

ages the details involved in dividing the work into separate tasks that run in parallel. Intel TBB has both commercial and open-source versions that run on Windows, Linux, and macOS. Refer to the bibliography for further details on how to develop parallel applications using TBB.

4.6 Threading Issues

In this section, we discuss some of the issues to consider in designing multi-threaded programs.

4.6.1 The `fork()` and `exec()` System Calls

In Chapter 3, we described how the `fork()` system call is used to create a separate, duplicate process. The semantics of the `fork()` and `exec()` system calls change in a multithreaded program.

If one thread in a program calls `fork()`, does the new process duplicate all threads, or is the new process single-threaded? Some UNIX systems have chosen to have two versions of `fork()`, one that duplicates all threads and another that duplicates only the thread that invoked the `fork()` system call.

The `exec()` system call typically works in the same way as described in Chapter 3. That is, if a thread invokes the `exec()` system call, the program specified in the parameter to `exec()` will replace the entire process—including all threads.

Which of the two versions of `fork()` to use depends on the application. If `exec()` is called immediately after forking, then duplicating all threads is unnecessary, as the program specified in the parameters to `exec()` will replace the process. In this instance, duplicating only the calling thread is appropriate. If, however, the separate process does not call `exec()` after forking, the separate process should duplicate all threads.

4.6.2 Signal Handling

A **signal** is used in UNIX systems to notify a process that a particular event has occurred. A signal may be received either synchronously or asynchronously, depending on the source of and the reason for the event being signaled. All signals, whether synchronous or asynchronous, follow the same pattern:

1. A signal is generated by the occurrence of a particular event.
2. The signal is delivered to a process.
3. Once delivered, the signal must be handled.

Examples of synchronous signals include illegal memory access and division by 0. If a running program performs either of these actions, a signal is generated. Synchronous signals are delivered to the same process that performed the operation that caused the signal (that is the reason they are considered synchronous).

When a signal is generated by an event external to a running process, that process receives the signal asynchronously. Examples of such signals include terminating a process with specific keystrokes (such as `<control><C>`) and

having a timer expire. Typically, an asynchronous signal is sent to another process.

A signal may be *handled* by one of two possible handlers:

1. A default signal handler
2. A user-defined signal handler

Every signal has a **default signal handler** that the kernel runs when handling that signal. This default action can be overridden by a **user-defined signal handler** that is called to handle the signal. Signals are handled in different ways. Some signals may be ignored, while others (for example, an illegal memory access) are handled by terminating the program.

Handling signals in single-threaded programs is straightforward: signals are always delivered to a process. However, delivering signals is more complicated in multithreaded programs, where a process may have several threads. Where, then, should a signal be delivered?

In general, the following options exist:

1. Deliver the signal to the thread to which the signal applies.
2. Deliver the signal to every thread in the process.
3. Deliver the signal to certain threads in the process.
4. Assign a specific thread to receive all signals for the process.

The method for delivering a signal depends on the type of signal generated. For example, synchronous signals need to be delivered to the thread causing the signal and not to other threads in the process. However, the situation with asynchronous signals is not as clear. Some asynchronous signals—such as a signal that terminates a process (<control><C>, for example)—should be sent to all threads.

The standard UNIX function for delivering a signal is

```
kill(pid_t pid, int signal)
```

This function specifies the process (`pid`) to which a particular signal (`signal`) is to be delivered. Most multithreaded versions of UNIX allow a thread to specify which signals it will accept and which it will block. Therefore, in some cases, an asynchronous signal may be delivered only to those threads that are not blocking it. However, because signals need to be handled only once, a signal is typically delivered only to the first thread found that is not blocking it. POSIX Pthreads provides the following function, which allows a signal to be delivered to a specified thread (`tid`):

```
pthread_kill(pthread_t tid, int signal)
```

Although Windows does not explicitly provide support for signals, it allows us to emulate them using **asynchronous procedure calls (APCs)**. The APC facility enables a user thread to specify a function that is to be called when the user thread receives notification of a particular event. As indicated

by its name, an APC is roughly equivalent to an asynchronous signal in UNIX. However, whereas UNIX must contend with how to deal with signals in a multithreaded environment, the APC facility is more straightforward, since an APC is delivered to a particular thread rather than a process.

4.6.3 Thread Cancellation

Thread cancellation involves terminating a thread before it has completed. For example, if multiple threads are concurrently searching through a database and one thread returns the result, the remaining threads might be canceled. Another situation might occur when a user presses a button on a web browser that stops a web page from loading any further. Often, a web page loads using several threads—each image is loaded in a separate thread. When a user presses the stop button on the browser, all threads loading the page are canceled.

A thread that is to be canceled is often referred to as the **target thread**. Cancellation of a target thread may occur in two different scenarios:

1. **Asynchronous cancellation.** One thread immediately terminates the target thread.
2. **Deferred cancellation.** The target thread periodically checks whether it should terminate, allowing it an opportunity to terminate itself in an orderly fashion.

The difficulty with cancellation occurs in situations where resources have been allocated to a canceled thread or where a thread is canceled while in the midst of updating data it is sharing with other threads. This becomes especially troublesome with asynchronous cancellation. Often, the operating system will reclaim system resources from a canceled thread but will not reclaim all resources. Therefore, canceling a thread asynchronously may not free a necessary system-wide resource.

With deferred cancellation, in contrast, one thread indicates that a target thread is to be canceled, but cancellation occurs only after the target thread has checked a flag to determine whether or not it should be canceled. The thread can perform this check at a point at which it can be canceled safely.

In Pthreads, thread cancellation is initiated using the `pthread_cancel()` function. The identifier of the target thread is passed as a parameter to the function. The following code illustrates creating—and then canceling—a thread:

```
pthread_t tid;

/* create the thread */
pthread_create(&tid, 0, worker, NULL);

. . .

/* cancel the thread */
pthread_cancel(tid);

/* wait for the thread to terminate */
pthread_join(tid, NULL);
```

Invoking `pthread_cancel()` indicates only a request to cancel the target thread, however; actual cancellation depends on how the target thread is set up to handle the request. When the target thread is finally canceled, the call to `pthread_join()` in the canceling thread returns. Pthreads supports three cancellation modes. Each mode is defined as a state and a type, as illustrated in the table below. A thread may set its cancellation state and type using an API.

Mode	State	Type
Off	Disabled	–
Deferred	Enabled	Deferred
Asynchronous	Enabled	Asynchronous

As the table illustrates, Pthreads allows threads to disable or enable cancellation. Obviously, a thread cannot be canceled if cancellation is disabled. However, cancellation requests remain pending, so the thread can later enable cancellation and respond to the request.

The default cancellation type is deferred cancellation. However, cancellation occurs only when a thread reaches a **cancellation point**. Most of the blocking system calls in the POSIX and standard C library are defined as cancellation points, and these are listed when invoking the command `man pthreads` on a Linux system. For example, the `read()` system call is a cancellation point that allows cancelling a thread that is blocked while awaiting input from `read()`.

One technique for establishing a cancellation point is to invoke the `pthread_testcancel()` function. If a cancellation request is found to be pending, the call to `pthread_testcancel()` will not return, and the thread will terminate; otherwise, the call to the function will return, and the thread will continue to run. Additionally, Pthreads allows a function known as a **cleanup handler** to be invoked if a thread is canceled. This function allows any resources a thread may have acquired to be released before the thread is terminated.

The following code illustrates how a thread may respond to a cancellation request using deferred cancellation:

```
while (1) {
    /* do some work for awhile */

    . . .

    /* check if there is a cancellation request */
    pthread_testcancel();
}
```

Because of the issues described earlier, asynchronous cancellation is not recommended in Pthreads documentation. Thus, we do not cover it here. An interesting note is that on Linux systems, thread cancellation using the Pthreads API is handled through signals (Section 4.6.2).

Thread cancellation in Java uses a policy similar to deferred cancellation in Pthreads. To cancel a Java thread, you invoke the `interrupt()` method, which sets the interruption status of the target thread to true:

```

Thread worker;

. . .

/* set the interruption status of the thread */
worker.interrupt()

```

A thread can check its interruption status by invoking the `isInterrupted()` method, which returns a boolean value of a thread's interruption status:

```

while (!Thread.currentThread().isInterrupted()) {
    . . .
}

```

4.6.4 Thread-Local Storage

Threads belonging to a process share the data of the process. Indeed, this data sharing provides one of the benefits of multithreaded programming. However, in some circumstances, each thread might need its own copy of certain data. We will call such data **thread-local storage** (or **TLS**). For example, in a transaction-processing system, we might service each transaction in a separate thread. Furthermore, each transaction might be assigned a unique identifier. To associate each thread with its unique transaction identifier, we could use thread-local storage.

It is easy to confuse TLS with local variables. However, local variables are visible only during a single function invocation, whereas TLS data are visible across function invocations. Additionally, when the developer has no control over the thread creation process—for example, when using an implicit technique such as a thread pool—then an alternative approach is necessary.

In some ways, TLS is similar to static data; the difference is that TLS data are unique to each thread. (In fact, TLS is usually declared as `static`.) Most thread libraries and compilers provide support for TLS. For example, Java provides a `ThreadLocal<T>` class with `set()` and `get()` methods for `ThreadLocal<T>` objects. Pthreads includes the type `pthread_key_t`, which provides a key that is specific to each thread. This key can then be used to access TLS data. Microsoft's C# language simply requires adding the storage attribute `[ThreadStatic]` to declare thread-local data. The gcc compiler provides the storage class keyword `__thread` for declaring TLS data. For example, if we wished to assign a unique identifier for each thread, we would declare it as follows:

```
static __thread int threadID;
```

4.6.5 Scheduler Activations

A final issue to be considered with multithreaded programs concerns communication between the kernel and the thread library, which may be required