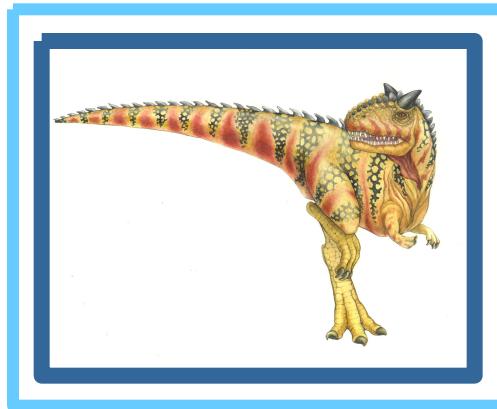


Chapter 4: Threads

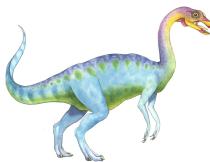




Chapter 4: Threads

- n Overview
- n Multicore Programming
- n Multithreading Models
- n Thread Libraries
- n Implicit Threading
- n Threading Issues
- n Operating System Examples

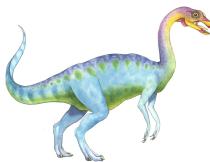




Objectives

- n To introduce the notion of a thread—a fundamental unit of CPU utilization that forms the basis of multithreaded computer systems
- n To discuss the APIs for the Pthreads, Windows, and Java thread libraries
- n To explore several strategies that provide implicit threading
- n To examine issues related to multithreaded programming
- n To cover operating system support for threads in Windows and Linux





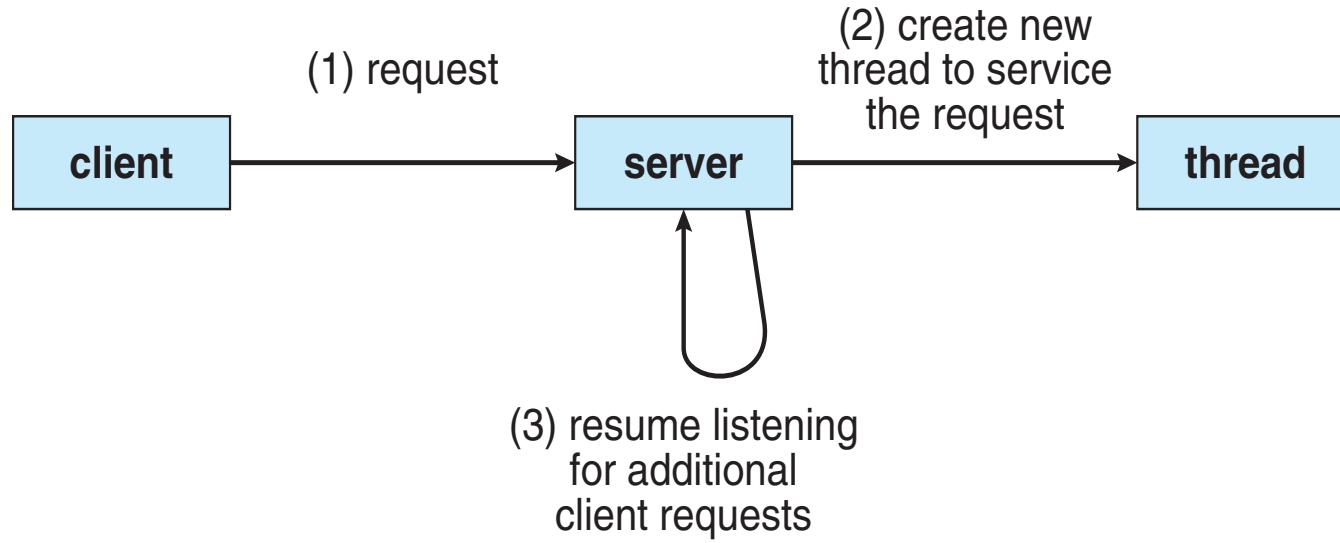
Motivation

- n Most modern applications are multithreaded
- n Threads run within application
- n Multiple tasks within the application can be implemented by separate threads
 - | Update display
 - | Fetch data
 - | Spell checking
 - | Answer a network request
- n Process creation is heavy-weight while thread creation is light-weight
- n Can simplify code, increase efficiency
- n Kernels are generally multithreaded





Multithreaded Server Architecture





Benefits

- n **Responsiveness** – may allow continued execution if part of process is blocked, especially important for user interfaces
- n **Resource Sharing** – threads share resources of process, easier than shared memory or message passing
- n **Economy** – cheaper than process creation, thread switching lower overhead than context switching
- n **Scalability** – process can take advantage of multiprocessor architectures





Multicore Programming

- n **Multicore** or **multiprocessor** systems putting pressure on programmers, challenges include:
 - | **Dividing activities**
 - | **Balance**
 - | **Data splitting**
 - | **Data dependency**
 - | **Testing and debugging**
- n **Parallelism** implies a system can perform more than one task simultaneously
- n **Concurrency** supports more than one task making progress
 - | Single processor / core, scheduler providing concurrency

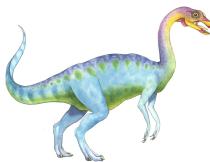




Multicore Programming (Cont.)

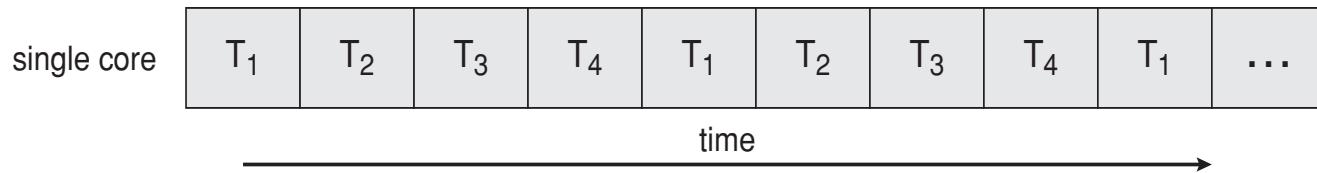
- n Types of parallelism
 - | **Data parallelism** – distributes subsets of the same data across multiple cores, same operation on each
 - | **Task parallelism** – distributing threads across cores, each thread performing unique operation
- n As # of threads grows, so does architectural support for threading
 - | CPUs have cores as well as ***hardware threads***
 - | Consider Oracle SPARC T4 with 8 cores, and 8 hardware threads per core



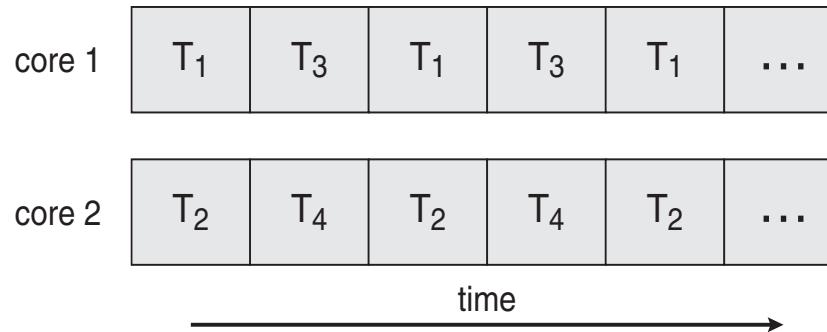


Concurrency vs. Parallelism

- Concurrent execution on single-core system:

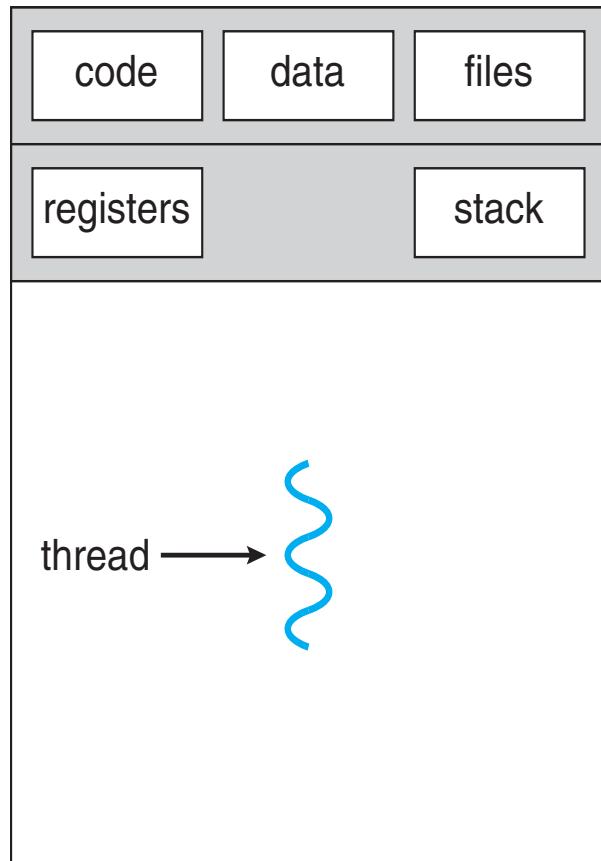


- Parallelism on a multi-core system:

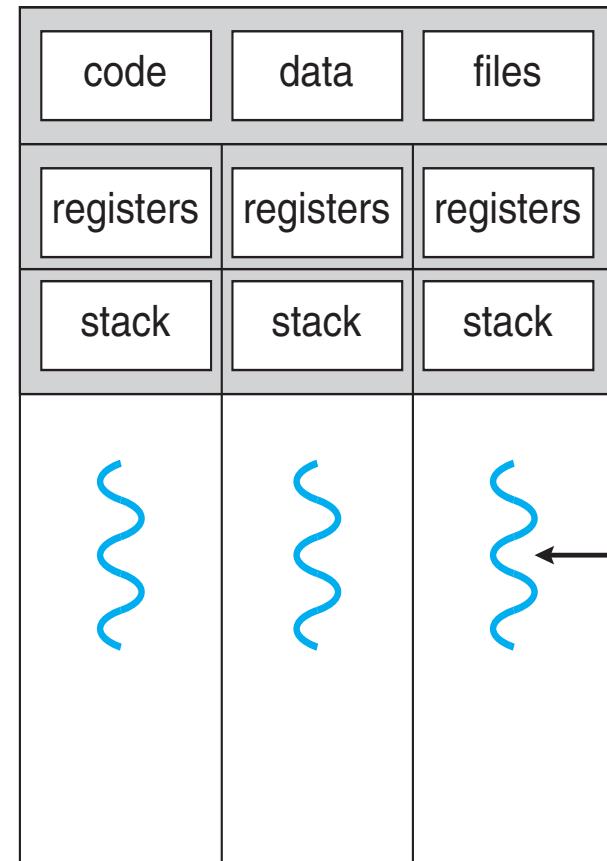




Single and Multithreaded Processes



single-threaded process



multithreaded process





Amdahl's Law

- n Identifies performance gains from adding additional cores to an application that has both serial and parallel components
- n S is serial portion
- n N processing cores

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

- n That is, if application is 75% parallel / 25% serial, moving from 1 to 2 cores results in speedup of 1.6 times
- n As N approaches infinity, speedup approaches $1 / S$

Serial portion of an application has disproportionate effect on performance gained by adding additional cores

But does the law take into account contemporary multicore systems?





User Threads and Kernel Threads

- n **User threads** - management done by user-level threads library
- n Three primary thread libraries:
 - | POSIX **Pthreads**
 - | Windows threads
 - | Java threads
- n **Kernel threads** - Supported by the Kernel
- n Examples – virtually all general purpose operating systems, including:
 - | Windows
 - | Solaris
 - | Linux
 - | Tru64 UNIX
 - | Mac OS X





Multithreading Models

- n Many-to-One

- n One-to-One

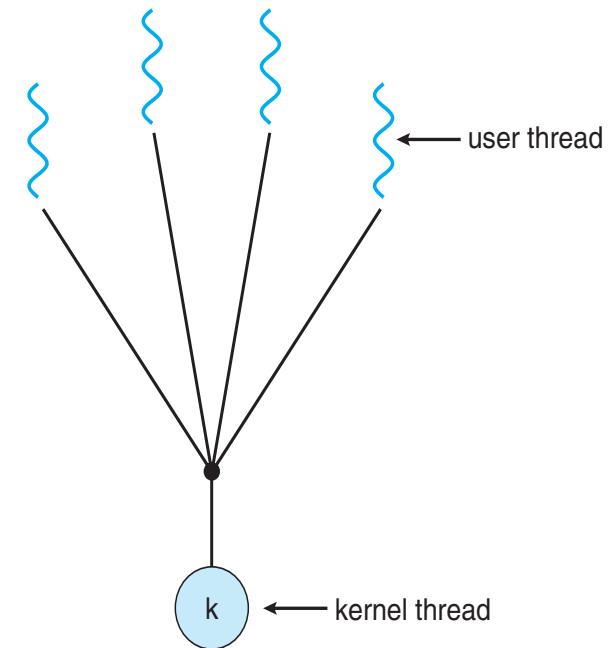
- n Many-to-Many

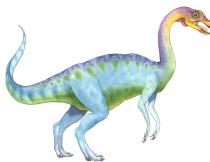




Many-to-One

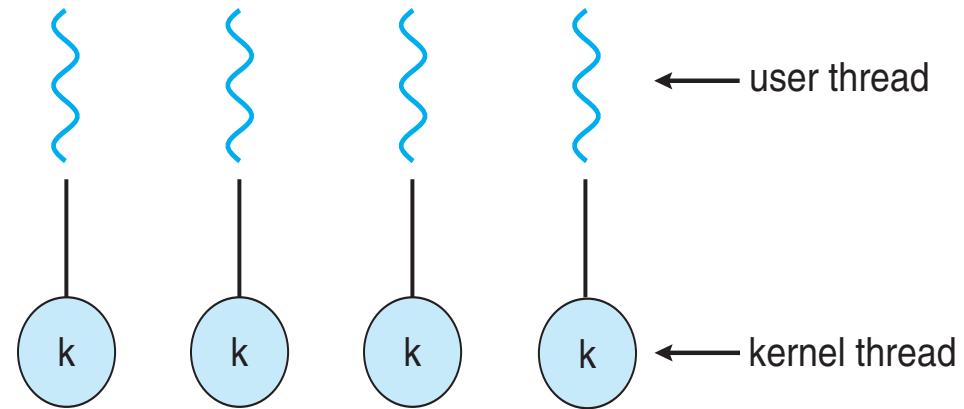
- n Many user-level threads mapped to single kernel thread
- n One thread blocking causes all to block
- n Multiple threads may not run in parallel on multicore system because only one may be in kernel at a time
- n Few systems currently use this model
- n Examples:
 - | Solaris Green Threads
 - | GNU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





One-to-One

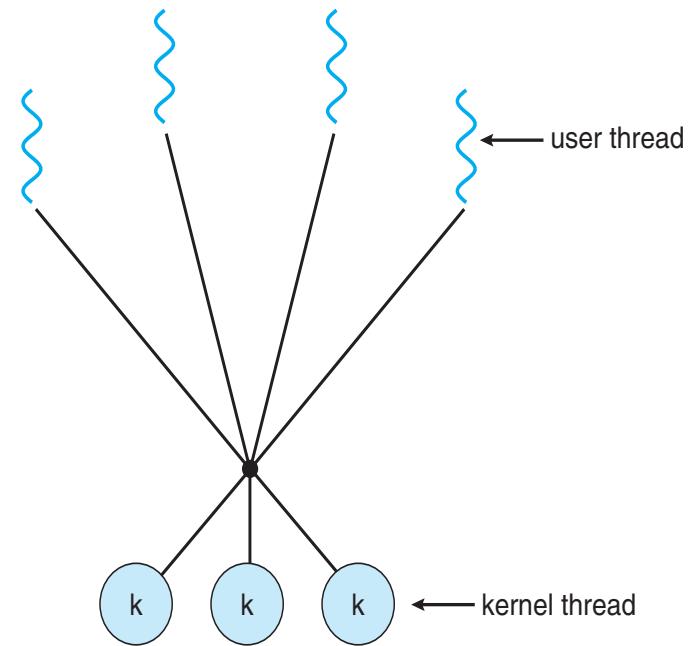
- n Each user-level thread maps to kernel thread
- n Creating a user-level thread creates a kernel thread
- n More concurrency than many-to-one
- n Number of threads per process sometimes restricted due to overhead
- n Examples
 - | Windows
 - | Linux
 - | Solaris 9 and later





Many-to-Many Model

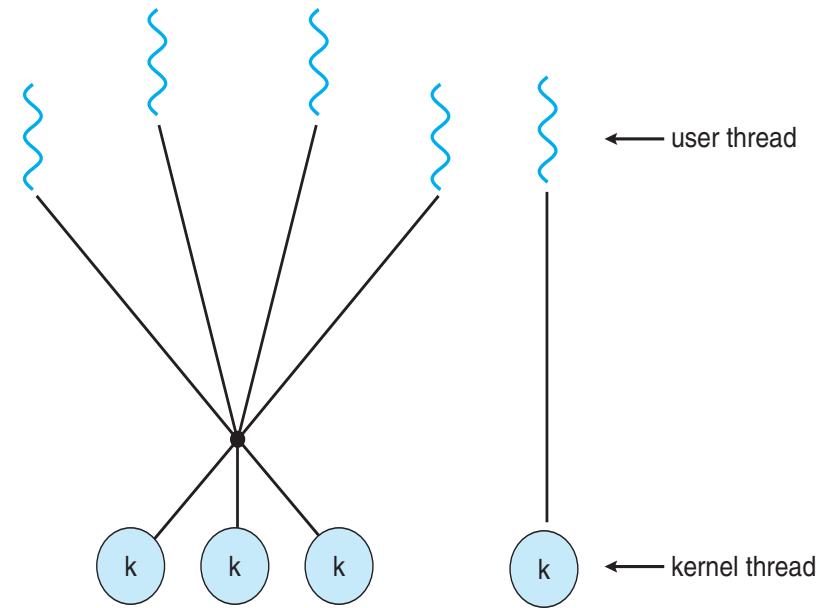
- n Allows many user level threads to be mapped to many kernel threads
- n Allows the operating system to create a sufficient number of kernel threads
- n Solaris prior to version 9
- n Windows with the *ThreadFiber* package

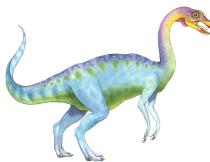




Two-level Model

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

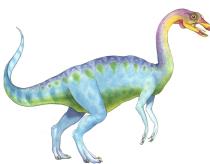




Thread Libraries

- n **Thread library** provides programmer with API for creating and managing threads
- n Two primary ways of implementing
 - | Library entirely in user space
 - | Kernel-level library supported by the OS





Pthreads

- n May be provided either as user-level or kernel-level
- n A POSIX standard (IEEE 1003.1c) API for thread creation and synchronization
- n ***Specification***, not *implementation*
- n API specifies behavior of the thread library, implementation is up to development of the library
- n Common in UNIX operating systems (Solaris, Linux, Mac OS X)





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);
}
```





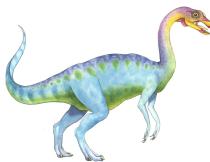
Pthreads Code for Joining 10 Threads

```
#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);
```





Windows Multithreaded C Program

```
#include <windows.h>
#include <stdio.h>
DWORD Sum; /* data is shared by the thread(s) */

/* the thread runs in this separate function */
DWORD WINAPI Summation(LPVOID Param)
{
    DWORD Upper = *(DWORD*)Param;
    for (DWORD i = 0; i <= Upper; i++)
        Sum += i;
    return 0;
}

int main(int argc, char *argv[])
{
    DWORD ThreadId;
    HANDLE ThreadHandle;
    int Param;

    if (argc != 2) {
        fprintf(stderr,"An integer parameter is required\n");
        return -1;
    }
    Param = atoi(argv[1]);
    if (Param < 0) {
        fprintf(stderr,"An integer >= 0 is required\n");
        return -1;
    }
}
```





Windows Multithreaded C Program (Cont.)

```
/* create the thread */
ThreadHandle = CreateThread(
    NULL, /* default security attributes */
    0, /* default stack size */
    Summation, /* thread function */
    &Param, /* parameter to thread function */
    0, /* default creation flags */
    &ThreadId); /* returns the thread identifier */

if (ThreadHandle != NULL) {
    /* now wait for the thread to finish */
    WaitForSingleObject(ThreadHandle, INFINITE);

    /* close the thread handle */
    CloseHandle(ThreadHandle);

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

}
```





Java Threads

- n Java threads are managed by the JVM
- n Typically implemented using the threads model provided by underlying OS
- n Java threads may be created by:

```
public interface Runnable
{
    public abstract void run();
}
```

- | Extending Thread class
- | Implementing the Runnable interface





Java Multithreaded Program

```
class Sum
{
    private int sum;

    public int getSum() {
        return sum;
    }

    public void setSum(int sum) {
        this.sum = sum;
    }
}

class Summation implements Runnable
{
    private int upper;
    private Sum sumValue;

    public Summation(int upper, Sum sumValue) {
        this.upper = upper;
        this.sumValue = sumValue;
    }

    public void run() {
        int sum = 0;
        for (int i = 0; i <= upper; i++)
            sum += i;
        sumValue.setSum(sum);
    }
}
```





Java Multithreaded Program (Cont.)

```
public class Driver
{
    public static void main(String[] args) {
        if (args.length > 0) {
            if (Integer.parseInt(args[0]) < 0)
                System.err.println(args[0] + " must be >= 0.");
            else {
                Sum sumObject = new Sum();
                int upper = Integer.parseInt(args[0]);
                Thread thrd = new Thread(new Summation(upper, sumObject));
                thrd.start();
                try {
                    thrd.join();
                    System.out.println
                        ("The sum of "+upper+" is "+sumObject.getSum());
                } catch (InterruptedException ie) { }
            }
        }
        else
            System.err.println("Usage: Summation <integer value>"); }
    }
}
```





Implicit Threading

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





Thread Pools

- n Create a number of threads in a pool where they await work
- n 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
- n Windows API supports thread pools:

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





OpenMP

- n Set of compiler directives and an API for C, C++, FORTRAN
- n Provides support for parallel programming in shared-memory environments
- n 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>

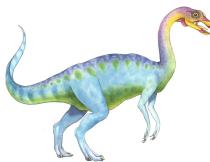
int main(int argc, char *argv[])
{
    /* sequential code */

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

    /* sequential code */

    return 0;
}
```





Grand Central Dispatch

- Apple technology for Mac OS X and iOS operating systems
- Extensions to C, C++ languages, API, and run-time library
- Allows identification of parallel sections
- Manages most of the details of threading
- Block is in “^{ }” - ^{ printf("I am a block") ; }
- Blocks placed in dispatch queue
 - | Assigned to available thread in thread pool when removed from queue





Grand Central Dispatch

- n Two types of dispatch queues:
 - | serial – blocks removed in FIFO order, queue is per process, called **main queue**
 - ▶ Programmers can create additional serial queues within program
 - | concurrent – removed in FIFO order but several may be removed at a time
 - ▶ Three system wide queues with priorities low, default, high

```
dispatch_queue_t queue = dispatch_get_global_queue
    (DISPATCH_QUEUE_PRIORITY_DEFAULT, 0);

dispatch_async(queue, ^{
    printf("I am a block.");
});
```





Threading Issues

- n Semantics of **fork()** and **exec()** system calls
- n Signal handling
 - | Synchronous and asynchronous
- n Thread cancellation of target thread
 - | Asynchronous or deferred
- n Thread-local storage
- n Scheduler Activations





Semantics of fork() and exec()

- n Does `fork()` duplicate only the calling thread or all threads?
 - | Some UNIXes have two versions of fork
- n `exec()` usually works as normal – replace the running process including all threads





Signal Handling

- n **Signals** are used in UNIX systems to notify a process that a particular event has occurred.
- n A **signal handler** is used to process signals
 1. Signal is generated by particular event
 2. Signal is delivered to a process
 3. Signal is handled by one of two signal handlers:
 1. default
 2. user-defined
- n Every signal has **default handler** that kernel runs when handling signal
 - | **User-defined signal handler** can override default
 - | For single-threaded, signal delivered to process





Signal Handling (Cont.)

- n Where should a signal be delivered for multi-threaded?
 - | Deliver the signal to the thread to which the signal applies
 - | Deliver the signal to every thread in the process
 - | Deliver the signal to certain threads in the process
 - | Assign a specific thread to receive all signals for the process





Thread Cancellation

- n Terminating a thread before it has finished
- n Thread to be canceled is **target thread**
- n Two general approaches:
 - | **Asynchronous cancellation** terminates the target thread immediately
 - | **Deferred cancellation** allows the target thread to periodically check if it should be cancelled
- n Pthread code to create and cancel a thread:

```
pthread_t tid;  
  
/* create the thread */  
pthread_create(&tid, 0, worker, NULL);  
  
.  
.  
.  
  
/* cancel the thread */  
pthread_cancel(tid);
```





Thread Cancellation (Cont.)

- Invoking thread cancellation requests cancellation, but actual cancellation depends on thread state

| Mode | State | Type |
|--------------|----------|--------------|
| Off | Disabled | - |
| Deferred | Enabled | Deferred |
| Asynchronous | Enabled | Asynchronous |

- If thread has cancellation disabled, cancellation remains pending until thread enables it
- Default type is deferred
 - Cancellation only occurs when thread reaches **cancellation point**
 - i.e. `pthread_testcancel()`
 - Then **cleanup handler** is invoked
- On Linux systems, thread cancellation is handled through signals

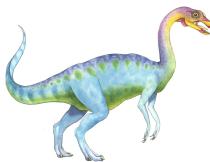




Thread-Local Storage

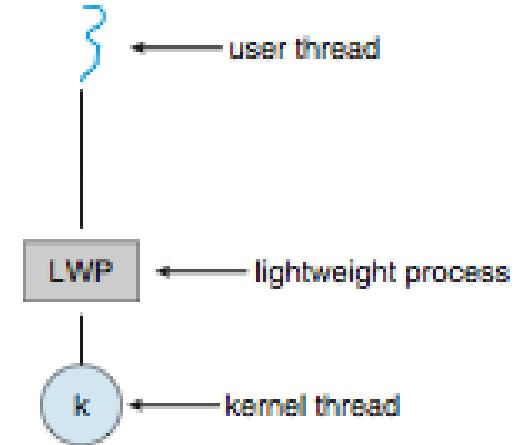
- n **Thread-local storage (TLS)** allows each thread to have its own copy of data
- n Useful when you do not have control over the thread creation process (i.e., when using a thread pool)
- n Different from local variables
 - | Local variables visible only during single function invocation
 - | TLS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





Scheduler Activations

- n Both M:M and Two-level models require communication to maintain the appropriate number of kernel threads allocated to the application
- n Typically use an intermediate data structure between user and kernel threads – **lightweight process (LWP)**
 - | Appears to be a virtual processor on which process can schedule user thread to run
 - | Each LWP attached to kernel thread
 - | How many LWPs to create?
- n Scheduler activations provide **upcalls** - a communication mechanism from the kernel to the **upcall handler** in the thread library
- n This communication allows an application to maintain the correct number kernel threads





Operating System Examples

- n Windows Threads
- n Linux Threads





Windows Threads

- n Windows implements the Windows API – primary API for Win 98, Win NT, Win 2000, Win XP, and Win 7
- n Implements the one-to-one mapping, kernel-level
- n 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)
- n The register set, stacks, and private storage area are known as the **context** of the thread





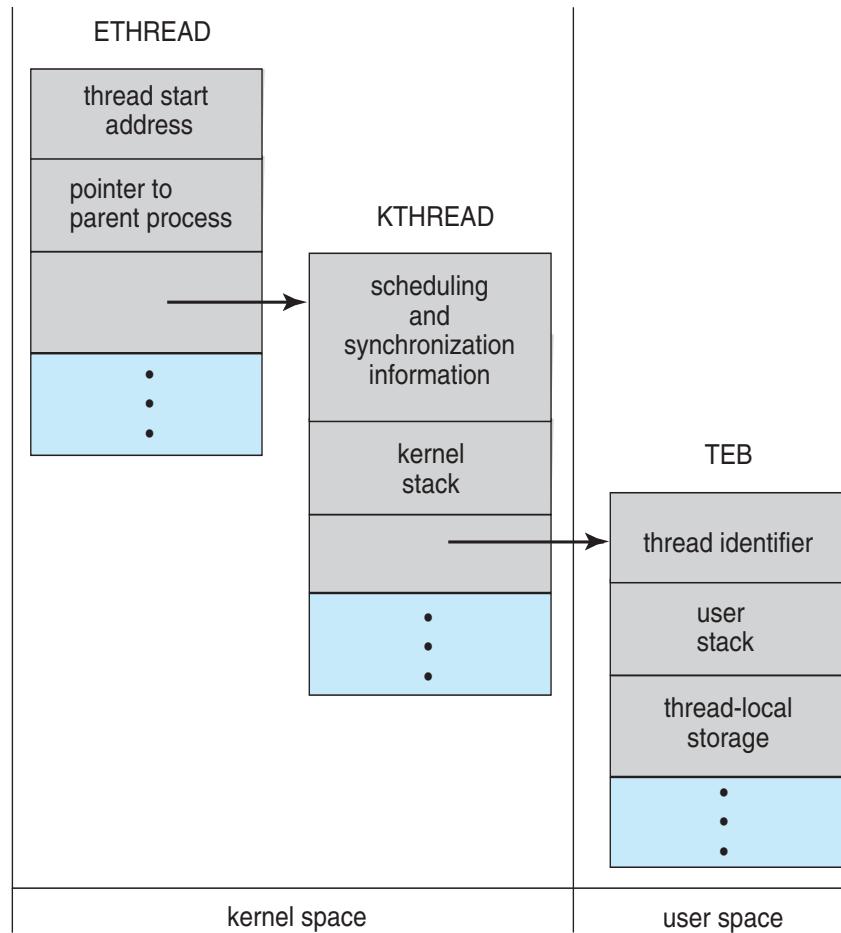
Windows Threads (Cont.)

- n 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 Threads Data Structures





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)



End of Chapter 4

