

```
import java.util.concurrent.*;

class Summation implements Callable<Integer>
{
    private int upper;
    public Summation(int upper) {
        this.upper = upper;
    }

    /* The thread will execute in this method */
    public Integer call() {
        int sum = 0;
        for (int i = 1; i <= upper; i++)
            sum += i;

        return new Integer(sum);
    }
}

public class Driver
{
    public static void main(String[] args) {
        int upper = Integer.parseInt(args[0]);

        ExecutorService pool = Executors.newSingleThreadExecutor();
        Future<Integer> result = pool.submit(new Summation(upper));

        try {
            System.out.println("sum = " + result.get());
        } catch (InterruptedException | ExecutionException ie) { }
    }
}
```

---

**Figure 4.14** Illustration of Java Executor framework API.

Additionally, this approach separates the creation of threads from the results they produce: rather than waiting for a thread to terminate before retrieving results, the parent instead only waits for the results to become available. Finally, as we shall see in Section 4.5.1, this framework can be combined with other features to create robust tools for managing a large number of threads.

## 4.5 Implicit Threading

With the continued growth of multicore processing, applications containing hundreds—or even thousands—of threads are looming on the horizon. Designing such applications is not a trivial undertaking: programmers must

### THE JVM AND THE HOST OPERATING SYSTEM

The JVM is typically implemented on top of a host operating system (see Figure 18.10). This setup allows the JVM to hide the implementation details of the underlying operating system and to provide a consistent, abstract environment that allows Java programs to operate on any platform that supports a JVM. The specification for the JVM does not indicate how Java threads are to be mapped to the underlying operating system, instead leaving that decision to the particular implementation of the JVM. For example, the Windows operating system uses the one-to-one model; therefore, each Java thread for a JVM running on Windows maps to a kernel thread. In addition, there may be a relationship between the Java thread library and the thread library on the host operating system. For example, implementations of a JVM for the Windows family of operating systems might use the Windows API when creating Java threads; Linux and macOS systems might use the Pthreads API.

address not only the challenges outlined in Section 4.2 but additional difficulties as well. These difficulties, which relate to program correctness, are covered in Chapter 6 and Chapter 8.

One way to address these difficulties and better support the design of concurrent and parallel applications is to transfer the creation and management of threading from application developers to compilers and run-time libraries. This strategy, termed **implicit threading**, is an increasingly popular trend. In this section, we explore four alternative approaches to designing applications that can take advantage of multicore processors through implicit threading. As we shall see, these strategies generally require application developers to identify *tasks*—not threads—that can run in parallel. A task is usually written as a function, which the run-time library then maps to a separate thread, typically using the many-to-many model (Section 4.3.3). The advantage of this approach is that developers only need to identify parallel tasks, and the libraries determine the specific details of thread creation and management.

#### 4.5.1 Thread Pools

In Section 4.1, we described a multithreaded web server. In this situation, whenever the server receives a request, it creates a separate thread to service the request. Whereas creating a separate thread is certainly superior to creating a separate process, a multithreaded server nonetheless has potential problems. The first issue concerns the amount of time required to create the thread, together with the fact that the thread will be discarded once it has completed its work. The second issue is more troublesome. If we allow each concurrent request to be serviced in a new thread, we have not placed a bound on the number of threads concurrently active in the system. Unlimited threads could exhaust system resources, such as CPU time or memory. One solution to this problem is to use a **thread pool**.

### ANDROID THREAD POOLS

In Section 3.8.2.1, we covered RPCs in the Android operating system. You may recall from that section that Android uses the Android Interface Definition Language (AIDL), a tool that specifies the remote interface that clients interact with on the server. AIDL also provides a thread pool. A remote service using the thread pool can handle multiple concurrent requests, servicing each request using a separate thread from the pool.

The general idea behind a thread pool is to create a number of threads at start-up and place them into a pool, where they sit and wait for work. When a server receives a request, rather than creating a thread, it instead submits the request to the thread pool and resumes waiting for additional requests. If there is an available thread in the pool, it is awakened, and the request is serviced immediately. If the pool contains no available thread, the task is queued until one becomes free. Once a thread completes its service, it returns to the pool and awaits more work. Thread pools work well when the tasks submitted to the pool can be executed asynchronously.

Thread pools offer these benefits:

1. Servicing a request with an existing thread is often faster than waiting to create a thread.
2. A thread pool limits the number of threads that exist at any one point. This is particularly important on systems that cannot support a large number of concurrent threads.
3. Separating the task to be performed from the mechanics of creating the task allows us to use different strategies for running the task. For example, the task could be scheduled to execute after a time delay or to execute periodically.

The number of threads in the pool can be set heuristically based on factors such as the number of CPUs in the system, the amount of physical memory, and the expected number of concurrent client requests. More sophisticated thread-pool architectures can dynamically adjust the number of threads in the pool according to usage patterns. Such architectures provide the further benefit of having a smaller pool—thereby consuming less memory—when the load on the system is low. We discuss one such architecture, Apple’s Grand Central Dispatch, later in this section.

The Windows API provides several functions related to thread pools. Using the thread pool API is similar to creating a thread with the `Thread.Create()` function, as described in Section 4.4.2. Here, a function that is to run as a separate thread is defined. Such a function may appear as follows:

```
DWORD WINAPI PoolFunction(PVOID Param) {  
    /* this function runs as a separate thread. */  
}
```

A pointer to `PoolFunction()` is passed to one of the functions in the thread pool API, and a thread from the pool executes this function. One such member in the thread pool API is the `QueueUserWorkItem()` function, which is passed three parameters:

- `LPTHREAD_START_ROUTINE` Function—a pointer to the function that is to run as a separate thread
- `PVOID` Param—the parameter passed to Function
- `ULONG` Flags—flags indicating how the thread pool is to create and manage execution of the thread

An example of invoking a function is the following:

```
QueueUserWorkItem(&PoolFunction, NULL, 0);
```

This causes a thread from the thread pool to invoke `PoolFunction()` on behalf of the programmer. In this instance, we pass no parameters to `PoolFunction()`. Because we specify 0 as a flag, we provide the thread pool with no special instructions for thread creation.

Other members in the Windows thread pool API include utilities that invoke functions at periodic intervals or when an asynchronous I/O request completes.

#### 4.5.1.1 Java Thread Pools

The `java.util.concurrent` package includes an API for several varieties of thread-pool architectures. Here, we focus on the following three models:

1. Single thread executor—`newSingleThreadExecutor()`—creates a pool of size 1.
2. Fixed thread executor—`newFixedThreadPool(int size)`—creates a thread pool with a specified number of threads.
3. Cached thread executor—`newCachedThreadPool()`—creates an unbounded thread pool, reusing threads in many instances.

We have, in fact, already seen the use of a Java thread pool in Section 4.4.3, where we created a `newSingleThreadExecutor` in the program example shown in Figure 4.14. In that section, we noted that the Java executor framework can be used to construct more robust threading tools. We now describe how it can be used to create thread pools.

A thread pool is created using one of the factory methods in the `Executors` class:

- `static ExecutorService newSingleThreadExecutor()`
- `static ExecutorService newFixedThreadPool(int size)`
- `static ExecutorService newCachedThreadPool()`

Each of these factory methods creates and returns an object instance that implements the `ExecutorService` interface. `ExecutorService` extends the `Execu-`

```
import java.util.concurrent.*;

public class ThreadPoolExample
{
    public static void main(String[] args) {
        int numTasks = Integer.parseInt(args[0].trim());

        /* Create the thread pool */
        ExecutorService pool = Executors.newCachedThreadPool();

        /* Run each task using a thread in the pool */
        for (int i = 0; i < numTasks; i++)
            pool.execute(new Task());

        /* Shut down the pool once all threads have completed */
        pool.shutdown();
    }
}
```

---

**Figure 4.15** Creating a thread pool in Java.

tor interface, allowing us to invoke the `execute()` method on this object. In addition, `ExecutorService` provides methods for managing termination of the thread pool.

The example shown in Figure 4.15 creates a cached thread pool and submits tasks to be executed by a thread in the pool using the `execute()` method. When the `shutdown()` method is invoked, the thread pool rejects additional tasks and shuts down once all existing tasks have completed execution.

## 4.5.2 Fork Join

The strategy for thread creation covered in Section 4.4 is often known as the **fork-join** model. Recall that with this method, the main parent thread creates (*forks*) one or more child threads and then waits for the children to terminate and *join* with it, at which point it can retrieve and combine their results. This synchronous model is often characterized as explicit thread creation, but it is also an excellent candidate for implicit threading. In the latter situation, threads are not constructed directly during the fork stage; rather, parallel tasks are designated. This model is illustrated in Figure 4.16. A library manages the number of threads that are created and is also responsible for assigning tasks to threads. In some ways, this fork-join model is a synchronous version of thread pools in which a library determines the actual number of threads to create—for example, by using the heuristics described in Section 4.5.1.

### 4.5.2.1 Fork Join in Java

Java introduced a fork-join library in Version 1.7 of the API that is designed to be used with recursive divide-and-conquer algorithms such as Quicksort and Mergesort. When implementing divide-and-conquer algorithms using this