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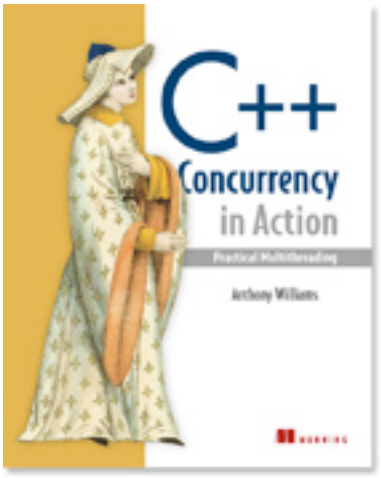

C++ Concurrency in Action
EARLY ACCESS EDITION
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These are exciting times for C++ users. Eleven years after the original C++ Standard was published in 1998, the C++ Standards committee is giving the language and its supporting library a major overhaul. The new C++ Standard (referred to as C++0x) is due to be published in 2010 and will bring with it a whole swathe of changes that will make working with C++ easier and more productive.

One of the most significant new features in the C++0x Standard is the support of multi-threaded programs. For the first time, the C++ Standard will acknowledge the existence of multi-threaded applications in the language, and provide components for writing multi-threaded applications in the library. This will make it possible to write multi-threaded C++ programs without relying on platform-specific extensions, and thus allow us to write portable multi-threaded code with guaranteed behaviour. It also comes at a time when programmers are increasingly looking to concurrency in general, and multi-threaded programming in particular in order to improve application performance.

So, what do I mean by *concurrency* and *multi-threading*?

What is Concurrency?

At the simplest and most basic level, concurrency is about two or more separate activities happening at the same time. We encounter concurrency as a natural part of life: we can walk and talk at the same time or perform different actions with each hand, and of course we each go about our lives independently of each other — you can watch football whilst I go swimming, and so on.

Concurrency in Computer Systems

When we talk about concurrency in terms of computers, we mean a single system performing multiple independent activities in parallel, rather than sequentially one after the other. It is not a new phenomenon: multi-tasking operating systems that allow a single computer to run multiple applications at the same time have been common place for many years, and high-end server machines with multiple processors have been available for

even longer. What *is* new is the increased prevalence of computers that can genuinely run multiple tasks in parallel rather than just giving the illusion of doing so.

Historically, most computers have had one processor, with a single processing unit or core, and this remains true for many desktop machines today. Such a machine can really only perform one task at a time, but they can switch between tasks many times per second. By doing a bit of one task and then a bit of another and so on, it appears they are happening concurrently. This is called *task switching*. We still talk about *concurrency* with such systems: since the task switches are so fast, you can't tell at which point a task may be suspended as the processor switches to another one. The task switching provides an illusion of concurrency both to the user and the applications themselves.

Computers containing multiple processors have been used for servers and high-performance computing tasks for a number of years, and now computers based around processors with more than one core on a single chip are becoming increasingly common as desktop machines too. Whether they have multiple processors or multiple cores within a processor (or both), these computers are capable of genuinely running more than one task in parallel. We call this *hardware concurrency*.

Figure A shows an idealized scenario of a computer with precisely two task to do, each divided into ten equally-sized chunks. On a dual-core machine, each task can execute on its own core. On a single-core machine doing task-switching, the chunks from each task are interleaved. However, they are also spaced out a bit (in the diagram this is shown by the grey bars separating the chunks being thicker): in order to do the interleaving, the system has to perform a *context switch* every time it changes from one task to another, and this takes time.

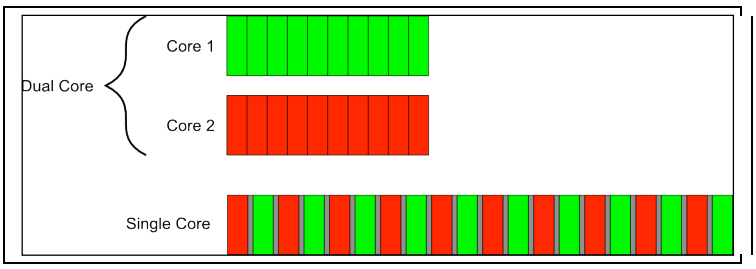

Figure A Two approaches to concurrency: parallel execution on a dual-core machine vs task-switching on a single core machine.

Even with a system that has genuine hardware concurrency, it is easy to have more tasks than the hardware can run in parallel, so task switching is still used in these cases. For example, on a typical desktop computer there may be hundreds of tasks running, performing background operations, even when the computer is nominally idle. It is the task-switching that allows these background tasks to run, and allows you to run your word processor, compiler, editor and web browser (or any combination of applications) all at once. Figure B shows task switching between four tasks on a dual-core machine.

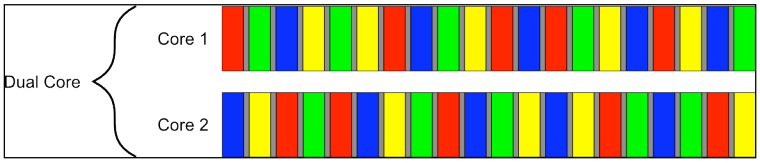

Figure B Task switching with two cores

All the techniques, functions and classes covered in this book can be used whether you're application is running on a machine with one single-core processor, or a machine with many multi-core processors, and are not affected by whether the concurrency is achieved through task switching or by genuine hardware concurrency. However, as you may imagine, how you make use of concurrency in your application may well depend on the amount of hardware concurrency available.

Approaches to Concurrency

Imagine for a moment a pair of programmers working together on a software project. If your developers are in separate offices, they can go about their work peacefully, without being disturbed by each other, and they each have their own set of reference manuals. However, communication is not straightforward: rather than just turning round and talking, they have to use the phone or email or get up and walk. Also, you've got the overhead of two offices to manage, and multiple copies of reference manuals to purchase.

Now imagine that you move your developers in to the same office. They can now talk to each other freely to discuss the design of the application, and can easily draw diagrams on paper or on a whiteboard to help with design ideas or explanations. You've now only got one office to manage, and one set of resources will often suffice. On the negative side, they might find it harder to concentrate, and there may be issues with sharing resources ("Where's the reference manual gone now?").

These two ways of organising your developers illustrate the two basic approaches to concurrency. Each developer represents a thread, and each office represents a process. The first approach is to have multiple single-threaded processes, which is similar to having each developer in his own office, and the second approach is to have multiple threads in a single process, which is like having two developers in the same room. Let's now have a brief look at these two approaches to concurrency in an application.

Concurrency with Multiple Processes

The first way to make use of concurrency within an application is to divide the application into multiple separate single-threaded processes which are run at the same time, much as you can run your web browser and word processor at the same time. These separate processes can then pass messages to each other through all the normal interprocess communication channels (signals, sockets, files, pipes, etc.), as shown in figure C. One downside is that such communication between processes is often either complicated to set up, slow, or both, since operating systems typically provide a lot of protection between processes to avoid one process accidentally modifying data belonging to another process. Another downside is that there is an inherent overhead in running multiple processes: it takes time to start a process, the operating system must devote internal resources to managing the process, and so forth.

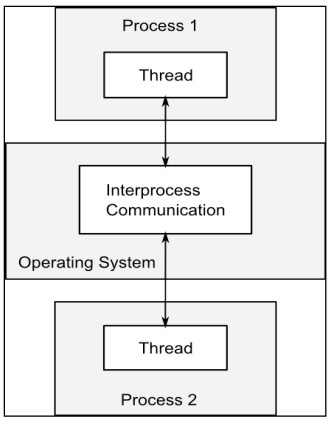

Figure C Communication between a pair of processes running concurrently

Of course, it's not all downside: the added protection operating systems typically provide between processes and the higher-level communication mechanisms mean that it can be easier to write *safe* concurrent code with processes rather than threads.

Concurrency with Multiple Threads

The alternative approach to concurrency is to run multiple threads in a single process. Threads are very much like lightweight processes — each thread runs independently of the others, and each thread may run a different sequence of instructions. However, all threads in a process share the same address space, and the majority of data can be accessed directly from all threads — global variables remain global, and pointers or references to objects or data can be passed around between threads. Though it is often possible to share memory between processes, this is more complicated to set up, and often harder to manage, as memory addresses of the same data are not necessarily the same in different processes. Figure D shows two threads within a process communicating through shared memory.

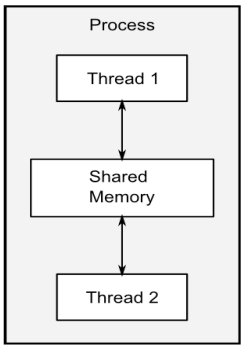

Figure D Communication between a pair of threads running concurrently in a single process

The shared address space and lack of protection of data between threads makes the overhead associated with using multiple threads much smaller than that from using multiple processes, as the operating system has less

book-keeping to do. However, the flexibility of shared memory also comes with a price — if data is accessed by multiple threads, then the application programmer must ensure that the view of data seen by each thread is consistent whenever it is accessed.

The low overhead associated with communicating between multiple threads within a process compared to multiple single-threaded processes means that this is the favoured approach to concurrency in mainstream languages including C++.

Why Use Concurrency?

There are two main reasons to use concurrency in an application: separation of concerns and performance. In fact, I'd go so far as to say they are the pretty much the *only* reasons to use concurrency: anything else boils down to one or the other (or maybe even both) when you look hard enough (well, except for reasons like "because I want to").

Using Concurrency for Separation of Concerns

Separation of concerns is almost always a good idea when writing software: by grouping related bits of code together, and keeping unrelated bits of code apart we can make our programs easier to understand and test, and thus less likely to contain bugs. We can use concurrency to separate distinct areas of functionality even when the operations in these distinct areas need to happen at the same time: without the explicit use of concurrency we either have to write a task-switching framework, or actively make calls to unrelated areas of code during an operation.

Consider a processing-intensive application with a user-interface, such as a DVD player application for a desktop computer. Such an application fundamentally has two sets of responsibilities: not only does it have to read the data from the disk, decode the images and sound and send them to the graphics and sound hardware in a timely fashion so the DVD plays without glitches, but it must also take input from the user, such as when the user clicks "pause" or "return to menu", or even "quit". In a single thread, the application has to check for user input at regular intervals during the playback, thus conflating the DVD playback code with the user interface code. By using multi-threading to separate these concerns, the user interface code and DVD playback code no longer have to be so closely intertwined: one thread can handle the user interface, and another the DVD playback. Of course there will have to be interaction between them, such as when the user clicks "pause", but now these interactions are directly related to the task at hand.

This gives the illusion of responsiveness, as the user-interface thread can typically respond immediately to a user request, even if the response is simply to display a "busy" cursor or "please wait" message whilst the request is conveyed to the thread doing the work. Similarly, separate threads are often used to run tasks which must run continuously in the background, such as monitoring the filesystem for changes in a desktop search application. Using threads in this way generally makes the logic in each thread much simpler, as the interactions between them can be limited to clearly identifiable points, rather than having to intersperse the logic of the different tasks.

In this case, the number of threads is independent of the number of CPU cores available, since the division into threads is based on the conceptual design, rather than an attempt to increase throughput.

Using Concurrency for Performance

Multi-processor systems have existed for decades, but until recently they were mostly only found in supercomputers, mainframes and large server systems. However, chip manufacturers have increasingly been favouring multi-core designs with 2, 4, 16 or more processors on a single chip over better performance with a single core. Consequently, multi-core desktop computers, and even multi-core embedded devices, are now increasingly prevalent. The increased computing power of these machines comes not from running a single task faster, but from running multiple tasks in parallel. In the past, programmers have been able to sit back and watch their programs get faster with each new generation of processors, without any effort on their part, but now, as Herb Sutter put it: "The free lunch is over." [Sutter2005] **If software is to take advantage of this increased computing power, it must be designed to run multiple tasks concurrently.** Programmers must therefore take heed, and those who have hitherto ignored concurrency must now look to add it to their toolbox.

There are two ways to use concurrency for performance. The first, and most obvious, is to divide a single task into parts, and run each in parallel, thus reducing the total runtime. Though this sounds straight-forward, it can be quite a complex process, as there may be many dependencies between the various parts. The divisions may be either in terms of processing — one thread performs one part of the algorithm, whilst another thread performs a different part — or in terms of data: each thread performs the same operation on different parts of the data. This latter is called *data parallelism*.

Algorithms which are readily susceptible to such parallelism are frequently called *Embarrassingly Parallel*. Despite the implications that you might be embarrassed to have code so easy to parallelize, this is a good thing: other terms I've encountered for such algorithms are *naturally parallel* and *conveniently concurrent.* Embarrassingly parallel algorithms have very good scalability properties — as the number of available hardware threads goes up, the parallelism in the algorithm can be increased to match. Such an algorithm is the perfect embodiment of "Many hands make light work". For those parts of the algorithm that aren't embarrassingly parallel, you might be able to divide the algorithm into a fixed (and therefore not scalable) number of parallel tasks, for example by making use of a pipeline.

The second way to use concurrency for performance is to use the available parallelism to solve bigger problems — rather than processing one file at a time, process two or ten or twenty, as appropriate. Though this is really just an application of *data parallelism*, by performing the same operation on multiple sets of data concurrently, there's a different focus. It still takes the same amount of time to process one chunk of data, but now more data can be processed in the same amount of time. Obviously, there are limits to this approach too, and this will not be beneficial in all cases, but the increase in throughput that comes from such an approach can actually make new things possible — increased resolution in video processing, for example, if different areas of the picture can be processed in parallel.

When Not to use Concurrency

It is just as important to know when *not* to use concurrency as it is to know when *to* use it. Fundamentally, the one and only reason not to use concurrency is when the benefit is not worth the cost. Code using concurrency is harder to understand in many cases, so there is a direct intellectual cost to writing and maintaining multi-threaded code, and the additional complexity can also lead to more bugs. Unless the potential performance gain is large enough or separation of concerns clear enough to justify the additional development time required to get it right, and the additional costs associated with maintaining multi-threaded code, don't use concurrency.

Also, the performance gain might not be as large as expected: there is an inherent overhead associated with launching a thread, as the OS has to allocate the associated kernel resources and stack space, and then add the new thread to the scheduler, all of which takes time. If the task being run on the thread is completed quickly, then

the actual time taken by the task may be dwarfed by the overhead of launching the thread, possibly making the overall performance of the application worse than if the task had been executed directly by the spawning thread.

Furthermore, threads are a limited resource. If you have too many threads running at once, this consumes OS resources, and may make the system as a whole run slower. Not only that, but using too many threads can exhaust the available memory or address space for a process, since each thread requires a separate stack space. This is particularly a problem for 32-bit processes, where there is a 4Gb limit in the available address space: if each thread has a 1Mb stack (as is typical on many systems), then the address space would be all used up with 4096 threads, without allowing for any space for code or static data or heap data. Though 64-bit (or larger) systems don't have this direct address-space limit, they still have finite resources: if you run too many threads this will eventually cause problems.

If the server side of a client-server application launched a separate thread for each connection, this works fine for a small number of connections, but can quickly exhaust system resources by launching too many threads if the same technique is used for a high-demand server which has to handle many connections. In this scenario, careful use of thread pools can provide optimal performance .

Finally, the more threads you have running, the more context switching the operating system has to do. Each context switch takes time that could be spent doing useful work, so at some point adding an extra thread will actually *reduce* the overall application performance rather than increase it. For this reason, if you are trying to achieve the best possible performance of the system, it is necessary to adjust the number of threads running to take account of the available hardware concurrency (or lack of it).

Use of concurrency for performance is just like any other optimization strategy — it has potential to greatly improve the performance of your application, but it can also complicate the code, making it harder to understand, and more prone to bugs. Therefore it is only worth doing for those performance-critical parts of the application where there is measurable gain.