Multithreading: Taking Advantage of Intel® Architecture-based Multiprocessor Workstations

March 1999 Intel Corporation

Contents

Abstract 5

Introduction 5
Goals 5
Background and Terminology 6

Enablers 8
Processor Hardware Readily Available 8
Less Expensive Memory 9
Multithreading–capable OSes and System Software 9

Applying Multithreading 10
When to Use Multithreading 10
When Not to Use Multithreading 10
Examples of Some Techniques 10
Resources to Build Threaded Applications 13
Warnings, Risks and Remedies 13

References 15
On-Line References 15
Books 15

List of Figures
Figure 1: Processor Cycles Wasted by Single-threading 10
Figure 2: Processor Cycles Gained Back by Multithreading 11
Figure 3: Serial Data Processing 11
Figure 4: Parallelized Data Processing 12
Figure 5: Single-threaded Producer/Consumer 12
Figure 6: Multithreaded Producer/Consumer 12

List of Tables
Table 1: Resource Sharing Scope 8
Table 2: Principal Threading-related Calls 14

Abstract

Multithreading is introduced as a way to take best advantage of the processor or processors in an Intel® Architecture-based technical workstation. Multithreading concepts and terminology are introduced, and are contrasted with "multitasking". Emphasis is placed on writing applications having single executables that run on *either* single or multiprocessor systems. Examples and "rules of thumb" are given of existing application usage which lend themselves well to multithreading, as well as situations where multithreading should not be applied. The programming interfaces (calls) which an application can use are introduced. For additional information including specific performance tests comparing uni- and dual processor Intel® Pentium® III Xeon™ workstations, please go to http://www.intel.com/go/workstations

Introduction

Today's operating systems strive and compete to make most efficient use of a computer's resources. While much has been done to efficiently share a machine's resources among several tasks (multitasking), this "large grained" resource sharing is the most operating systems are able to do without additional information from the applications themselves. Recent operating systems provide mechanisms allowing an application to control and share machine resources at a "finer grain" — threads. This paper discusses how use of threads on multiprocessor Intel architecture-based workstations can improve an application's performance, responsiveness and throughput.

Prior to the introduction of the Pentium® II processor (and its architectural predecessor, the Pentium® Pro processor), technical workstations featuring more than one processor were relatively expensive. Usually, these multi-processor systems were reserved for applications specially developed for those machines. As multi-processor machines have become more available, OS support for threading has become standardized, making this technique available and approachable by all application writers. With the introduction of the Pentium® III and Pentium III Xeon processors from Intel, workstations based on the Intel Architecture offer even more compelling platform for developing and running multithreaded applications.

While this paper follows existing technical workstation market trends and places slightly more emphasis on Microsoft* Windows NT*, we also discuss features available from modern UNIX* operating systems.

Goals

Like most programming techniques, the primary goal of multithreading is to allow a user to take best advantage of the resources of a computer system and its attached network. This technique is inspired by observations that — for much of the time — the majority of the resources of today's machines are idle, and the speeds (throughput, transfer rate, etc.) of the various parts of the machine vary widely. Threads express the work done by individual portions of a task (process), and allow for finer grained scheduling. Thus, the goals of multithreading are improvements in:

- Resource utilization: Effectively and consistently use all available processing power
- Throughput: Mask delays due to slow peripheral devices (or other data producers) by enabling other work to be done in the mean time
- Responsiveness: Maintain excellent GUI responsiveness while other computation continues
- Communication: reliable, responsive cross-process or cross-net communication

And to do this in a way that assures:

- Scalability: performance that improves in proportion to added compute power
- Compatibility: same binary for single and multi-processors
- Portability: source code for an application varies minimally from platform to platform

Background and Terminology

Multithreading vs. Multitasking

Loosely speaking, multitasking refers to running multiple, unrelated jobs on one system or display unit — for example, a simulation and an email client. Multitasking is by definition, "large grained parallelism"; independent jobs are executing at the same time. By contrast, multithreading usually refers to a single job that is managing multiple, usually shared resources (memory, processors, etc.) at a finer grain size than multi-tasking.

Process as an Address Space

Today's operating systems model a running application — a task or *process* — as:

- An address space or work area where data can be manipulated,
- The executable code running within it; and
- Descriptors for OS and machine resources used by the process.

The three interact with the OS to do the work of the task — receiving input data, transforming it and delivering it to some consumer or storage area. The executable code may have to spend significant amounts of time waiting: for I/O to complete, for higher priority jobs to run, for user input, for communication media, etc. Unless a task is very carefully written — or the machine is constantly busy with work for other tasks — processor and other machine resources can become idle.

Thread as a "Program Counter" Within the Process

All of the executable code for a process is brought into its address space. Applications usually do their work in segments or stages — modifying data for that segment or stage, and recording or sharing progress by updating global data. If the segments or stages of work operate without (or minimally) disturbing other units of work, each of these smaller units of work can run in parallel as *threads*. Each unit of work has its own program counter tracking the instructions being executed, and its own call/return stack — in essence, its own state.

Definitions

Address Space – a region of (virtual) memory that is protected from other address spaces and process on a machine, in which a task's executable instructions and data are stored.

Process – synonym for:

Job – synonym for:

Task – An executing application that consists of a private virtual address space, executable code, data, and other operating system resources, such as files, pipes, and synchronization objects that are visible to the process. This includes call/return stack(s), shared objects, I/O handles and environment variables, program counter(s), etc. The "classic" OS process has one thread of execution doing its work.

Multitasking – the ability of a machine and OS to run multiple, independent processes — conceptually at the same time — by sharing a machine's resources among those processes, usually by some time-slice strategy.

Symmetric MultiProcessing (SMP) – a computer system constructed so that every processor has equivalent, full access to machine resources - memory, peripherals, graphics and other controllers. Additionally, any unshared resources (like L2 cache) have mechanisms to inform all processors of any need to synchronize content. As a result, any processor can perform OS work equivalently well. (This is a slightly more general definition than a different "SMP" Shared Memory Parallel Processing.)

Thread – one flow of control through a program and that flow's current state (represented by a current program counter, a call/return stack and, occasionally, some thread-private data). A process has one or more threads doing its work.

Multithreading – having more than one flow of control within a process, allowing parts of the process to be independently performed.

Asynchronous I/O – an "indirect" form of threading where an application makes calls to special I/O routines that initiate an operation and return immediately. The application may proceed doing calculations on other data, and is expected to make a later I/O call which checks whether the I/O operation has completed. This programming paradigm is gradually being displaced by use of threads (which are more general). Instead of using special asynchronous

I/O calls, a thread is used to make "regular" I/O calls and synchronize upon completion the same way all other threads do.

Producer / Consumer – data processing is often performed as a sequence of *filters*, each performing a localized, well-defined operation. In such chains, each stage reads (consumes) some incoming data, processes it and emits or writes (produces) data for the next stage. 3D geometry is a classic example of this, with each stage doing operations like scale, rotate, transform, hidden line removal, texturing, etc.

Scalability – is a measure of the performance of doing work on multiple processors, relative to doing the same work on a single processor. For example, if a given application run takes two seconds on a single processor, and the same application takes one second on two processors, then the scalability for this task is 2. However, since there is work done by the OS and by the task to coordinate and synchronize work (i.e. overhead), the scaling factor never reaches *m* (the number of processors). This limitation is described more fully by Amdahl's Law, which relates processors, parallelism and synchronization. The quality of an implementation of threading is often measured by its scaling factor.

Concurrency – running activities in parallel.

Synchronization – coordination of all the individual work by each of a set of threads into some merged result. One example is waiting for one thread to finish filling a segment of a buffer before another begins using the newly-buffered data. Synchronization is also necessary when any thread has to alter data visible to another thread.

Semaphore – a synchronization mechanism — usable across processes — that maintains a count between zero and some maximum value, limiting the number of threads that are simultaneously accessing a shared resource.

Mutex – a specially handled binary variable that all threads agree to use to guard access to a shared structure, handle or other resource. This differs from a semaphore in that there is only one owner of the mutex at a time, but is like a semaphore in that it is usable across processes. A thread can only manipulate the resource if it holds the lock on the associated mutex; other threads await the release of the mutex variable. (In POSIX.1c UNIX, a mutex may optionally be intra-process -only.)

Critical Section – a special form of a mutex that offers very low overhead and is usable *only* among the threads of one process. (This is somewhat more direct to code in Windows* NT than UNIX*.)

Race Condition – a bug in use of threading where the code of one thread "A" relies on another thread "B" to complete some action, but where there is no synchronization between the two threads. The process operates correctly if thread B "wins the race" by completing its action before thread A needs it, but the process produces incorrect or varying results if thread A wins the race.

Programming and Hardware Features:

Visible Throughout a Machine	Visible Throughout a Process	Individually Owned by Each Thread
▪ name space for file system, network machines, named pipes, etc. ▪ multiprocess shared memory ▪ memory for, and names of, semaphores and mutexes ▪ pipes	▪ address space ▪ oaded executable code ▪ Win32* resources like string and icon tables, loaded fonts, etc. ▪ heap-allocated memory file handles or OS descriptors (including sockets and shared memory) and their state ▪ the ANSI C `errno` ▪ process arguments and environment list ▪ global and file-scope data ▪ memory for critical section variables	▪ program counter call/return stack ▪ thread-local storage (on some OSes) ▪ state/content of CPU registers ▪ scheduling priority ▪ UNIX signal masks ▪ various runtime statistics - CPU time, etc. ▪ ownership of mutexes and critical sections (when locked by that thread)

Table 1: Resource Sharing Scope

Shared Resources

A key difference between multitasking and multithreading is how application resources are shared. The above table contrasts different resource sharing scopes:

In most cases, this resource sharing can be of significant value; for example, all threads of a process can share work done to set up in-memory (heap allocated) data structures. With traditional multitasking, additional work — inter-process communication, shared memory, semaphores, etc. — must be done to arrange such sharing.

Care must be exercised, however: applications can be written to assume no sharing is happening. Updating such applications to use threading can result in unsynchronized changes to such shared data and the threads seeing inconsistent data. This risk can be minimized by:

- Re-coding global data as a set of structures, each gathering related data
- Guarding access to these structures by mutexes
- Use of thread-safe libraries of functions and macros

Enablers

Multithreading requires that the underlying machine and OS supply certain features allowing applications to coordinate or describe their activities. These include:

- Primitives on which to build safe synchronization methods
- Protection of tasks from one another — controlling object sharing
- Hardware allowing multiple processors to communicate and identify themselves and their saved state
- Primitives describing start, termination, synchronization and control of individual units of work

Processor Hardware Readily Available

These enablers are now available in workstations based on the Intel® Architecture:

Processors and Chipsets

- A wide variety of interlocked compare-and-exchange instructions
- Built-in cross-processor communication, allowing "*glueless*" multiprocessing
- Cache consistency can be guaranteed in multiprocessor systems, and synchronization variables can be safely held in cache, via "snoop" hardware assuring cache coherency
- Processor state is easily saved and restored, including a processor identifier

- Virtual memory hardware protects processes from each other
- High speed (100MHz), wide (8 byte) system busses implemented by advanced chipsets supporting multiple processors

The incremental cost of getting a second processor is a fraction of the whole-system cost — from about $600 to about $1,000 for today's workstations.

If a second processor allows tools to run an average of 30% faster, that amounts to about one work-day per week of improved user productivity.

System Motherboards

Multiprocessor motherboards are widely available — frequently the standard offering for technical workstations. Cooling, mechanical and electrical requirements for these boards are very similar to existing system-integrator experience, facilitating ease of use.

Complete Systems

In the technical workstation marketplace, multiprocessor systems are becoming the norm. Most suppliers of Intel® Architecture-based workstations offer such machines to their technical customers, either pre-configured with two processors or as an upgrade option. Recent research sponsored by Intel indicates that over sixty percent of dual processor workstations were purchased as dual processor systems — in other words, they were not upgraded.

Less Expensive Memory

Multithreaded applications place more demand on the memory subsystem. They require:

- **More memory** – to save the state of the various threads — primarily its call/return stack. With complex workstation applications, this state can become sizable — many megabytes. Additionally, more heap allocations are simultaneously present.
- **More memory bandwidth** – due to a higher number of active memory transactions per second.

Today's Intel® hardware supports both at a low cost.

Multithreading-capable OSes and System Software

Operating systems now supply well-defined methods for applications to start, control, terminate and synchronize *threads* of execution within one task. These individual units of control can share resources (like memory and I/O devices) and can communicate easily and cheaply. There are two major families of thread implementations — that of Windows NT* and UNIX*; they are *not* equivalent, but offer very similar services. Both are available on Intel Architecture-based systems. (on page 14 lists and compares the threading calls of the two OS families.)

Windows* NT

The Win32 Application Programming Interface (API) provides a complete set of threading primitives, which is identical across all platforms implementing Win32.

Threads in UNIX*

Threading on UNIX systems is a bit more complicated: there are two primary threading APIs available today:

- The POSIX*.1c threading standard, agreed-upon by all major UNIX implementers, and a feature of UNIX/98, now being standardized by the members of *The Open Group*
- "UNIX International" or "Solaris*" threads, available on some platforms, is a superset of POSIX.1c threads

An application written to POSIX.1c threads will be portable across UNIX variants.

Portability Libraries

Besides each OS' native interfaces, API libraries are available from third parties that present portable interfaces to the programmer. While applying them is not automated, code written to those APIs becomes portable across Windows NT and most UNIX systems. Some examples:

- Threads.h++ from Rogue Wave* Software http://www.roguewave.com
- Mthread from the book *Multithreading Programming Techniques* by Shashi Prasad; download MThread from http://165.254.151.1/people/shashi/book/mpt.html

As a special case, implementations of the Win32 API are available on UNIX, and of POSIX.1c threads on Windows NT.

Applying Multithreading

Many applications are currently written single-threaded. They can offer the user improved performance and responsiveness were they to be threaded. Key examples in this category include applications that spend most of their time doing array mathematics and region-by-region processing of graphical images.

Because of Amdahl's Law — bounding the parallelization-based improvement of an application by the portion that cannot be parallelized — some applications are not good candidates for threading. A classic example is any application whose data merge or synchronization stages are larger than all the potentially parallel work to be done.

Here are some guidelines, some illustrated examples where threading is a "win" and statistics from commercially available threaded applications.

When to Use Multithreading

- Algorithms that can be independently applied to segments within a large data set (rows or columns of arrays, bands or regions of 2-dimensional data, etc)
- Pipelines with stages having similar amounts of work
- Maintaining GUI responsiveness even while long computations are ongoing
- When I/O can occur in parallel with processing of earlier-buffered data
- Multithread the parts of your code that consume the most time; they *often* are the easiest to parallelize and scale best

When not to Use Multithreading

Although multithreading is usually beneficial, there are some situations where it is not advised:

- Parallel tasks which would each do only a small amount of work (compared to the time needed to synchronize or merge the parallel tasks' operations)
- Tasks where synchronization overhead is as large, or larger than the parallelized execution
- Algorithms that change significant amounts of global state with each iteration (You can try to fix this in your application, then look at multithreading it.)
- Applications having only isolated regions that could be parallelized

Additionally, if a workstation solution is assembled from several independent applications, multithreading is not applicable. A cooperative multitasking strategy might be appropriate in this case.

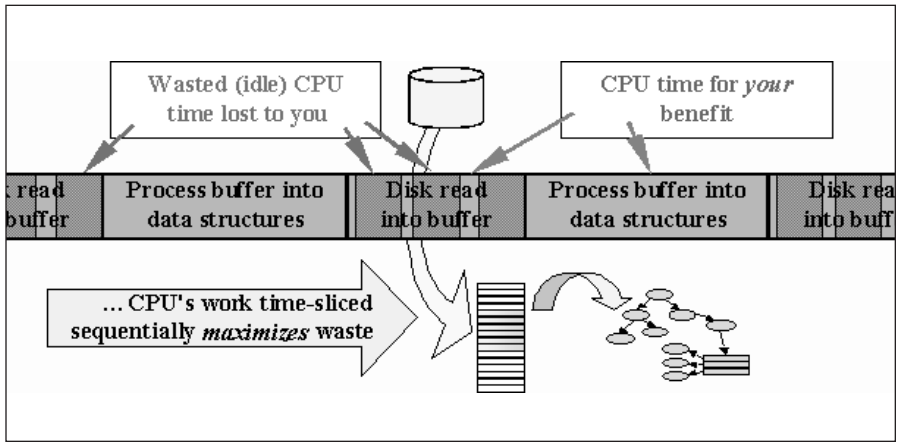
Examples of Some Techniques

Masking delays of slow peripheral devices

Although today's hard disks are quite fast, processor speeds have advanced more rapidly. As a result, there are (roughly) 100's of "spare" cycles of processor time for *each byte* read off of disk. The processor usually spends this spare time in an "idle" loop in the OS or in some other, lower priority application — instead of doing productive work for the application.

You can overlap CPU processing with the otherwise-wasted I/O wait time by using threads or "asynchronous" I/O. Overlapping processing and I/O usually involves double buffering; at the modest cost of today's inexpensive memory, you can cause the processor to spend *most* of its time doing work for your application.

Figure 1: Processor cycles wasted by single-threading



The example to the right shows how you can regain otherwise idle cycles of a processor. Double buffering can be easily extended to additional buffers. However, the time to complete the buffer read and the processing of the buffer must remain balanced; if not, a full buffer can waste time awaiting processing resource. Adding an additional processor can provide that compute resource, gaining additional application performance improvement with *no further source code change*.

This example also illustrates that employing multithreading can be of significant aid *even on uni-processor systems*, because otherwise-idle CPU cycles are used to do work while the I/O subsystem proceeds independently.

Figure 2: Processor cycles gained back by multithreading

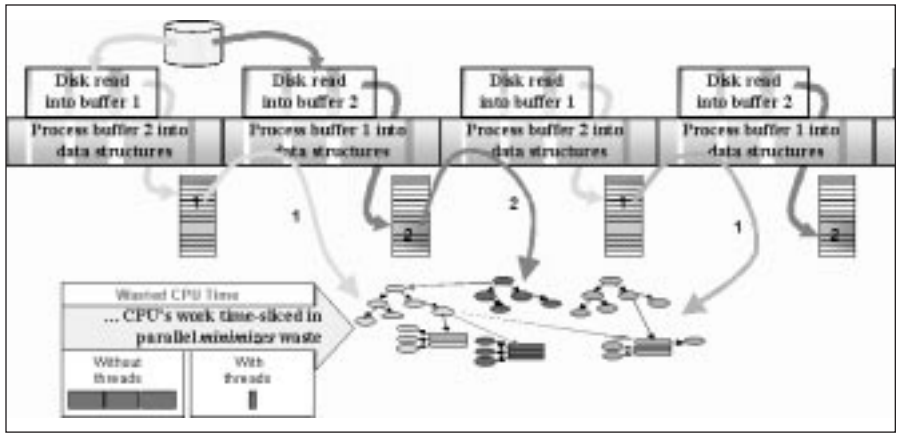
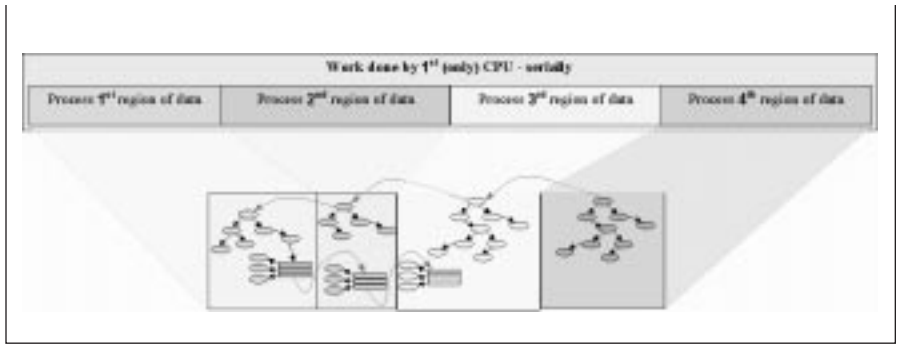


Figure 3: Serial data processing



Maintain GUI responsiveness during computation

Even when applications perform long computation sequences, users still want the application GUI to be responsive — if for no other reason than to control or stop an incorrect operation. In the absence of threading, the application has to resort to unpredictable mechanisms like timers or asynchronous `signal()`s, sporadic pauses in computation to check for input events, etc. While these mechanisms can be made to work, they usually result in:

- Undesirably complex checks for external events injected into otherwise clean algorithmic code
- Irregular or unpredictable GUI responsiveness

Largely for these reasons, today's GUIs are multithreaded. For example, applications built with the Microsoft* Foundation Classes (MFC) are actually multithreaded — though the application coder is often unaware of this. On multiprocessor machines, GUI behaviour is almost flawlessly smooth.

Effectively use available processing power

Many algorithms are applied serially on large data sets in memory. If applying the algorithm to the data results in (predominantly) localized changes in the data, the application can be parallelized.

Multithreading allows a second processor to operate on the data structures in parallel with the first processor. As with all parallelized operations, there is some overhead due to:

- Thread start-up and state retention
- Checks in the algorithm that operations are staying in the localized data, postponing or queuing cross-thread operations
- Intermediate synchronization, if any
- Final synchronization and merging of results

The example to the right illustrates several of these concerns, but still produces an overall improvement in processing time of some 45% — significantly more if additional processors were available.

This technique can be applied to many workstation applications and drivers:

- Fault simulation (which is highly localized)
- Stress analysis (after meshing has happened)
- Many graphical algorithms where data is coordinate sorted (processing can be done in *bands* or regions); for example IC CAD design rule check
- Many types of array calculations

Improving Producer/ Consumer Sequences

Some applications consist of sequences of data transformations. Without threading, the applications run each stage in sequence, completely buffering each intermediate data transformation. See figure 5.

By employing multithreading, the overall throughput can be improved (here, by roughly 40%), and the intermediate memory consumption can often be reduced (with corresponding cache and swapping benefits). See figure 6.

The cost of added synchronization and buffer management is usually significantly lower than the advantage gained in parallelization. These kinds of problems easily attain more improvement with additional processors, up to the depth of the pipeline.

Figure 4: Parallelized Data Processing

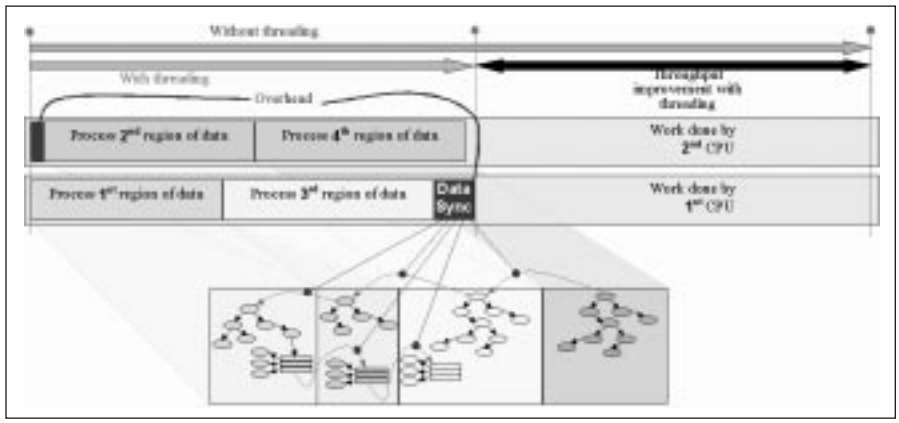


Figure 5: Single-threaded Producer/Consumer

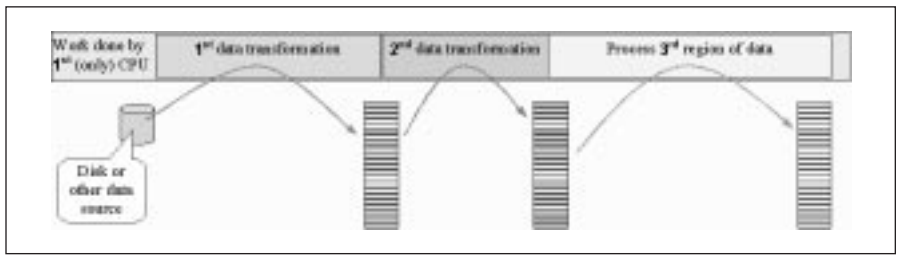
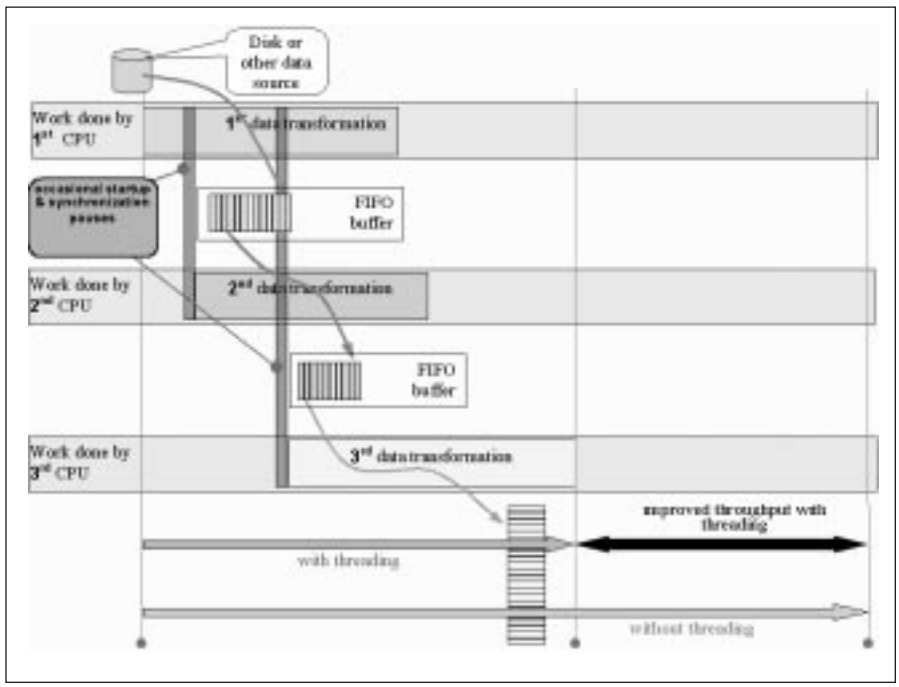


Figure 6: Multithreaded Producer/Consumer



Resources to Build Threaded Applications

To build a threaded application, the OS must supply mechanisms to:

- Query machine capabilities (number of processors, etc.)
- Start, exit from and terminate threads
- Control thread scheduling and priority
- Synchronize access to shared resources
- Handle asynchronous events and signals
- Accurately time (or time*out*) operations

These facilities can be used directly — or indirectly — from your application source code.

Automated Parallelization Tools

Automated parallelization tools are becoming more common. These tools examine application source for actions that can be independently performed and loop iterations (particularly nested loops) that can be done in parallel. They transform your source by reordering operations and inserting compiler directives or API calls to specify start, synchronization, join and termination of parallel tasks. While these tools can do some parallelization autonomously, the application benefits greatly if the developer provides "hints" (directives) in the source code. For example, see:

- Kuck & Associates*; http://www.kai.com
- Pacific Sierra Research*; http://www.psrv.com
- The Portland Group*; http://www.pgroup.com

To date, most of these tools work on FORTRAN source code, but efforts are underway to make parallelization directives portable and usable from within C and C++ also. Visit the *OpenMP* web site for more information, including specifications:

- OpenMP Consortium; http://www.openmp.org

Independent Software Vendors (ISVs) can benefit from using directives in 3 ways:

1. Directives are a form of higher-level programming which can speed application development. Programmers still need to know their code, but parallel decomposition can be done more quickly than "hand coding."
2. Directives like OpenMP are portable; coding done once will work on multiple platforms.
3. Directives allow the compiler to do the bookkeeping work of threading and synchronization — one of the most error prone coding tasks.

Threading API Features

While automated threading tools can produce acceptable results, they work best only for "classic" multithreading styles — nested loops, independent basic blocks, etc. Applications have greatest flexibility and control if they make threading calls directly. The table below describes many of the threading-related calls available to the users of Windows NT* and POSIX.1c-compatible UNIX*: (See the Win32 API documentation and *The Single UNIX Specification, Ver. 2* for more complete information.)

Warnings, Risks and Remedies

At first glance, the risks and problems of multithreaded code appear formidable. However, this technology has been available for many years and the risk and remedies are well known. An observant programming team can easily review code to minimize these risks.

Rapid creation and destruction of threads – Because thread creation and termination can be expensive, use a pool of pre-created threads that "sleep" until they are told what to do. This can be especially valuable in Windows NT* "services" (in UNIX*, "daemons") that use threads to connect to a requestor, hold the state of the request, and send back some result. The incoming request can be quickly delegated to a pre-created thread.

Many more ready-to-run threads than processors available – the overhead of scheduling the threads becomes significant. (By contrast, the number of threads sleeping on programmed — for events is less of an issue.)

Producer/consumer pipelines with unbalanced work – if each stage in a producer/consumer pipeline is not doing similar amounts of work, the pipeline's overall performance will settle to the throughput of the slowest stage

Link applications with thread-safe libraries – many bugs are due to linking a multithreaded application with the "standard" (i.e. *not* thread-safe) versions of the C library, etc.

Table 2: Principal Threading-related Calls

OS Family: / Purpose:	Windows NT*	UNIX* (POSIX.1c)
create thread	`CreateThread(), _beginthread()`	`Pthread_create()`
thread terminates itself	`ExitThread(), _endthread()`	`pthread_exit()`
suspend and resume a thread to do work	`SignalObjectAndWait(), SuspendThread(), ResumeThread()`	`Pause(), sigsuspend(), pthread_kill(…,SIGSTOP), pthread_kill(…,SIGCONT)`
thread attribute control	`GetThreadPriority(), SetThreadPriority(), SetThreadPriorityBoost()`	various `pthread_attr_…()` calls
await thread termination	the various general-purpose `…Wait…()` functions - like `SignalObjectAndWait(), WaitForSingleObject(), WaitForMultipleObjects()`	`pthread_join()`
kill a thread	`TerminateThread()`	`pthread_cancel()`
thread explicit yield	`SwitchToThread(), Sleep(0)`	`pause()`
semaphore manipulation	`CreateSemaphore(), OpenSemaphore(),` the various general-purpose `…Wait…()` functions, `ReleaseSemaphore()`	`sem_init(), sem_open(), sem_wait(), sem_trywait(), sem_post(),sem_destroy(), sem_unlink()`
mutex manipulation	`CreateMutex(),OpenMutex(),` the various general-purpose `…Wait…()` functions, `ReleaseMutex(), CloseHandle()`	`pthread_mutex_init(), pthread_mutex_destroy(), pthread_mutex_lock(), pthread_mutex_trylock(), pthread_mutex_unlock()`
critical sections	`InitializeCriticalSection(), Initialize…AndSpinCount(), DeleteCriticalSection()`	*use in-process options on mutexes*
create and manage thread-local storage	`TlsAlloc(), TlsSetValue(), TlsGetValue(), TlsFree()`	`pthread_key_create(), pthread_setspecific(), pthread_getspecific(), pthread_key_delete()`

***Still* holding a mutex when a thread waits for something else** – holding a mutex blocks any other user of the object the mutex is guarding. If you are still holding a mutex when you are blocked by something else — a slow I/O operation, a network communication, etc. — performance is lost. This also places you at risk of deadlock (see below). Do mutex locking at a fine-enough grain to avoid having to hold a lock while sleeping for something else.

Race conditions – if a thread writes result data that affects the computations of another thread, access to the first thread's result data must be guarded by some synchronization mechanism. If it is not, an application will produce one result if the first thread "happens" to get done before the second reads the data, and a different result if the first thread happened to take longer on a different run. It is important to develop QA test cases for a variety of load extremes.

Deadlocks – if a thread holds a synchronization lock "A" when it "goes to sleep" awaiting on another synchronization object "B", there is some risk that another thread holding the lock "B" will go to sleep awaiting the first lock "A"; this is a classic deadlock. A common remedy for such deadlocks is to make the locks guard "smaller" objects, holding the locks for smaller amounts of time.

`signal()` or event mis-delivery – UNIX signals and many GUI events are delivered to the *process*; if a particular thread has not been coded to receive or handle these events, they can be lost or mis-delivered to whatever thread happens to be running at the time. This

can be corrected by having a designated thread receive these asynchronous events; set thread-specific signal delivery masks or event handlers.

Failure to check API return values – most threading APIs check parameters and process state, and return error indications if they detect any problems. Because multithreaded applications are more complicated to test and debug, you can help yourself dramatically by coding checks for these API-reported error conditions.

Shared data must always be guarded – an audit of an application for global or file-scope data that might be shared is very important. Many errors are made in assuming that such data is not shared, and "saving time" by omitting a synchronization guard that later turns out to be important.

Other problems, and techniques to avoid or correct them, are described in the following references.

References

On-Line References

***An Introduction to Programming with Threads*, by Andrew Birrell;**

- http://gatekeeper.dec.com/pub/DEC/SRC/research-reports/abstracts/src-rr-035.html

News:comp.programming.threads

- FAQ @ http://www.serpentine.com/~bos/threads-faq

Win32 API documentation is available on-line to MSDN subscribers at

- http://premium.microsoft.com/msdn/library

***The Single UNIX* Specification, Version 2*, by The Open Group**

- http://www.rdg.opengroup.org/onlinepubs/7908799/toc.htm

Applied Parallel Research

- http://www.apri.com

Kuck & Associates

- http://www.kai.com

Pacific Sierra Research

- http://www.psrv.com

The Portland Group

- http://www.pgroup.com

OpenMP Consortium

- http://www.openmp.org

Rogue Wave Software

- http://www.roguewave.com

Books

- *Programming with Threads*, by Kleiman, Shah and Smaalders; ISBN 0-13-172389-8
- *Threads Primer: A Guide to Multi-Threaded Programming*, by Lewis and Berg, ISBN 0-13-443698-9
- *Multithreading Applications in Win32*, by Beveridge and Wiener; ISBN 0-201-44234-5, see http://www.awl.com/cseng/titles/0-201-44234-5
- *Win32 Multithreaded Programming*, by Cohen and Woodring; ISBN 1-56592-296-4, see http://www.oreilly.com/catalog/multithread
- *Multithreading Programming Techniques* by Shashi Prasad; ISBN 0-07-912250-7, see http://mcgraw-hill.inforonics.com/cgi/getarec?mgh27812

Intel Corporation
P.O. Box 7641
Mt. Prospect, IL 60056-7641
or call 1-800-879-4683

Order Number 283996-001