Maya Posch

Mastering C++ Multithreading

A comprehensive guide to developing effective multithreading applications in C++

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Maya Posch is a software engineer by trade and a self-professed electronics, robotics, and AI nut, running her own software development company, Nyanko, with her good friend, Trevor Purdy, where she works on various game development projects and some non-game projects. Apart from this, she does various freelance jobs for companies around the globe. You can visit her LinkedIn profile for more work-related details.

Aside from writing software, she likes to play with equations and write novels, such as her awesome reimagining of the story of the Nintendo classic, Legend of Zelda: Ocarina of Time, and the survival-horror novel she recently started, Viral Desire. You can check out her Scribd profile for a full listing of her writings.

Maya is also interested in biochemistry, robotics, and reverse-engineering of the human body. To know more about her, visit her blog, Artificial Human. If there's anything she doesn't lack, it has to be sheer ambition, it seems.

About the Reviewer

Louis E. Mauget learned to program a long time ago at the Michigan State University as a physics major learning to use software in designing a cyclotron. Later, he worked for 34 years at IBM. He went on to work for several consulting firms, including a long-term engagement with the railroad industry. He is currently consulting for Keyhole Software at Leawood, Kansas.

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Table of Contents

Preface

Multithreaded applications execute multiple threads in a single processor environment, to achieve. Filled with practical examples, this book will help you become a master at writing robust concurrent and parallel applications in C++. In this book, you will delve into the fundamentals of multithreading and concurrency and find out how to implement them. While doing so, you will explore atomic operations to optimize code performance and also apply concurrency to both distributed computing and GPGPU processing.

What this book covers

`Chapter 1`, *Revisiting Multithreading*, summarizes multithreading in C++, revisiting all the concepts you should already be familiar with and going through a basic example of multithreading using the native threading support added in the 2011 revision of C++.

`Chapter 2`, *Multithreading Implementation on the Processor and OS*, builds upon the fundamentals provided by the hardware implementations discussed in the preceding chapter, showing how OSes have used the capabilities to their advantage and made them available to applications. It also discusses how processes and threads are allowed to use the memory and processor in order to prevent applications and threads from interfering with each other.

`Chapter 3`, *C++ Multithreading APIs*, explores the wide variety of multithreading APIs available as OS-level APIs (for example, Win32 and POSIX) or as provided by a framework (for example, Boost, Qt, and POCO). It briefly runs through each API, listing the differences compared to the others as well as the advantages and disadvantages it may have for your application.

`Chapter 4`, *Thread Synchronization and Communication*, takes the topics learned in the previous chapters and explores an advanced multithreading implementation implemented using C++ 14's native threading API, which allows multiple threads to communicate without any thread-safety issues. It also covers the differences between the many types of synchronization mechanisms, including mutexes, locks, and condition variables.

`Chapter 5`, *Native C++ Threads and Primitives*, includes threads, concurrency, local storage, as well as thread-safety supported by this API. Building upon the example in the preceding chapter, it discusses and explores extending and optimizing thread-safty using the features offered by the full feature set in C++ 11 and C++ 14.

`Chapter 6`, *Debugging Multithreaded Code*, teaches you how to use tools such as Valgrind (Memcheck, DRD, Helgrind, and so on) to analyze the multithreaded performance of an application, find hotspots, and resolve or prevent issues resulting from concurrent access.

`Chapter 7`, *Best Practices*, covers common pitfalls and gotchas and how to spot them before they come back to haunt you. It also explores a number of common and less common scenarios using examples.

`Chapter 8`, *Atomic Operations – Working with the Hardware*, covers atomic operations in detail: what they are and how they are best used. Compiler support is looked at across CPU architectures and an evaluation is made of when it is worth to invest time in implementing atomic operations in your code. It also looks at how such optimizations will limit the portability of your code.

`Chapter 9`, *Multithreading with Distributed Computing*, takes many of the lessons learned in the preceding chapters and applies them on a multi-system, cluster-level scale. Using an OpenMPI-based example, it shows how multithreading can be done across multiple systems, such as the nodes in a computer cluster.

`Chapter 10`, *Multithreading with GPGPU*, shows the use of multithreading in GPGPU applications (for example, CUDA and OpenCL). Using an OpenCL-based example, a basic multithreaded application is explored that can execute tasks in parallel. This chapter takes lessons learned in the preceding chapters and applies them to processing on video cards and derived hardware (for example, rack-mounted vector processor hardware).

What you need for this book

To follow the instructions in this book, you will need any OS (Windows, Linux, or macOS) and any C++ compiler installed on your systems.

Who this book is for

This book is for intermediate C++ developers who wish to extend their knowledge of multithreading and concurrent processing. You should have basic experience with multithreading and be comfortable using C++ development toolchains on the command line.

Conventions

In this book, you will find a number of text styles that distinguish between different kinds of information. Here are some examples of these styles and an explanation of their meaning.

Code words in text, database table names, folder names, filenames, file extensions, pathnames, dummy URLs, user input, and Twitter handles are shown as follows: "The `randGen()` method takes two parameters, defining the range of the returned value:"

A block of code is set as follows:

```
cout_mtx.lock();
 cout << "Thread " << tid << " adding " << rval << ". New value: " << val
<< ".\n";
 cout_mtx.unlock();

 values_mtx.lock();
 values.push_back(val);
 values_mtx.unlock();
}
```

When we wish to draw your attention to a particular part of a code block, the relevant lines or items are set in bold:

```
cout_mtx.lock();
 cout << "Thread " << tid << " adding " << rval << ". New value: " << val
<< ".\n";
 cout_mtx.unlock();

 values_mtx.lock();
 values.push_back(val);
 values_mtx.unlock();
}
```

Any command-line input or output is written as follows:

```
$ make
g++ -o ch01_mt_example -std=c++11 ch01_mt_example.cpp
```

New terms and **important words** are shown in bold. Words that you see on the screen, for example, in menus or dialog boxes, appear in the text.

Warnings or important notes appear like this.

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1

Revisiting Multithreading

Chances are that if you're reading this book, you have already done some multithreaded programming in C++, or, possibly, other languages. This chapter is meant to recap the topic purely from a C++ point of view, going through a basic multithreaded application, while also covering the tools we'll be using throughout the book. At the end of this chapter, you will have all the knowledge and information needed to proceed with the further chapters.

Topics covered in this chapter include the following:

- Basic multithreading in C++ using the native API
- Writing basic makefiles and usage of GCC/MinGW
- Compiling a program using `make` and executing it on the command-line

Getting started

During the course of this book, we'll be assuming the use of a GCC-based toolchain (GCC or MinGW on Windows). If you wish to use alternative toolchains (clang, MSVC, ICC, and so on), please consult the documentation provided with these for compatible commands.

To compile the examples provided in this book, makefiles will be used. For those unfamiliar with makefiles, they are a simple but powerful text-based format used with the `make` tool for automating build tasks including compiling source code and adjusting the build environment. First released in 1977, `make` remains among the most popular build automation tools today.

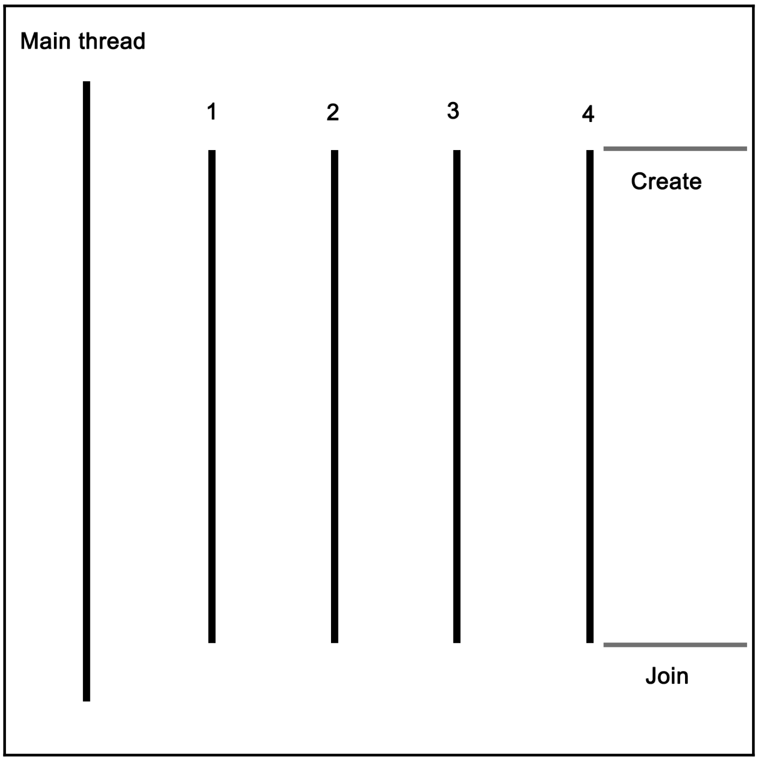
Familiarity with the command line (Bash or equivalent) is assumed, with MSYS2 (Bash on Windows) recommended for those using Windows.

The multithreaded application

In its most basic form, a multithreaded application consists of a singular process with two or more threads. These threads can be used in a variety of ways; for example, to allow the process to respond to events in an asynchronous manner by using one thread per incoming event or type of event, or to speed up the processing of data by splitting the work across multiple threads.

Examples of asynchronous responses to events include the processing of the graphical user interface (GUI) and network events on separate threads so that neither type of event has to wait on the other, or can block events from being responded to in time. Generally, a single thread performs a single task, such as the processing of GUI or network events, or the processing of data.

For this basic example, the application will start with a singular thread, which will then launch a number of threads, and wait for them to finish. Each of these new threads will perform its own task before finishing.



Let's start with the includes and global variables for our application:

```
#include <iostream>
#include <thread>
#include <mutex>
#include <vector>
#include <random>

using namespace std;

// --- Globals
mutex values_mtx;
mutex cout_mtx;
vector<int> values;
```

Both the I/O stream and vector headers should be familiar to anyone who has ever used C++: the former is here used for the standard output (`cout`), and the vector for storing a sequence of values.

The random header is new in `c++11`, and as the name suggests, it offers classes and methods for generating random sequences. We use it here to make our threads do something interesting.

Finally, the thread and mutex includes are the core of our multithreaded application; they provide the basic means for creating threads, and allow for thread-safe interactions between them.

Moving on, we create two mutexes: one for the global vector and one for `cout`, since the latter is not thread-safe.

Next we create the main function as follows:

```
int main() {
    values.push_back(42);
```

We push a fixed value onto the vector instance; this one will be used by the threads we create in a moment:

```
    thread tr1(threadFnc, 1);
    thread tr2(threadFnc, 2);
    thread tr3(threadFnc, 3);
    thread tr4(threadFnc, 4);
```

We create new threads, and provide them with the name of the method to use, passing along any parameters--in this case, just a single integer:

```
        tr1.join();
        tr2.join();
        tr3.join();
        tr4.join();
```

Next, we wait for each thread to finish before we continue by calling `join()` on each thread instance:

```
        cout << "Input: " << values[0] << ", Result 1: " << values[1] << ",
    Result 2: " << values[2] << ", Result 3: " << values[3] << ", Result 4: "
    << values[4] << "\n";


        return 1;
    }
```

At this point, we expect that each thread has done whatever it's supposed to do, and added the result to the vector, which we then read out and show the user.

Of course, this shows almost nothing of what really happens in the application, mostly just the essential simplicity of using threads. Next, let's see what happens inside this method that we pass to each thread instance:

```
    void threadFnc(int tid) {
        cout_mtx.lock();
        cout << "Starting thread " << tid << ".\n";
        cout_mtx.unlock();
```

In the preceding code, we can see that the integer parameter being passed to the thread method is a thread identifier. To indicate that the thread is starting, a message containing the thread identifier is output. Since we're using a `non-thread-safe` method for this, we use the `cout_mtx` mutex instance to do this safely, ensuring that just one thread can write to `cout` at any time:

```
        values_mtx.lock();
        int val = values[0];
        values_mtx.unlock();
```

When we obtain the initial value set in the vector, we copy it to a local variable so that we can immediately release the mutex for the vector to enable other threads to use the vector:

```
        int rval = randGen(0, 10);
        val += rval;
```

These last two lines contain the essence of what the threads created do: they take the initial value, and add a randomly generated value to it. The `randGen()` method takes two parameters, defining the range of the returned value:

```
        cout_mtx.lock();
        cout << "Thread " << tid << " adding " << rval << ". New value: " <<
    val << ".\n";
        cout_mtx.unlock();

        values_mtx.lock();
        values.push_back(val);
        values_mtx.unlock();
    }
```

Finally, we (safely) log a message informing the user of the result of this action before adding the new value to the vector. In both cases, we use the respective mutex to ensure that there can be no overlap when accessing the resource with any of the other threads.

Once the method reaches this point, the thread containing it will terminate, and the main thread will have one less thread to wait for to rejoin. The joining of a thread basically means that it stops existing, usually with a return value passed to the thread which created the thread. This can happen explicitly, with the main thread waiting for the child thread to finish, or in the background.

Lastly, we'll take a look at the `randGen()` method. Here we can see some multithreaded specific additions as well:

```
    int randGen(const int& min, const int& max) {
        static thread_local mt19937
    generator(hash<thread::id>()(this_thread::get_id()));
        uniform_int_distribution<int> distribution(min, max);
        return distribution(generator)
    }
```

This preceding method takes a minimum and maximum value as explained earlier, which limits the range of the random numbers this method can return. At its core, it uses a mt19937-based `generator`, which employs a 32-bit **Mersenne Twister** algorithm with a state size of 19937 bits. This is a common and appropriate choice for most applications.

Of note here is the use of the `thread_local` keyword. What this means is that even though it is defined as a static variable, its scope will be limited to the thread using it. Every thread will thus create its own `generator` instance, which is important when using the random number API in the STL.

A hash of the internal thread identifier is used as a seed for the `generator`. This ensures that each thread gets a fairly unique seed for its `generator` instance, allowing for better random number sequences.

Finally, we create a new `uniform_int_distribution` instance using the provided minimum and maximum limits, and use it together with the `generator` instance to generate the random number which we return.

Makefile

In order to compile the code described earlier, one could use an IDE, or type the command on the command line. As mentioned in the beginning of this chapter, we'll be using makefiles for the examples in this book. The big advantages of this are that one does not have to repeatedly type in the same extensive command, and it is portable to any system which supports `make`.

Further advantages include being able to have previous generated artifacts removed automatically and to only compile those source files which have changed, along with a detailed control over build steps.

The makefile for this example is rather basic:

```
GCC := g++

OUTPUT := ch01_mt_example
SOURCES := $(wildcard *.cpp)
CCFLAGS := -std=c++11 -pthread

all: $(OUTPUT)

$(OUTPUT):
    $(GCC) -o $(OUTPUT) $(CCFLAGS) $(SOURCES)

clean:
    rm $(OUTPUT)

.PHONY: all
```

From the top down, we first define the compiler that we'll use (`g++`), set the name of the output binary (the `.exe` extension on Windows will be post-fixed automatically), followed by the gathering of the sources and any important compiler flags.

The wildcard feature allows one to collect the names of all files matching the string following it in one go without having to define the name of each source file in the folder individually.

For the compiler flags, we're only really interested in enabling the `c++11` features, for which GCC still requires one to supply this compiler flag.

For the `all` method, we just tell `make` to run `g++` with the supplied information. Next we define a simple clean method which just removes the produced binary, and finally, we tell `make` to not interpret any folder or file named `all` in the folder, but to use the internal method with the `.PHONY` section.

When we run this makefile, we see the following command-line output:

```
$ make
g++ -o ch01_mt_example -std=c++11 ch01_mt_example.cpp
```

Afterwards, we find an executable file called `ch01_mt_example` (with the `.exe` extension attached on Windows) in the same folder. Executing this binary will result in a command-line output akin to the following:

```
$ ./ch01_mt_example.exe

Starting thread 1.

Thread 1 adding 8. New value: 50.

Starting thread 2.

Thread 2 adding 2. New value: 44.

Starting thread 3.

Starting thread 4.

Thread 3 adding 0. New value: 42.

Thread 4 adding 8. New value: 50.

Input: 42, Result 1: 50, Result 2: 44, Result 3: 42, Result 4: 50
```

What one can see here already is the somewhat asynchronous nature of threads and their output. While threads `1` and `2` appear to run synchronously, starting and quitting seemingly in order, threads `3` and `4` clearly run asynchronously as both start simultaneously before logging their action. For this reason, and especially in longer-running threads, it's virtually impossible to say in which order the log output and results will be returned.

While we use a simple vector to collect the results of the threads, there is no saying whether `Result 1` truly originates from the thread which we assigned ID 1 in the beginning. If we need this information, we need to extend the data we return by using an information structure with details on the processing thread or similar.

One could, for example, use `struct` like this:

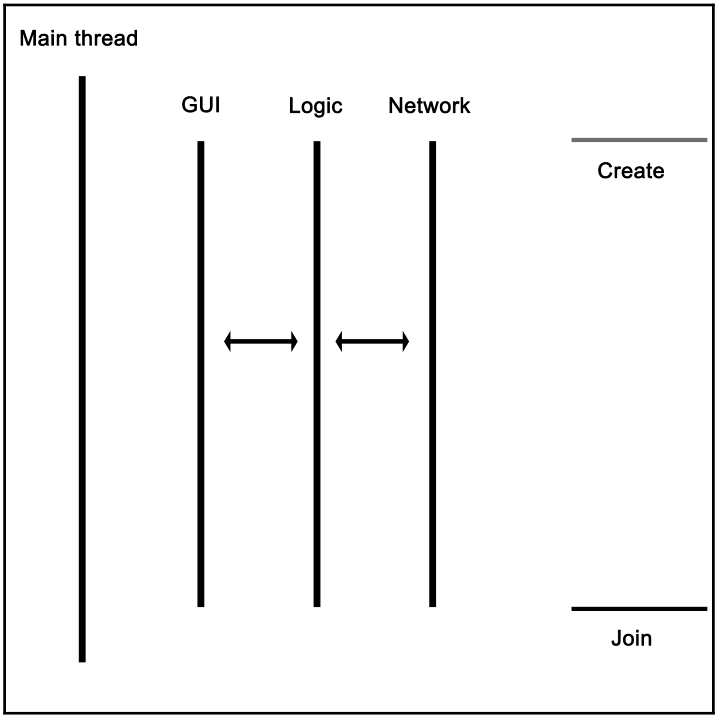
```
struct result {
    int tid;
    int result;
};
```

The vector would then be changed to contain result instances rather than integer instances. One could pass the initial integer value directly to the thread as part of its parameters, or pass it via some other way.

Other applications

The example in this chapter is primarily useful for applications where data or tasks have to be handled in parallel. For the earlier mentioned use case of a GUI-based application with business logic and network-related features, the basic setup of a main application, which launches the required threads, would remain the same. However, instead of having each thread to be the same, each would be a completely different method.

For this type of application, the thread layout would look like this:



As the graphic shows, the main thread would launch the GUI, network, and business logic thread, with the latter communicating with the network thread to send and receive data. The business logic thread would also receive user input from the GUI thread, and send updates back to be displayed on the GUI.

Summary

In this chapter, we went over the basics of a multithreaded application in C++ using the native threading API. We looked at how to have multiple threads perform a task in parallel, and also explored how to properly use the random number API in the STL within a multithreaded application.

In the next chapter, we'll discuss how multithreading is implemented both in hardware and in operating systems. We'll see how this implementation differs per processor architecture and operating system, and how this affects our multithreaded application.

2

Multithreading Implementation on the Processor and OS

The foundation of any multithreaded application is formed by the implementation of the required features by the hardware of the processor, as well as by the way these features are translated into an API for use by applications by the operating system. An understanding of this foundation is crucial for developing an intuitive understanding of how to best implement a multithreaded application.

This chapter looks at how hardware and operating systems have evolved over the years to arrive at the current implementations and APIs as they are in use today. It shows how the example code of the previous chapter ultimately translates into commands to the processor and related hardware.

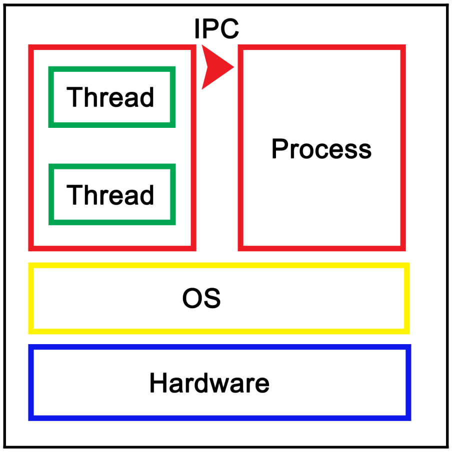
Topics covered in this chapter include the following:

- The evolution of processor hardware in order to support multithreading concepts
- How operating systems changed to use these hardware features
- Concepts behind memory safety and memory models in various architectures
- Differences between various process and threading models by OSes

Defining processes and threads

Essentially, to the **operating system** (**OS**), a process consists of one or more threads, each thread processing its own state and variables. One would regard this as a hierarchical configuration, with the OS as the foundation, providing support for the running of (user) processes. Each of these processes then consists of one or more threads. Communication between processes is handled by **inter-process communication** (**IPC**), which is provided by the operating system.

In a graphical view, this looks like the following:



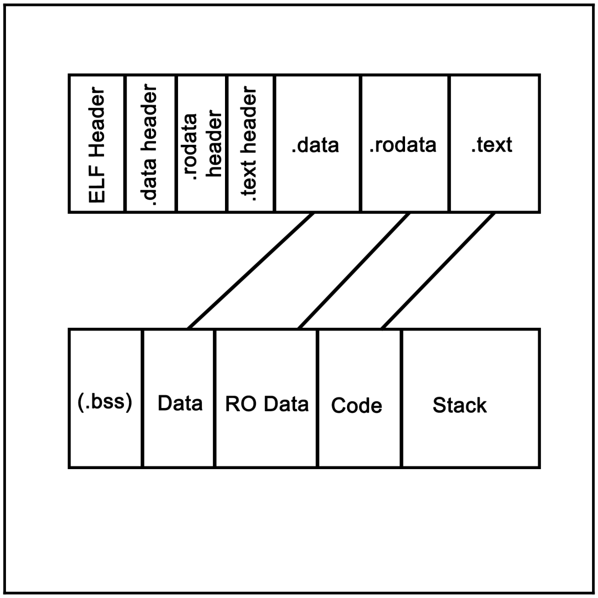
Each process within the OS has its own state, with each thread in a process having its own state as well as the relative to the other threads within that same process. While IPC allows processes to communicate with each other, threads can communicate with other threads within the process in a variety of ways, which we'll explore in more depth in upcoming chapters. This generally involves some kind of shared memory between threads.

An application is loaded from binary data in a specific executable format such as, for example, **Executable and Linkable Format** (**ELF**) which is generally used on Linux and many other operating systems. With ELF binaries, the following number of sections should always be present:

- `.bss`
- `.data`
- `.rodata`
- `.text`

The `.bss` section is, essentially, allocated with uninitialized memory including empty arrays which thus do not take up any space in the binary, as it makes no sense to store rows of pure zeroes in the executable. Similarly, there is the `.data` section with initialized data. This contains global tables, variables, and the like. Finally, the `.rodata` section is like `.data`, but it is, as the name suggests, read-only. It contains things such as hardcoded strings.

In the `.text` section, we find the actual application instructions (code) which will be executed by the processor. The whole of this will get loaded by the operating system, thus creating a process. The layout of such a process looks like the following diagram:



This is what a process looks like when launched from an ELF-format binary, though the final format in memory is roughly the same in basically any OS, including for a Windows process launched from a PE-format binary. Each of the sections in the binary are loaded into their respective sections, with the BSS section allocated to the specified size. The `.text` section is loaded along with the other sections, and its initial instruction is executed once this is done, which starts the process.

In system languages such as C++, one can see how variables and other program state information within such a process are stored both on the stack (variables exist within the scope) and heap (using the new operator). The stack is a section of memory (one allocated per thread), the size of which depends on the operating system and its configuration. One can generally also set the stack size programmatically when creating a new thread.

In an operating system, a process consists of a block of memory addresses, the size of which is constant and limited by the size of its memory pointers. For a 32-bit OS, this would limit this block to 4 GB. Within this virtual memory space, the OS allocates a basic stack and heap, both of which can grow until all memory addresses have been exhausted, and further attempts by the process to allocate more memory will be denied.

The stack is a concept both for the operating system and for the hardware. In essence, it's a collection (stack) of so-called stack frames, each of which is composed of variables, instructions, and other data relevant to the execution frame of a task.

In hardware terms, the stack is part of the task (x86) or process state (ARM), which is how the processor defines an execution instance (program or thread). This hardware-defined entity contains the entire state of a singular thread of execution. See the following sections for further details on this.

Tasks in x86 (32-bit and 64-bit)

A task is defined as follows in the Intel IA-32 System Programming guide, Volume 3A:

"A task is a unit of work that a processor can dispatch, execute, and suspend. It can be used to execute a program, a task or process, an operating-system service utility, an interrupt or exception handler, or a kernel or executive utility."

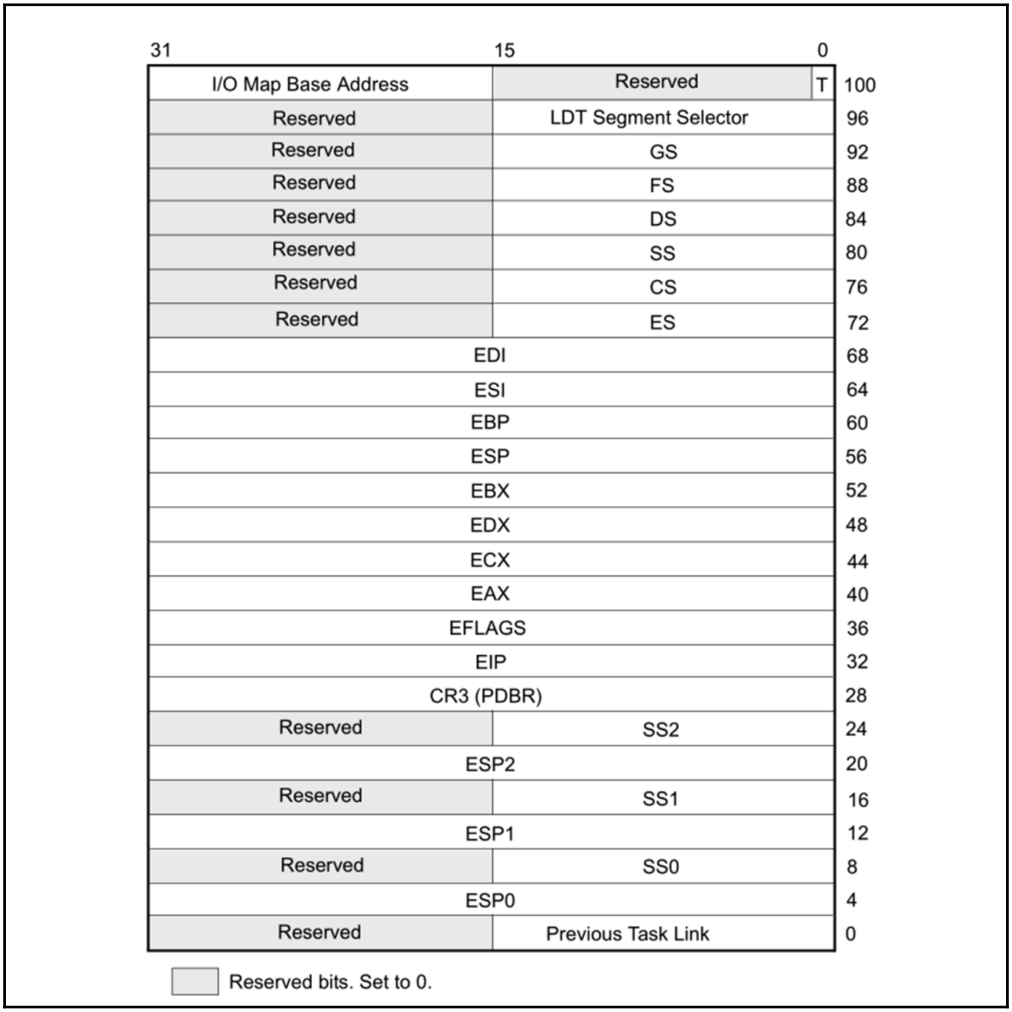
"The IA-32 architecture provides a mechanism for saving the state of a task, for dispatching tasks for execution, and for switching from one task to another. When operating in protected mode, all processor execution takes place from within a task. Even simple systems must define at least one task. More complex systems can use the processor's task management facilities to support multitasking applications."

This excerpt from the IA-32 (Intel x86) manual summarizes how the hardware supports and implements support for operating systems, processes, and the switching between these processes.

It's important to realize here that, to the processor, there's no such thing as a process or thread. All it knows of are threads of execution, defined as a series of instructions. These instructions are loaded into memory somewhere, and the current position in these instructions is kept track of along with the variable data (variables) being created, as the application is executed within the data section of the process.

Each task also runs within a hardware-defined protection ring, with the OS's tasks generally running on ring 0, and user tasks on ring 3. Rings 1 and 2 are rarely used except for specific use cases with modern OSes on the x86 architecture. These rings are privilege-levels enforced by the hardware and allow for example for the strict separation of kernel and user-level tasks.

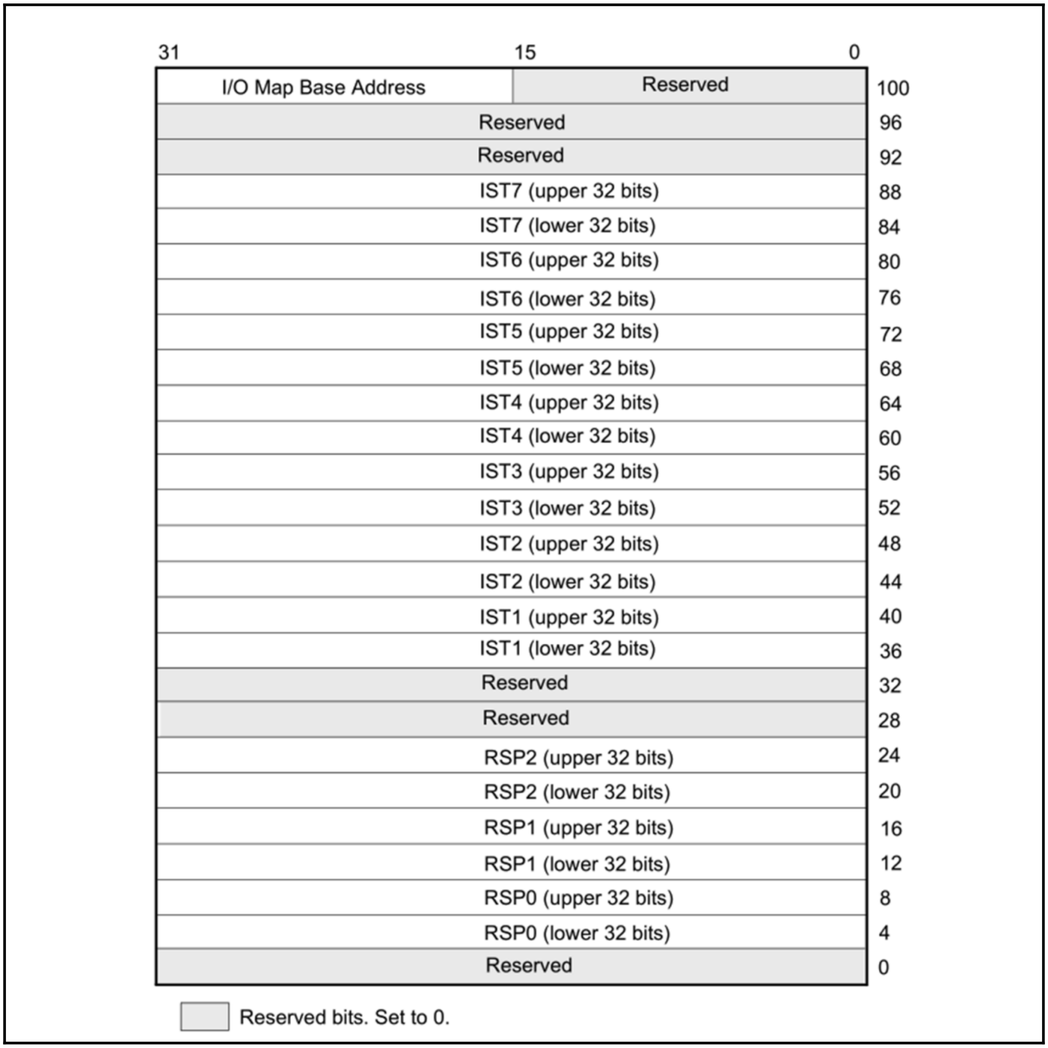
The task structure for both 32-bit and 64-bit tasks are quite similar in concept. The official name for it is the **Task State Structure** (**TSS**). It has the following layout for 32-bit x86 CPUs:



Following are the firlds:

- **SS0**: The first stack segment selector field
- **ESP0**: The first SP field

For 64-bit x86_64 CPUs, the TSS layout looks somewhat different, since hardware-based task switching is not supported in this mode:



Here, we have similar relevant fields, just with different names:

- **RSPn**: SP for privilege levels 0 through 2
- **ISTn**: Interrupt stack table pointers

Even though on x86 in 32-bit mode, the CPU supports hardware-based switching between tasks, most operating systems will use just a single TSS structure per CPU regardless of the mode, and do the actual switching between tasks in software. This is partially due to efficiency reasons (swapping out only pointers which change), partially due to features which are only possible this way, such as measuring CPU time used by a process/thread, and to adjust the priority of a thread or process. Doing it in software also simplifies the portability of code between 64-bit and 32-bit systems, since the former do not support hardware-based task switching.

During a software-based task switch (usually via an interrupt), the ESP/RSP, and so on are stored in memory and replaced with the values for the next scheduled task. This means that once execution resumes, the TSS structure will now have the **Stack Pointer** (**SP**), segment pointer(s), register contents, and all other details of the new task.

The source of the interrupt can be based in hardware or software. A hardware interrupt is usually used by devices to signal to the CPU that they require attention by the OS. The act of calling a hardware interrupt is called an Interrupt Request, or IRQ.

A software interrupt can be due to an exceptional condition in the CPU itself, or as a feature of the CPU's instruction set. The action of switching tasks by the OS's kernel is also performed by triggering a software interrupt.

Process state in ARM

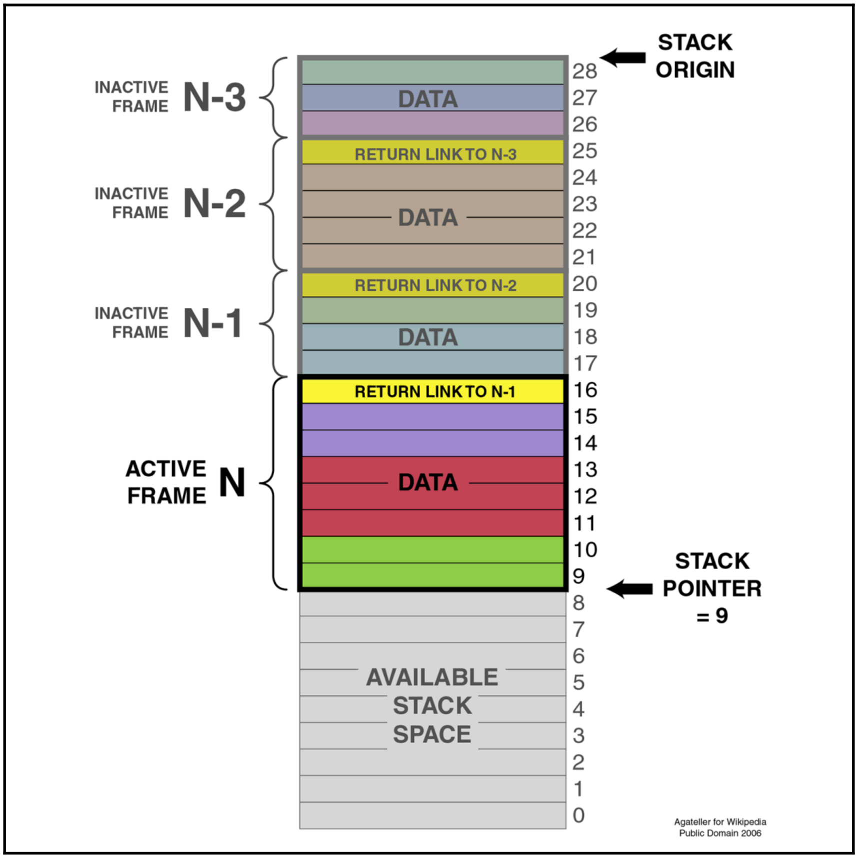
In ARM architectures, applications usually run in the unprivileged **Exception Level 0** (**EL0**) level, which is comparable to ring 3 on x86 architectures, and the OS kernel in EL1. The ARMv7 (AArch32, 32-bit) architecture has the SP in the general purpose register 13. For ARMv8 (AArch64, 64-bit), a dedicated SP register is implemented for each exception level: `SP_EL0`, `SP_EL1`, and so on.

For task state, the ARM architecture uses **Program State Register** (**PSR**) instances for the **Current Program State Register** (**CPSR**) or the **Saved Program State Register** (**SPSR**) program state's registers. The PSR is part of the **Process State** (**PSTATE**), which is an abstraction of the process state information.

While the ARM architecture is significantly different from the x86 architecture, when using software-based task switching, the basic principle does not change: save the current task's SP, register state, and put the next task's detail in there instead before resuming processing.

The stack

As we saw in the preceding sections, the stack together with the CPU registers define a task. As mentioned earlier, this stack consists of stack frames, each of which defines the (local) variables, parameters, data, and instructions for that particular instance of task execution. Of note is that although the stack and stack frames are primarily a software concept, it is an essential feature of any modern OS, with hardware support in many CPU instruction sets. Graphically, it can be be visualized like the following:



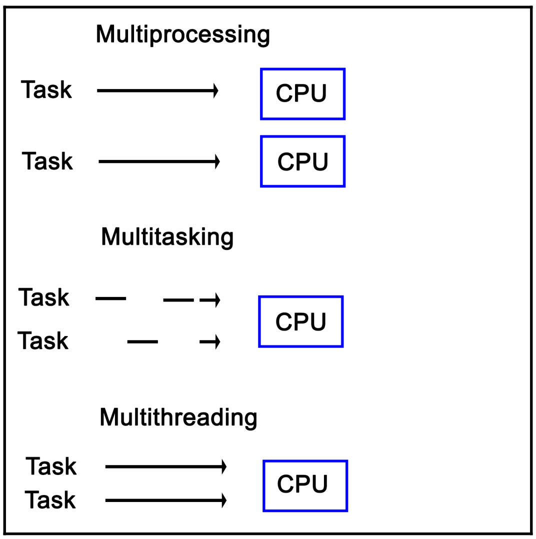
The SP (ESP on x86) points to the top of the stack, with another pointer (**Extended Base Pointer** (**EBP**) for x86). Each frame contains a reference to the preceding frame (caller return address), as set by the OS.

When using a debugger with one's C++ application, this is basically what one sees when requesting the backtrack--the individual frames of the stack showing the initial stack frame leading up until the current frame. Here, one can examine each individual frame's details.

Defining multithreading

Over the past decades, a lot of different terms related to the way tasks are processed by a computer have been coined and come into common use. Many of these are also used interchangeably, correctly or not. An example of this is multithreading in comparison with multiprocessing.

Here, the latter means running one task per processor in a system with multiple physical processors, while the former means running multiple tasks on a singular processor simultaneously, thus giving the illusion that they are all being executed simultaneously:



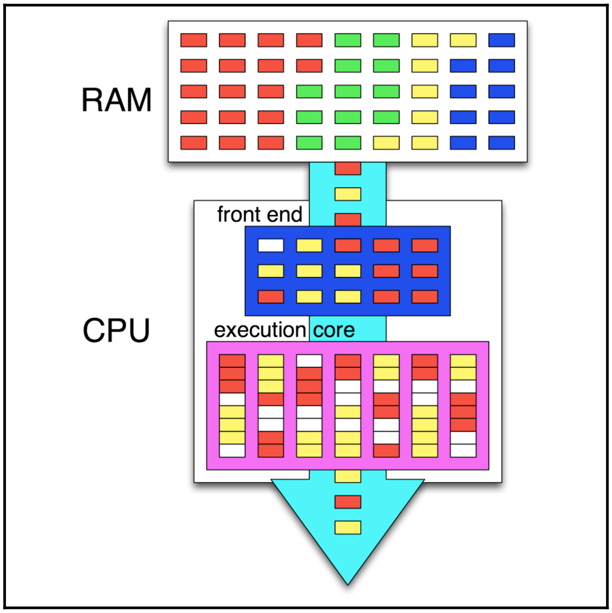
Another interesting distinction between multiprocessing and multitasking is that the latter uses time-slices in order to run multiple threads on a single processor core. This is different from multithreading in the sense that in a multitasking system, no tasks will ever run in a concurrent fashion on the same CPU core, though tasks can still be interrupted.

The concept of a process and a shared memory space between the threads contained within the said process is at the very core of multithreaded systems from a software perspective. Though the hardware is often not aware of this--seeing just a single task to the OS. However, such a multithreaded process contains two or many more threads. Each of these threads then perform its own series of tasks.

In other implementations, such as Intel's **Hyper-Threading** (**HT**) on x86 processors, this multithreading is implemented in the hardware itself, where it's commonly referred to as SMT (see the section *Simultaneous multithreading (SMT)* for details). When HT is enabled, each physical CPU core is presented to the OS as being two cores. The hardware itself will then attempt to execute the tasks assigned to these so-called virtual cores concurrently, scheduling operations which can use different elements of a processing core at the same time. In practice, this can give a noticeable boost in performance without the operating system or application requiring any type of optimization.

The OS can of course still do its own scheduling to further optimize the execution of task, since the hardware is not aware of many details about the instructions it is executing.

Having HT enabled looks like this in the visual format:



In this preceding graphic, we see the instructions of four different tasks in memory (RAM). Out of these, two tasks (threads) are being executed simultaneously, with the CPU's scheduler (in the frontend) attempting to schedule the instructions so that as many instructions as possible can be executed in parallel. Where this is not possible, so-called pipeline bubbles (in white) appear where the execution hardware is idle.

Together with internal CPU optimizations, this leads to a very high throughput of instructions, also called **Instructions Per Second** (**IPC**). Instead of the GHz rating of a CPU, this IPC number is generally far more significant for determining the sheer performance of a CPU.

Flynn's taxonomy

Different types of computer architecture are classified using a system which was first proposed by Michael J. Flynn, back in 1966. This classification system knows four categories, defining the capabilities of the processing hardware in terms of the number of input and output streams:

- **Single Instruction, Single Data** (**SISD**): A single instruction is fetched to operate on a single data stream. This is the traditional model for CPUs.
- **Single Instruction, Multiple Data** (**SIMD**): With this model, a single instruction operates on multiple data streams in parallel. This is what vector processors such as **graphics processing units** (**GPUs**) use.
- **Multiple Instruction, Single Data** (**MISD**): This model is most commonly used for redundant systems, whereby the same operation is performed on the same data by different processing units, validating the results at the end to detect hardware failure. This is commonly used by avionics systems and similar.
- **Multiple Instruction, Multiple Data** (**MIMD**): For this model, a multiprocessing system lends itself very well. Multiple threads across multiple processors process multiple streams of data. These threads are not identical, as is the case with SIMD.

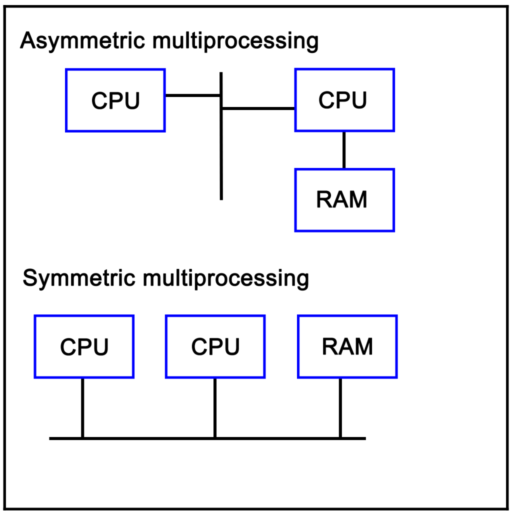
An important thing to note with these categories is that they are all defined in terms of multiprocessing, meaning that they refer to the intrinsic capabilities of the hardware. Using software techniques, virtually any method can be approximated on even a regular SISD-style architecture. This is, however, part of multithreading.

Symmetric versus asymmetric multiprocessing

Over the past decades, many systems were created which contained multiple processing units. These can be broadly divided into **Symmetric Multiprocessing** (**SMP**) and **Asymmetric Multiprocessing** (**AMP**) systems.

AMP's main defining feature is that a second processor is attached as a peripheral to the primary CPU. This means that it cannot run control software, but only user applications. This approach has also been used to connect CPUs using a different architecture to allow one to, for example, run x86 applications on an Amiga, 68k-based system.

With an SMP system, each of the CPUs are peers having access to the same hardware resources, and set up in a cooperative fashion. Initially, SMP systems involved multiple physical CPUs, but later, multiple processor cores got integrated on a single CPU die:



With the proliferation of multi-core CPUs, SMP is the most common type of processing outside of embedded development, where uniprocessing (single core, single processor) is still very common.

Technically, the sound, network, and graphic processors in a system can be considered to be asymmetric processors related to the CPU. With an increase in **General Purpose GPU** (**GPGPU**) processing, AMP is becoming more relevant.

Loosely and tightly coupled multiprocessing

A multiprocessing system does not necessarily have to be implemented within a single system, but can also consist of multiple systems which are connected in a network. Such a cluster is then called a loosely coupled multiprocessing system. We cover distributing computing in `Chapter 9`, *Multithreading with Distributed Computing*.

This is in contrast with a tightly coupled multiprocessing system, whereby the system is integrated on a single **printed circuit board** (**PCB**), using the same low-level, high-speed bus or similar.

Combining multiprocessing with multithreading

Virtually any modern system combines multiprocessing with multithreading, courtesy of multi-core CPUs, which combine two or more processing cores on a single processor die. What this means for an operating system is that it has to schedule tasks both across multiple processing cores while also scheduling them on specific cores in order to extract maximum performance.

This is the area of task schedulers, which we will look at in a moment. Suffice it to say that this is a topic worthy of its own book.

Multithreading types

Like multiprocessing, there is not a single implementation, but two main ones. The main distinction between these is the maximum number of threads the processor can execute concurrently during a single cycle. The main goal of a multithreading implementation is to get as close to 100% utilization of the processor hardware as reasonably possible. Multithreading utilizes both thread-level and process-level parallelism to accomplish this goal.

The are two types of multithreading, which we will cover in the following sections.

Temporal multithreading

Also known as super-threading, the main subtypes for **temporal multithreading** (**TMT**) are coarse-grained and fine-grained (or interleaved). The former switches rapidly between different tasks, saving the context of each before switching to another task's context. The latter type switches tasks with each cycle, resulting in a CPU pipeline containing instructions from various tasks from which the term *interleaved* is derived.

The fine-grained type is implemented in barrel processors. They have an advantage over x86 and other architectures that they can guarantee specific timing (useful for hard real-time embedded systems) in addition to being less complex to implement due to assumptions that one can make.

Simultaneous multithreading (SMT)

SMT is implemented on superscalar CPUs (implementing instruction-level parallelism), which include the x86 and ARM architectures. The defining characteristic of SMT is also indicated by its name, specifically, its ability to execute multiple threads in parallel, per core.

Generally, two threads per core is common, but some designs support up to eight concurrent threads per core. The main advantage of this is being able to share resources among threads, with an obvious disadvantage of conflicting needs by multiple threads, which has to be managed. Another advantage is that it makes the resulting CPU more energy efficient due to a lack of hardware resource duplication.

Intel's HT technology is essentially Intel's SMT implementation, providing a basic two thread SMT engine starting with some Pentium 4 CPUs in 2002.

Schedulers

A number of task-scheduling algorithms exist, each focusing on a different goal. Some may seek to maximize throughput, others minimize latency, while others may seek to maximize response time. Which scheduler is the optimal choice solely depends on the application the system is being used for.

For desktop systems, the scheduler is generally kept as general-purpose as possible, usually prioritizing foreground applications over background applications in order to give the user the best possible desktop experience.

For embedded systems, especially in real-time, industrial applications would instead seek to guarantee timing. This allows processes to be executed at exactly the right time, which is crucial in, for example, driving machinery, robotics, or chemical processes where a delay of even a few milliseconds could be costly or even fatal.

The scheduler type is also dependent on the multitasking state of the OS--a cooperative multitasking system would not be able to provide many guarantees about when it can switch out a running process for another one, as this depends on when the active process yields.

With a preemptive scheduler, processes are switched without them being aware of it, allowing the scheduler more control over when processes run at which time points.

Windows NT-based OSes (Windows NT, 2000, XP, and so on) use what is called a multilevel feedback queue, featuring 32 priority levels. This type of priority scheduler allows one to prioritize tasks over other tasks, allowing one to fine-tune the resulting experience.

Linux originally (kernel 2.4) also used a multilevel feedback queue-based priority scheduler like Windows NT with an O(n) scheduler. With version 2.6, this was replaced with an O(1) scheduler, allowing processes to be scheduled within a constant amount of time. Starting with Linux kernel 2.6.23, the default scheduler is the **Completely Fair Scheduler** (**CFS**), which ensures that all tasks get a comparable share of CPU time.

The type of scheduling algorithm used for a number of commonly used or well-known OSes is listed in this table:

Operating System	**Preemption**	**Algorithm**
Amiga OS	Yes	Prioritized round-robin scheduling
FreeBSD	Yes	Multilevel feedback queue
Linux kernel before 2.6.0	Yes	Multilevel feedback queue
Linux kernel 2.6.0-2.6.23	Yes	O(1) scheduler
Linux kernel after 2.6.23	Yes	Completely Fair Scheduler
classic Mac OS pre-9	None	Cooperative scheduler
Mac OS 9	Some	Preemptive scheduler for MP tasks, and cooperative for processes and threads
OS X/macOS	Yes	Multilevel feedback queue
NetBSD	Yes	Multilevel feedback queue
Solaris	Yes	Multilevel feedback queue
Windows 3.1x	None	Cooperative scheduler
Windows 95, 98, Me	Half	Preemptive scheduler for 32-bit processes, and cooperative for 16-bit processes
Windows NT (including 2000, XP, Vista, 7, and Server)	Yes	Multilevel feedback queue

(Source: `https://en.wikipedia.org/wiki/Scheduling_(computing)`)

The preemptive column indicates whether the scheduler is preemptive or not, with the next column providing further details. As one can see, preemptive schedulers are very common, and used by all modern desktop operating systems.

Tracing the demo application

In the demonstration code of `Chapter 1`, *Revisiting Multithreading*, we looked at a simple `c++11` application which used four threads to perform some processing. In this section, we will look at the same application, but from a hardware and OS perspective.

When we look at the start of the code in the `main` function, we see that we create a data structure containing a single (integer) value:

```
int main() {
    values.push_back(42);
```

After the OS creates a new task and associated stack structure, an instance of a vector data structure (customized for integer types) is allocated on the stack. The size of this was specified in the binary file's global data section (BSS for ELF).

When the application's execution is started using its entry function (`main()` by default), the data structure is modified to contain the new integer value.

Next, we create four threads, providing each with some initial data:

```
    thread tr1(threadFnc, 1);
    thread tr2(threadFnc, 2);
    thread tr3(threadFnc, 3);
    thread tr4(threadFnc, 4);
```

For the OS, this means creating new data structures, and allocating a stack for each new thread. For the hardware, this initially does not change anything if no hardware-based task switching is used.

At this point, the OS's scheduler and the CPU can combine to execute this set of tasks (threads) as efficiently and quickly as possible, employing features of the hardware including SMP, SMT, and so on.

After this, the main thread waits until the other threads stop executing:

```
    tr1.join();
    tr2.join();
    tr3.join();
    tr4.join();
```

These are blocking calls, which mark the main thread as being blocked until these four threads (tasks) finish executing. At this point, the OS's scheduler will resume execution of the main thread.

In each newly created thread, we first output a string on the standard output, making sure that we lock the mutex to ensure synchronous access:

```
void threadFnc(int tid) {
    cout_mtx.lock();
    cout << "Starting thread " << tid << ".\n";
    cout_mtx.unlock();
```

A mutex, in essence, is a singular value being stored on the stack of heap, which then is accessed using an atomic operation. This means that some form of hardware support is required. Using this, a task can check whether it is allowed to proceed yet, or has to wait and try again.

In this last particular piece of code, this mutex lock allows us to output on the standard C++ output stream without other threads interfering.

After this, we copy the initial value in the vector to a local variable, again ensuring that it's done synchronously:

```
    values_mtx.lock();
    int val = values[0];
    values_mtx.unlock();
```

The same thing happens here, except now the mutex lock allows us to read the first value in the vector without risking another thread accessing or even changing it while we use it.

This is followed by the generating of a random number as follows:

```
    int rval = randGen(0, 10);
    val += rval;
```

This uses the `randGen()` method, which is as follows:

```
int randGen(const int& min, const int& max) {
    static thread_local mt19937 generator(hash<thread::id>()
(this_thread::get_id()));
    uniform_int_distribution<int> distribution(min, max);
    return distribution(generator);
}
```

This method is interesting due to its use of a thread-local variable. Thread-local storage is a section of a thread's memory which is specific to it, and used for global variables, which, nevertheless, have to remain limited to that specific thread.

This is very useful for a static variable like the one used here. That the `generator` instance is static is because we do not want to reinitialize it every single time we use this method, yet we do not want to share this instance across all threads. By using a thread-local, static instance, we can accomplish both goals. A static instance is created and used, but separately for each thread.

The `Thread` function then ends with the same series of mutexes being locked, and the new value being copied to the array.

```
    cout_mtx.lock();
    cout << "Thread " << tid << " adding " << rval << ". New value: " <<
val << ".\n";
    cout_mtx.unlock();

    values_mtx.lock();
    values.push_back(val);
    values_mtx.unlock();
}
```

Here we see the same synchronous access to the standard output stream, followed by synchronous access to the values data structure.

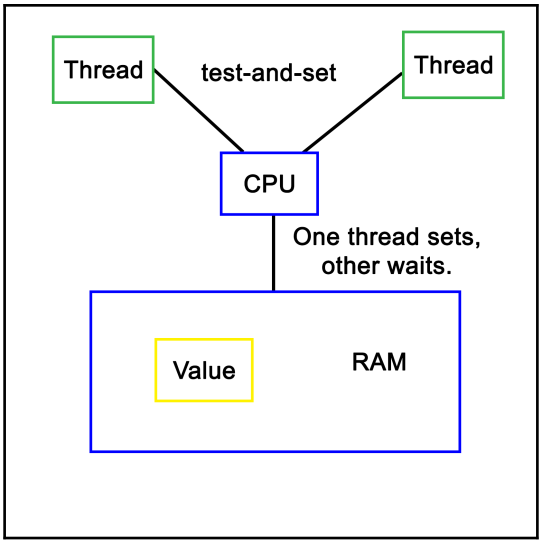
Mutual exclusion implementations

Mutual exclusion is the principle which underlies thread-safe access of data within a multithreaded application. One can implement this both in hardware and software. The **mutual exclusion** (**mutex**) is the most elementary form of this functionality in most implementations.

Hardware

The simplest hardware-based implementation on a uniprocessor (single processor core), non-SMT system is to disable interrupts, and thus, prevent the task from being changed. More commonly, a so-called busy-wait principle is employed. This is the basic principle behind a mutex--due to how the processor fetches data, only one task can obtain and read/write an atomic value in the shared memory, meaning, a variable sized the same (or smaller) as the CPU's registers. This is further detailed in `Chapter 8`, *Atomic Operations - Working with the Hardware*.

When our code tries to lock a mutex, what this does is read the value of such an atomic section of memory, and try to set it to its locked value. Since this is a single operation, only one task can change the value at any given time. Other tasks will have to wait until they can gain access in this busy-wait cycle, as shown in this diagram:



Software

Software-defined mutual exclusion implementations are all based on busy-waiting. An example is **Dekker's** algorithm, which defines a system in which two processes can synchronize, employing busy-wait to wait for the other process to leave the critical section.

The pseudocode for this algorithm is as follows:

```
    variables
        wants_to_enter : array of 2 booleans
        turn : integer

    wants_to_enter[0] ← false
    wants_to_enter[1] ← false
    turn ← 0 // or 1

p0:
    wants_to_enter[0] ← true
    while wants_to_enter[1] {
        if turn ≠ 0 {
            wants_to_enter[0] ← false
            while turn ≠ 0 {
                // busy wait
            }
            wants_to_enter[0] ← true
        }
    }
    // critical section
    ...
    turn ← 1
    wants_to_enter[0] ← false
    // remainder section

p1:
    wants_to_enter[1] ← true
    while wants_to_enter[0] {
        if turn ≠ 1 {
            wants_to_enter[1] ← false
            while turn ≠ 1 {
                // busy wait
            }
            wants_to_enter[1] ← true
        }
    }
    // critical section
    ...
    turn ← 0
    wants_to_enter[1] ← false
    // remainder section
```

(Referenced from: `https://en.wikipedia.org/wiki/Dekker's_algorithm`)

In this preceding algorithm, processes indicate the intent to enter a critical section, checking whether it's their turn (using the process ID), then setting their intent to enter the section to false after they have entered it. Only once a process has set its intent to enter to true again will it enter the critical section again. If it wishes to enter, but `turn` does not match its process ID, it'll busy-wait until the condition becomes true.

A major disadvantage of software-based mutual exclusion algorithms is that they only work if **out-of-order** (**OoO**) execution of code is disabled. OoO means that the hardware actively reorders incoming instructions in order to optimize their execution, thus changing their order. Since these algorithms require that various steps are executed in order, they no longer work on OoO processors.

Summary

In this chapter, we saw how processes and threads are implemented both in operating systems and in hardware. We also looked at various configurations of processor hardware and elements of operating systems involved in scheduling to see how they provide various types of task processing.

Finally, we took the multithreaded program example of the previous chapter, and ran through it again, this time considering what happens in the OS and processor while it is being executed.

In the next chapter, we will take a look at the various multithreading APIs being offered via OS and library-based implementations, along with examples comparing these APIs.

3 C++ Multithreading APIs

While C++ has a native multithreading implementation in the **Standard Template Library** (**STL**), OS-level and framework-based multithreading APIs are still very common. Examples of these APIs include Windows and **POSIX** (**Portable Operating System Interface**) threads, and those provided by the `Qt`, `Boost`, and `POCO` libraries.

This chapter takes a detailed look at the features provided by each of these APIs, as well as the similarities and differences between each of them. Finally, we'll look at common usage scenarios using example code.

Topics covered by this chapter include the following:

- A comparison of the available multithreading APIs
- Examples of the usage of each of these APIs

API overview

Before the **C++ 2011** (**C++11**) standard, many different threading implementations were developed, many of which are limited to a specific software platform. Some of these are still relevant today, such as Windows threads. Others have been superseded by standards, of which **POSIX Threads** (**Pthreads**) has become the de facto standard on UNIX-like OSes. This includes Linux-based and BSD-based OS, as well as OS X (macOS) and Solaris.

Many libraries were developed to make cross-platform development easier. Although Pthreads helps to make UNIX-like OS more or less compatible one of the prerequisites to make software portable across all major operating systems, a generic threading API is needed. This is why libraries such as Boost, POCO, and Qt were created. Applications can use these and rely on the library to handle any differences between platforms.

POSIX threads

Pthreads were first defined in the `POSIX.1c` standard (*Threads extensions*, IEEE Std 1003.1c-1995) from 1995 as an extension to the POSIX standard. At the time, UNIX had been chosen as a manufacturer-neutral interface, with POSIX unifying the various APIs among them.

Despite this standardization effort, differences still exist in Pthread implementations between OS's which implement it (for example, between Linux and OS X), courtesy of non-portable extensions (marked with `_np` in the method name).

For the `pthread_setname_np` method, the Linux implementation takes two parameters, allowing one to set the name of a thread other than the current thread. On OS X (since 10.6), this method only takes one parameter, allowing one to set the name of the current thread only. If portability is a concern, one has to be mindful of such differences.

After 1997, the POSIX standard revisions were managed by the Austin Joint Working Group. These revisions merge the threads extension into the main standard. The current revision is 7, also known as POSIX.1-2008 and IEEE Std 1003.1, 2013 edition--with a free copy of the standard available online.

OS's can be certified to conform to the POSIX standard. Currently, these are as mentioned in this table:

Name	**Developer**	**Since version**	**Architecture(s) (current)**	**Notes**
AIX	IBM	5L	POWER	Server OS
HP-UX	Hewlett-Packard	11i v3	PA-RISC, IA-64 (Itanium)	Server OS
IRIX	Silicon Graphics (SGI)	6	MIPS	Discontinued
Inspur K-UX	Inspur	2	X86_64,	Linux based
Integrity	Green Hills Software	5	ARM, XScale, Blackfin, Freescale Coldfire, MIPS, PowerPC, x86.	Real-time OS
OS X/MacOS	Apple	10.5 (Leopard)	X86_64	Desktop OS

QNX Neutrino	BlackBerry	1	Intel 8088, x86, MIPS, PowerPC, SH-4, ARM, StrongARM, XScale	Real-time, embedded OS
Solaris	Sun/Oracle	2.5	SPARC, IA-32 (<11), x86_64, PowerPC (2.5.1)	Server OS
Tru64	DEC, HP, IBM, Compaq	5.1B-4	Alpha	Discontinued
UnixWare	Novell, SCO, Xinuos	7.1.3	x86	Server OS

Other operating systems are mostly compliant. The following are examples of the same:

Name	**Platform**	**Notes**
Android	ARM, x86, MIPS	Linux based. Bionic C-library.
BeOS (Haiku)	IA-32, ARM, x64_64	Limited to GCC 2.x for x86.
Darwin	PowerPC, x86, ARM	Uses the open source components on which macOS is based.
FreeBSD	IA-32, x86_64, sparc64, PowerPC, ARM, MIPS, and so on	Essentially POSIX compliant. One can rely on documented POSIX behavior. More strict on compliance than Linux, in general.
Linux	Alpha, ARC, ARM, AVR32, Blackfin, H8/300, Itanium, m68k, Microblaze, MIPS, Nios II, OpenRISC, PA-RISC, PowerPC, s390, S+core, SuperH, SPARC, x86, Xtensa, and so on	Some Linux distributions (see previous table) are certified as being POSIX compliant. This does not imply that every Linux distribution is POSIX compliant. Some tools and libraries may differ from the standard. For Pthreads, this may mean that the behavior is sometimes different between Linux distributions (different scheduler, and so on) as well as compared to other OS's implementing Pthreads.
MINIX 3	IA-32, ARM	Conforms to POSIX specification standard 3 (SUSv3, 2004).

NetBSD	Alpha, ARM, PA-RISC, 68k, MIPS, PowerPC, SH3, SPARC, RISC-V, VAX, x86, and so on	Almost fully compatible with POSX.1 (1990), and mostly compliant with POSIX.2 (1992).
Nuclear RTOS	ARM, MIPS, PowerPC, Nios II, MicroBlaze, SuperH, and so on	Proprietary RTOS from Mentor Graphics aimed at embedded applications.
NuttX	ARM, AVR, AVR32, HCS12, SuperH, Z80, and so on	Light-weight RTOS, scalable from 8 to 32-bit systems with strong focus on POSIX compliance.
OpenBSD	Alpha, x86_64, ARM, PA-RISC, IA-32, MIPS, PowerPC, SPARC, and so on	Forked from NetBSD in 1995. Similar POSIX support.
OpenSolaris/illumos	IA-32, x86_64, SPARC, ARM	Compliant with the commercial Solaris releases being certified compatible.
VxWorks	ARM, SH-4, x86, x86_64, MIPS, PowerPC	POSIX compliant, with certification for user-mode execution environment.

From this it should be obvious that it's not a clear matter of following the POSIX specification, and being able to count on one's code compiling on each of these platforms. Each platform will also have its own set of extensions to the standard for features which were omitted in the standard, but are still desirable. Pthreads are, however, widely used by Linux, BSD, and similar software.

Windows support

It's also possible to use the POSIX APIs in a limited fashion using, for example, the following:

Name	**Compliance**
Cygwin	Mostly complete. Provides a full runtime environment for a POSIX application, which can be distributed as a normal Windows application.
MinGW	With MinGW-w64 (a redevelopment of MinGW), Pthreads support is fairly complete, though some functionality may be absent.

Windows Subsystem for Linux	WSL is a Windows 10 feature, which allows a Ubuntu Linux 14.04 (64-bit) image's tools and utilities to run natively on top of it though not those using GUI features or missing kernel features. Otherwise, it offers similar compliance as Linux. This feature currently requires that one runs the Windows 10 Anniversary Update and install WSL by hand using instructions provided by Microsoft.

POSIX on Windows is generally not recommended. Unless there are good reasons to use POSIX (large existing code base, for example), it's far easier to use one of the cross-platform APIs (covered later in this chapter), which smooth away any platform issues.

In the following sections, we'll look at the features offered by the Pthreads API.

PThreads thread management

These are all the functions which start with either `pthread_` or `pthread_attr_`. These functions all apply to threads themselves and their attribute objects.

The basic use of threads with Pthreads looks like the following:

```
#include <pthread.h>
#include <stdlib.h>
#define NUM_THREADS     5
```

The main Pthreads header is `pthread.h`. This gives access to everything but semaphores (covered later in this section). We also define a constant for the number of threads we wish to start here:

```
void* worker(void* arg) {
    int value = *((int*) arg);
    // More business logic.
    return 0;
}
```

We define a simple `Worker` function, which we'll pass to the new thread in a moment. For demonstration and debugging purposes one could first add a simple `cout` or `printf`-based bit of business logic to print out the value sent to the new thread.

Next, we define the `main` function as follows:

```
int main(int argc, char** argv) {
    pthread_t threads[NUM_THREADS];
    int thread_args[NUM_THREADS];
    int result_code;
    for (unsigned int i = 0; i < NUM_THREADS; ++i) {
        thread_args[i] = i;
        result_code = pthread_create(&threads[i], 0, worker, (void*)
&thread_args[i]);
    }
```

We create all of the threads in a loop in the preceding function. Each thread instance gets a thread ID assigned (first argument) when created in addition to a result code (zero on success) returned by the `pthread_create()` function. The thread ID is the handle to reference the thread in future calls.

The second argument to the function is a `pthread_attr_t` structure instance, or 0 if none. This allows for configuration characteristics of the new thread, such as the initial stack size. When zero is passed, default parameters are used, which differ per platform and configuration.

The third parameter is a pointer to the function which the new thread will start with. This function pointer is defined as a function which returns a pointer to void data (that is, custom data), and accepts a pointer to void data. Here, the data being passed to the new thread as an argument is the thread ID:

```
    for (int i = 0; i < NUM_THREADS; ++i) {
        result_code = pthread_join(threads[i], 0);
    }

    exit(0);
}
```

Next, we wait for each worker thread to finish using the `pthread_join()` function. This function takes two parameters, the ID of the thread to wait for, and a buffer for the return value of the `Worker` function (or zero).

Other functions to manage threads are as follows:

- `void pthread_exit(void *value_ptr)`:
  This function terminates the thread calling it, making the provided argument's value available to any thread calling `pthread_join()` on it.

- `int pthread_cancel(pthread_t` thread):
  This function requests that the specified thread will be canceled. Depending on the state of the target thread, this will invoke its cancellation handlers.

Beyond this, there are the `pthread_attr_*` functions to manipulate and obtain information about a `pthread_attr_t` structure.

Mutexes

These are functions prefixed with either `pthread_mutex_` or `pthread_mutexattr_`. They apply to mutexes and their attribute objects.

Mutexes in Pthreads can be initialized, destroyed, locked, and unlocked. They can also have their behavior customized using a `pthread_mutexattr_t` structure, which has its corresponding `pthread_mutexattr_*` functions for initializing and destroying an attribute on it.

A basic use of a Pthread mutex using static initialization looks as follows:

```
static pthread_mutex_t func_mutex = PTHREAD_MUTEX_INITIALIZER;

void func() {
    pthread_mutex_lock(&func_mutex);

    // Do something that's not thread-safe.

    pthread_mutex_unlock(&func_mutex);
}
```

In this last bit of code, we use the `PTHREAD_MUTEX_INITIALIZER` macro, which initializes the mutex for us without having to type out the code for it every time. In comparison to other APIs, one has to manually initialize and destroy mutexes, though the use of macros helps somewhat.

After this, we lock and unlock the mutex. There's also the `pthread_mutex_trylock()` function, which is like the regular lock version, but which will return immediately if the referenced mutex is already locked instead of waiting for it to be unlocked.

In this example, the mutex is not explicitly destroyed. This is, however, a part of normal memory management in a Pthreads-based application.

Condition variables

These are functions which are prefixed with either `pthread_cond_` or `pthread_condattr_`. They apply to condition variables and their attribute objects.

Condition variables in Pthreads follow the same pattern of having an initialization and a `destroy` function in addition to having the same for managing a `pthread_condattr_t` attribution structure.

This example covers basic usage of Pthreads condition variables:

```
#include <pthread.h>
#include <stdlib.h>
#include <unistd.h>

   #define COUNT_TRIGGER 10
   #define COUNT_LIMIT 12

   int count = 0;
   int thread_ids[3] = {0,1,2};
   pthread_mutex_t count_mutex;
   pthread_cond_t count_cv;
```

In the preceding code, we get the standard headers, and define a count trigger and limit, whose purpose will become clear in a moment. We also define a few global variables: a count variable, the IDs for the threads we wish to create, as well as a mutex and condition variable:

```
void* add_count(void* t)  {
    int tid = (long) t;
    for (int i = 0; i < COUNT_TRIGGER; ++i) {
        pthread_mutex_lock(&count_mutex);
        count++;
        if (count == COUNT_LIMIT) {
            pthread_cond_signal(&count_cv);
        }

        pthread_mutex_unlock(&count_mutex);
        sleep(1);
    }

    pthread_exit(0);
}
```

This preceding function, essentially, just adds to the global counter variable after obtaining exclusive access to it with the `count_mutex`. It also checks whether the count trigger value has been reached. If it has, it will signal the condition variable.

To give the second thread, which also runs this function, a chance to get the mutex, we sleep for 1 second in each cycle of the loop:

```
void* watch_count(void* t) {
    int tid = (int) t;

    pthread_mutex_lock(&count_mutex);
    if (count < COUNT_LIMIT) {
        pthread_cond_wait(&count_cv, &count_mutex);
    }

    pthread_mutex_unlock(&count_mutex);
    pthread_exit(0);
}
```

In this second function, we lock the global mutex before checking whether we have reached the count limit yet. This is our insurance in case the thread running this function does not get called before the count reaches the limit.

Otherwise, we wait on the condition variable providing the condition variable and locked mutex. Once signaled, we unlock the global mutex, and exit the thread.

A point to note here is that this example does not account for spurious wake-ups. Pthreads condition variables are susceptible to such wake-ups which necessitate one to use a loop and check whether some kind of condition has been met:

```
int main (int argc, char* argv[]) {
    int tid1 = 1, tid2 = 2, tid3 = 3;
    pthread_t threads[3];
    pthread_attr_t attr;

    pthread_mutex_init(&count_mutex, 0);
    pthread_cond_init (&count_cv, 0);

    pthread_attr_init(&attr);
    pthread_attr_setdetachstate(&attr, PTHREAD_CREATE_JOINABLE);
    pthread_create(&threads[0], &attr, watch_count, (void *) tid1);
    pthread_create(&threads[1], &attr, add_count, (void *) tid2);
    pthread_create(&threads[2], &attr, add_count, (void *) tid3);

    for (int i = 0; i < 3; ++i) {
        pthread_join(threads[i], 0);
    }
```

```
    pthread_attr_destroy(&attr);
    pthread_mutex_destroy(&count_mutex);
    pthread_cond_destroy(&count_cv);
    return 0;
}
```

Finally, in the `main` function, we create the three threads, with two running the function which adds to the counter, and the third running the function which waits to have its condition variable signaled.

In this method, we also initialize the global mutex and condition variable. The threads we create further have the "joinable" attribute explicitly set.

Finally, we wait for each thread to finish, after which we clean up, destroying the attribute structure instance, mutex, and condition variable before exiting.

Using the `pthread_cond_broadcast()` function, it's further possible to signal all threads which are waiting for a condition variable instead of merely the first one in the queue. This enables one to use condition variables more elegantly with some applications, such as where one has a lot of worker threads waiting for new dataset to arrive without having to notify every thread individually.

Synchronization

Functions which implement synchronization are prefixed with `pthread_rwlock_` or `pthread_barrier_`. These implement read/write locks and synchronization barriers.

A **read/write lock** (**rwlock**) is very similar to a mutex, except that it has the additional feature of allowing infinite threads to read simultaneously, while only restricting write access to a singular thread.

Using `rwlock` is very similar to using a mutex:

```
#include <pthread.h>
int pthread_rwlock_init(pthread_rwlock_t* rwlock, const
pthread_rwlockattr_t* attr);
pthread_rwlock_t rwlock = PTHREAD_RWLOCK_INITIALIZER;
```

In the last code, we include the same general header, and either use the initialization function, or the generic macro. The interesting part is when we lock `rwlock`, which can be done for just read-only access:

```
int pthread_rwlock_rdlock(pthread_rwlock_t* rwlock);
int pthread_rwlock_tryrdlock(pthread_rwlock_t* rwlock);
```

Here, the second variation returns immediately if the lock has been locked already. One can also lock it for write access as follows:

```
int pthread_rwlock_wrlock(pthread_rwlock_t* rwlock);
int pthread_rwlock_trywrlock(pthread_rwlock_t * rwlock);
```

These functions work basically the same, except that only one writer is allowed at any given time, whereas multiple readers can obtain a read-only lock.

Barriers are another concept with Pthreads. These are synchronization objects which act like a barrier for a number of threads. All of these have to reach the barrier before any of them can proceed past it. In the barrier initialization function, the thread count is specified. Only once all of these threads have called the `barrier` object using the `pthread_barrier_wait()` function will they continue executing.

Semaphores

Semaphores were, as mentioned earlier, not part of the original Pthreads extension to the POSIX specification. They are declared in the `semaphore.h` header for this reason.

In essence, semaphores are simple integers, generally used as a resource count. To make them thread-safe, atomic operations (check and lock) are used. POSIX semaphores support the initializing, destroying, incrementing and decrementing of a semaphore as well as waiting for the semaphore to reach a non-zero value.

Thread local storage (TLC)

With Pthreads, TLS is accomplished using keys and methods to set thread-specific data:

```
pthread_key_t global_var_key;
void* worker(void* arg) {
    int *p = new int;
    *p = 1;
    pthread_setspecific(global_var_key, p);
    int* global_spec_var = (int*) pthread_getspecific(global_var_key);
    *global_spec_var += 1;
```

```
        pthread_setspecific(global_var_key, 0);
        delete p;
        pthread_exit(0);
    }
```

In the worker thread, we allocate a new integer on the heap, and set the global key to its own value. After increasing the global variable by 1, its value will be 2, regardless of what the other threads do. We can set the global variable to 0 once we're done with it for this thread, and delete the allocated value:

```
    int main(void) {
        pthread_t threads[5];
        pthread_key_create(&global_var_key, 0);
        for (int i = 0; i < 5; ++i)
            pthread_create(&threads[i],0,worker,0);
        for (int i = 0; i < 5; ++i) {
            pthread_join(threads[i], 0);
        }
        return 0;
    }
```

A global key is set and used to reference the TLS variable, yet each of the threads we create can set its own value for this key.

While a thread can create its own keys, this method of handling TLS is fairly involved compared to the other APIs we're looking at in this chapter.

Windows threads

Relative to Pthreads, Windows threads are limited to Windows operating systems and similar (for example ReactOS, and other OS's using Wine). This provides a fairly consistent implementation, easily defined by the Windows version that the support corresponds to.

Prior to Windows Vista, threading support missed features such as condition variables, while having features not found in Pthreads. Depending on one's perspective, having to use the countless "type def" types defined by the Windows headers can be a bother as well.

Thread management

A basic example of using Windows threads, as adapted from the official MSDN documentation sample code, looks like this:

```
#include <windows.h>
#include <tchar.h>
#include <strsafe.h>

#define MAX_THREADS 3
#define BUF_SIZE 255
```

After including a series of Windows-specific headers for the thread functions, character strings, and more, we define the number of threads we wish to create as well as the size of the message buffer in the `Worker` function.

We also define a struct type (passed by `void pointer: LPVOID`) to contain the sample data we pass to each worker thread:

```
typedef struct MyData {
 int val1;
 int val2;
} MYDATA, *PMYDATA;

DWORD WINAPI worker(LPVOID lpParam) {
    HANDLE hStdout = GetStdHandle(STD_OUTPUT_HANDLE);
    if (hStdout == INVALID_HANDLE_VALUE) {
        return 1;
    }

    PMYDATA pDataArray =  (PMYDATA) lpParam;

    TCHAR msgBuf[BUF_SIZE];
    size_t cchStringSize;
    DWORD dwChars;
    StringCchPrintf(msgBuf, BUF_SIZE, TEXT("Parameters = %d, %dn"),
    pDataArray->val1, pDataArray->val2);
    StringCchLength(msgBuf, BUF_SIZE, &cchStringSize);
    WriteConsole(hStdout, msgBuf, (DWORD) cchStringSize, &dwChars, NULL);

    return 0;
}
```

In the `Worker` function, we cast the provided parameter to our custom struct type before using it to print its values to a string, which we output on the console.

We also validate that there's an active standard output (console or similar). The functions used to print the string are all thread safe.

```
void errorHandler(LPTSTR lpszFunction) {
    LPVOID lpMsgBuf;
    LPVOID lpDisplayBuf;
    DWORD dw = GetLastError();

    FormatMessage(
        FORMAT_MESSAGE_ALLOCATE_BUFFER |
        FORMAT_MESSAGE_FROM_SYSTEM |
        FORMAT_MESSAGE_IGNORE_INSERTS,
        NULL,
        dw,
        MAKELANGID(LANG_NEUTRAL, SUBLANG_DEFAULT),
        (LPTSTR) &lpMsgBuf,
        0, NULL);

        lpDisplayBuf = (LPVOID) LocalAlloc(LMEM_ZEROINIT,
        (lstrlen((LPCTSTR) lpMsgBuf) + lstrlen((LPCTSTR) lpszFunction) +
40) * sizeof(TCHAR));
        StringCchPrintf((LPTSTR)lpDisplayBuf,
        LocalSize(lpDisplayBuf) / sizeof(TCHAR),
        TEXT("%s failed with error %d: %s"),
        lpszFunction, dw, lpMsgBuf);
        MessageBox(NULL, (LPCTSTR) lpDisplayBuf, TEXT("Error"), MB_OK);

        LocalFree(lpMsgBuf);
        LocalFree(lpDisplayBuf);
}
```

Here, an error handler function is defined, which obtains the system error message for the last error code. After obtaining the code for the last error, the error message to be output is formatted, and shown in a message box. Finally, the allocated memory buffers are freed.

Finally, the `main` function is as follows:

```
int _tmain() {
         PMYDATA pDataArray[MAX_THREADS];
         DWORD dwThreadIdArray[MAX_THREADS];
         HANDLE hThreadArray[MAX_THREADS];
         for (int i = 0; i < MAX_THREADS; ++i) {
               pDataArray[i] = (PMYDATA) HeapAlloc(GetProcessHeap(),
                           HEAP_ZERO_MEMORY, sizeof(MYDATA));
if (pDataArray[i] == 0) {
                           ExitProcess(2);
             }
             pDataArray[i]->val1 = i;
```

```
                pDataArray[i]->val2 = i+100;
                hThreadArray[i] = CreateThread(
                     NULL,          // default security attributes
                     0,             // use default stack size
                     worker,        // thread function name
                     pDataArray[i], // argument to thread function
                     0,             // use default creation flags
                     &dwThreadIdArray[i]);// returns the thread identifier
                if (hThreadArray[i] == 0) {
                            errorHandler(TEXT("CreateThread"));
                            ExitProcess(3);
                }
      }
            WaitForMultipleObjects(MAX_THREADS, hThreadArray, TRUE, INFINITE);
            for (int i = 0; i < MAX_THREADS; ++i) {
                  CloseHandle(hThreadArray[i]);
                  if (pDataArray[i] != 0) {
                              HeapFree(GetProcessHeap(), 0, pDataArray[i]);
                  }
            }
            return 0;
   }
```

In the `main` function, we create our threads in a loop, allocate memory for thread data, and generate unique data for each thread before starting the thread. Each thread instance is passed its own unique parameters.

After this, we wait for the threads to finish and rejoin. This is essentially the same as calling the `join` function on singular threads with Pthreads--only here, a single function call suffices.

Finally, each thread handle is closed, and we clean up the memory we allocated earlier.

Advanced management

Advanced thread management with Windows threads includes jobs, fibers, and thread pools. Jobs essentially allow one to link multiple threads together into a singular unit, enabling one to change properties and the status of all these threads in one go.

Fibers are light-weight threads, which run within the context of the thread which creates them. The creating thread is expected to schedule these fibers itself. Fibers also have **Fiber Local Storage** (**FLS**) akin to TLS.

Finally, the Windows threads API provides a Thread Pool API, allowing one to easily use such a thread pool in one's application. Each process is also provided with a default thread pool.

Synchronization

With Windows threads, mutual exclusion and synchronization can be accomplished using critical sections, mutexes, semaphores, **slim reader/writer** (**SRW**) locks, barriers, and variations.

Synchronization objects include the following:

Name	**Description**
Event	Allows for signaling of events between threads and processes using named objects.
Mutex	Used for inter-thread and process synchronization to coordinate access to shared resources.
Semaphore	Standard semaphore counter object, used for inter-thread and process synchronization.
Waitable timer	Timer object usable by multiple processes with multiple usage modes.
Critical section	Critical sections are essentially mutexes which are limited to a single process, which makes them faster than using a mutex due to lack of kernel space calls.
Slim reader/writer lock	SRWs are akin to read/write locks in Pthreads, allowing multiple readers or a single writer thread to access a shared resource.
Interlocked variable access	Allows for atomic access to a range of variables which are otherwise not guaranteed to be atomic. This enables threads to share a variable without having to use mutexes.

Condition variables

The implementation of condition variables with Windows threads is fairly straightforward. It uses a critical section (`CRITICAL_SECTION`) and condition variable (`CONDITION_VARIABLE`) along with the condition variable functions to wait for a specific condition variable, or to signal it.

Thread local storage

Thread local storage (**TLS**) with Windows threads is similar to Pthreads in that a central key (TLS index) has to be created first after which individual threads can use that global index to store and retrieve local values.

Like with Pthreads, this involves a similar amount of manual memory management, as the TLS value has to be allocated and deleted by hand.

Boost

Boost threads is a relatively small part of the Boost collection of libraries. It was, however, used as the basis for what became the multithreading implementation in C++11, similar to how other Boost libraries ultimately made it, fully or partially, into new C++ standards. Refer to the C++ threads section in this chapter for details on the multithreading API.

Features missing in the C++11 standard, which are available in Boost threads, include the following:

- Thread groups (like Windows jobs)
- Thread interruption (cancellation)
- Thread join with timeout
- Additional mutual exclusion lock types (improved with C++14)

Unless one absolutely needs such features, or if one cannot use a compiler which supports the C++11 standard (including STL threads), there is little reason to use Boost threads over the C++11 implementation.

Since Boost provides wrappers around native OS features, using native C++ threads would likely reduce overhead depending on the quality of the STL implementation.

Qt

Qt is a relatively high-level framework, which also reflects in its multithreading API. Another defining feature of Qt is that it wraps its own code (QApplication and QMainWindow) along with the use of a meta-compiler (`qmake`) to implement its signal-slot architecture and other defining features of the framework.

As a result, Qt's threading support cannot be added into existing code as-is, but requires one to adapt one's code to fit the framework.

QThread

A `QThread` class in Qt is not a thread, but an extensive wrapper around a thread instance, which adds signal-slot communication, runtime support, and other features. This is reflected in the basic usage of a QThread, as shown in the following code:

```
class Worker : public QObject {
    Q_OBJECT
    public:
        Worker();
        ~Worker();
    public slots:
        void process();
    signals:
        void finished();
        void error(QString err);
    private:
};
```

This preceding code is a basic `Worker` class, which will contain our business logic. It derives from the `QObject` class, which also allows us to use signal-slot and other intrinsic `QObject` features. Signal-slot architecture at its core is simply a way for listeners to register on (connect to) signals declared by QObject-derived classes, allowing for cross-module, cross-thread and asynchronous communication.

It has a single, which can be called to start processing, and two signals--one to signal completion, and one to signal an error.

The implementation would look like the following:

```
Worker::Worker() { }
Worker::~Worker() { }
void Worker::process() {
    qDebug("Hello World!");
    emit finished();
}
```

The constructor could be extended to include parameters. Any heap-allocated variables (using `malloc` or `new`) must be allocated in the `process()` method, and not in the constructor due to the thread context the `Worker` instance will be operating in, as we will see in a moment.

To create a new QThread, we would use the following setup:

```
QThread* thread = new QThread;
Worker* worker = new Worker();
worker->moveToThread(thread);
connect(worker, SIGNAL(error(QString)), this, SLOT(errorString(QString)));
connect(thread, SIGNAL(started()), worker, SLOT(process()));
connect(worker, SIGNAL(finished()), thread, SLOT(quit()));
connect(worker, SIGNAL(finished()), worker, SLOT(deleteLater()));
connect(thread, SIGNAL(finished()), thread, SLOT(deleteLater()));
thread->start();
```

The basic procedure is to create a new QThread instance on the heap (so it won't go out of scope) along with a heap-allocated instance of our `Worker` class. This new worker would then be moved to the new thread instance using its `moveToThread()` method.

Next, one will connect the various signals to relevant slots including our own `finished()` and `error()` signals. The `started()` signal from the thread instance would be connected to the slot on our worker which will start it.

Most importantly, one has to connect some kind of completion signal from the worker to the `quit()` and `deleteLater()` slots on the thread. The `finished()` signal from the thread will then be connected to the `deleteLater()` slot on the worker. This will ensure that both the thread and worker instances are cleaned up when the worker is done.

Thread pools

Qt offers thread pools. These require one to inherit from the `QRunnable` class, and implement the `run()` function. An instance of this custom class is then passed to the `start` method of the thread pool (global default pool, or a new one). The life cycle of this worker is then handled by the thread pool.

Synchronization

Qt offers the following synchronization objects:

- `QMutex`
- `QReadWriteLock`
- `QSemaphore`
- `QWaitCondition` (condition variable)

These should be fairly self-explanatory. Another nice feature of Qt's signal-slot architecture is that these also allow one to communicate asynchronously between threads without having to concern oneself with the low-level implementation details.

QtConcurrent

The QtConcurrent namespace contains high-level API aimed at making writing multithreading applications possible without having to concern oneself with the low-level details.

Functions include concurrent filtering and mapping algorithms as well as a method to allow running a function in a separate thread. All of these return a `QFuture` instance, which contains the result of an asynchronous operation.

Thread local storage

Qt offers TLS through its `QThreadStorage` class. Memory management of pointer type values is handled by it. Generally, one would set some kind of data structure as a TLS value to store more than one value per thread, as described, for example, in the `QThreadStorage` class documentation:

```
QThreadStorage<QCache<QString, SomeClass> > caches;

void cacheObject(const QString &key, SomeClass* object) {
    caches.localData().insert(key, object);
}

void removeFromCache(const QString &key) {
    if (!caches.hasLocalData()) { return; }

    caches.localData().remove(key);
}
```

POCO

The POCO library is a fairly lightweight wrapper around operating system functionality. It does not require a C++11 compatible compiler or any kind of pre-compiling or meta-compiling.

Thread class

The `Thread` class is a simple wrapper around an OS-level thread. It takes `Worker` class instances which inherit from the `Runnable` class. The official documentation provides a basic example of this as follows:

```
#include "Poco/Thread.h"
#include "Poco/Runnable.h"
#include <iostream>

class HelloRunnable: public Poco::Runnable {
    virtual void run() {
        std::cout << "Hello, world!" << std::endl;
    }
};

int main(int argc, char** argv) {
    HelloRunnable runnable;
    Poco::Thread thread;
    thread.start(runnable);
    thread.join();
    return 0;
}
```

This preceding code is a very simple "Hello world" example with a worker which only outputs a string via the standard output. The thread instance is allocated on the stack, and kept within the scope of the entry function waiting for the worker to finish using the `join()` function.

With many of its thread functions, POCO is quite reminiscent of Pthreads, though it does deviate significantly on points such as configuring a thread and other objects. Being a C++ library, it sets properties using class methods rather than filling in a struct and passing it as a parameter.

Thread pool

POCO provides a default thread pool with 16 threads. This number can be changed dynamically. Like with regular threads, a thread pool requires one to pass a `Worker` class instance which inherits from the `Runnable` class:

```
#include "Poco/ThreadPool.h"
#include "Poco/Runnable.h"
#include <iostream>
```

```
class HelloRunnable: public Poco::Runnable {
    virtual void run() {
        std::cout << "Hello, world!" << std::endl;
    }
};

int main(int argc, char** argv) {
    HelloRunnable runnable;
    Poco::ThreadPool::defaultPool().start(runnable);
    Poco::ThreadPool::defaultPool().joinAll();
    return 0;
}
```

The worker instance is added to the thread pool, which runs it. The thread pool cleans up threads which have been idle for a certain time when we add another worker instance, change the capacity, or call `joinAll()`. As a result, the single worker thread will join, and with no active threads left, the application exits.

Thread local storage (TLS)

With POCO, TLS is implemented as a class template, allowing one to use it with almost any type.

As detailed by the official documentation:

```
#include "Poco/Thread.h"
#include "Poco/Runnable.h"
#include "Poco/ThreadLocal.h"
#include <iostream>

class Counter: public Poco::Runnable {
    void run() {
        static Poco::ThreadLocal<int> tls;
        for (*tls = 0; *tls < 10; ++(*tls)) {
            std::cout << *tls << std::endl;
        }
    }
};

int main(int argc, char** argv) {
    Counter counter1;
    Counter counter2;
    Poco::Thread t1;
    Poco::Thread t2;
    t1.start(counter1);
    t2.start(counter2);
```

```
    t1.join();
    t2.join();
    return 0;
}
```

In this preceding worker example, we create a static TLS variable using the `ThreadLocal` class template, and define it to contain an integer.

Because we define it as static, it will only be created once per thread. In order to use our TLS variable, we can use either the arrow (`->`) or asterisk (`*`) operator to access its value. In this example, we increase the TLS value once per cycle of the `for` loop until the limit has been reached.

This example demonstrates that both threads will generate their own series of 10 integers, counting through the same numbers without affecting each other.

Synchronization

The synchronization primitives offered by POCO are listed as follows:

- Mutex
- FastMutex
- Event
- Condition
- Semaphore
- RWLock

Noticeable here is the `FastMutex` class. This is generally a non-recursive mutex type, except on Windows, where it is recursive. This means one should generally assume either type to be recursive in the sense that the same mutex can be locked multiple times by the same thread.

One can also use mutexes with the `ScopedLock` class, which ensures that a mutex which it encapsulates is released at the end of the current scope.

Events are akin to Windows events, except that they are limited to a single process. They form the basis of condition variables in POCO.

POCO condition variables function much in the same way as they do with Pthreads and others, except that they are not subject to spurious wake-ups. Normally condition variables are subject to these random wake-ups for optimization reasons. By not having to deal with explicitly having to check whether its condition was met or not upon a condition variable wait returning less burden is placed on the developer.

C++ threads

The native multithreading support in C++ is covered extensively in `Chapter 5`, *Native C++ Threads and Primitives*.

As mentioned earlier in the Boost section of this chapter, the C++ multithreading support is heavily based on the Boost threads API, using virtually the same headers and names. The API itself is again reminiscent of Pthreads, though with significant differences when it comes to, for example, condition variables.

Upcoming chapters will use the C++ threading support exclusively for examples.

Putting it together

Of the APIs covered in this chapter, only the Qt multithreading API can be considered to be truly high level. Although the other APIs (including C++11) have some higher-level concepts including thread pools and asynchronous runners which do not require one to use threads directly, Qt offers a full-blown signal-slot architecture, which makes inter-thread communication exceptionally easy.

As covered in this chapter, this ease also comes with a cost, namely, that of having to develop one's application to fit the Qt framework. This may not be acceptable depending on the project.

Which of these APIs is the right one depends on one's requirements. It is, however, relatively fair to say that using straight Pthreads, Windows threads, and kin does not make a lot of sense when one can use APIs such as C++11 threads, POCO, and so on, which ease the development process with no significant reduction in performance while also gaining extensive portability across platforms.

All the APIs are at least somewhat comparable at their core in what they offer in features.

Summary

In this chapter, we looked in some detail at a number of the more popular multithreading APIs and frameworks, putting them next to each other to get an idea of their strengths and weaknesses. We went through a number of examples showing how to implement basic functionality using each of these APIs.

In the next chapter, we will look in detail at how to synchronize threads and communicate between them.

4

Thread Synchronization and Communication

While, generally, threads are used to work on a task more or less independently from other threads, there are many occasions where one would want to pass data between threads, or even control other threads, such as from a central task scheduler thread. This chapter looks at how such tasks are accomplished with the C++11 threading API.

Topics covered in this chapter include the following:

- Using mutexes, locks, and similar synchronization structures
- Using condition variables and signals to control threads
- Safely passing and sharing data between threads

Safety first

The central problem with concurrency is that of ensuring safe access to shared resources even when communicating between threads. There is also the issue of threads being able to communicate and synchronize themselves.

What makes multithreaded programming such a challenge is to be able to keep track of each interaction between threads, and to ensure that each and every form of access is secured while not falling into the trap of deadlocks and data races.

In this chapter, we will look at a fairly complex example involving a task scheduler. This is a form of high-concurrency, high-throughput situation where many different requirements come together with many potential traps, as we will see in a moment.

The scheduler

A good example of multithreading with a significant amount of synchronization and communication between threads is the scheduling of tasks. Here, the goal is to accept incoming tasks and assign them to work threads as quickly as possible.

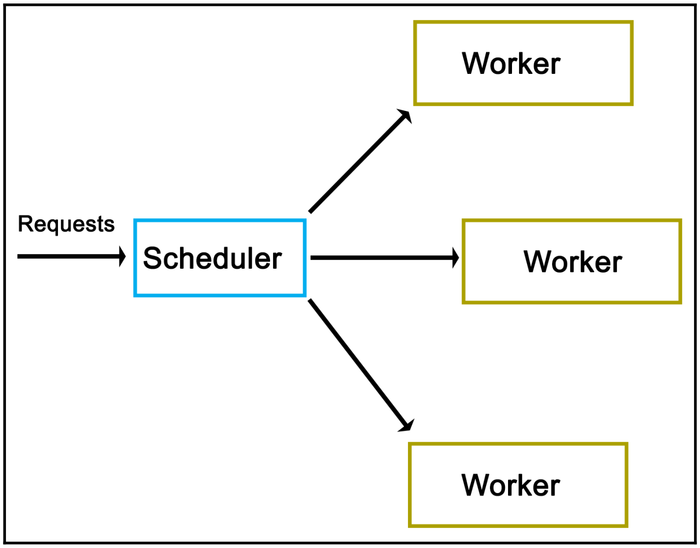
In this scenario, a number of different approaches are possible. Often one has worker threads running in an active loop, constantly polling a central queue for new tasks. Disadvantages of this approach include wasting of processor cycles on the said polling, and the congestion which forms at the synchronization mechanism used, generally a mutex. Furthermore, this active polling approach scales very poorly when the number of worker threads increase.

Ideally, each worker thread would wait idly until it is needed again. To accomplish this, we have to approach the problem from the other side: not from the perspective of the worker threads, but from that of the queue. Much like the scheduler of an operating system, it is the scheduler which is aware of both the tasks which require processing as well as the available worker threads.

In this approach, a central scheduler instance would accept new tasks and actively assign them to worker threads. The said scheduler instance may also manage these worker threads, such as their number and priority, depending on the number of incoming tasks and the type of task or other properties.

High-level view

At its core, our scheduler or dispatcher is quite simple, functioning like a queue with all of the scheduling logic built into it, as seen in the following diagram:



As one can see from the preceding high-level view, there really isn't much to it. However, as we'll see in a moment, the actual implementation does have a number of complications.

Implementation

As is usual, we start off with the `main` function, contained in `main.cpp`:

```
#include "dispatcher.h"
#include "request.h"

#include <iostream>
#include <string>
#include <csignal>
#include <thread>
#include <chrono>

using namespace std;

sig_atomic_t signal_caught = 0;
mutex logMutex;
```

The custom headers we include are those for our dispatcher implementation, as well as the `request` class that we'll use.

Globally, we define an atomic variable to be used with the signal handler, as well as a mutex which will synchronize the output (on the standard output) from our logging method:

```
void sigint_handler(int sig) {
    signal_caught = 1;
}
```

Our signal handler function (for `SIGINT` signals) simply sets the global atomic variable that we defined earlier:

```
void logFnc(string text) {
    logMutex.lock();
    cout << text << "\n";
    logMutex.unlock();
}
```

In our logging function, we use the global mutex to ensure that writing to the standard output is synchronized:

```
int main() {
    signal(SIGINT, &sigint_handler);
    Dispatcher::init(10);
```

In the `main` function, we install the signal handler for `SIGINT` to allow us to interrupt the execution of the application. We also call the static `init()` function on the `Dispatcher` class to initialize it:

```
    cout << "Initialised.\n";
        int cycles = 0;
    Request* rq = 0;
    while (!signal_caught && cycles < 50) {
        rq = new Request();
        rq->setValue(cycles);
        rq->setOutput(&logFnc);
        Dispatcher::addRequest(rq);
        cycles++;
    }
```

Next, we set up the loop in which we will create new requests. In each cycle, we create a new `Request` instance, and use its `setValue()` function to set an integer value (current cycle number). We also set our logging function on the request instance before adding this new request to `Dispatcher` using its static `addRequest()` function.

This loop will continue until the maximum number of cycles have been reached, or `SIGINT` has been signaled using *Ctrl*+*C* or similar:

```
        this_thread::sleep_for(chrono::seconds(5));
        Dispatcher::stop();
    cout << "Clean-up done.\n";
    return 0;
}
```

Finally, we wait for 5 seconds using the thread's `sleep_for()` function, and the `chrono::seconds()` function from the `chrono` STL header.

We also call the `stop()` function on `Dispatcher` before returning.

Request class

A request for `Dispatcher` always derives from the pure virtual `AbstractRequest` class:

```
#pragma once
#ifndef ABSTRACT_REQUEST_H
#define ABSTRACT_REQUEST_H

class AbstractRequest {
    //
    public:
    virtual void setValue(int value) = 0;
    virtual void process() = 0;
    virtual void finish() = 0;
};
#endif
```

This `AbstractRequest` class defines an API with three functions, which a deriving class always has to implement. Out of these, the `process()` and `finish()` functions are the most generic and likely to be used in any practical implementation. The `setValue()` function is specific to this demonstration implementation, and would likely be adapted or extended to fit a real-life scenario.

The advantage of using an abstract class as the basis for a request is that it allows the `Dispatcher` class to handle many different types of requests as long as they all adhere to this same basic API.

Using this abstract interface, we implement a basic `Request` class as follows:

```
#pragma once
#ifndef REQUEST_H
#define REQUEST_H

#include "abstract_request.h"

#include <string>

using namespace std;

typedef void (*logFunction)(string text);

class Request : public AbstractRequest {
    int value;
    logFunction outFnc;
    public:    void setValue(int value) { this->value = value; }
    void setOutput(logFunction fnc) { outFnc = fnc; }
    void process();
    void finish();
};
#endif
```

In its header file, we first define the function pointer's format. After this, we implement the request API, and add the `setOutput()` function to the base API, which accepts a function pointer for logging. Both setter functions merely assign the provided parameter to their respective private class members.

Next, the class function implementations are given as follows:

```
#include "request.h"
void Request::process() {
    outFnc("Starting processing request " + std::to_string(value) + "...");
    //
}
void Request::finish() {
    outFnc("Finished request " + std::to_string(value));
}
```

Both of these implementations are very basic; they merely use the function pointer to output a string indicating the status of the worker thread.

In a practical implementation, one would add the business logic to the `process()` function with the `finish()` function containing any functionality to finish up a request such as writing a map into a string.

Worker class

Next is the `Worker` class. This contains the logic which will be called by `Dispatcher` in order to process a request.

```
#pragma once
#ifndef WORKER_H
#define WORKER_H

#include "abstract_request.h"

#include <condition_variable>
#include <mutex>

using namespace std;

class Worker {
    condition_variable cv;
    mutex mtx;
    unique_lock<mutex> ulock;
    AbstractRequest* request;
    bool running;
    bool ready;
    public:
    Worker() { running = true; ready = false; ulock =
unique_lock<mutex>(mtx); }
    void run();
    void stop() { running = false; }
    void setRequest(AbstractRequest* request) { this->request = request;
ready = true; }
    void getCondition(condition_variable* &cv);
};
#endif
```

Whereas the adding of a request to `Dispatcher` does not require any special logic, the `Worker` class does require the use of condition variables to synchronize itself with the dispatcher. For the C++11 threads API, this requires a condition variable, a mutex, and a unique lock.

The unique lock encapsulates the mutex, and will ultimately be used with the condition variable as we will see in a moment.

Beyond this, we define methods to start and stop the worker, to set a new request for processing, and to obtain access to its internal condition variable.

Moving on, the rest of the implementation is written as follows:

```
#include "worker.h"
#include "dispatcher.h"

#include <chrono>

using namespace std;

void Worker::getCondition(condition_variable* &cv) {
    cv = &(this)->cv;
}

void Worker::run() {
    while (running) {
        if (ready) {
            ready = false;
            request->process();
            request->finish();
        }
        if (Dispatcher::addWorker(this)) {
            // Use the ready loop to deal with spurious wake-ups.
            while (!ready && running) {
                if (cv.wait_for(ulock, chrono::seconds(1)) ==
cv_status::timeout) {
                    // We timed out, but we keep waiting unless
                    // the worker is
                    // stopped by the dispatcher.
                }
            }
        }
    }
}
```

Beyond the `getter` function for the condition variable, we define the `run()` function, which `dispatcher` will run for each worker thread upon starting it.

Its main loop merely checks that the `stop()` function hasn't been called yet, which would have set the running Boolean value to `false`, and ended the work thread. This is used by `Dispatcher` when shutting down, allowing it to terminate the worker threads. Since Boolean values are generally atomic, setting and checking can be done simultaneously without risk or requiring a mutex.

Moving on, the check of the `ready` variable is to ensure that a request is actually waiting when the thread is first run. On the first run of the worker thread, no request will be waiting, and thus, attempting to process one would result in a crash. Upon `Dispatcher` setting a new request, this Boolean variable will be set to `true`.

If a request is waiting, the `ready` variable will be set to `false` again, after which the request instance will have its `process()` and `finish()` functions called. This will run the business logic of the request on the worker thread's thread, and finalize it.

Finally, the worker thread adds itself to the dispatcher using its static `addWorker()` function. This function will return `false` if no new request is available, and cause the worker thread to wait until a new request has become available. Otherwise, the worker thread will continue with the processing of the new request that `Dispatcher` will have set on it.

If asked to wait, we enter a new loop. This loop will ensure that when the condition variable is woken up, it is because we got signaled by `Dispatcher` (`ready` variable set to `true`), and not because of a spurious wake-up.

Last of all, we enter the actual `wait()` function of the condition variable using the unique lock instance we created before along with a timeout. If a timeout occurs, we can either terminate the thread, or keep waiting. Here, we choose to do nothing and just re-enter the waiting loop.

Dispatcher

As the last item, we have the `Dispatcher` class itself:

```
#pragma once
#ifndef DISPATCHER_H
#define DISPATCHER_H

#include "abstract_request.h"
#include "worker.h"

#include <queue>
#include <mutex>
#include <thread>
#include <vector>

using namespace std;

class Dispatcher {
```

```
        static queue<AbstractRequest*> requests;
        static queue<Worker*> workers;
        static mutex requestsMutex;
        static mutex workersMutex;
        static vector<Worker*> allWorkers;
        static vector<thread*> threads;
        public:
        static bool init(int workers);
        static bool stop();
        static void addRequest(AbstractRequest* request);
        static bool addWorker(Worker* worker);
    };
    #endif
```

Most of this will look familiar. As you will have surmised by now, this is a fully static class.

Moving on, its implementation is as follows:

```
    #include "dispatcher.h"

    #include <iostream>
    using namespace std;

    queue<AbstractRequest*> Dispatcher::requests;
    queue<Worker*> Dispatcher::workers;
    mutex Dispatcher::requestsMutex;
    mutex Dispatcher::workersMutex;
    vector<Worker*> Dispatcher::allWorkers;
    vector<thread*> Dispatcher::threads;

    bool Dispatcher::init(int workers) {
        thread* t = 0;
        Worker* w = 0;
        for (int i = 0; i < workers; ++i) {
            w = new Worker;
            allWorkers.push_back(w);
            t = new thread(&Worker::run, w);
            threads.push_back(t);
        }
   return true;
 }
```

After setting up the static class members, the `init()` function is defined. It starts the specified number of worker threads keeping a reference to each worker and thread instance in their respective vector data structures:

```
bool Dispatcher::stop() {
    for (int i = 0; i < allWorkers.size(); ++i) {
        allWorkers[i]->stop();
    }
        cout << "Stopped workers.\n";
        for (int j = 0; j < threads.size(); ++j) {
        threads[j]->join();
                cout << "Joined threads.\n";
    }
}
```

In the `stop()` function, each worker instance has its `stop()` function called. This will cause each worker thread to terminate, as we saw earlier in the `Worker` class description.

Finally, we wait for each thread to join (that is, finish) prior to returning:

```
void Dispatcher::addRequest(AbstractRequest* request) {
    workersMutex.lock();
    if (!workers.empty()) {
        Worker* worker = workers.front();
        worker->setRequest(request);
        condition_variable* cv;
        worker->getCondition(cv);
        cv->notify_one();
        workers.pop();
        workersMutex.unlock();
    }
    else {
        workersMutex.unlock();
        requestsMutex.lock();
        requests.push(request);
        requestsMutex.unlock();
    }
}
```

The `addRequest()` function is where things get interesting. In this function, a new request is added. What happens next depends on whether a worker thread is waiting for a new request or not. If no worker thread is waiting (worker queue is empty), the request is added to the request queue.

The use of mutexes ensures that the access to these queues occurs safely, as the worker threads will simultaneously try to access both queues as well.

An important `gotcha` to note here is the possibility of a deadlock. That is, a situation where two threads will hold the lock on a resource, with the second thread waiting for the first one to release its lock before releasing its own. Every situation where more than one mutex is used in a single scope holds this potential.

In this function, the potential for a deadlock lies in releasing of the lock on the workers mutex, and when the lock on the requests mutex is obtained. In the case that this function holds the workers mutex and tries to obtain the requests lock (when no worker thread is available), there is a chance that another thread holds the requests mutex (looking for new requests to handle) while simultaneously trying to obtain the workers mutex (finding no requests and adding itself to the workers queue).

The solution here is simple: release a mutex before obtaining the next one. In the situation where one feels that more than one mutex lock has to be held, it is paramount to examine and test one's code for potential deadlocks. In this particular situation, the workers mutex lock is explicitly released when it is no longer needed, or before the requests mutex lock is obtained, thus preventing a deadlock.

Another important aspect of this particular section of code is the way it signals a worker thread. As one can see in the first section of the if/else block, when the workers queue is not empty, a worker is fetched from the queue, has the request set on it, and then has its condition variable referenced and signaled, or notified.

Internally, the condition variable uses the mutex we handed it before in the `Worker` class definition to guarantee only atomic access to it. When the `notify_one()` function (generally called `signal()` in other APIs) is called on the condition variable, it will notify the first thread in the queue of threads waiting for the condition variable to return and continue.

In the `Worker` class `run()` function, we would be waiting for this notification event. Upon receiving it, the worker thread would continue and process the new request. The thread reference will then be removed from the queue until it adds itself again once it is done processing the request:

```
bool Dispatcher::addWorker(Worker* worker) {
    bool wait = true;
    requestsMutex.lock();
    if (!requests.empty()) {
        AbstractRequest* request = requests.front();
        worker->setRequest(request);
        requests.pop();
        wait = false;
        requestsMutex.unlock();
    }
```

```
        else {
            requestsMutex.unlock();
            workersMutex.lock();
            workers.push(worker);
            workersMutex.unlock();
        }
            return wait;
    }
```

With this last function, a worker thread will add itself to the queue once it is done processing a request. It is similar to the earlier function in that the incoming worker is first actively matched with any request which may be waiting in the request queue. If none are available, the worker is added to the worker queue.

It is important to note here that we return a Boolean value which indicates whether the calling thread should wait for a new request, or whether it already has received a new request while trying to add itself to the queue.

While this code is less complex than that of the previous function, it still holds the same potential deadlock issue due to the handling of two mutexes within the same scope. Here, too, we first release the mutex we hold before obtaining the next one.

Makefile

The makefile for this `Dispatcher` example is very basic again--it gathers all C++ source files in the current folder, and compiles them into a binary using `g++`:

```
GCC := g++

OUTPUT := dispatcher_demo
SOURCES := $(wildcard *.cpp)
CCFLAGS := -std=c++11 -g3

all: $(OUTPUT)
    $(OUTPUT):
    $(GCC) -o $(OUTPUT) $(CCFLAGS) $(SOURCES)
    clean:
    rm $(OUTPUT)
    .PHONY: all
```

Output

After compiling the application, running it produces the following output for the 50 total requests:

```
$ ./dispatcher_demo.exe
Initialised.
Starting processing request 1...
Starting processing request 2...
Finished request 1
Starting processing request 3...
Finished request 3
Starting processing request 6...
Finished request 6
Starting processing request 8...
Finished request 8
Starting processing request 9...
Finished request 9
Finished request 2
Starting processing request 11...
Finished request 11
Starting processing request 12...
Finished request 12
Starting processing request 13...
Finished request 13
Starting processing request 14...
Finished request 14
Starting processing request 7...
Starting processing request 10...
Starting processing request 15...
Finished request 7
Finished request 15
Finished request 10
Starting processing request 16...
Finished request 16
Starting processing request 17...
Starting processing request 18...
Starting processing request 0...
```

At this point, we can already clearly see that even with each request taking almost no time to process, the requests are clearly being executed in parallel. The first request (request 0) only starts being processed after the sixteenth request, while the second request already finishes after the ninth request, long before this.

The factors which determine which thread, and thus, which request is processed first depends on the OS scheduler and hardware-based scheduling as described in `chapter 2`, *Multithreading Implementation on the Processor and OS*. This clearly shows just how few assumptions can be made about how a multithreaded application will be executed even on a single platform.

```
Starting processing request 5...
Finished request 5
Starting processing request 20...
Finished request 18
Finished request 20
Starting processing request 21...
Starting processing request 4...
Finished request 21
Finished request 4
```

In the preceding code, the fourth and fifth requests also finish in a rather delayed fashion.

```
Starting processing request 23...
Starting processing request 24...
Starting processing request 22...
Finished request 24
Finished request 23
Finished request 22
Starting processing request 26...
Starting processing request 25...
Starting processing request 28...
Finished request 26
Starting processing request 27...
Finished request 28
Finished request 27
Starting processing request 29...
Starting processing request 30...
Finished request 30
Finished request 29
Finished request 17
Finished request 25
Starting processing request 19...
Finished request 0
```

At this point, the first request finally finishes. This may indicate that the initialization time for the first request will always be delayed as compared to the successive requests. Running the application multiple times can confirm this. It's important that if the order of processing is relevant, this randomness does not negatively affect one's application.

```
Starting processing request 33...
Starting processing request 35...
Finished request 33
Finished request 35
Starting processing request 37...
Starting processing request 38...
Finished request 37
Finished request 38
Starting processing request 39...
Starting processing request 40...
Starting processing request 36...
Starting processing request 31...
Finished request 40
Finished request 39
Starting processing request 32...
Starting processing request 41...
Finished request 32
Finished request 41
Starting processing request 42...
Finished request 31
Starting processing request 44...
Finished request 36
Finished request 42
Starting processing request 45...
Finished request 44
Starting processing request 47...
Starting processing request 48...
Finished request 48
Starting processing request 43...
Finished request 47
Finished request 43
Finished request 19
Starting processing request 34...
Finished request 34
Starting processing request 46...
Starting processing request 49...
Finished request 46
Finished request 49
Finished request 45
```

Request 19 also became fairly delayed, showing once again just how unpredictable a multithreaded application can be. If we were processing a large dataset in parallel here, with chunks of data in each request, we might have to pause at some points to account for these delays, as otherwise, our output cache might grow too large.

As doing so would negatively affect an application's performance, one might have to look at low-level optimizations, as well as the scheduling of threads on specific processor cores in order to prevent this from happening.

```
Stopped workers.
Joined threads.
Joined threads.
Joined threads.
Joined threads.
Joined threads.
Joined threads.
Joined threads.
Joined threads.
Joined threads.
Joined threads.
Clean-up done.
```

All 10 worker threads which were launched in the beginning terminate here as we call the `stop()` function of the `Dispatcher`.

Sharing data

In the example given in this chapter, we saw how to share information between threads in addition to synchronizing threads--this in the form of the requests we passed from the main thread into the dispatcher from which each request gets passed on to a different thread.

The essential idea behind the sharing of data between threads is that the data to be shared exists somewhere in a way which is accessible to two threads or more. After this, we have to ensure that only one thread can modify the data, and that the data does not get modified while it's being read. Generally, we would use mutexes or similar to ensure this.

Using r/w-locks

Read-write locks are a possible optimization here, because they allow multiple threads to read simultaneously from a single data source. If one has an application in which multiple worker threads read the same information repeatedly, it would be more efficient to use read-write locks than basic mutexes, because the attempts to read the data will not block the other threads.

A read-write lock can thus be used as a more advanced version of a mutex, namely, as one which adapts its behavior to the type of access. Internally, it builds on mutexes (or semaphores) and condition variables.

Using shared pointers

First available via the Boost library and introduced natively with C++11, shared pointers are an abstraction of memory management using reference counting for heap-allocated instances. They are partially thread-safe in that creating multiple shared pointer instances can be created, but the referenced object itself is not thread-safe.

Depending on the application, this may suffice, however. To make them properly thread-safe, one can use atomics. We will look at this in more detail in `Chapter 8`, *Atomic Operations - Working with the Hardware*.

Summary

In this chapter, we looked at how to pass data between threads in a safe manner as part of a fairly complex scheduler implementation. We also looked at the resulting asynchronous processing of the said scheduler, and considered some potential alternatives and optimizations for passing data between threads.

At this point, you should be able to safely pass data between threads, as well as synchronize access to other shared resources.

In the next chapter, we will look at native C++ threading and the primitives API.

5
Native C++ Threads and Primitives

Starting with the 2011 revision of the C++ standard, a multithreading API is officially part of the C++ **Standard Template Library** (**STL**). This means that threads, thread primitives, and synchronization mechanisms are available to any new C++ application without the need to install a third-party library, or to rely on the operating system's APIs.

This chapter looks at the multithreading features available in this native API up to the features added by the 2014 standard. A number of examples will be shown to use these features in detail.

Topics in this chapter include the following:

- The features covered by the multithreading API in C++'s STL
- Detailed examples of the usage of each feature

The STL threading API

In `Chapter 3`, *C++ Multithreading APIs*, we looked at the various APIs that are available to us when developing a multithreaded C++ application. In `Chapter 4`, *Thread Synchronization and Communication*, we implemented a multithreaded scheduler application using the native C++ threading API.

Boost.Thread API

By including the `<thread>` header from the STL, we gain access to the `std::thread` class with facilities for mutual exclusion (mutex, and so on) provided by further headers. This API is, essentially, the same as the multithreading API from `Boost.Thread`, the main differences being more control over threads (join with timeout, thread groups, and thread interruption), and a number of additional lock types implemented on top of primitives such as mutexes and condition variables.

In general, `Boost.Thread` should be used as a fall back for when C++11 support isn't present, or when these additional `Boost.Thread` features are a requirement of one's application, and not easily added otherwise. Since `Boost.Thread` builds upon the available (native) threading support, it's also likely to add overhead as compared to the C++11 STL implementation.

The 2011 standard

The 2011 revision to the C++ standard (commonly referred to as C++11) adds a wide range of new features, the most crucial one being the addition of native multithreading support, which adds the ability to create, manage, and use threads within C++ without the use of third-party libraries.

This standard standardizes the memory model for the core language to allow multiple threads to coexist as well as enables features such as thread-local storage. Initial support was added in the C++03 standard, but the C++11 standard is the first to make full use of this.

As noted earlier, the actual threading API itself is implemented in the STL. One of the goals for the C++11 (C++0x) standard was to have as many of the new features as possible in the STL, and not as part of the core language. As a result, in order to use threads, mutexes, and kin, one has to first include the relevant STL header.

The standards committee which worked on the new multithreading API each had their own sets of goals, and as a result, a few features which were desired by some did not make it into the final standard. This includes features such as terminating another thread, or thread cancellation, which was strongly opposed by the POSIX representatives on account of canceling threads likely to cause issues with resource clean-up in the thread being destroyed.

Following are the features provided by this API implementation:

- `std::thread`
- `std::mutex`
- `std::recursive_mutex`
- `std::condition_variable`
- `std::condition_variable_any`
- `std::lock_guard`
- `std::unique_lock`
- `std::packaged_task`
- `std::async`
- `std::future`

In a moment, we will look at detailed examples of each of these features. First we will see what the next revisions of the C++ standard have added to this initial set.

C++14

The 2014 standard adds the following features to the standard library:

- `std::shared_lock`
- `std::shared_timed_mutex`

Both of these are defined in the `<shared_mutex>` STL header. Since locks are based on mutexes, a shared lock is, therefore, reliant on a shared mutex.

C++17

The 2017 standard adds another set of features to the standard library, namely:

- `std::shared_mutex`
- `std::scoped_lock`

Here, a scoped lock is a mutex wrapper providing an RAII-style mechanism to own a mutex for the duration of a scoped block.

STL organization

In the STL, we find the following header organization, and their provided functionality:

Header	Provides
`<thread>`	The `std::thread` class. Methods under `std::this_thread` namespace: • `yield` • `get_id` • `sleep_for` • `sleep_until`
`<mutex>`	Classes: • `mutex` • `timed_mutex` • `recursive_mutex` • `recursive_timed_mutex` • `lock_guard` • `scoped_lock` (C++17) • `unique_lock` Functions: • `try_lock` • `lock` • `call_once` • `std::swap` (`std::unique_lock`)
`<shared_mutex>`	Classes: • `shared_mutex` (C++17) • `shared_timed_mutex` (C++14) • `shared_lock` (C++14) Functions: • `std::swap` (`std::shared_lock`)

`<future>`	Classes: • `promise` • `packaged_task` • `future` • `shared_future` Functions: • `async` • `future_category` • `std::swap` (`std::promise`) • `std::swap` (`std::packaged_task`)
`<condition_variable>`	Classes: • `condition_variable` • `condition_variable_any` Function: • `notify_all_at_thread_exit`

In the preceding table, we can see the functionality provided by each header along with the features introduced with the 2014 and 2017 standards. In the following sections, we will take a detailed look at each function and class.

Thread class

The `thread` class is the core of the entire threading API; it wraps the underlying operating system's threads, and provides the functionality we need to start and stop threads.

This functionality is made accessible by including the `<thread>` header.

Basic use

Upon creating a thread it is started immediately:

```
#include <thread>

void worker() {
   // Business logic.
}

int main () {
   std::thread t(worker);
```

```
    return 0;
}
```

This preceding code would start the thread to then immediately terminate the application, because we are not waiting for the new thread to finish executing.

To do this properly, we need to wait for the thread to finish, or rejoin as follows:

```
#include <thread>

void worker() {
    // Business logic.
}

int main () {
    std::thread t(worker);
    t.join();
    return 0;
}
```

This last code would execute, wait for the new thread to finish, and then return.

Passing parameters

It's also possible to pass parameters to a new thread. These parameter values have to be move constructible, which means that it's a type which has a move or copy constructor (called for rvalue references). In practice, this is the case for all basic types and most (user-defined) classes:

```
#include <thread>
#include <string>

void worker(int n, std::string t) {
    // Business logic.
}

int main () {
    std::string s = "Test";
    int i = 1;
    std::thread t(worker, i, s);
    t.join();
    return 0;
}
```

In this preceding code, we pass an integer and string to the `thread` function. This function will receive copies of both variables. When passing references or pointers, things get more complicated with life cycle issues, data races, and such becoming a potential problem.

Return value

Any value returned by the function passed to the `thread` class constructor is ignored. To return information to the thread which created the new thread, one has to use inter-thread synchronization mechanisms (like mutexes) and some kind of a shared variable.

Moving threads

The 2011 standard adds `std::move` to the `<utility>` header. Using this template method, one can move resources between objects. This means that it can also move thread instances:

```
#include <thread>
#include <string>
#include <utility>

void worker(int n, string t) {
   // Business logic.
}

int main () {
   std::string s = "Test";
   std::thread t0(worker, 1, s);
   std::thread t1(std::move(t0));
   t1.join();
   return 0;
}
```

In this version of the code, we create a thread before moving it to another thread. Thread 0 thus ceases to exist (since it instantly finishes), and the execution of the `thread` function resumes in the new thread that we create.

As a result of this, we do not have to wait for the first thread to re join, but only for the second one.

Thread ID

Each thread has an identifier associated with it. This ID, or handle, is a unique identifier provided by the STL implementation. It can be obtained by calling the `get_id()` function of the `thread` class instance, or by calling `std::this_thread::get_id()` to get the ID of the thread calling the function:

```
#include <iostream>
#include <thread>
#include <chrono>
#include <mutex>

std::mutex display_mutex;

void worker() {
    std::thread::id this_id = std::this_thread::get_id();

    display_mutex.lock();
    std::cout << "thread " << this_id << " sleeping...\n";
    display_mutex.unlock();

    std::this_thread::sleep_for(std::chrono::seconds(1));
}

int main() {
   std::thread t1(worker);
   std::thread::id t1_id = t1.get_id();

   std::thread t2(worker);
   std::thread::id t2_id = t2.get_id();

   display_mutex.lock();
   std::cout << "t1's id: " << t1_id << "\n";
   std::cout << "t2's id: " << t2_id << "\n";
   display_mutex.unlock();

   t1.join();
   t2.join();

   return 0;
}
```