CSCI 340 Operating Systems

Chapter 4: Threads

Stewart Weiss

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Prologue: Processes Revisited

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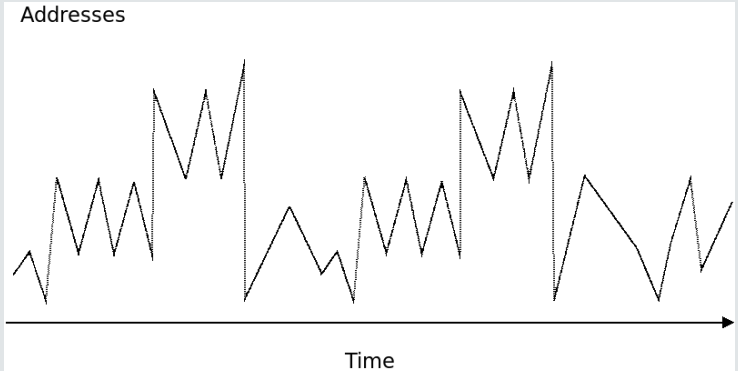
Imagine that when a program executes, each time a machine code instruction is executed, the time of execution and address of the machine code instruction are written to a line of output. A single thread of control through a program would generate a graph such as the one to the right.



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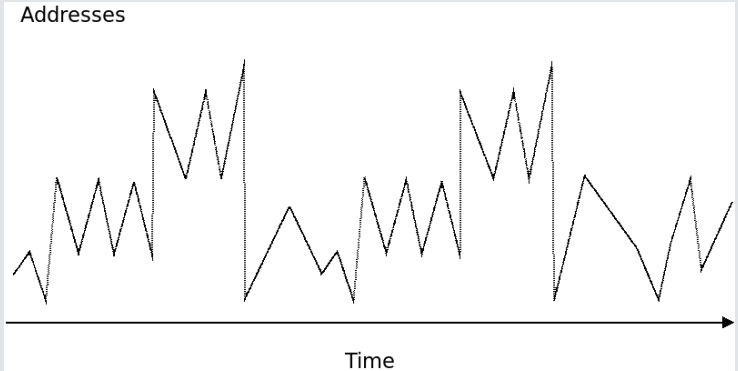

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Food for thought: Why does this graph have repeating patterns, and why does it make big jumps?

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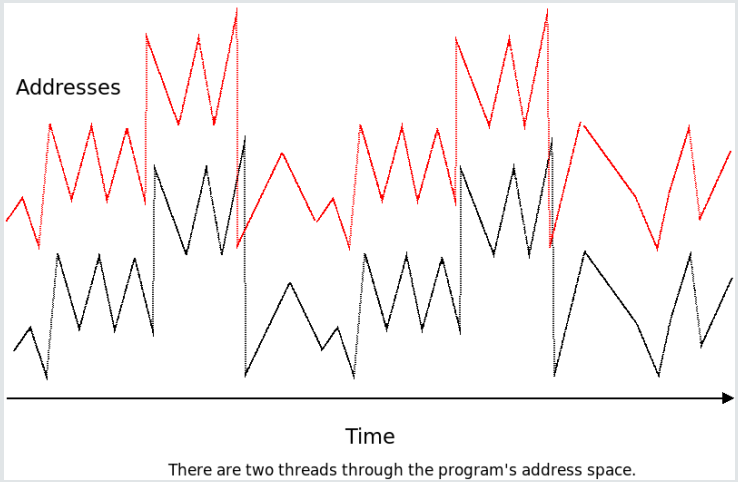

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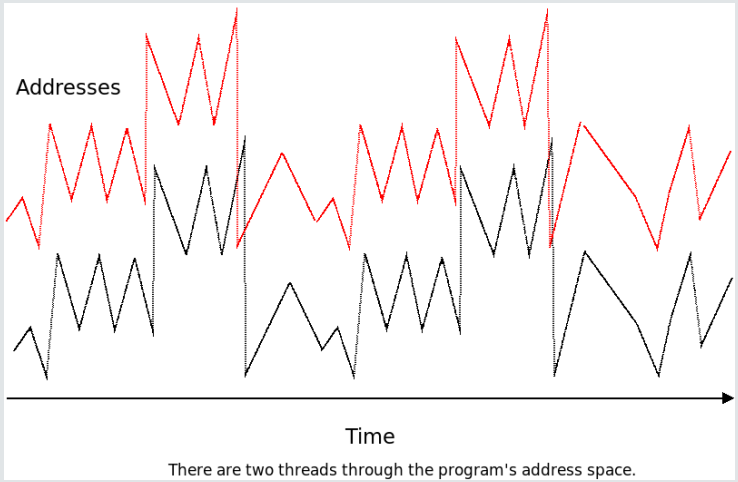

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Some programs can have hundreds or even thousands of threads. **Modern operating system kernels are always multithreaded.**

About This Chapter

Because threads are so ubiquitous and also so hard to understand, they are an important topic in an operating systems course, and this chapter is entirely devoted to their study. In particular, it will cover the following topics:

- Multicore programming
- Explicit Threading
- Thread libraries
- Implicit threading
- Threading issues

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- read and understand simple multithreaded programs that use the Linux threading API.

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- Because threads share many of the same resources, cooperation among the threads that share resources **can** be easier.
- **But multithreading a program is difficult and dangerous and requires great understanding. Hence it is important to understand how to use threads.**

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From this definition, it follows that a thread has resources. In particular, because it executes instructions, it needs access to an address space containing executable code, usually the address space of a parent process.

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We will use this definition of threads for now, but will present an alternative definition later.

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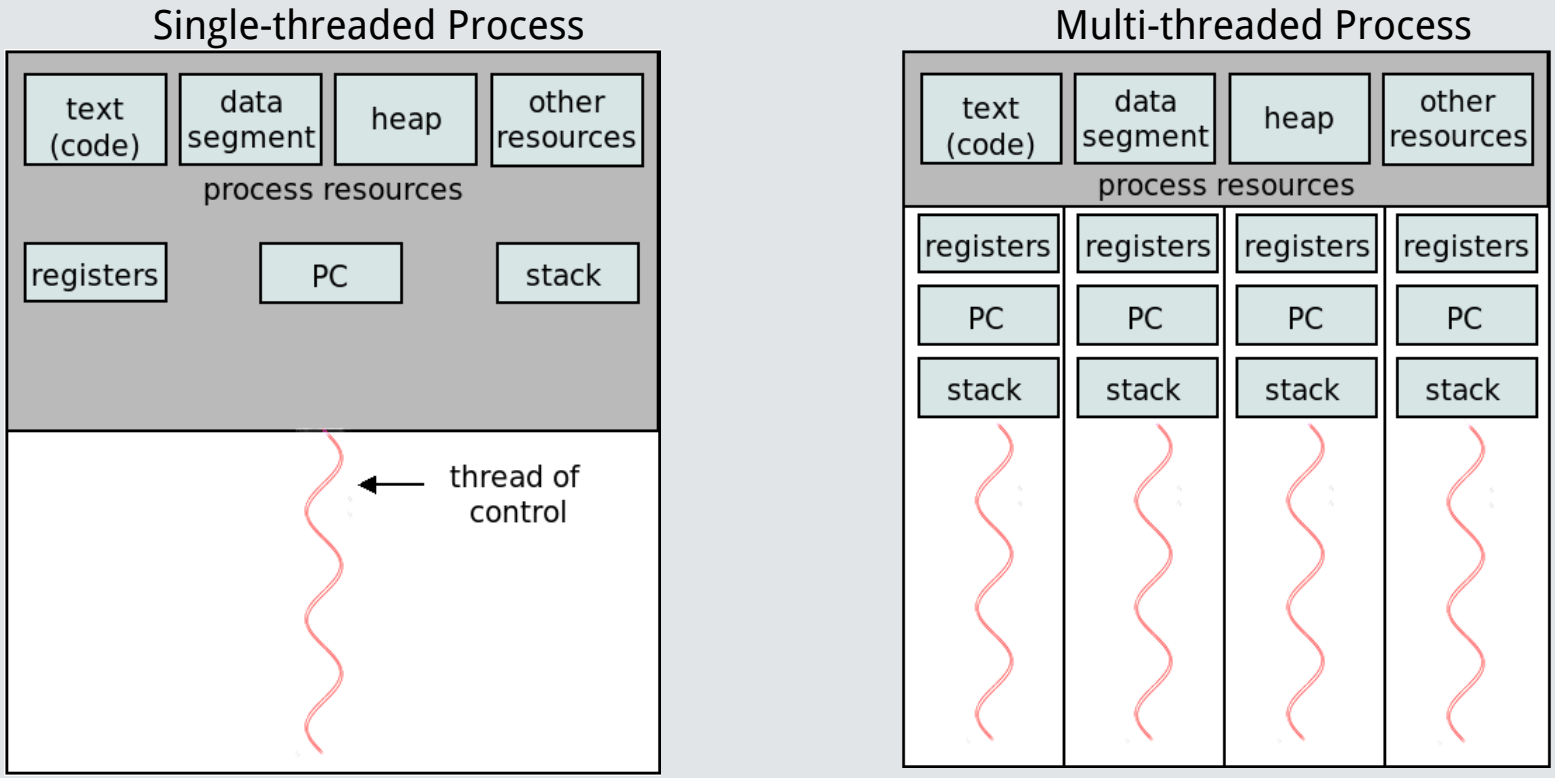
All threads **share** many process resources, but the most important are:

- the executable code, i.e., the **text segment**,
- the **heap** memory, where dynamically allocated data is stored,
- the **data segments**, containing initialized and uninitialized data,
- the **command line arguments**, **environment variables**, and **open files**.

Single- and Multi-Threaded Processes

We can visualize single-threaded and multithreaded processes as shown below:



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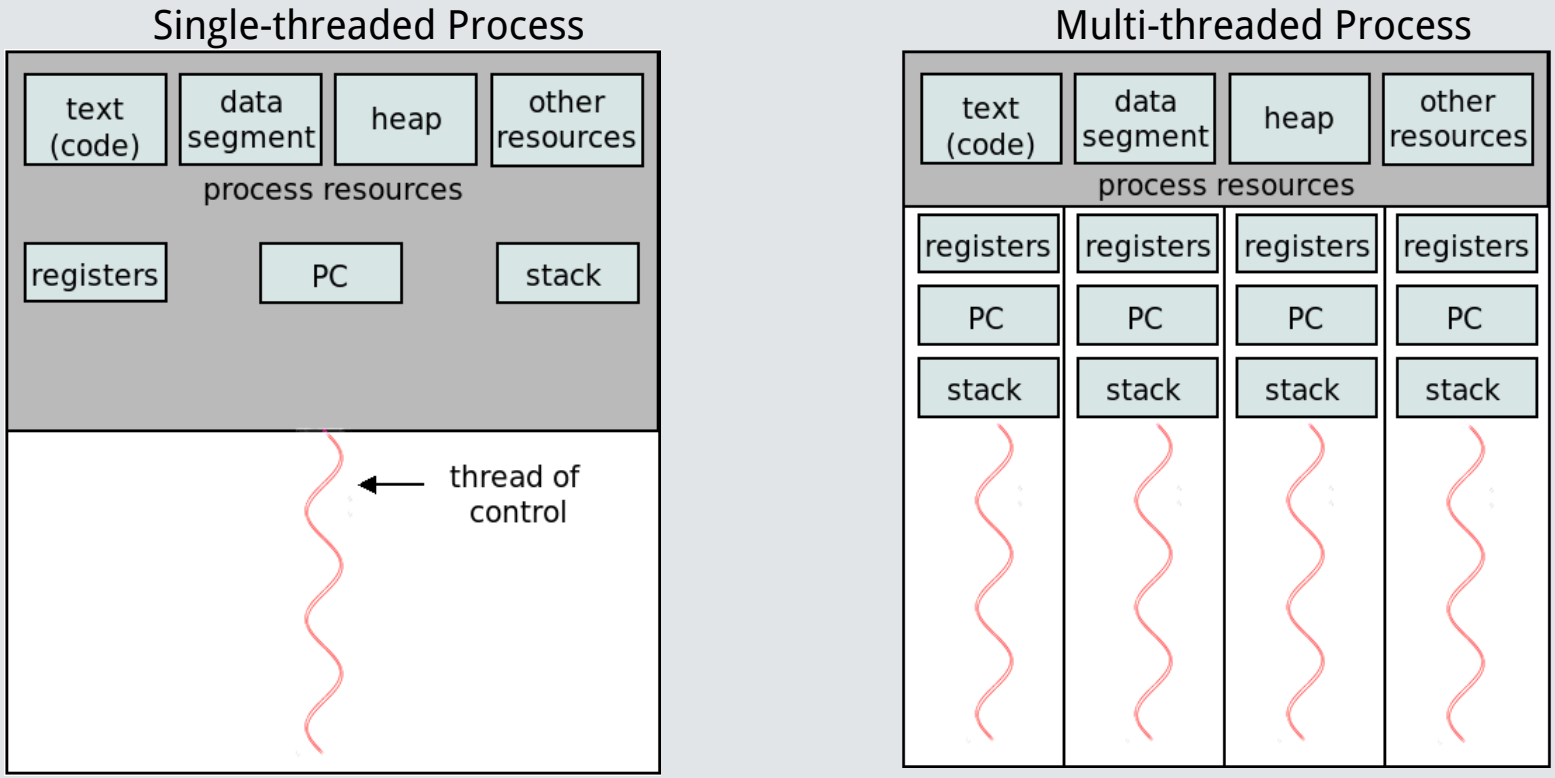
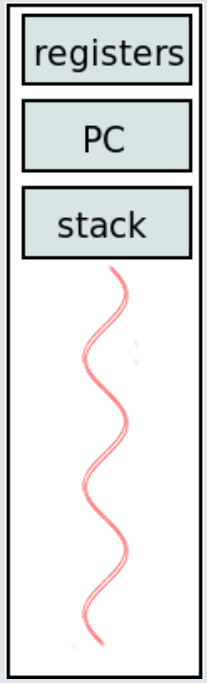


Notice that, in the multithreaded process to the right, each thread's stack, registers, and program counter are no longer process resources, but **thread-private** resources.

Visualizing Threads

In the preceding illustration of a multithreaded process, there were four threads, each of which was represented by the abstract figure to the right. In this figure, the curved line represents the thread of control through the set of instructions executed by the thread.



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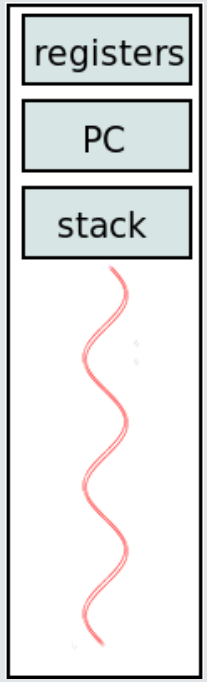

An individual thread is often depicted in a simpler way, eliminating the hardware resources, and just depicting it as just the squiggly flow of control:

We use this convention in the remainder of the notes.

A Thread Counting Activity

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In a few ways. In this activity you will count threads in one particular way.

Login to `eniac.cs.hunter.cuny.edu`. Then run the following command:

```
ps -efwL | more
```

You will see a list of all running processes on `eniac`, including their threads, one screenful at a time. (To advance to the next screen, press the `space` bar; to exit the command, type "`q`".) The last field on the line is the command that was executed to create the process (or thread).

The 6th field (with heading `NLWP`) is the number of threads that the given process has. A process with the value 1 in this column has one thread and is thus not multithreaded.

Which process has the most threads? What is the command that created it?

How many threads does `gnome-shell` have?

Reasons for Multi-threading

There are several good reasons to write programs that can contain multiple threads.

- Code to handle **asynchronous[1] events** can be executed by a separate thread. Each thread can handle its own event without using some type of asynchronous programming construct.

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- Even on a single processor machine, performance can be improved by putting calls to system functions with expected long waits into separate threads. This way, just the calling thread waits, not the whole process.
- The response time of interactive programs can be improved by splitting off threads to handle user I/O. By handling I/O in separate threads, the application can respond quickly, even when time-consuming operations are taking place in other threads.

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Multicore Programming

We explore how programs can be written that take advantage of the multiple cores and/or processors in a multiprocessor machine.

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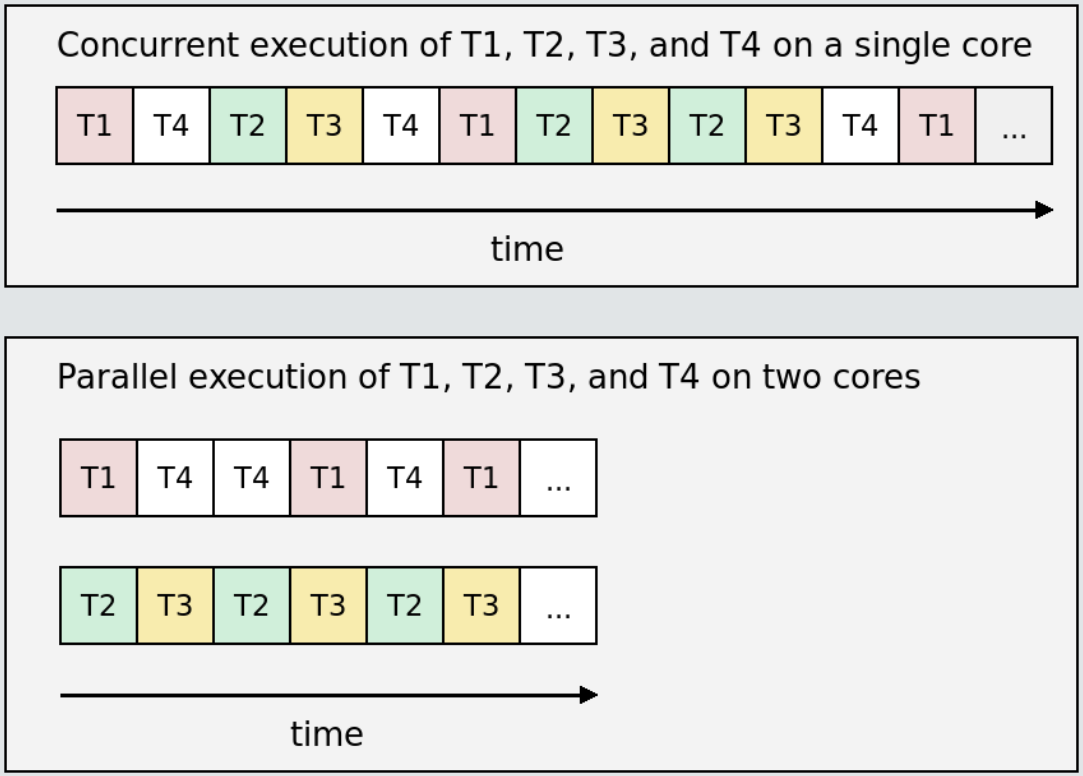
The next slide visualizes the distinction.

Visualizing Concurrency and Parallelism

Imagine four threads, T1, T2, T3, and T4, that can be executed in parallel. If they are executed on a single core, as the top figure illustrates, the system is called a concurrent system and the threads are executed **concurrently**. If they are executed on two cores, as shown in the bottom figure, with T1 and T4 on one core and T2 and T3 on the other, it is **parallel execution**.



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- **Testing and Debugging**. Unlike sequential software, parallel programs can have errors that depend on the relative rates of execution of the subtasks. Designing tests is very difficult and debugging when failure occur is even harder.

Sources of Parallelism in Problems

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- A digital image on which the same operation must be applied to all pixels or equal-size sub-regions of the image.
- The calculation of payroll taxes for all employees of a large company.
- A digital representation of a 3D shape that must be rotated through same angle in space, since every point in the object undergoes the same linear transformation.

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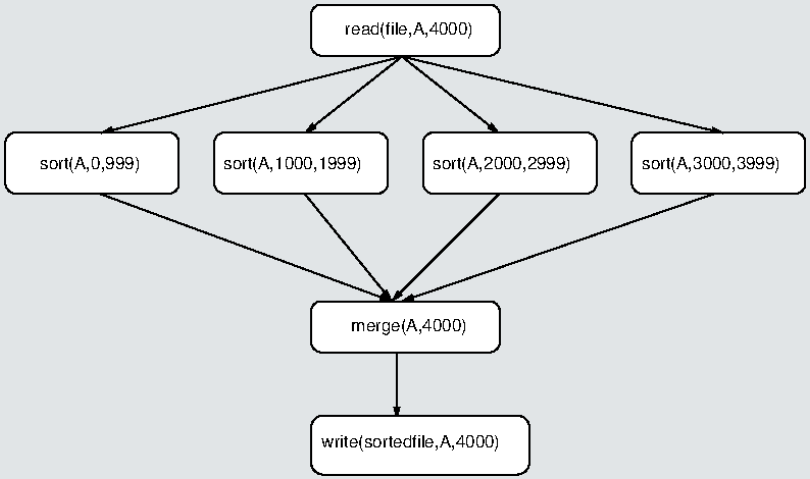
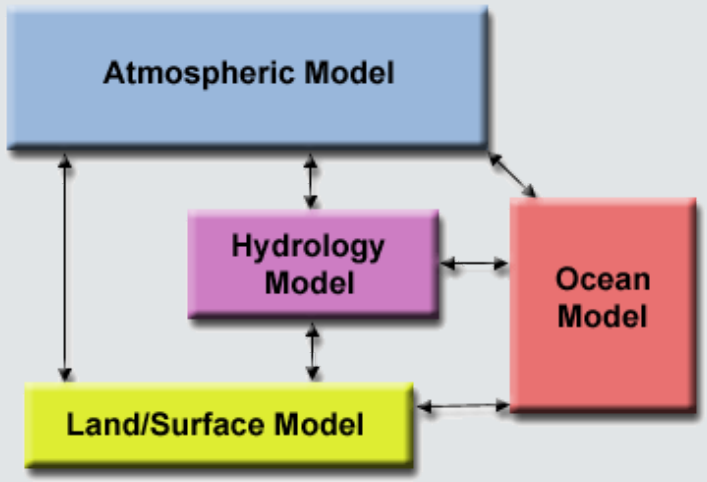
Task parallelism exists when a task can be decomposed into multiple subtasks such that each performs a different function, on the same or different data sets. Examples include

- Analysis of census data by data sub-type, such as demographic analysis, economic analysis, and geographic analysis.
- Audio data processing, in which audio data filters are applied one after another, in a pipeline.

Visual Comparison

A common source of data parallelism exists in linear arrays of data that need to be sorted. Certain sorting algorithms are more amenable than others to decomposition into subtasks that act on segments of the array. The diagram below depicts a variation of a parallel mergesort algorithm.





Meteorological data can be analyzed using a task decomposition. In the diagram above, the same data is input to four different modeling algorithms, to build four different types of environmental models.

Speed-Up

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The **speed-up** of a parallel program with respect to a sequential program on a computer with N identical processors with the exact same input data is the sequential program's running time on one processor divided by the parallel program's running time on N processors.

Limitations of Parallelization

In 1967, Gene Amdahl argued informally[1] that there was an inherent limitation to the amount of speedup that could be obtained by using more processors to perform a computation.

Although his original article contained no formulas whatsoever, his argument was subsequently formulated mathematically and became known as "Amdahl's Law".

The starting premise is the following observation.

Every program has some fraction of operations in it that must be executed sequentially. For example,

- reading from a file, and
- filling an array `A` such that `A[i+1]`'s value depends on `A[i]`'s value for all `i`

are both inherently sequential. In other words, we cannot simultaneously update `A[i]` and `A[i+1]`.

1 See the references at the end of the slides.

Amdahl's Law

Let f be the fraction of operations in a sequential program's computation on a given input that are inherently sequential. f is often called the **serial fraction**.

Let N be the number of processing cores on the computer on which a parallel version of this same program is run. The speed-up of this parallel version using all N processors has an upper bound given by the formula

$$\text{speedup} \leq \frac{1}{f + \frac{(1-f)}{N}}$$

The value $(1 - f)$ is defined as the **parallel fraction**. This represents the fraction of code that can be run in parallel.

Applications of Amdahl's Law

1. Suppose the serial fraction $f = 0.2$. Then the upper bound on speedup for a machine with 8 cores is given by

$$\text{speedup} \leq \frac{1}{0.2 + \frac{(1-0.2)}{8}} = \frac{1}{0.2 + \frac{(0.8)}{8}} = \frac{1}{0.2 + 0.1} = 3.33$$

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Maximum Possible Speedup

The serial fraction itself limits the maximum possible speedup. This is easy to prove.

Let f be the serial fraction of operations in a given program. Then the maximum possible speedup, given any number of processors, is the limit

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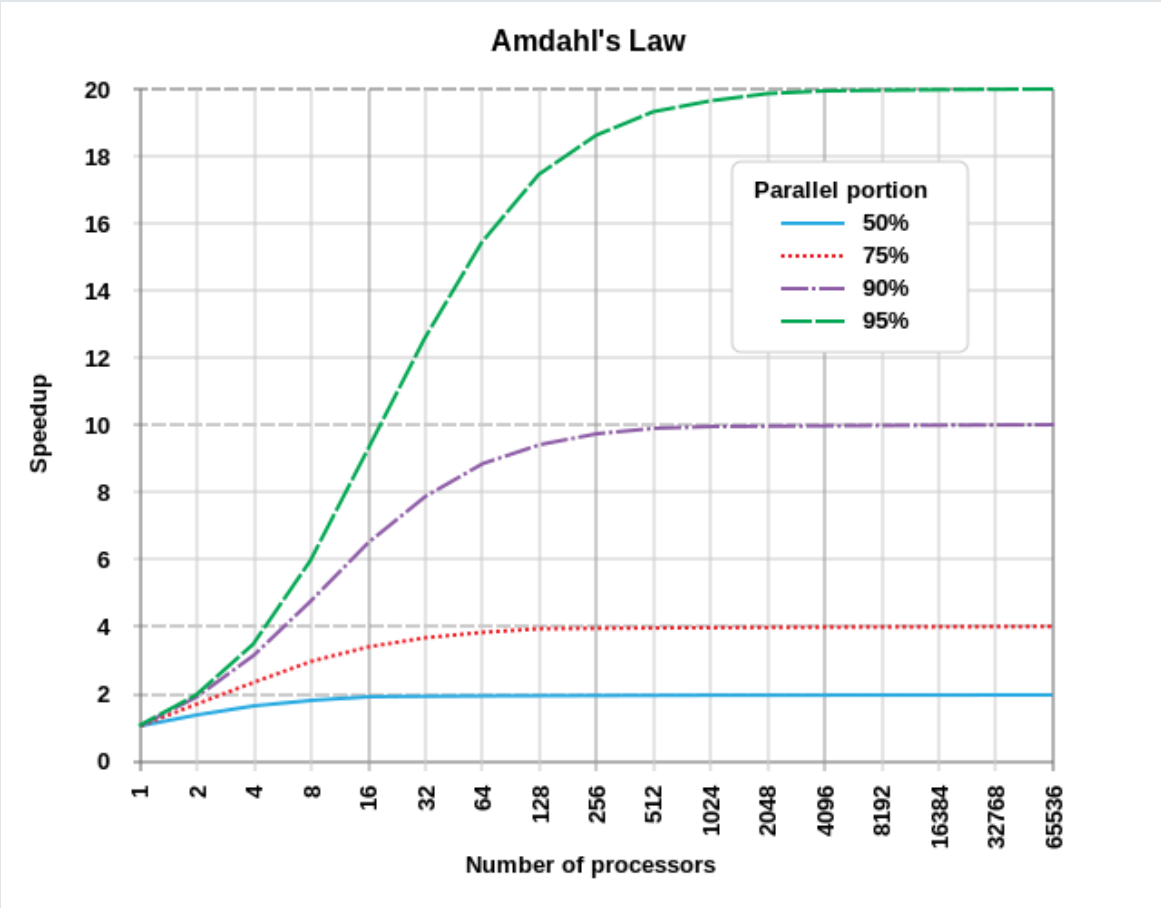
In short, you cannot speed up a program that has little opportunity to be parallelized!

Plot of Amdahl's Law

Below is a plot of the speedup predicted by Amdahl's Law for various fractions of inherently sequential code. The legend labels the curves using the parallel fraction $1 - f$ rather than f
.



Plot by Daniels220 at English Wikipedia, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=6678551

Inverting Amdahl's Law

Suppose that f is the serial fraction of operations in a given program. The maximum possible speedup is $\frac{1}{f}$.

Suppose we want to achieve a specific speedup S less than $\frac{1}{f}$.

How many processors are needed?

1. Use the formula for speedup to write N as a function of f and S.
2. For $f = 0.1$, find the least number of processors needed to obtain a speedup of 5.
3. What if we want a speedup of 8?

Multi-threading Models for Explicit Threading

We examine different methods of implementing support for programmer-defined threads.

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These are all valid questions, and by the end of this section you will understand what the various options are and what limitations each has.

We are about to explore two different methods by which computer systems allow programmers to create multithreaded programs. They are called **multithreading models**.

The difference between the methods is that, in one, threads are implemented in user space, and in the other, in kernel space.

Thread Implementations

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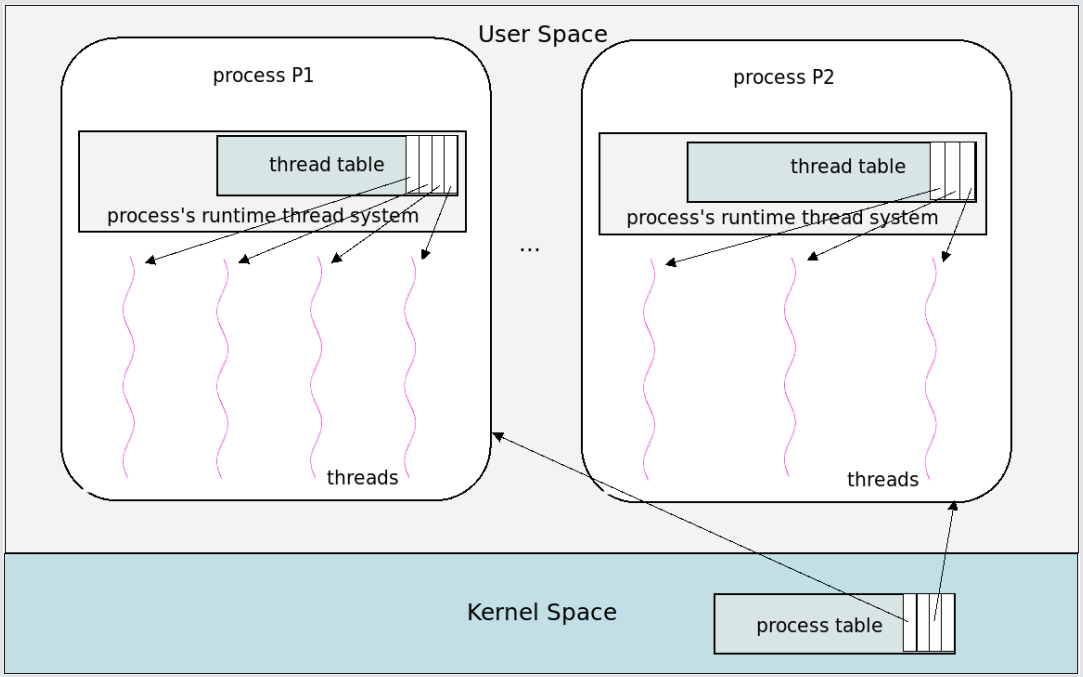
We begin by examining user level threads. After that we examine kernel level threads.

User Level Threads

User level threads are implemented by special thread libraries. A program with multiple threads is linked into the thread library, which handles all aspects of thread management. In the figure below, there are two processes, one with 4 user threads, the other, with 3.



The thread support is handled within the library entirely, in user space. Notice that there are no threads depicted in the kernel in this figure. With user level threads, it is possible to have a multithreaded program in an operating system that may or may not have kernel support for threading. It is independent of kernel support.

A POSIX Threads Example

One of the most common user thread libraries is the one standardized by POSIX, which specifies an API for multithreaded programs commonly known as POSIX threads or Pthreads. This interface is implemented in almost all modern operating systems.

Below is a simple example of a Pthreads program that creates a single child thread.

```
#include <pthread.h> /* Includes of other header files omitted to save space */

void * hello_world( void * unused)
{
    printf("The child says, \"Hello world!\"\n");
    pthread_exit(NULL) ;
}

int main( int argc, char *argv[])
{
    pthread_t  child_thread;
    /* Create and launch thread */
    if ( 0 != pthread_create(&child_thread, NULL, hello_world, NULL ) ){
        exit(1);
    }
    printf("This is the parent thread.\n");
    pthread_join(child_thread, NULL);  /* Wait for the child thread to terminate. */
    return 0;
}
```

Some Explanation

In the preceding program, we highlighted the three calls to functions from the Pthreads API:

```
pthread_exit()
pthread_create()
pthread_join()
```

The `pthread_exit()` call terminates the calling thread. The `pthread_create()` call creates a new thread, called the **child** thread. The caller is the **parent** thread. The `pthread_join()` call makes the main program wait until the child thread makes a call to `pthread_exit()`.

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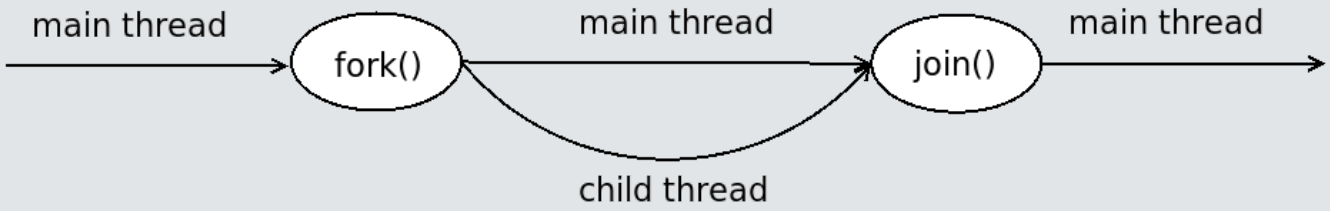
An important point about these functions is that the library implements them by making calls to the underlying operating system thread support system, if it exists. If not, it simulates the operations within the process. This will be explained more later.

Fork-Join Flow

The parallel flow when `pthread_create()` and `pthread_join()` are used is illustrated by the diagram below.



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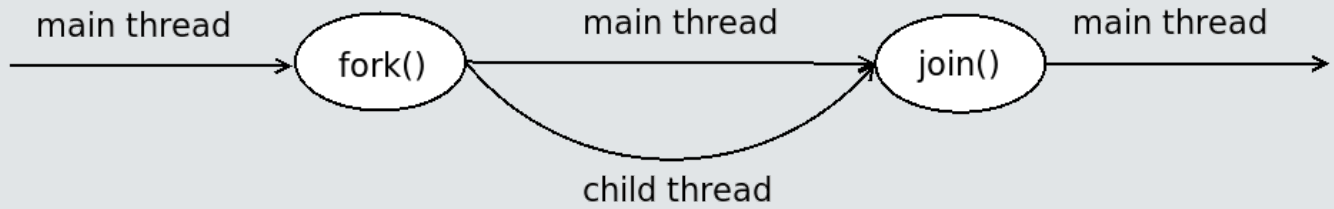
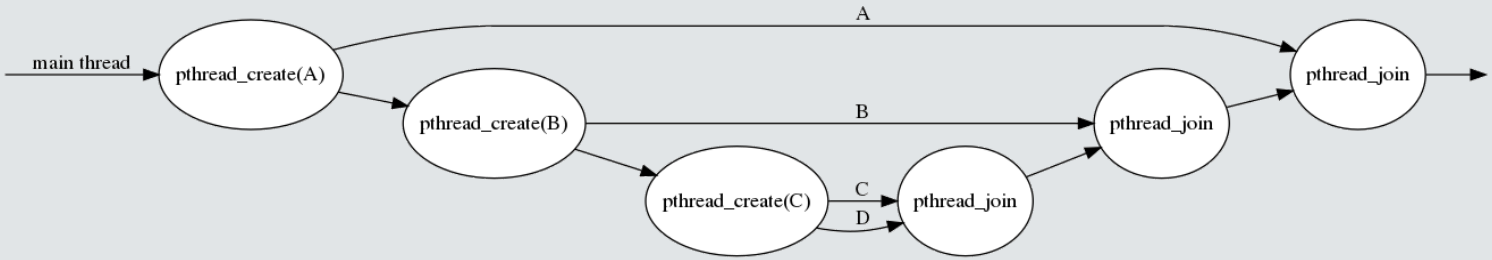


Notice that, after the `join()` call, only the parent thread continues. In this paradigm, a thread creates a child thread and waits for it to finish, after which only the parent thread continues. When multiple threads need to be created, the flow looks something like the diagram below. There is no way to create more than one thread at a time.



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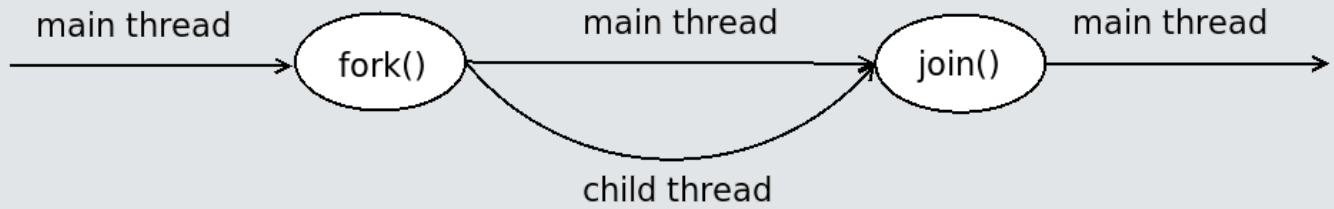

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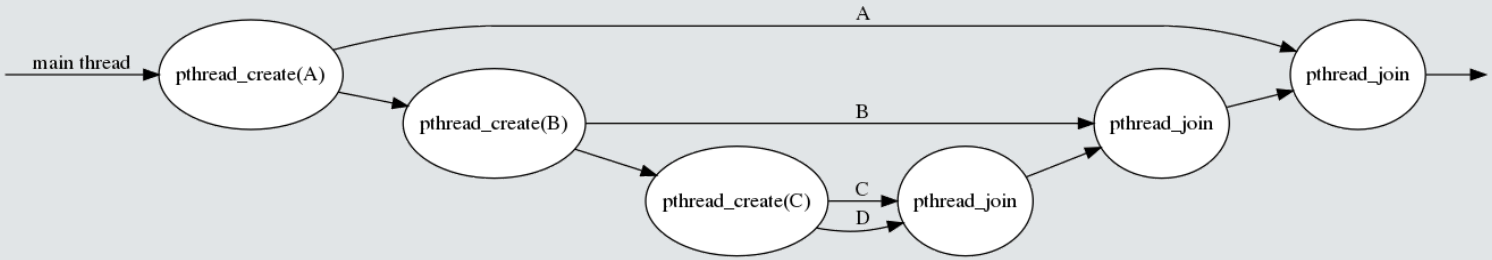

The fork-join paradigm is fundamental to how multithreading is achieved in thread libraries such as Pthreads. It also underlies a type of threading model known as **fork-join parallelism** which we will discuss later in this chapter.

Pthread Activity

The Pthreads program from the Example slide can be found on the network in the `demos` directory. Copy it to your own directory and modify it so that it creates two threads. The second thread will print "Goodbye".

The main program should be designed so that the first thread to print will be the one that prints "Hello World". Look up the `sleep()` function.

The main program should wait for each child thread to terminate.

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- The kernel does not need to have any support for threads for user programs to be multithreaded. All threads run in the process's context.
- Because the library is in user space, code written to run against its API can be run on any computer system for which the library has been implemented.

User Level Threads: Cons

The drawbacks of user threads are that:

- A process with dozens of threads may get the same amount of time on the processor as one with a single thread, depending on the implementation, so the fact that it has many threads does not give it more processor time.

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- A program with multiple threads may not be able to take advantage of multiple processors, since all threads may be mapped to a single processor, depending on the implementation.
- The application programmer generally has no control over how threads are mapped to processors.

Kernel Level Threads

Whereas user level threads are implemented in a user level library, kernel level threads are implemented directly within the kernel. Unlike user level threads, each thread can be individually scheduled.

The kernel also performs thread creation, thread deletion, and all thread management in general. There is no code in the user space for managing the threads, although they exist in user space.

In this sense they are like user processes: processes are created and managed by system calls to the kernel, but they exist in user space and have user privileges.

Kernel Level Threads: The Confusion

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- Threads that run as part of the kernel, in its address space, are called **kernel threads**.
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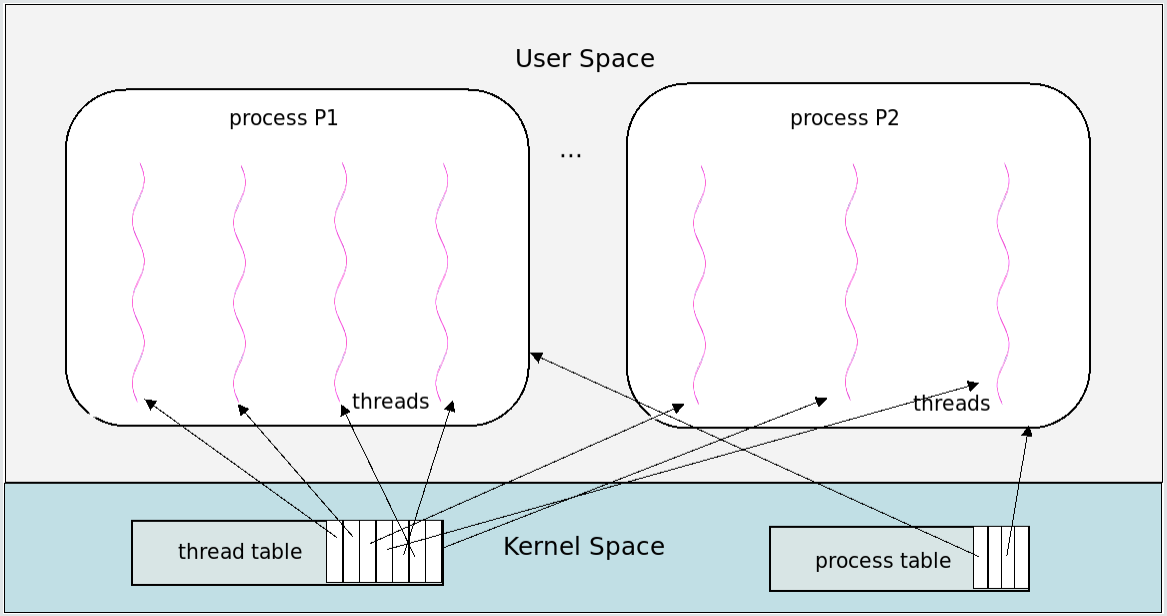
Kernel threads are not the same thing as kernel level threads. The former are threads inside kernel space; the latter are user-space threads scheduled and managed by the kernel.

Kernel Level Threads: A Visualization



In the above figure, the two process's threads are kernel level threads. You can tell this because the thread table that keeps track of the threads is in the kernel's space, not user space.

The figure shows the entries in the kernel's thread table as pointers to the threads in the processes. In practice, the thread table consists of data structures that represent these threads. The pointers in the figure are for illustration only.

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What distinguishes threads from ordinary processes in Linux is that **threads can share resources, such as their address space, whereas processes do not share any resources.**

The implication for the programmer is that the same system call can be used to create kernel level threads as is used to create processes:

```
#define _GNU_SOURCE
#include <sched.h>

int clone(int (*fn)(void *), void *child_stack,
              int flags, void *arg, ...
             /* pid_t *ptid, void *newtls, pid_t *ctid */ );
```

Because it is so generic, it is complicated to use; the `flags` parameter has many possible values that tell the kernel which resources are shared.

The next slide has a small program that demonstrates using `clone()` to create a thread.

Linux Kernel Level Thread Example

```
/* #includes of all header files omitted to save space */

static int child_function(void* arg) /* Function executed by child thread */
{
    char* buf = (char*) arg;
    printf("Child gets buffer containing the string:\n   \"%s\"\n\n", buf);
    strcpy(buf, "Teach your parents well");
    return 0;
}

int main(int argc, char* argv[])
{
    const int STACK_SIZE = 65536;    /* Allocate stack for child thread */
    char* stack = malloc(STACK_SIZE);
    if ( NULL == stack )   exit(1);

    unsigned long flags = CLONE_VM | SIGCHLD; /* share address space */
    char buf[256];
    strcpy(buf, "You, who are on the road must have a code that you can live by.");
    if (-1 == clone(child_function, stack + STACK_SIZE, flags, buf) )  exit(1);

    int status;
    if (-1 == wait(&status) )  exit(1);
    printf("Thread exited with status %d. It filled buffer with:\n   \"%s\"\n",status,buf);
    return 0;
}
```

Linux Kernel Level Thread Example

When the preceding program is run, the session looks like

```
$ kernel_thread_demo
Child gets buffer containing the string:
   "You, who are on the road must have a code that you can live by."

Child exited with status 0. It filled the buffer with:
   "Teach your parents well"
$
```

Some Notes:

- The program must dynamically create a stack for the cloned thread. Because stacks grow from high to low memory, the starting address of the stack is the value of the address returned by `malloc()` plus the stack size.
- The `CLONE_VM` flag is passed to `clone()`. This tells the kernel that the parent's memory is to be shared with the child rather than copied.
- The `SIGCHLD` flag tells the kernel that the child will call `exit()` and the parent is going to `wait()` for the `SIGCHLD` signal to receive the child's termination status.

Kernel Level Threads: Pros and Cons

The benefits of kernel level threads are that:

- Kernel level threads from a single process can be scheduled simultaneously on multiple processors, taking advantage of the hardware.
- A thread that blocks as a result of a service request does not prevent other threads in the same process from being scheduled to run. This is a big advantage to highly interactive programs that can block frequently for short durations.
- The kernel can allocate more processor time to processes with larger numbers of threads.
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- The kernel can allocate more processor time to processes with larger numbers of threads.
- The kernel itself can be multithreaded.

The drawbacks of kernel level threads are that:

- It is slower to create kernel level threads and more work to manage them because there is more work in the kernel.
- Switching between threads in the same process requires kernel intervention and is therefore slower.
- Representing threads within the kernel requires a complete PCB.

Implementation of User Level Threads

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Implementation of User Level Threads

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If the underlying kernel has no support for threading at all, then the user level thread library must simulate all thread operations in user space. The library in this case uses what we call the Many-to-One threading model, which we explain first.

If, on the other hand, the kernel has support for threading, there are two different choices of thread implementation:

- The One-to-One Model
- The Many-to-Many Model

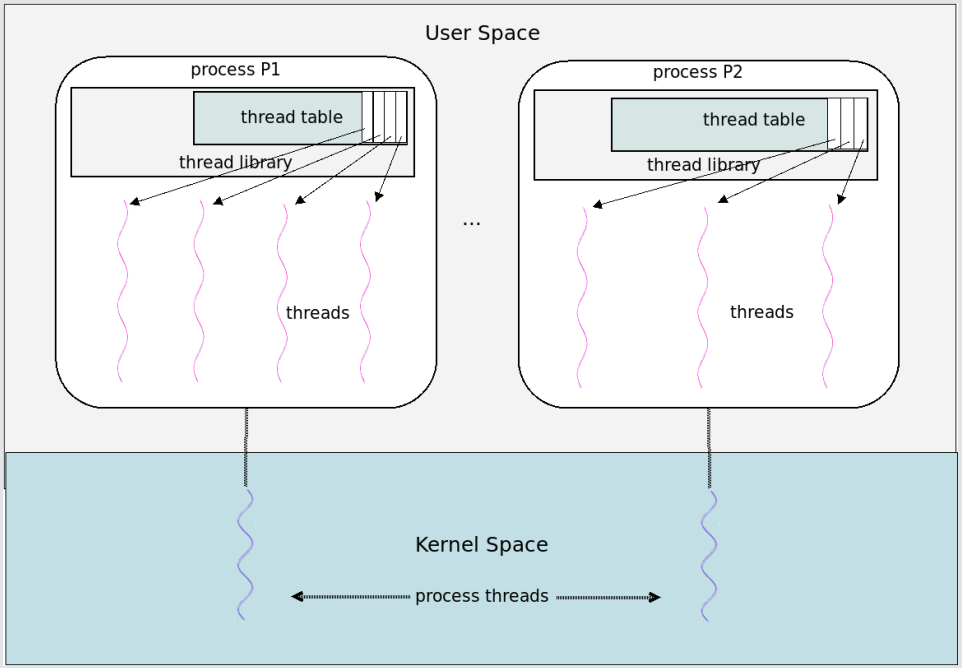
The differences between the different models have to do with how user level threads are related to kernel level threads.

Many-to-One (M:1) Threading Model

This method is rarely used anymore and is mostly of historical interest[1]. It was used originally because it requires no support for multithreading at the kernel level and is the most portable, but it has significant performance problems.

All threads are implemented in user space within the process, which appears to the kernel to be an ordinary, single-threaded process.

In the figure to the right, we draw the process threads on which the user-level threads run, inside the kernel space. This does not mean that the process executes kernel code. It means that the data structures that represent the process are in kernel space.



1 The Green Threads library in Solaris and early Pthreads on Linux used this approach.

Many-to-One (M:1) Threading Model Pros and Cons

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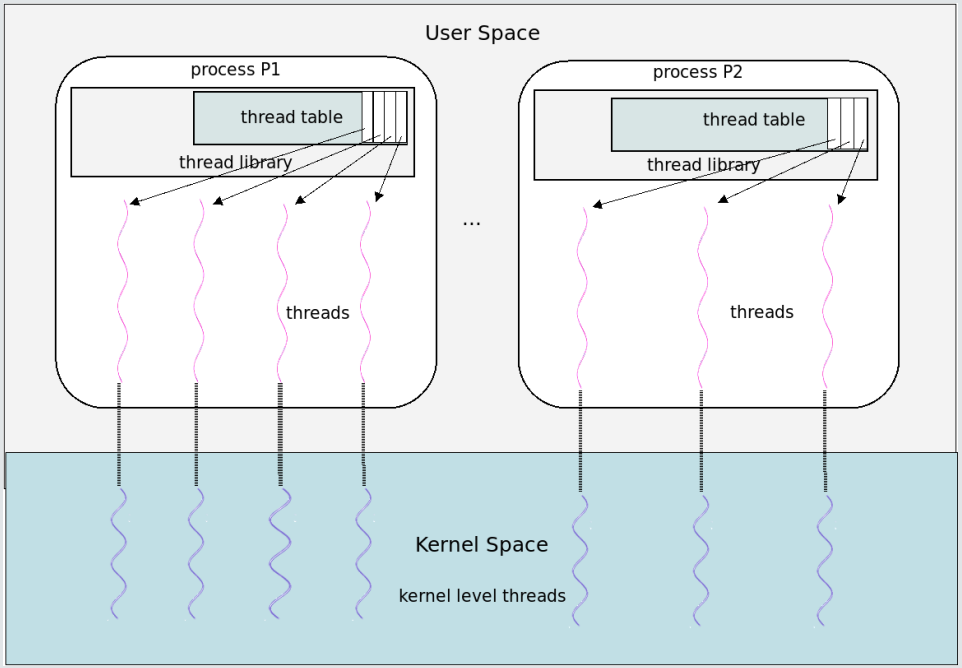
- A second is a consequence of the first. Some **blocking system calls cannot be simulated by non-blocking system calls**; as a result, when a thread makes such a call the entire process is blocked.
- A third, major drawback is that a **program cannot take advantage of more than a single processor** because the kernel sees it as a single-threaded process (as a single schedulable unit.)

One-to-One (1:1) Threading Model

The **One-to-One model** assigns a kernel level thread to each user level thread. Implementations of `Pthreads` in current Linux versions and **Windows** systems use this approach.

From now on, kernel level threads are drawn in kernel space to indicate that the data structures and code that represent and manage them is in kernel space.



In the figure above, each user level thread is associated with a real kernel level thread. In Linux, this simply means that the library uses the `clone()` system call to create the threads. **Each thread is seen by the kernel as a separately schedulable entity.**

One-to-One (1:1) Threading Model Pros and Cons

This model has several **benefits**:

- It is the simplest to implement within a library,
- It provides the greatest possible concurrency because it can use as many processors as are available, up to the number of threads, and
- One thread's blocking does not block other threads.

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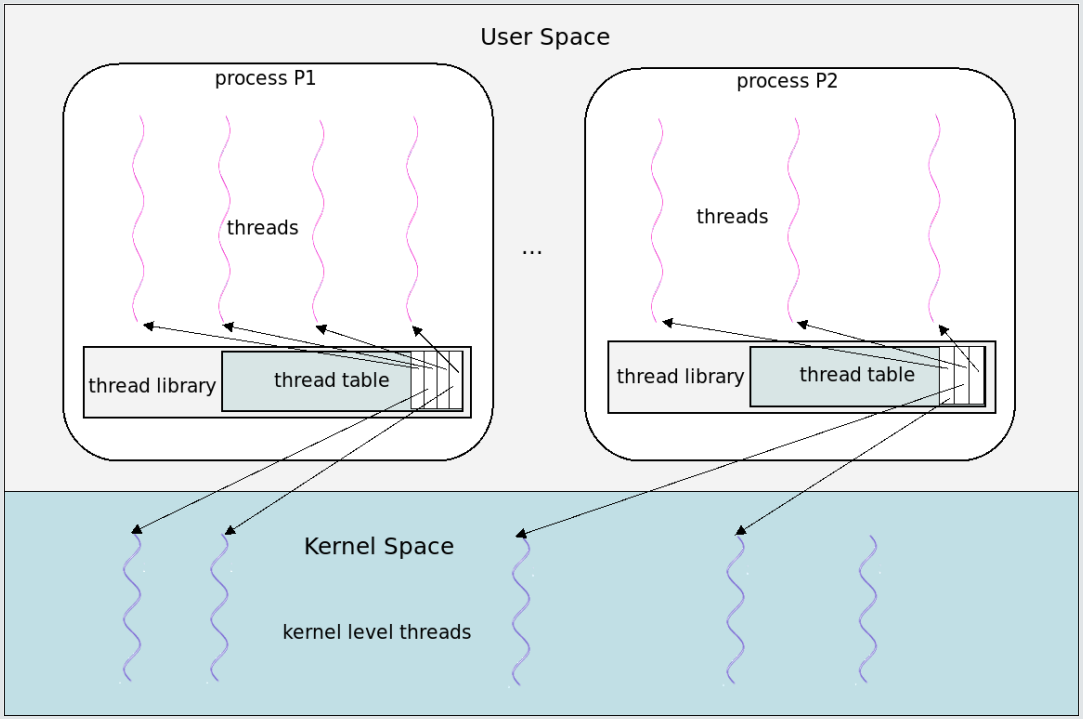
However, the **drawbacks** are the following.

- Creating each thread is more expensive in terms of kernel resources,
- Thread management is slower because most operations on threads require system calls, and
- It is dependent on the multithreading model of the underlying kernel.

Many-to-Many (M:N) Threading Model

The **Many-to-Many model** is the most flexible of these models. It does not create a kernel level thread for each user level thread like the (1:1) model, nor does it force all of a program's threads to be scheduled on a single kernel level thread.

Instead, the library **creates multiple kernel level threads and schedules user level threads on top of them.** Most M:N thread libraries will dynamically allocate as many kernel level threads as necessary to service the user level threads that are ready to run.



Many-to-Many (M:N) Threading Model Pros and Cons

This model has several benefits. The most significant include:

- It does not use kernel resources for user level threads that are not actually runnable.
- The library-level scheduler can switch between threads much faster because it does not make system calls.
- It performs better than the others when user level threads synchronize with each other.
- Applications that create large numbers of threads that only run occasionally perform better on this model than in the others.

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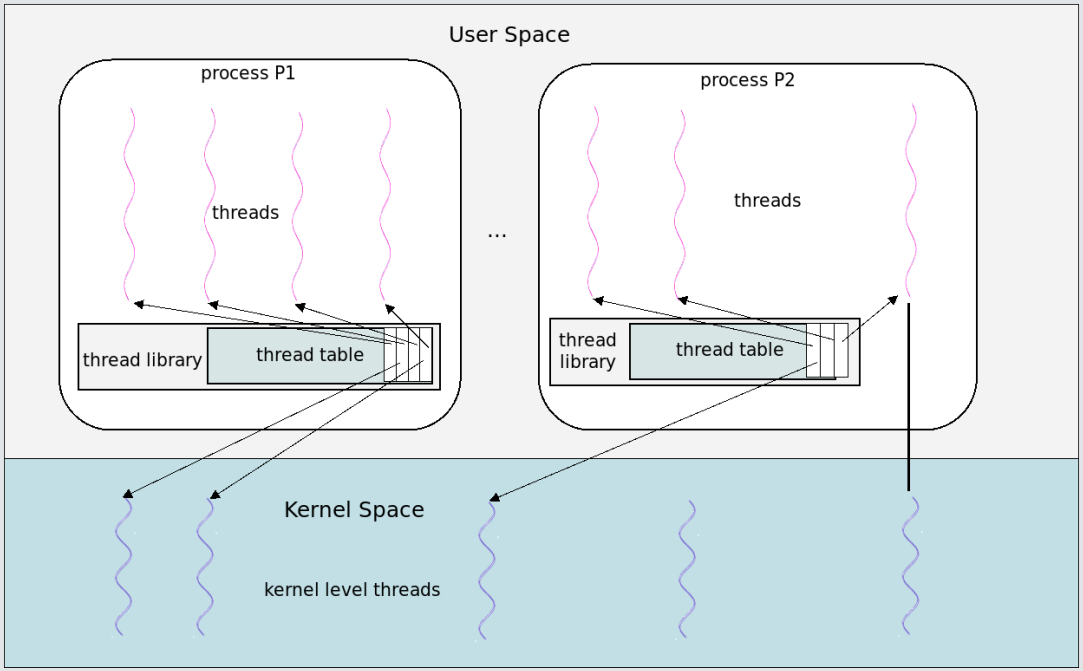
The drawbacks of this model include:

- It has more overhead and consumes more system resources because scheduling takes place in both the kernel among the kernel level threads for the process and in the library for the user level threads.
- User level threads that are bound to the same kernel level thread can still be blocked when the thread that is running makes a blocking system call.

Two-Level Threading Model

The two-level model is similar to the M:N model except that it also allows some user-level threads to be bound to a single kernel-level thread. This is useful when certain threads should not be prevented from running because a thread that is sharing its kernel level thread blocks.



Scheduler Activations

In the M:N and two-level models, when an underlying kernel level thread blocks, there is no way for the kernel to notify the user level thread manager that the thread has blocked, so that it can allocate more kernel level threads.

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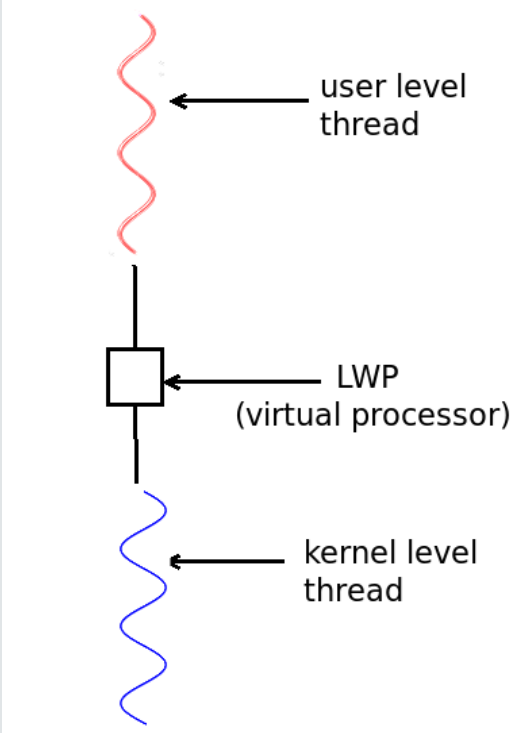
In 1991, a model called **scheduler activations**[1] was proposed to overcome this problem.

In this model, the kernel provides the process with the abstraction of **virtual processors**. To a user process, a virtual processor acts like an actual processor on which a user level thread can run. It is however just a data structure, sometimes called a **Light Weight Process** (**LWP**).

Each LWP is bound to a kernel level thread. The kernel level thread is scheduled to run on an available processor. If it blocks, the LWP blocks, and the user level thread attached to the LWP blocks.



1 Thomas E. Anderson, Brian N. Bershad, Edward D. Lazowska, and Henry M. Levy. "Scheduler activations: Effective kernel support for the user-level management of parallelism." *Proc. 19th ACM Symposium on Operating System Principles*, pp. 95-109, 1991.

Scheduler Activation Use

Kernel events that could affect the number of runnable threads, such as blocking system calls, are communicated directly to the user process using **upcalls**, which are messages sent to the user level thread manager.

Upcalls are handled within the thread manager by an **upcall handler** (which is like a signal handler). The upcall handlers must run on a virtual processor.

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6. The user level thread manager moves the other threads to the new virtual processor and schedules one of the ready threads to run on it.

Implicit Threading

In this section we examine ways in which multithreaded programs can be generated from single-threaded programs with varying amounts of programmer direction.

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One way to overcome these difficulties is to **offload some of the programming tasks from developers to compilers and run-time libraries.**

Implicit threading refers to any of several different methods of multithreading a program in which compilers and/or libraries create and manage concurrent threads with little or no explicit guidance from the programmer.

The "implicit" aspect of it is the creation and management of threads, not the specification of parallelism.

Parallelizing Compilers

Much research has been put into the design of compilers that free programmers completely from the tasks of multithreading programs.

For example, it is possible for a compiler to detect that, in a sequential loop such as this:

```
for ( int i = 0; i < 100; i++)
    a[i] = b[i] + c[i];
```

the loop body can be executed in parallel by up to 100 different threads simultaneously[1].

These parallelizing compilers analyze the code and determine automatically where fine-grained parallelism[2] exists. They can then arrange for selected instructions to be executed by separate threads.

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Studies have shown that 90% of the execution time of most programs is spent in 10% of the code, mostly in loops. Therefore, much of the effort is in detecting the parallelism in loops. Unfortunately there are many difficulties with this, particularly in the presence of pointers and recursion.

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- **Intel Threading Building Blocks** (TBB) is a template library that supports the design of multithreaded, shared-memory programs inC++.

Types of Implicit Threading

Greater success is achieved when the programmer can assist the compiler in detecting parallelism.

Implicit threading systems typically require some guidance from the programmer. Usually the programmer must identify tasks that can be executed in parallel. Often these tasks are either functions or structured code blocks, like the body of a loop.

Some well-known implicit threading systems include:

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- **Intel Threading Building Blocks** (TBB) is a template library that supports the design of multithreaded, shared-memory programs in`C++`.
- **Java Concurrency** refers to the multithreading, concurrency and parallelism available from the `Java Virtul Machine`, which is entirely thread-based. `java.util.concurrent` is the class that provides this concurrency.

Underlying Technology

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The first problem leads to poor CPU utilization and wasted memory resources. The second could lead to system degradation.

To solve this, rather than constantly creating and deleting threads, the implementation can maintain a pool of threads, like a collection of workers sitting in a room waiting to be assigned work to do. When work comes in, the **worker thread** is assigned to it. When it finishes, it goes back to the waiting room.

Thread Pools

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- If there is an available thread in the pool, it is awakened and assigned to the process to execute the task.
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Benefits

- Servicing a request with an existing thread is faster than creating a thread.
- A thread pool limits the number of threads that exist at any one point.
- Separating the task to be performed from the mechanics of creating the task means different strategies can be used for running and scheduling the task.

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The Fork-Join Model

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The **fork–join model**, also known as **fork-join parallelism**, is like the explicit thread creation that we saw earlier in the Pthreads library in that threads are created by a parent thread, and their executions reach a join point after which only one thread continues.

Unlike Pthreads, the model does not limit the creation of threads to just one thread at a time.

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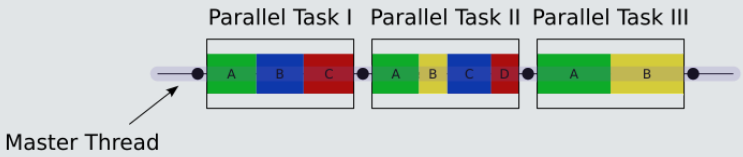
Unlike Pthreads, the model does not limit the creation of threads to just one thread at a time.

The example we give is based on the following figure from the Wikipedia article about the fork-join model[1].

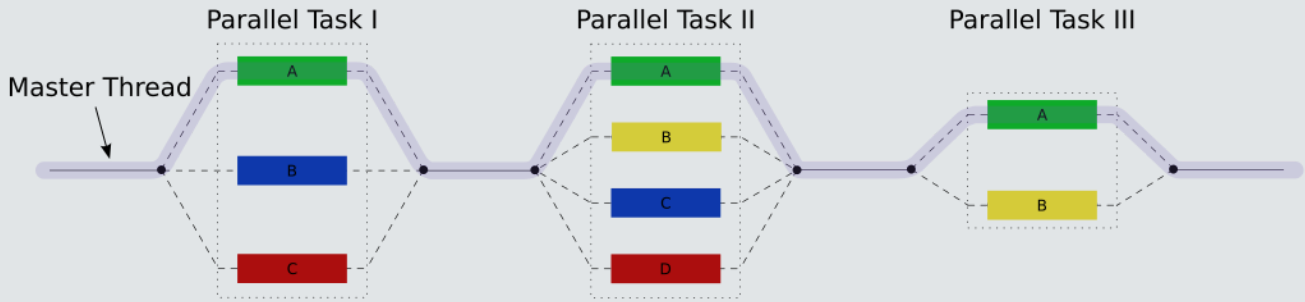


In the figure above, a sequential program has been analyzed, and it is determined that the program has three regions that must be executed sequentially, but that within each region there are varying numbers of parallel tasks, randomly colored and labelled A,B,C, and D.

1 https://en.wikipedia.org/wiki/Fork%E2%80%93join_model#/media/File:Fork_join.svg

Fork-Join Parallelism

A multithreaded program following the fork-join model can be created based on this analysis. The flow through it would be represented by the diagram below.



In the above figure we see that the master thread (always green) forks two new threads and continues to run, so that there are three threads. They join, the master thread executes alone and then forks three threads. The threads join, master runs again and finally just forks one thread and runs with it. After they join, the master thread continues on its own.

This model is used in the implicit threading library employed by Java. It is also the paradigm defined in OpenMP.

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OpenMP Overview

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  - **Compiler directives**, used by programmers to define **parallel regions**
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- It has three primary API components:
  - **Compiler directives**, used by programmers to define **parallel regions**
  - **Runtime library routines**, which extend the language with OpenMP functions
  - **Environment variables**, used to control the behavior of OpenMP programs
- The parallelism in OpenMP programs is exclusively through the use of threads. Most implementations (such as GNU) use thread pools to manage the threads.
- OpenMP uses the **fork-join** model of parallel execution. An OpenMP program begins as a single thread called the **master thread**. The master thread executes sequentially until the first parallel region is encountered.

OpenMP Key Features

- OpenMP defines **parallel regions** as blocks of code that may run in parallel.
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- Programmers insert compiler directives into their code at parallel regions; these directives instruct the OpenMP run-time library to execute the region in parallel.
- Parallel regions are specified using compiler directives, known as **pragmas**. For example, a simple directive is

```
#pragma omp parallel
```

  which specifies that the following statement is to be executed by some number of threads in parallel.

- Because OpenMP is a shared memory programming model, most data within a parallel region is shared by default. It can also be made explicit:

```
// declare a and i before
#pragma omp parallel shared(a) private(i)
```

  is a `C/C++` pragma that specifies the start of a parallel region with a variable `a` shared by all threads and a thread-private variable named `i` of which each thread has a private copy.

OpenMP Run-time Routines

OpenMP has a rich set of compiler directives for specifying parallel for-loops, critical sections of code, nested parallel regions, and much more.

The run-time library has routines for such things as

- Setting and querying the number of threads
- Querying a thread's unique identifier (thread ID)
- Querying if execution is within a parallel region, and at what level
- Setting and querying nested parallelism
- Setting, initializing and terminating locks and nested locks
- Querying clock time

OpenMP Example Program

Following is a simple OpenMP program, demonstrating two parallel regions with sequential code in between. OpenMP creates a thread for each core by default.

```
#include <omp.h>
#include <stdio.h>

int main (int argc, char *argv[])
{
    #pragma omp parallel  // executed by default number of threads
    {
        printf("I am a distinct thread.\n");
    }

    // The following code is executed only by the master thread.
    omp_set_num_threads(8);        // set number of threads to 8
    int N = omp_get_max_threads(); // get max num threads
    printf("There are %d threads\n", N);

    #pragma omp parallel   // Executed by 8 threads
    {
        int ID = omp_get_thread_num();  // get thread id of executing thread
        printf("hello world from thread %d\n ", ID);
    }
    return 0;
}
```

Grand Central Dispatch

Grand Central Dispatch (**GCD**) is a technology developed by Apple Inc. for use on symmetric multiprocessors/cores. In 2009, the underlying library, `libdispatch`, was released as open source under the `Apache 2.0` license.

- It provides support for programs written in various languages, including `C`, `C++`, `Objective-C`, and `Swift`.

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- A task can be expressed either as a function or as a **block**. A **block** is an extension to the syntax of C, C++, and Objective-C that encapsulates code and data into a single object. A block is specified by a caret `^` inserted in front of a pair of braces `{ }`:

```
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- GCD queues the designated tasks for execution and schedules them onto an available thread to run on any available processor.
- The underlying support for `libdispatch` is the POSIX threads library, but most of the support comes from non-POSIX compliant Apple extensions.

Example of a GCD Program

This is an example of a Grand Central Dispatch program. It creates a block that just prints a message with the id of the thread that it is assigned to. The block is dispatched onto a concurrent queue.

The code is designed to show a bit of the internals of GCD. It is based on code written by Jonathan Levin (http://newosxbook.com/articles/GCD.html).

```
#include <stdio.h>
#include <dispatch/dispatch.h>
#include <pthread.h>

int main (int argc, char *argv[])
{
    void (^myblock) (void) =
         ^{ printf("My pthread id is %d\n", (int) pthread_self()); };
    dispatch_queue_t myqueue =
       dispatch_queue_create("example of queue",  DISPATCH_QUEUE_CONCURRENT);

    dispatch_group_t dgroup = dispatch_group_create();
    dispatch_group_async(dgroup, myqueue, myblock);

    int rc= dispatch_group_wait(dgroup, DISPATCH_TIME_FOREVER);
    return rc;
}
```

Threading Issues

We explore some of the issues that arise in the design and implementation of threading systems, whether they are in user level libraries or kernels.

Issues with `fork()`

The `fork()` system call was designed for processes. Threads were not part of UNIX when it was invented. When a process calls `fork()`, a new one is created that is nearly identical to the original.

When a thread that is part of a process issues a `fork()` system call, a new process is created. **Should just the calling thread be duplicated in the child process or should all threads be duplicated?**

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- Most implementations duplicate just the calling thread. Duplicating all threads is more complex and costly.
- But some systems provide both possibilities with `fork()`. For example, **Oracle Solaris**'s `fork()` duplicates all threads but its `fork1()` duplicates just the calling thread.

Issues with the `exec()` Family

The various system calls in the `exec()` family for processes replace the process's address space entirely, giving it a new program to execute. For example, the call

```
execve("/bin/echo", argv, envp);
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would cause the calling process to execute the `/bin/echo` program with the arguments passed in `argv` using the environment variables pointed to by `envp`.

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Earlier versions of Linux detached the calling thread from the original process and ran the new program in it, letting all other threads continue to run in the old address space.

Signals

Signals are a complex topic, even just for single-threaded programs. We will explain signals in an intuitive way to start.

You should think of yourself as a process. Assume that when the phone rings, your default behavior is to answer it. Assume too that you are a responsible driver and that when you are driving a car you always keep your seat belt buckled. Lastly, you will not answer the phone when you are driving.

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You stop and answer it. The phone ringing is a **signal** sent to you. Your answering the call means that the signal was **delivered** to you. The act of answering the call is called **handling the signal**.

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The fact that you answer the phone is part of your **disposition** towards the phone ringing signal.

Image from Wikimedia Commons by Videoplasty.com, CC-BY-SA 4.0.

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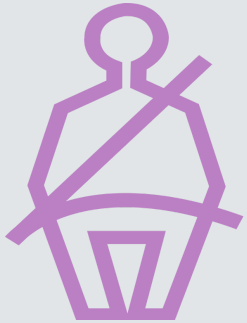
Now you get in the car and start to drive. An annoying horn sounds to remind you that your seat belt is not fastened.



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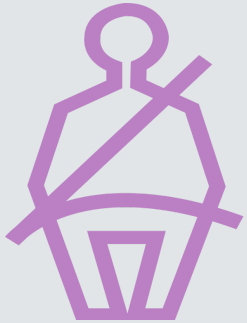

You fasten the seat belt. The horn sounding is a **signal** as well, and your fastening the seat belt means that the horn signal was **delivered** to you, and that you **handled the signal** as well.

Unlike the phone ringing, the horn sounding is a **synchronous** signal. It happened because of your failure to buckle up. As a process, you skipped a step you were supposed to do, the operating system (the car) intervened and reminded you of it.

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You silence the phone. You have just temporarily **blocked** the phone-ringing signal from being **delivered** to you. While the phone is silenced, people can still call, but you do not answer the phone. When you finish driving, you can restore the phone's volume, unblocking the signal.

Blocking a signal does not prevent someone from calling; it just prevents the signal from being delivered to you.

Signal Handling

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The sequence of actions with respect to any type of signal is:

1. A signal is **generated** by some event.
2. The signal is **sent** to a process by the kernel.
3. The signal is **pending** until the next step.
4. The signal is **delivered** to the process when the process takes some action with respect to it, which is either performing the **default action**, **ignoring** it, or catching the signal with a **signal handler**. The **disposition** of the signal is how the process behaves when the signal is delivered.

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A **signal** is an empty message sent to a process because an event occurred. It has type and nothing more.

A signal may be received either **synchronously** or **asynchronously**. Traps and other exceptions are examples of signals received synchronously. Timer interrupts (`SIGALRM`), keyboard interrupts Control-C (`SIGINT`), and terminal disconnections (`SIGHUP`) are examples of asynchronously received signals.

The sequence of actions with respect to any type of signal is:

1. A signal is **generated** by some event.
2. The signal is **sent** to a process by the kernel.
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Each signal type has a **pending flag** indicating whether or not it is pending, and a **blocked flag** indicating whether or not it is blocked.

Signals and Threads: Issues

The question of how to handle signals in a multithreaded process has been debated since the early days of POSIX threading, and there have been extensive changes in the POSIX standard over the past few decades.

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- Can threads send signals to specific threads or to all threads in a process?

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- The dispositions of all signals are process-wide, meaning that all threads share the same signal handler, or all ignore the signal, and so on.
- In Linux, there are functions (system calls and library routines) that allow a process or thread to send signals to one or more other processes (`kill`) or to specific threads (`tgkill`). A thread can send a signal to itself (`raise`) or to a thread in its same process (`pthread_kill`).

Thread Cancellation

Sometimes a thread might need to be terminated by another thread before it has finished its work.

Thread cancellation is the act of terminating a thread that has not yet terminated itself. With thread cancellation, one thread can **try to terminate** another.

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There are many reasons to allow thread cancellation. For example, suppose threads are searching in parallel for a key in a large database. Each is searching through a different portion of the data. Only one thread can find the key. When it does, the others should not continue to run, because they will accomplish nothing.

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Terminology: A thread is **canceled** if it is terminated. The thread to be canceled is called the **target thread**.

Thread Cancelability

Most thread systems provide some means for one thread to request cancellation of another. One issue is whether cancellation should be immediate, or should be delayed. Sometimes a thread is in the middle of a computation that should not be interrupted or else shared data will be corrupted.

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POSIX defines two types of cancellation:

- **Asynchronous cancellation**: A thread can cancel the target thread immediately.
- **Deferred cancellation**: A thread attempts to cancel the target thread, but the target thread is not canceled immediately. Instead, it terminates when it reached a point in its execution when it is safe to do so.

Thread Cancelability Control

In POSIX, a thread decides its own fate.

- It can set its **cancelability type** to be either asynchronous or deferred. For example, this code is used by a thread to give it deferred cancelability:

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When threads have deferred cancelability, they terminate when they reach safe points in their code, called **cancellation points**. Cancellation points are calls to selected functions. When the thread calls one of these functions, it terminates.

Thread Cancellation Points

Most of the blocking system calls in the POSIX and standard C library are cancellation points. If you enter the command

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The Pthreads API has several functions related to thread cancellation. See the program `thread_cancel_demo.c` on the server for a complete, documented example.

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