and anticipates that it might throw an exception.[7] `Executors` includes several utility methods for wrapping other types of tasks, including `Runnable` and `java.security.PrivilegedAction`, with a `Callable`.

`Runnable` and `Callable` describe abstract computational tasks. Tasks are usually finite: they have a clear starting point and they eventually terminate. The lifecycle of a task executed by an `Executor` has four phases: *created*, *submitted*, *started*, and *completed*. Since tasks can take a long time to run, we also want to be able to cancel a task. In the `Executor` framework, tasks that have been submitted but not yet started can always be cancelled, and tasks that have started can sometimes be cancelled if they are responsive to interruption. Cancelling a task that has already completed has no effect. (Cancellation is covered in greater detail in Chapter 7.)

`Future` represents the lifecycle of a task and provides methods to test whether the task has completed or been cancelled, retrieve its result, and cancel the task. `Callable` and `Future` are shown in Listing 6.11. Implicit in the specification of `Future` is that task lifecycle can only move forwards, not backwards—just like the `ExecutorService` lifecycle. Once a task is completed, it stays in that state forever.

The behavior of `get` varies depending on the task state (not yet started, running, completed). It returns immediately or throws an `Exception` if the task has already completed, but if not it blocks until the task completes. If the task completes by throwing an exception, `get` rethrows it wrapped in an `Execution-`

[7] To express a non-value-returning task with `Callable`, use `Callable<Void>`.

```
public interface Callable<V> {
    V call() throws Exception;
}

public interface Future<V> {
    boolean cancel(boolean mayInterruptIfRunning);
    boolean isCancelled();
    boolean isDone();
    V get() throws InterruptedException, ExecutionException,
                   CancellationException;
    V get(long timeout, TimeUnit unit)
        throws InterruptedException, ExecutionException,
               CancellationException, TimeoutException;
}
```

Listing 6.11. Callable and Future interfaces.

Exception; if it was cancelled, get throws CancellationException. If get throws ExecutionException, the underlying exception can be retrieved with getCause.

There are several ways to create a Future to describe a task. The submit methods in ExecutorService all return a Future, so that you can submit a Runnable or a Callable to an executor and get back a Future that can be used to retrieve the result or cancel the task. You can also explicitly instantiate a FutureTask for a given Runnable or Callable. (Because FutureTask implements Runnable, it can be submitted to an Executor for execution or executed directly by calling its run method.)

As of Java 6, ExecutorService implementations can override newTaskFor in AbstractExecutorService to control instantiation of the Future corresponding to a submitted Callable or Runnable. The default implementation just creates a new FutureTask, as shown in Listing 6.12.

```
protected <T> RunnableFuture<T> newTaskFor(Callable<T> task) {
    return new FutureTask<T>(task);
}
```

Listing 6.12. Default implementation of newTaskFor in ThreadPoolExecutor.

Submitting a Runnable or Callable to an Executor constitutes a safe publication (see Section 3.5) of the Runnable or Callable from the submitting thread to the thread that will eventually execute the task. Similarly, setting the result value for a Future constitutes a safe publication of the result from the thread in which it was computed to any thread that retrieves it via get.

6.3.3 Example: page renderer with `Future`

As a first step towards making the page renderer more concurrent, let's divide it into two tasks, one that renders the text and one that downloads all the images. (Because one task is largely CPU-bound and the other is largely I/O-bound, this approach may yield improvements even on single-CPU systems.)

`Callable` and `Future` can help us express the interaction between these cooperating tasks. In `FutureRenderer` in Listing 6.13, we create a `Callable` to download all the images, and submit it to an `ExecutorService`. This returns a `Future` describing the task's execution; when the main task gets to the point where it needs the images, it waits for the result by calling `Future.get`. If we're lucky, the results will already be ready by the time we ask; otherwise, at least we got a head start on downloading the images.

The state-dependent nature of `get` means that the caller need not be aware of the state of the task, and the safe publication properties of task submission and result retrieval make this approach thread-safe. The exception handling code surrounding `Future.get` deals with two possible problems: that the task encountered an `Exception`, or the thread calling `get` was interrupted before the results were available. (See Sections 5.5.2 and 5.4.)

`FutureRenderer` allows the text to be rendered concurrently with downloading the image data. When all the images are downloaded, they are rendered onto the page. This is an improvement in that the user sees a result quickly and it exploits some parallelism, but we can do considerably better. There is no need for users to wait for *all* the images to be downloaded; they would probably prefer to see individual images drawn as they become available.

6.3.4 Limitations of parallelizing heterogeneous tasks

In the last example, we tried to execute two different types of tasks in parallel—downloading the images and rendering the page. But obtaining significant performance improvements by trying to parallelize sequential heterogeneous tasks can be tricky.

Two people can divide the work of cleaning the dinner dishes fairly effectively: one person washes while the other dries. However, assigning a different type of task to each worker does not scale well; if several more people show up, it is not obvious how they can help without getting in the way or significantly restructuring the division of labor. Without finding finer-grained parallelism among similar tasks, this approach will yield diminishing returns.

A further problem with dividing heterogeneous tasks among multiple workers is that the tasks may have disparate sizes. If you divide tasks *A* and *B* between two workers but *A* takes ten times as long as *B*, you've only speeded up the total process by 9%. Finally, dividing a task among multiple workers always involves some amount of coordination overhead; for the division to be worthwhile, this overhead must be more than compensated by productivity improvements due to parallelism.

`FutureRenderer` uses two tasks: one for rendering text and one for downloading the images. If rendering the text is much faster than downloading the images,

```
public class FutureRenderer {
    private final ExecutorService executor = ...;

    void renderPage(CharSequence source) {
        final List<ImageInfo> imageInfos = scanForImageInfo(source);
        Callable<List<ImageData>> task =
                new Callable<List<ImageData>>() {
                    public List<ImageData> call() {
                        List<ImageData> result
                                = new ArrayList<ImageData>();
                        for (ImageInfo imageInfo : imageInfos)
                            result.add(imageInfo.downloadImage());
                        return result;
                    }
                };

        Future<List<ImageData>> future = executor.submit(task);
        renderText(source);

        try {
            List<ImageData> imageData = future.get();
            for (ImageData data : imageData)
                renderImage(data);
        } catch (InterruptedException e) {
            // Re-assert the thread's interrupted status
            Thread.currentThread().interrupt();
            // We don't need the result, so cancel the task too
            future.cancel(true);
        } catch (ExecutionException e) {
            throw launderThrowable(e.getCause());
        }
    }
}
```

Listing 6.13. Waiting for image download with Future.

as is entirely possible, the resulting performance is not much different from the sequential version, but the code is a lot more complicated. And the best we can do with two threads is speed things up by a factor of two. Thus, trying to increase concurrency by parallelizing heterogeneous activities can be a lot of work, and there is a limit to how much additional concurrency you can get out of it. (See Sections 11.4.2 and 11.4.3 for another example of the same phenomenon.)

> The real performance payoff of dividing a program's workload into tasks comes when there are a large number of independent, *homogeneous* tasks that can be processed concurrently.

6.3.5 `CompletionService`: `Executor` meets `BlockingQueue`

If you have a batch of computations to submit to an `Executor` and you want to retrieve their results as they become available, you could retain the `Future` associated with each task and repeatedly poll for completion by calling `get` with a timeout of zero. This is possible, but tedious. Fortunately there is a better way: a *completion service.*

`CompletionService` combines the functionality of an `Executor` and a `BlockingQueue`. You can submit `Callable` tasks to it for execution and use the queue-like methods `take` and `poll` to retrieve completed results, packaged as `Futures`, as they become available. `ExecutorCompletionService` implements `CompletionService`, delegating the computation to an `Executor`.

The implementation of `ExecutorCompletionService` is quite straightforward. The constructor creates a `BlockingQueue` to hold the completed results. `FutureTask` has a `done` method that is called when the computation completes. When a task is submitted, it is wrapped with a `QueueingFuture`, a subclass of `FutureTask` that overrides `done` to place the result on the `BlockingQueue`, as shown in Listing 6.14. The `take` and `poll` methods delegate to the `BlockingQueue`, blocking if results are not yet available.

```
private class QueueingFuture<V> extends FutureTask<V> {
    QueueingFuture(Callable<V> c) { super(c); }
    QueueingFuture(Runnable t, V r) { super(t, r); }

    protected void done() {
        completionQueue.add(this);
    }
}
```

LISTING 6.14. `QueueingFuture` class used by `ExecutorCompletionService`.

6.3.6 Example: page renderer with `CompletionService`

We can use a `CompletionService` to improve the performance of the page renderer in two ways: shorter total runtime and improved responsiveness. We can create a separate task for downloading *each* image and execute them in a thread pool, turning the sequential download into a parallel one: this reduces the amount of time to download all the images. And by fetching results from the `CompletionService` and rendering each image as soon as it is available, we can give the user a more dynamic and responsive user interface. This implementation is shown in `Renderer` in Listing 6.15.

```
public class Renderer {
    private final ExecutorService executor;

    Renderer(ExecutorService executor) { this.executor = executor; }

    void renderPage(CharSequence source) {
        List<ImageInfo> info = scanForImageInfo(source);
        CompletionService<ImageData> completionService =
            new ExecutorCompletionService<ImageData>(executor);
        for (final ImageInfo imageInfo : info)
            completionService.submit(new Callable<ImageData>() {
                 public ImageData call() {
                     return imageInfo.downloadImage();
                 }
            });

        renderText(source);

        try {
            for (int t = 0, n = info.size(); t < n; t++) {
                Future<ImageData> f = completionService.take();
                ImageData imageData = f.get();
                renderImage(imageData);
            }
        } catch (InterruptedException e) {
            Thread.currentThread().interrupt();
        } catch (ExecutionException e) {
            throw launderThrowable(e.getCause());
        }
    }
}
```

Listing 6.15. Using `CompletionService` to render page elements as they become available.

Multiple `ExecutorCompletionServices` can share a single `Executor`, so it is perfectly sensible to create an ExecutorCompletionService that is private to a particular computation while sharing a common Executor. When used in this way, a CompletionService acts as a handle for a batch of computations in much the same way that a Future acts as a handle for a single computation. By remembering how many tasks were submitted to the CompletionService and counting how many completed results are retrieved, you can know when all the results for a given batch have been retrieved, even if you use a shared Executor.

6.3.7 Placing time limits on tasks

Sometimes, if an activity does not complete within a certain amount of time, the result is no longer needed and the activity can be abandoned. For example, a web application may fetch its advertisements from an external ad server, but if the ad is not available within two seconds, it instead displays a default advertisement so that ad unavailability does not undermine the site's responsiveness requirements. Similarly, a portal site may fetch data in parallel from multiple data sources, but may be willing to wait only a certain amount of time for data to be available before rendering the page without it.

The primary challenge in executing tasks within a time budget is making sure that you don't wait longer than the time budget to get an answer or find out that one is not forthcoming. The timed version of Future.get supports this requirement: it returns as soon as the result is ready, but throws TimeoutException if the result is not ready within the timeout period.

A secondary problem when using timed tasks is to stop them when they run out of time, so they do not waste computing resources by continuing to compute a result that will not be used. This can be accomplished by having the task strictly manage its own time budget and abort if it runs out of time, or by cancelling the task if the timeout expires. Again, Future can help; if a timed get completes with a TimeoutException, you can cancel the task through the Future. If the task is written to be cancellable (see Chapter 7), it can be terminated early so as not to consume excessive resources. This technique is used in Listings 6.13 and 6.16.

Listing 6.16 shows a typical application of a timed Future.get. It generates a composite web page that contains the requested content plus an advertisement fetched from an ad server. It submits the ad-fetching task to an executor, computes the rest of the page content, and then waits for the ad until its time budget runs out.[8] If the get times out, it cancels[9] the ad-fetching task and uses a default advertisement instead.

6.3.8 Example: a travel reservations portal

The time-budgeting approach in the previous section can be easily generalized to an arbitrary number of tasks. Consider a travel reservation portal: the user en-

[8] The timeout passed to get is computed by subtracting the current time from the deadline; this may in fact yield a negative number, but all the timed methods in java.util.concurrent treat negative timeouts as zero, so no extra code is needed to deal with this case.

[9] The true parameter to Future.cancel means that the task thread can be interrupted if the task is currently running; see Chapter 7.

```
Page renderPageWithAd() throws InterruptedException {
    long endNanos = System.nanoTime() + TIME_BUDGET;
    Future<Ad> f = exec.submit(new FetchAdTask());
    // Render the page while waiting for the ad
    Page page = renderPageBody();
    Ad ad;
    try {
        // Only wait for the remaining time budget
        long timeLeft = endNanos - System.nanoTime();
        ad = f.get(timeLeft, NANOSECONDS);
    } catch (ExecutionException e) {
        ad = DEFAULT_AD;
    } catch (TimeoutException e) {
        ad = DEFAULT_AD;
        f.cancel(true);
    }
    page.setAd(ad);
    return page;
}
```

Listing 6.16. Fetching an advertisement with a time budget.

ters travel dates and requirements and the portal fetches and displays bids from a number of airlines, hotels or car rental companies. Depending on the company, fetching a bid might involve invoking a web service, consulting a database, performing an EDI transaction, or some other mechanism. Rather than have the response time for the page be driven by the slowest response, it may be preferable to present only the information available within a given time budget. For providers that do not respond in time, the page could either omit them completely or display a placeholder such as "Did not hear from Air Java in time."

Fetching a bid from one company is independent of fetching bids from another, so fetching a single bid is a sensible task boundary that allows bid retrieval to proceed concurrently. It would be easy enough to create *n* tasks, submit them to a thread pool, retain the `Future`s, and use a timed `get` to fetch each result sequentially via its `Future`, but there is an even easier way—`invokeAll`.

Listing 6.17 uses the timed version of `invokeAll` to submit multiple tasks to an `ExecutorService` and retrieve the results. The `invokeAll` method takes a collection of tasks and returns a collection of `Future`s. The two collections have identical structures; `invokeAll` adds the `Future`s to the returned collection in the order imposed by the task collection's iterator, thus allowing the caller to associate a `Future` with the `Callable` it represents. The timed version of `invokeAll` will return when all the tasks have completed, the calling thread is interrupted, or the timeout expires. Any tasks that are not complete when the timeout expires are cancelled. On return from `invokeAll`, each task will have either completed normally or been cancelled; the client code can call `get` or `isCancelled` to find out which.

Summary

Structuring applications around the execution of *tasks* can simplify development and facilitate concurrency. The `Executor` framework permits you to decouple task submission from execution policy and supports a rich variety of execution policies; whenever you find yourself creating threads to perform tasks, consider using an `Executor` instead. To maximize the benefit of decomposing an application into tasks, you must identify sensible task boundaries. In some applications, the obvious task boundaries work well, whereas in others some analysis may be required to uncover finer-grained exploitable parallelism.

```java
private class QuoteTask implements Callable<TravelQuote> {
    private final TravelCompany company;
    private final TravelInfo travelInfo;
    ...
    public TravelQuote call() throws Exception {
        return company.solicitQuote(travelInfo);
    }
}

public List<TravelQuote> getRankedTravelQuotes(
        TravelInfo travelInfo, Set<TravelCompany> companies,
        Comparator<TravelQuote> ranking, long time, TimeUnit unit)
        throws InterruptedException {
    List<QuoteTask> tasks = new ArrayList<QuoteTask>();
    for (TravelCompany company : companies)
        tasks.add(new QuoteTask(company, travelInfo));

    List<Future<TravelQuote>> futures =
        exec.invokeAll(tasks, time, unit);

    List<TravelQuote> quotes =
        new ArrayList<TravelQuote>(tasks.size());
    Iterator<QuoteTask> taskIter = tasks.iterator();
    for (Future<TravelQuote> f : futures) {
        QuoteTask task = taskIter.next();
        try {
            quotes.add(f.get());
        } catch (ExecutionException e) {
            quotes.add(task.getFailureQuote(e.getCause()));
        } catch (CancellationException e) {
            quotes.add(task.getTimeoutQuote(e));
        }
    }

    Collections.sort(quotes, ranking);
    return quotes;
}
```

Listing 6.17. Requesting travel quotes under a time budget.

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