Threads

Chapter 4

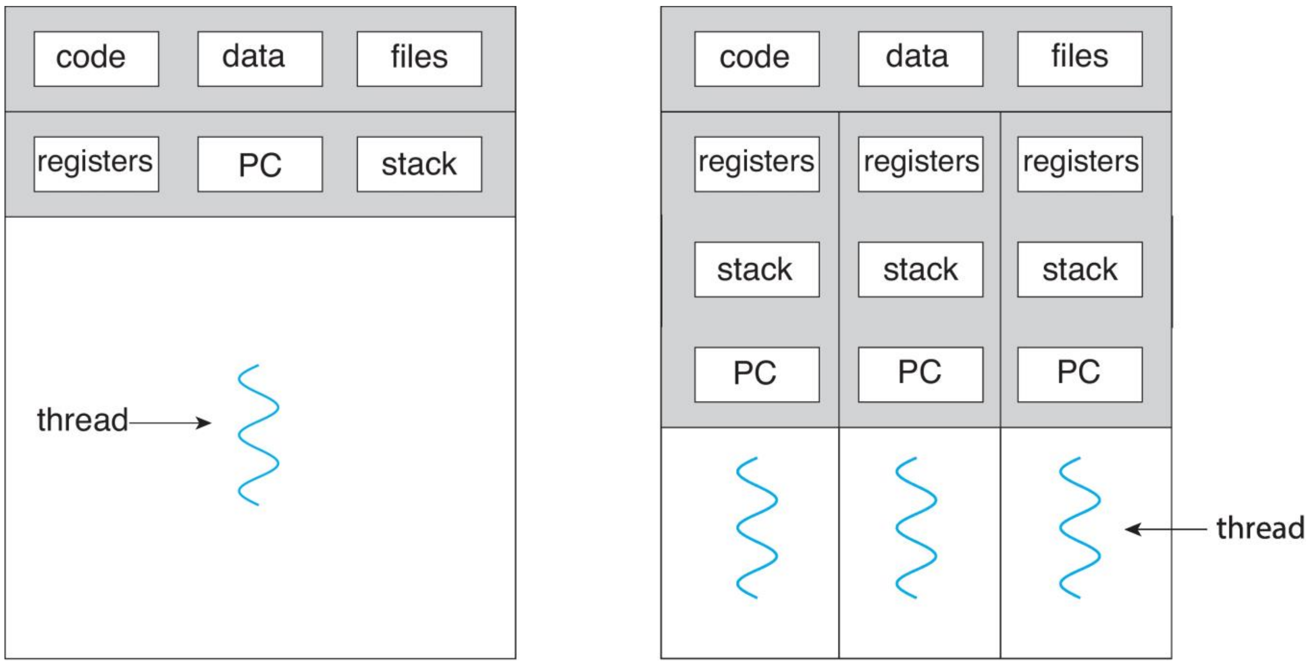
Review

- Process is a program in execution that can be in a number of states
  - New, running, waiting, ready, terminated
- Process creation
  - fork() and exec() system calls
- Inter-process communications
  - Shared memory, and message passing
- Client-server communication
  - Socket, RPC, …

Threads

- Traditional processes have a single thread of control. Most modern applications are multithreaded
- Multi-threaded processes have multiple threads of control
  - The threads share the address space and resources of the process that owns them.
- A **thread** (a lightweight process) is a basic unit of CPU utilization.
  - A thread has a single sequential flow of control.
  - A thread is comprised of: A thread ID, a program counter, a register set and a stack.
- A **process** becomes the execution environment in which threads run.
  - (Recall previous definition of process: program in execution).
- The **process** has the code section, data section, OS resources (e.g. open files and signals).

Single and Multithreaded Processes



single-threaded process

multithreaded process

Threads encapsulate concurrency: "Active" component

Address spaces encapsulate protection: "Passive" part Keeps buggy program from trashing the system

Processes vs. Threads

Which of the following belong to the process and which to the thread?

Program code:	Process
local or temporary data:	Thread
global data:	Process
allocated resources:	Process
execution stack:	Thread
memory management info:	Process
Program counter:	Thread
Parent identification:	Process
Thread state:	Thread
Registers:	Thread

Control Blocks

- The thread control block (*TCB*) contains:
  - Thread state, Program Counter, Registers

- *PCB*' = everything else (e.g. process id, open files, etc.)

- The process control block (PCB) = *PCB*' U *TCB*

Why use threads?

- Because threads have minimal internal state, it takes less time to create a thread than a process (10x speedup in UNIX).
- It takes less time to terminate a thread.
- It takes less time to switch to a different thread.
- A multi-threaded process is much cheaper than multiple (redundant) processes.
- Threads share an address space and thus make it easy to share data

Benefits of Multi-threads

- Responsiveness:
  - Threads allow a program to continue running even if part is blocked.
  - For example, a web browser can allow user input while loading an image.
- Resource Sharing:
  - Threads share memory and resources of the process to which they belong.
- Economy:
  - Allocating memory and resources to a process is costly.
  - Threads are faster to create and faster to switch between.
- Scalability:
  - Multi-thread process can take advantage of multiprocessor architectures

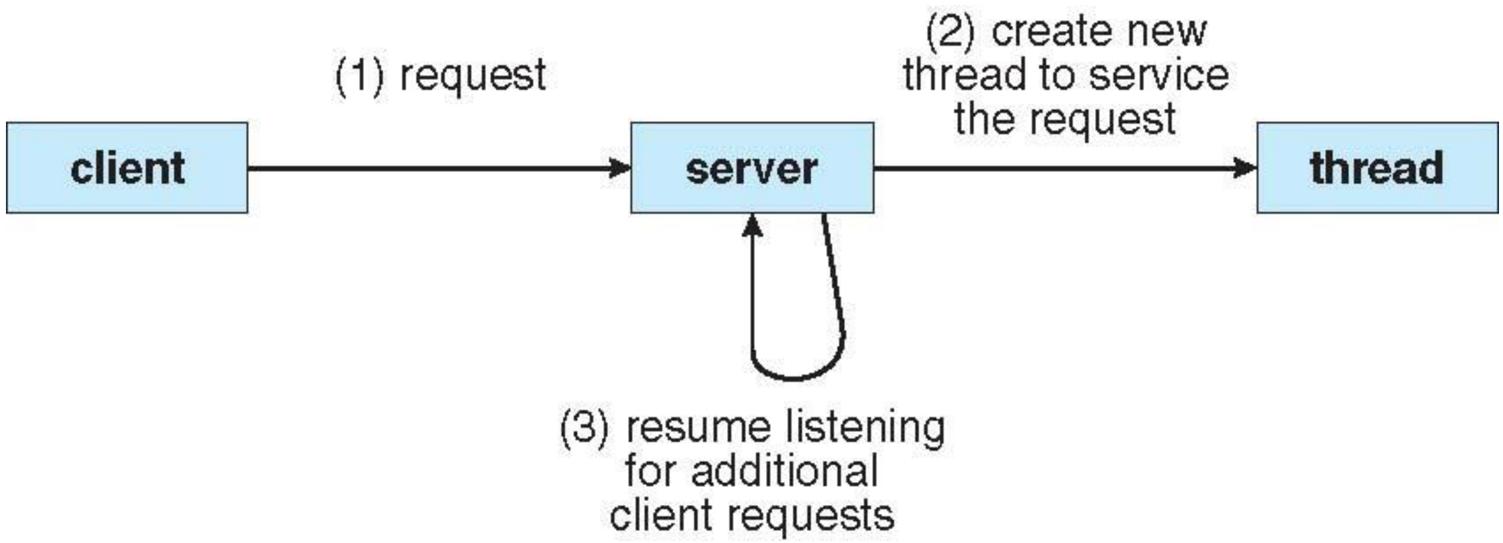
Examples of Using Threads

- Threads are useful for any application with multiple tasks that can be run with separate threads of control.
- A Word processor may have separate threads for:
  - User input
  - Spell and grammar check
  - displaying graphics
  - document layout
- A web server may spawn a thread for each client
  - Can serve clients concurrently with multiple threads.
  - It takes less overhead to use multiple threads than to use multiple processes.

Examples of multithreaded programs

- Most modern OS kernels
  - Internally concurrent because have to deal with concurrent requests by multiple users
  - But no protection needed within kernel
- Database Servers
  - Access to shared data by many concurrent users
  - Also background utility processing must be done
- Parallel Programming (More than one physical CPU)
  - Split program into multiple threads for parallelism. This is called Multiprocessing

Multithreaded Server Architecture



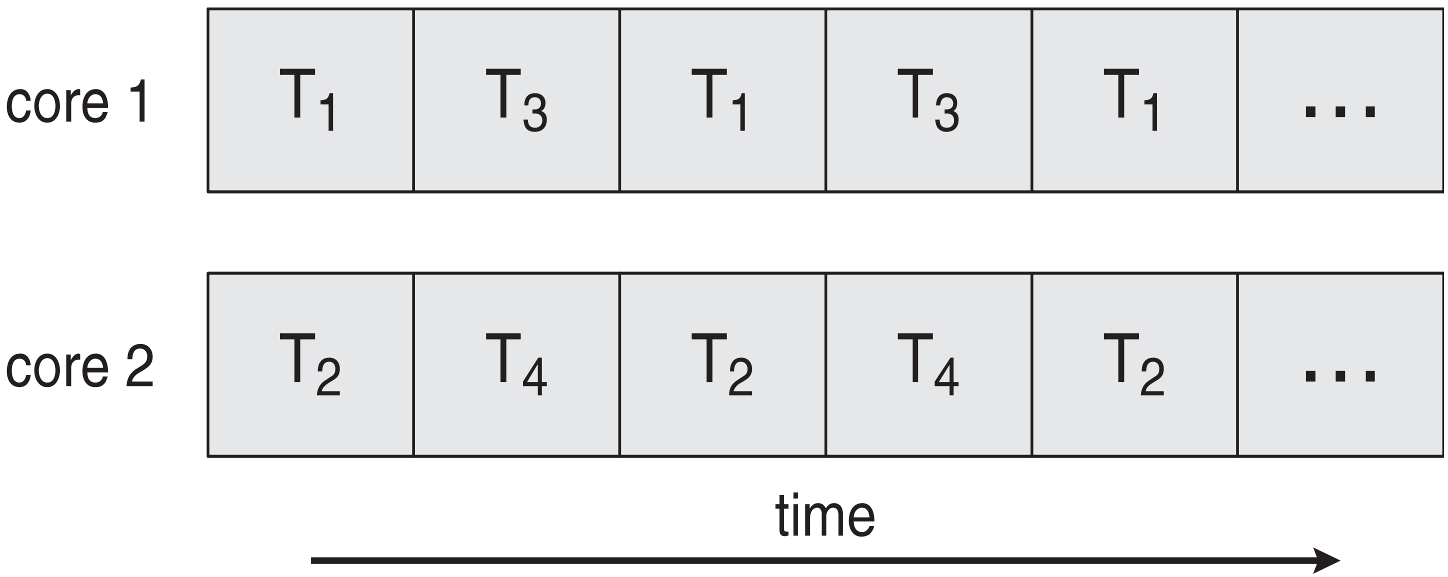
Parallel Programming

- **Multicore** or **multiprocessor** systems putting pressure on programmers, challenges include:
  - **Dividing activities**
  - **Balance**
  - **Data splitting**
  - **Data dependency**
  - **Testing and debugging**
- ***Parallelism*** implies a system can perform more than one task simultaneously
  - **Data parallelism** – distributes subsets of the same data across multiple cores, same operation on each
  - **Task parallelism** – distributing threads across cores, each thread performing unique operation
- ***Concurrency*** supports more than one task making progress
  - Single processor / core, scheduler providing concurrency

Concurrency vs. Parallelism

- **Concurrent execution on single-core system:**

- **Parallelism on a multi-core system:**



Thread Libraries

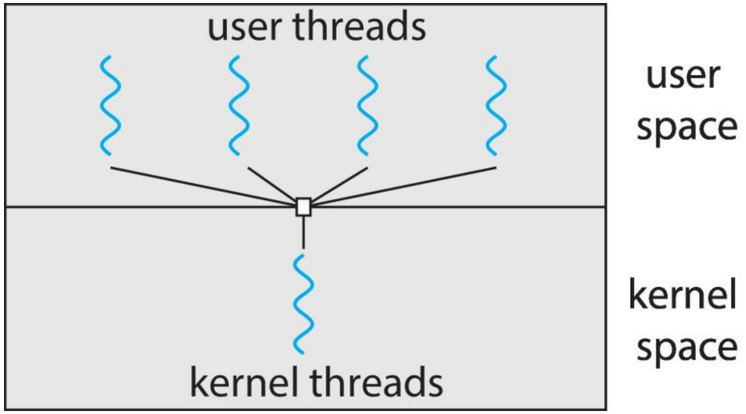
- Thread library provides programmer with API for creating and managing threads. Three primary thread libraries:
  - POSIX Pthreads
  - Win32 threads
  - Java threads
- Pthreads is a POSIX standard (IEEE 1003.1c) API for thread creation and synchronization
  - API specifies behavior of the thread library, implementation is up to development of the library
  - May be provided either as user-level or kernel-level
  - Common in UNIX operating systems (Solaris, Linux, Mac OS X)

User Threads and Kernel Threads

- Two primary ways of implementing Threads libraries
  - Library entirely in user space
  - Kernel-level library supported by the OS
- **User threads** - management done by user-level threads library
- **Kernel threads** - Supported by the Kernel
  - Threads managed by the OS Kernel.
    - Kernel does creation, scheduling and management of threads.
  - Examples – virtually all general purpose operating systems, including: Windows, Solaris, Linux, Mac OS X
  - User-level threads are mapped to kernel thread.

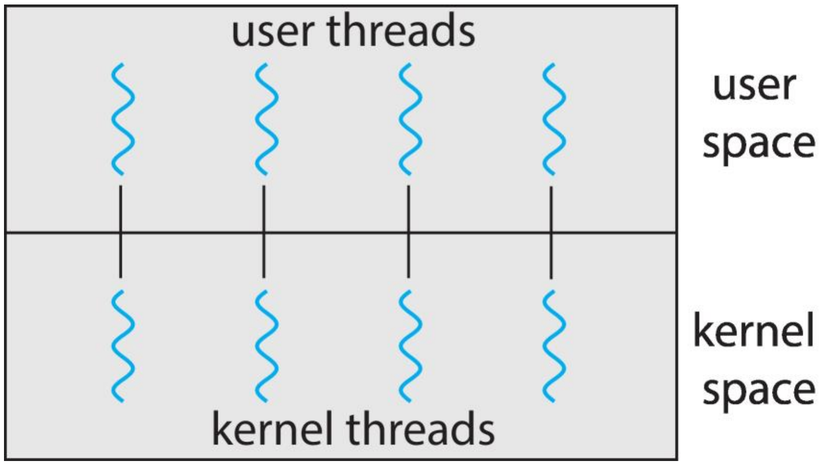
Many-to-One

- Many user-level threads mapped to single kernel thread
- One thread blocking causes all to block
- Multiple threads may not run in parallel on multicore system because only one may be in kernel at a time
- Few systems currently use this model
- Examples:
  - **Solaris Green Threads**
  - **GNU Portable Threads**



One-to-One

- Each user-level thread maps to kernel thread
- Creating a user-level thread creates a kernel thread
- More concurrency than many-to-one
- Number of threads per process sometimes restricted due to overhead
- Examples
  - Windows
  - Linux
  - Solaris 9 and later

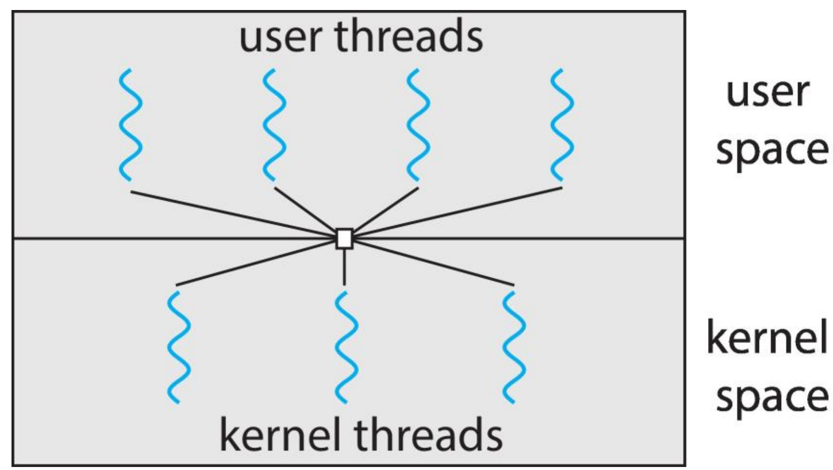


Pros and Cons of One-to-one Mapping

- Pros:
  - System call from a thread does not block other threads in the same process.
  - One process can use multiple processors.
  - Create/destroy/switch of threads is less expensive than for processes.
- Cons:
  - Create/destroy/switch of Kernel Level threads is more expensive than for user level threads.
  - CPU scheduling algorithms are unfair: Each thread is given the same time slice. Tasks with more threads are given more CPU time than those with fewer threads.

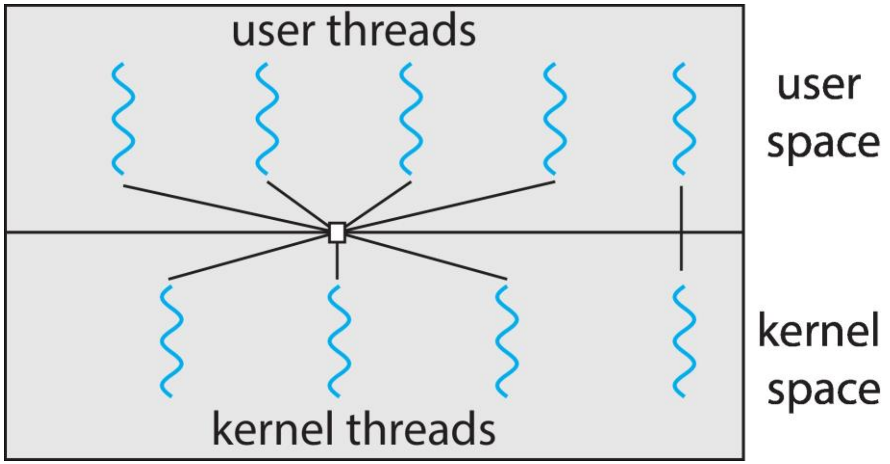
Many-to-Many Model

- Allows many user level threads to be mapped to many kernel threads
- Allows the operating system to create a sufficient number of kernel threads
- Solaris prior to version 9
- Windows NT/2000 with the *ThreadFiber* package
- Otherwise not very common



Two-level Model

- Similar to M:M, except that it allows a user thread to be **bound** to kernel thread
- Examples
  - IRIX
  - HP-UX
  - Tru64 UNIX
  - Solaris 8 and earlier



Summation Problem

- Compute summation 0+1+…+N
- N is a non-negative number provided as a command-line argument
- We want to create a new thread to compute the summation and print out the result in the main thread.

Pthreads Example

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

int sum; /* this data is shared by the thread(s) */
void *runner(void *param); /* threads call this function */

int main(int argc, char *argv[])
{
   pthread_t tid; /* the thread identifier */
   pthread_attr_t attr; /* set of thread attributes */

   if (argc != 2) {
      fprintf(stderr,"usage: a.out <integer value>\n");
      return -1;
   }
   if (atoi(argv[1]) < 0) {
      fprintf(stderr,"%d must be >= 0\n",atoi(argv[1]));
      return -1;
   }
```

Pthreads Example (Cont.)

```
   /* get the default attributes */
   pthread_attr_init(&attr);
   /* create the thread */
   pthread_create(&tid,&attr,runner,argv[1]);
   /* wait for the thread to exit */
   pthread_join(tid,NULL);

   printf("sum = %d\n",sum);
}

/* The thread will begin control in this function */
void *runner(void *param)
{
   int i, upper = atoi(param);
   sum = 0;

   for (i = 1; i <= upper; i++)
      sum += i;

   pthread_exit(0);
}
```

Figure 4.9 Multithreaded C program using the Pthreads API.

Pthreads Code for Joining 10 Threads

```
#define NUM_THREADS 10

/* an array of threads to be joined upon */
pthread_t workers[NUM_THREADS];

for (int i = 0; i < NUM_THREADS; i++)
   pthread_join(workers[i], NULL);
```

Figure 4.10 Pthread code for joining ten threads.

```c
int max;
int counter = 0; // shared global variable

void *mythread(void *arg) {
    char *letter = arg;
    int i; // stack (private per thread)
    printf("%s: begin [addr of i: %p]\n", letter, &i);
    for (i = 0; i < max; i++) {
        counter = counter + 1; // shared: only one
    }
    printf("%s: done\n", letter);
    return NULL;
}

int main(int argc, char *argv[]) {
    max = atoi(argv[1]);

    pthread_t p1, p2;
    printf("main: begin [counter = %d] [%x]\n", counter,
           (unsigned int) &counter);
    Pthread_create(&p1, NULL, mythread, "A");
    Pthread_create(&p2, NULL, mythread, "B");
    // join waits for the threads to finish
    Pthread_join(p1, NULL);
    Pthread_join(p2, NULL);
    printf("main: done\n [counter: %d]\n [should: %d]\n",
           counter, max*2);
    return 0;
}
```

What is the value of counter if max = 1,000,000?

Implicit Threading

- Growing in popularity as numbers of threads increase, program correctness more difficult with explicit threads
- Creation and management of threads done by compilers and run-time libraries rather than programmers
- Example methods explored
  - Thread Pools
  - OpenMP
- Other methods include Intel Threading Building Blocks (TBB), **`java.util.concurrent`** package

Thread Pools

- The **problem** with allowing a process (e.g. a multi-threading web server) to create as many threads as it wants:
  - It takes time to create a thread prior to handling a service request.
  - Unlimited number of threads could exhaust system resources.
- **Solution:** Thread pools.
- A **thread pool** contains a limited number of threads created at process startup.
  - When the program needs a thread, it takes one from the pool.
  - When the thread is done with its service, it is returned to the pool.
  - If no thread is available, the program must wait for one to be returned to the pool.

Thread Pools

- Advantages:
  - Usually slightly faster to service a request with an existing thread than create a new thread
  - Allows the number of threads in the application(s) to be bound to the size of the pool
  - Separating task to be performed from mechanics of creating task allows different strategies for running task
    - i.e. Tasks could be scheduled to run periodically
- Windows API supports thread pools:

```
DWORD WINAPI PoolFunction(AVOID Param) {
    /*
    * this function runs as a separate thread.
    */
}
```

```
QueueUserWorkItem(&PoolFunction, NULL, 0);
```

OpenMP

- Set of compiler directives and an API for C, C++, FORTRAN
- Provides support for parallel programming in shared-memory environments
- Identifies **parallel regions** – blocks of code that can run in parallel

```
#pragma omp parallel
```

Create as many threads as there are cores

```
#pragma omp parallel for
   for(i=0;i<N;i++) {

    c[i] = a[i] + b[i];

}
```

Run for loop in parallel

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

int main(int argc, char *argv[])
{
  /* sequential code */

  #pragma omp parallel
  {
    printf("I am a parallel region.");
  }

  /* sequential code */

  return 0;
}
```

Threading Issues

- Semantics of **fork()** and **exec()** system calls
- Thread cancellation
- Signal handling
- Thread specific data

Semantics of fork() and exec()

- If one thread in a multi-threaded program calls fork( ), does the new process duplicate all threads or only the thread that made the call?
- It depends on the version of UNIX.
- Some UNIX versions have 2 versions of fork( )—
  - one that duplicates all threads and
  - one that duplicates only one thread.
- What happens if exec( ) is called from a thread?
- The same as before--the entire process is replaced.
- If exec( ) is called immediately after fork( ) then it is not necessary to duplicate all threads.

Thread Cancellation

- **Thread cancellation** is terminating a thread before it is completed.
- The thread to be cancelled is called the **target thread.**
- **Asynchronous cancellation:** One thread immediately terminates the target thread. This can cause problems:
  - Cancellation may occur while the thread is in the middle of updating shared data.
  - The OS may not reclaim all resources from the cancelled thread.
- **Deferred cancellation:** Target thread can periodically check to determine whether it should terminate
  - This allows the target thread an opportunity to terminate itself in an orderly fashion.
  - Threads are only terminated at **cancellation points.**
  - `pthread_cancel` **and** `pthread_testcancel`

Signal Handling

- A **signal** in UNIX is used to notify a process that an event has occurred.
- A signal can be synchronous or asynchronous
  - synchronous signals are usually attributable to execution of code
    - E.g. illegal memory access and division by 0
  - Asynchronous signals are not usually attributable to execution of code;
    - E.g. ctrl + c
- Response to a signal:
  - A signal is generated by the occurrence of an event.
  - The generated signal is delivered to a process. The standard UNIX function for delivering a signal is
    - `kill(pid_t pid, int signal)`
  - Once delivered the signal must be handled. It is handled one of two ways:
    - The default signal handler (in the kernel)
    - A user-defined signal handler.

Signals and Threads

- Options for delivering signals to a multi-threaded process:
  - Deliver the signal to the thread to which the signal applies.
    - E.g. a divide by zero generates a synchronous signal.
  - Deliver the signal to every thread in the process
    - E.g. when the user hits <Control>-C
  - Deliver the signal to certain threads in the process.
    - some threads can specify which signals they will accept and which they will block.
    - Typically, the signal is delivered only to the first thread that is not blocking it.
  - Assign a specific thread to receive all signals for the process (Solaris 2)
    - A special thread gets the signals and then delivers them to the first thread not blocking the signal.

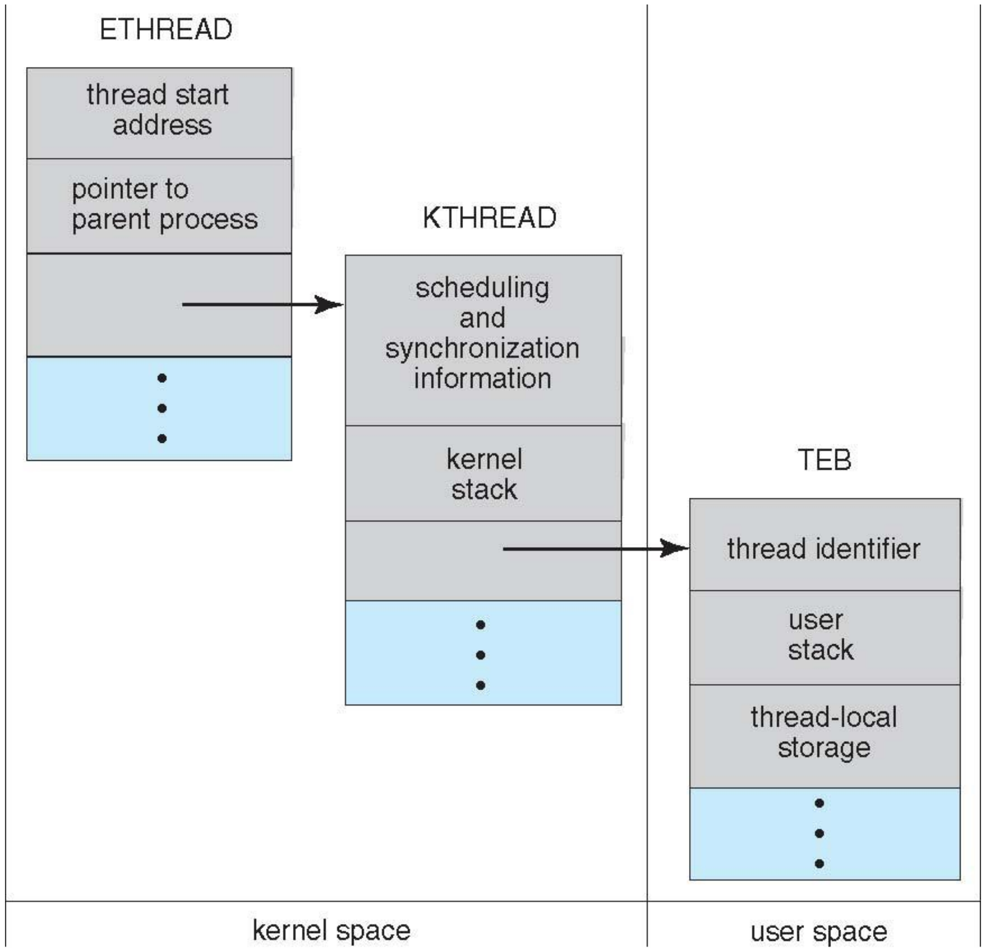
Thread-Local Storage

- **Thread-local storage** (**TLS**) allows each thread to have its own copy of data
- Useful when you do not have control over the thread creation process (i.e., when using a thread pool)
- Different from local variables
  - Local variables visible only during single function invocation
  - TLS visible across function invocations
- Similar to **`static`** data
  - TLS is unique to each thread
  - Use **`thread_local`** keyword in c++

Windows Threads

- Implements the one-to-one mapping, kernel-level
- Each thread contains
  - A thread id
  - Register set representing state of processor
  - Separate user and kernel stacks for when thread runs in user mode or kernel mode
  - Private data storage area used by run-time libraries and dynamic link libraries (DLLs)
- The register set, stacks, and private storage area are known as the context of the threads
- The primary data structures of a thread include:
  - ETHREAD (executive thread block) – includes pointer to process to which thread belongs and to KTHREAD, in kernel space
  - KTHREAD (kernel thread block) – scheduling and synchronization info, kernel-mode stack, pointer to TEB, in kernel space
  - TEB (thread environment block) – thread id, user-mode stack, thread-local storage, in user space

Windows XP Threads



Linux Threads

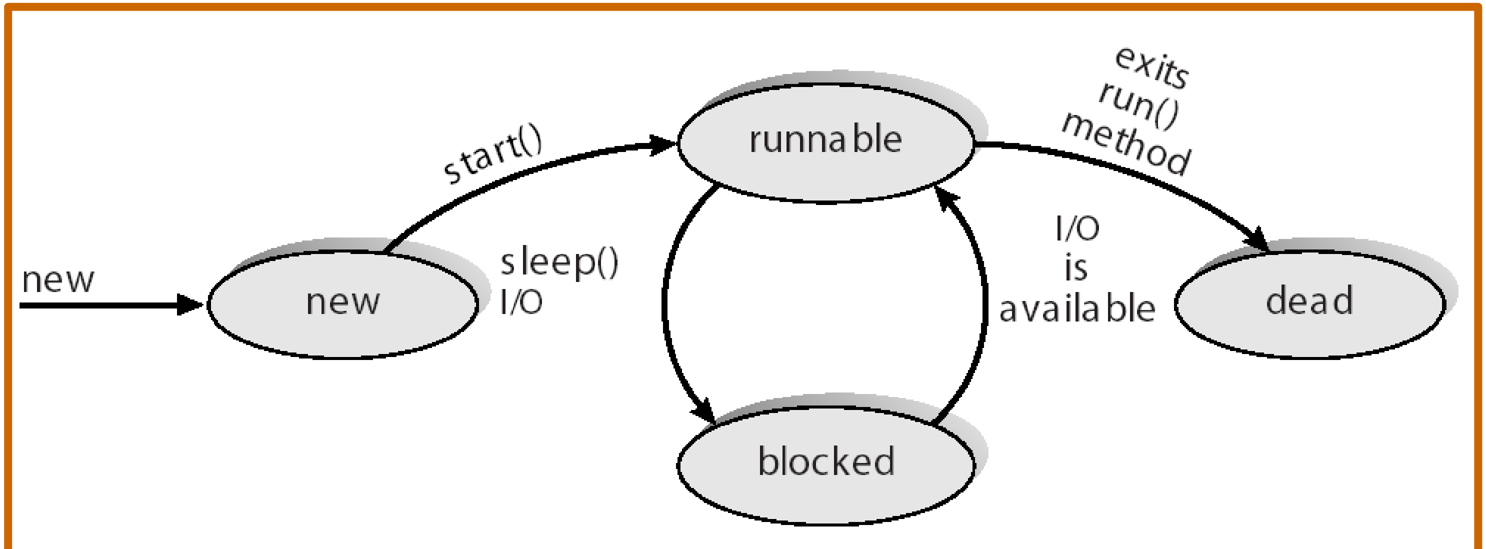
- Linux refers to them as ***tasks*** rather than ***threads***
- Thread creation is done through **`clone()`** system call
- **`clone()`** allows a child task to share the address space of the parent task (process)
  - Flags control behavior

flag	meaning
`CLONE_FS`	File-system information is shared.
`CLONE_VM`	The same memory space is shared.
`CLONE_SIGHAND`	Signal handlers are shared.
`CLONE_FILES`	The set of open files is shared.

- **`struct task_struct`** points to process data structures (shared or unique)

Java Threads

- Java threads are managed by the JVM
- Typically implemented using the threads model provided by underlying OS
- Java threads may be created by:
  - Extending Thread class
  - Implementing the Runnable interface



Summary

- A thread is a flow of control within a process
- A multithreaded process contains several different flows of control within the same address space
- User-level threads are threads visible to the programmer but unknown to the kernel
  - A thread library typically manages user-level threads
- The OS kernel supports and manages kernel-level threads
- In general, user-level threads are faster to create and manage than kernel threads

Summary (Con't)

- Three different models relate user and kernel threads
  - Many-to-one model: maps many user threads to a single kernel thread
  - One-to-one model: maps each user thread to a corresponding kernel thread
  - Many-to-many model: multiplexes many user threads to a smaller or equal number of kernel threads
  - Multithreaded program introduce challenges for the programmer
    - Semantics of fork and exec, thread cancellation, signal handling and thread-specific data
  - Many modern operating systems provide kernel support for threads