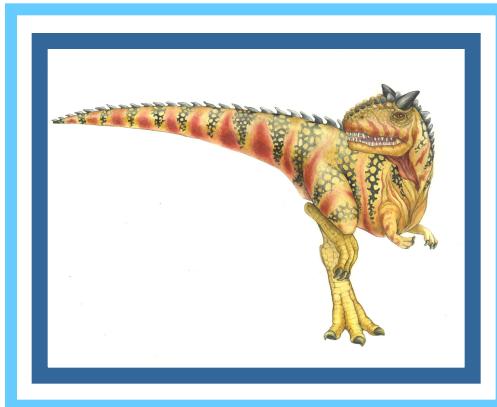


# Chapter 4: Threads & Concurrency





# Outline

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





# Objectives

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- Identify the basic components of a thread, and contrast threads and processes
- Describe the benefits and challenges of designing multithreaded applications
- Illustrate different approaches to implicit threading including thread pools, fork-join, and Grand Central Dispatch
- Describe how the Windows and Linux operating systems represent threads
- Designing multithreaded applications using the Pthreads, Java, and Windows threading APIs





# Motivation

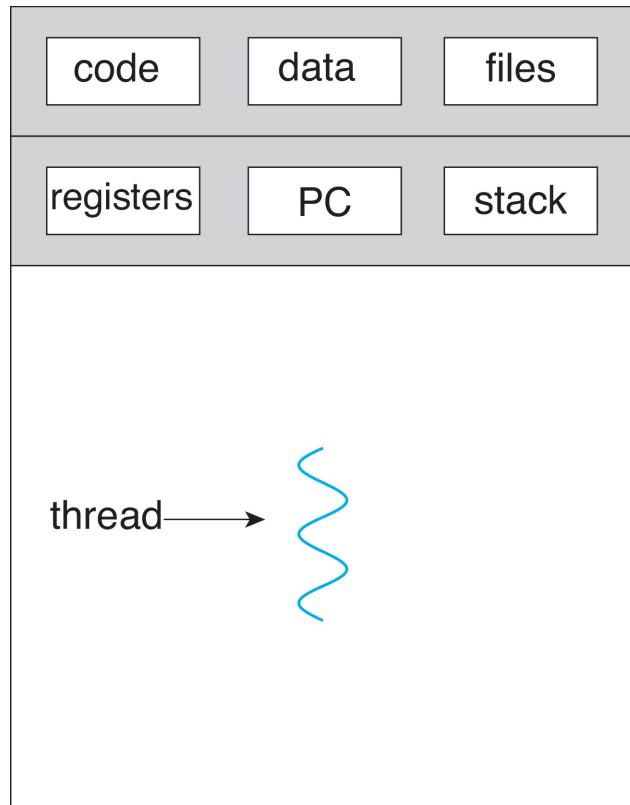
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- Most modern applications are multithreaded
- Threads run within application
- Multiple tasks within the application can be implemented by separate threads
  - Update display
  - Fetch data
  - Spell checking
  - Answer a network request
- Process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

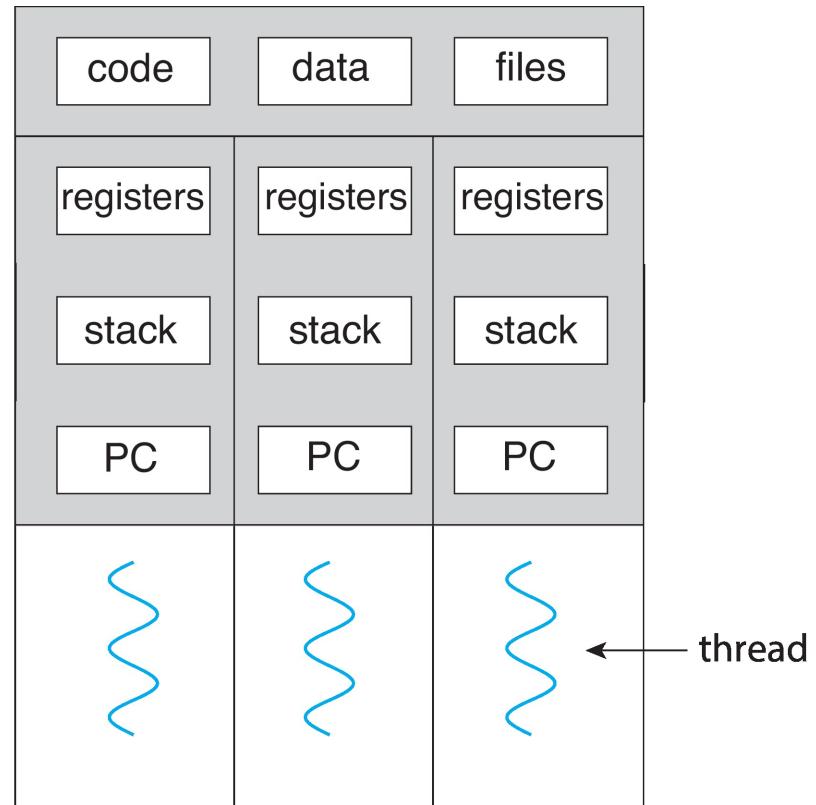




# Single and Multithreaded Processes



single-threaded process

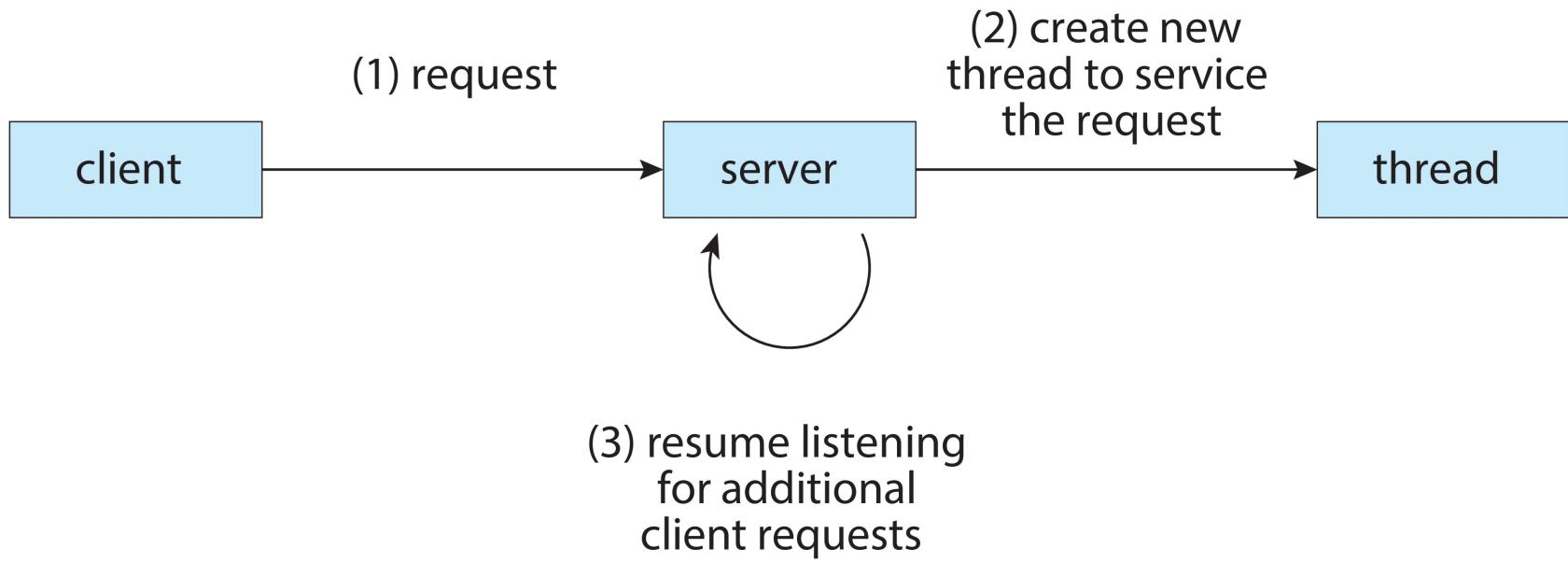


multithreaded process





# Multithreaded Server Architecture





## Benefits

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





# Multicore Programming

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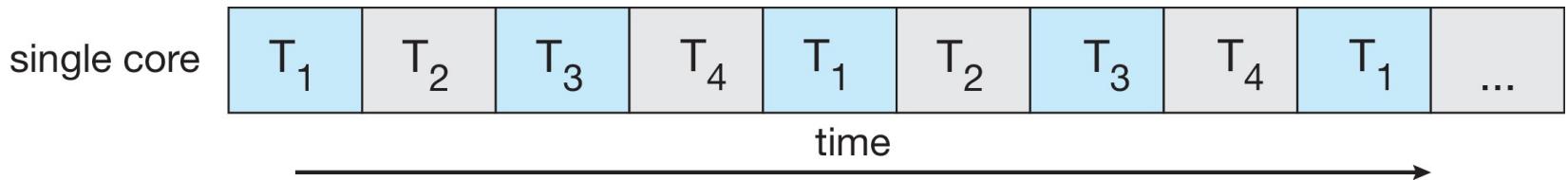
- **Multicore** or **multiprocessor** systems puts pressure on programmers, challenges include:
  - **Dividing activities**
  - **Balance**
  - **Data splitting**
  - **Data dependency**
  - **Testing and debugging**
- **Parallelism** implies a system can perform more than one task simultaneously
- **Concurrency**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



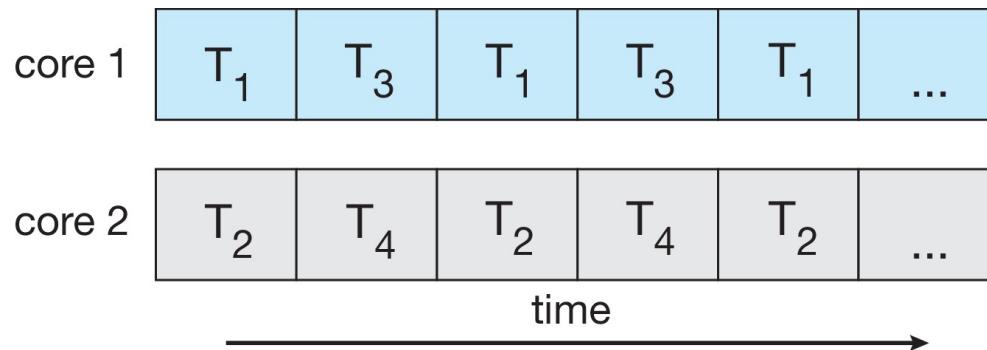


# Concurrency vs. Parallelism

- Concurrent execution on single-core system:



- Parallelism on a multi-core system:





# Multicore Programming

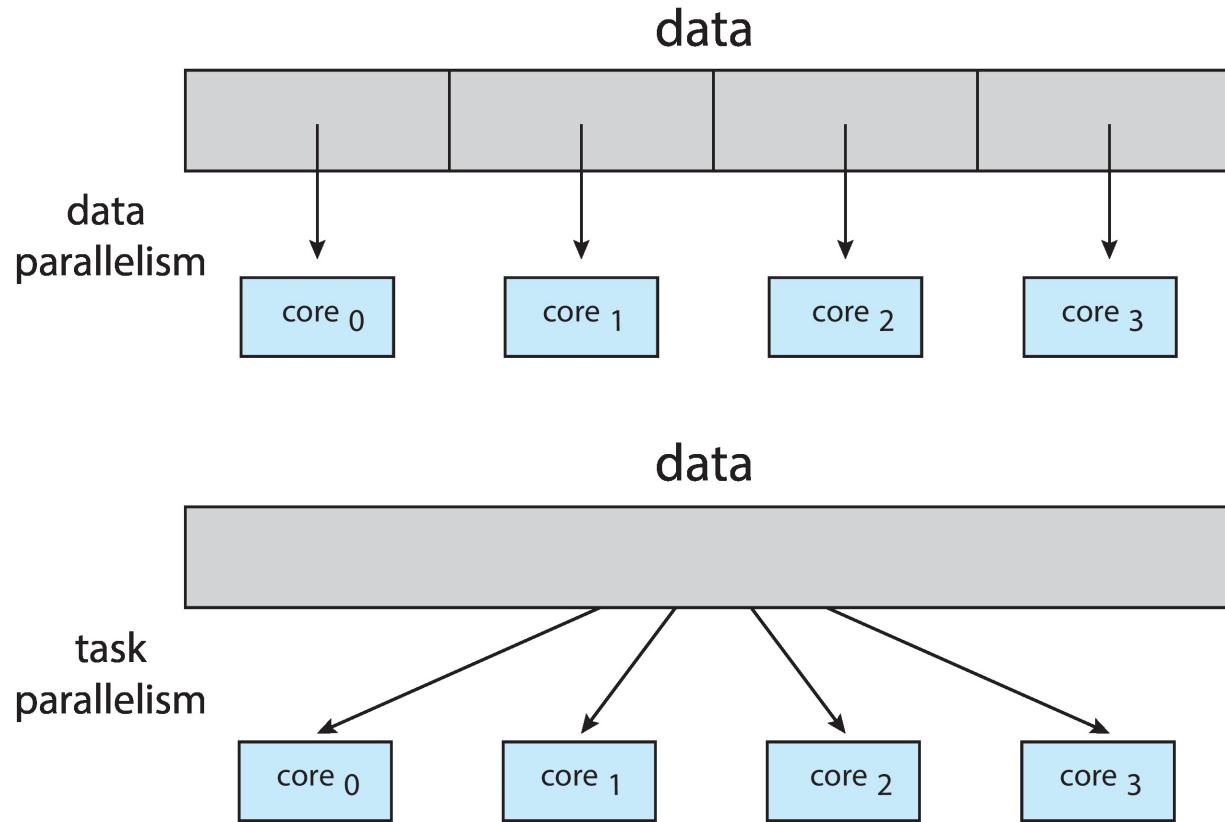
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- Types of parallelism
  - **Data parallelism** – distributes subsets of the same data across multiple cores, same operation on each
  - **Task parallelism** – distributing threads across cores, each thread performing unique operation





# Data and Task Parallelism





# Amdahl's Law

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

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

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

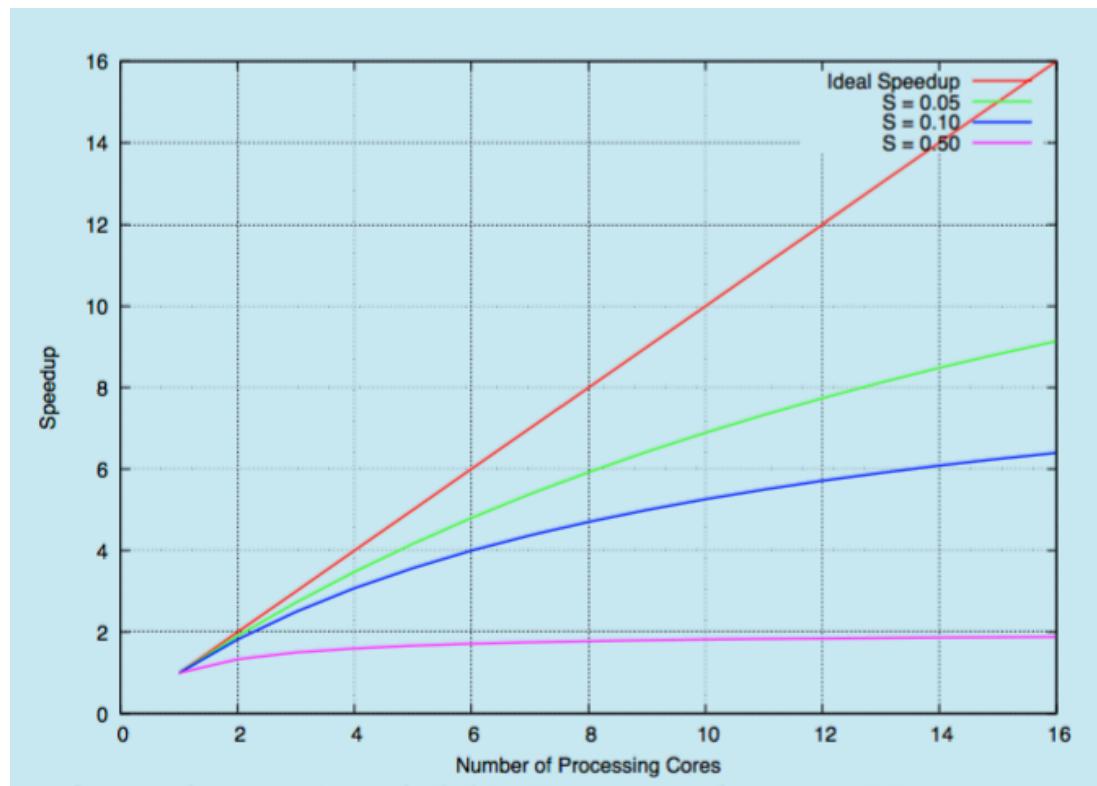
**Serial portion of an application has disproportionate effect on performance gained by adding additional cores**

- But does the law take into account contemporary multicore systems?





# Amdahl's Law





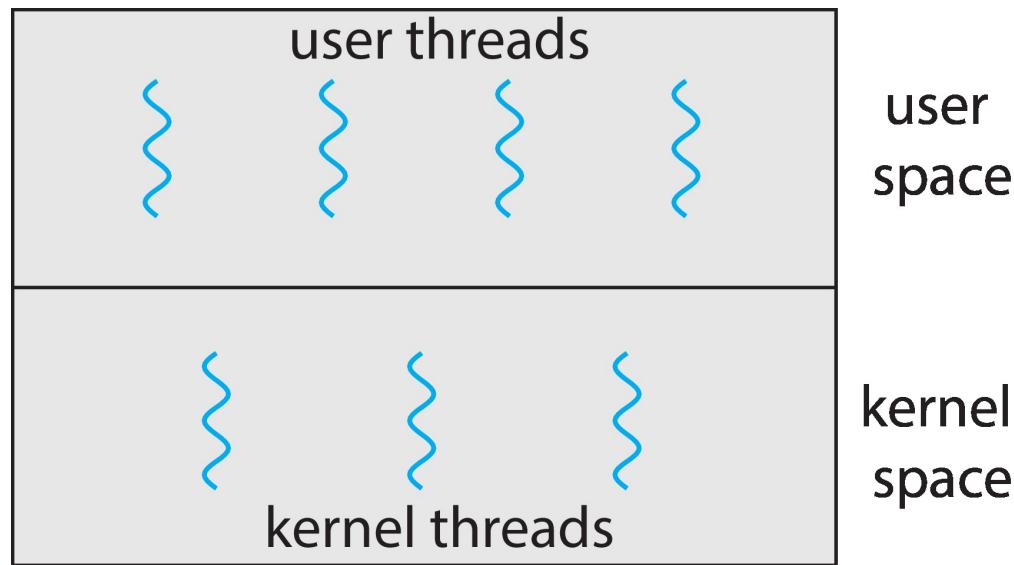
# User Threads and Kernel Threads

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





# User and Kernel Threads





# Multithreading Models

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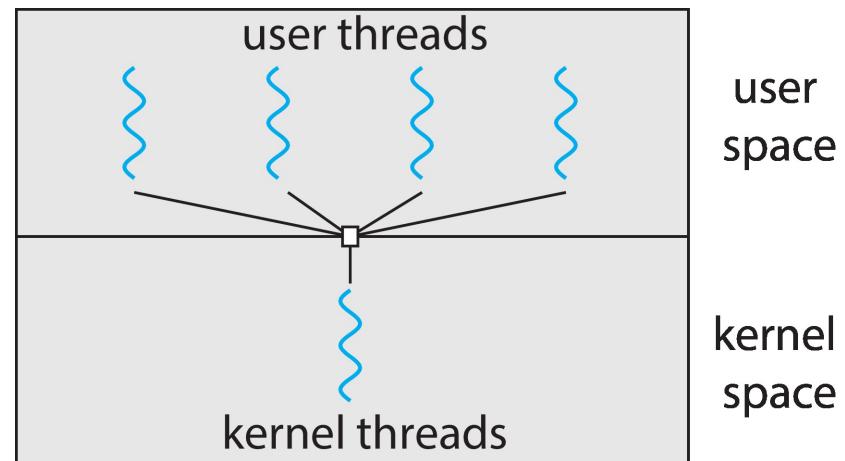
- Many-to-One
- One-to-One
- Many-to-Many





# Many-to-One

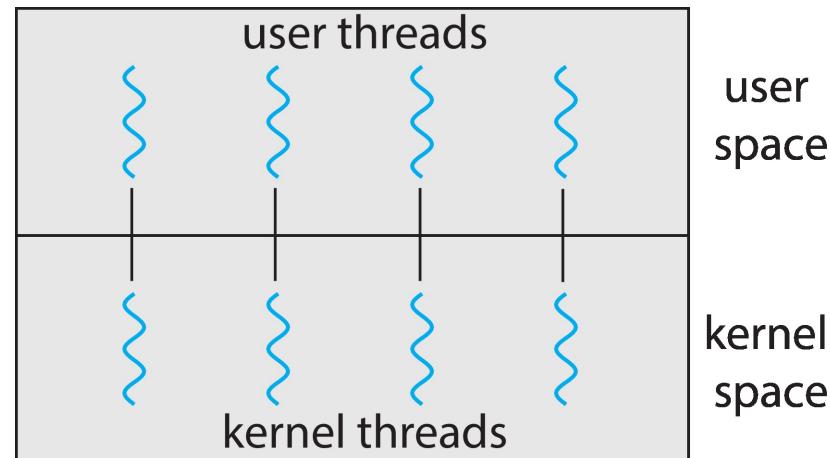
- Many user-level threads mapped to single kernel thread
- One thread blocking causes all to block
- Multiple threads may not run in parallel on multicore system because only one may be in kernel at a time
- Few systems currently use this model
- Examples:
  - **Solaris Green Threads**
  - **GNU Portable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





# One-to-One

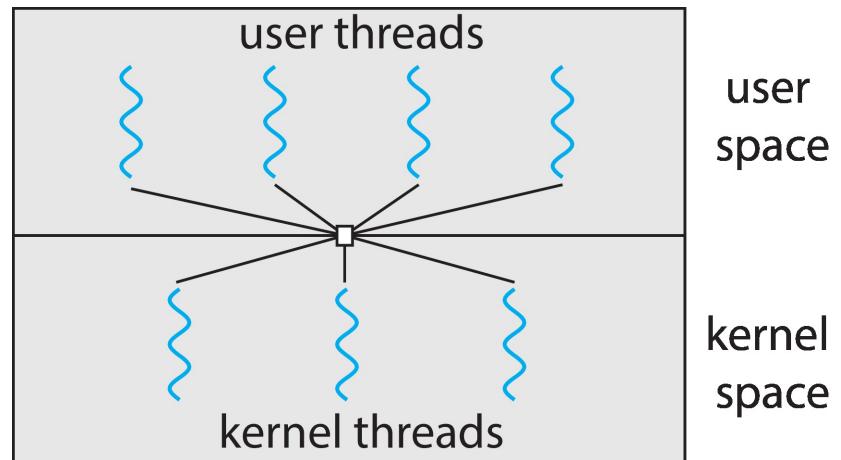
- Each user-level thread maps to kernel thread
- Creating a user-level thread creates a kernel thread
- More concurrency than many-to-one
- Number of threads per process sometimes restricted due to overhead
- Examples
  - Windows
  - Linux





# Many-to-Many Model

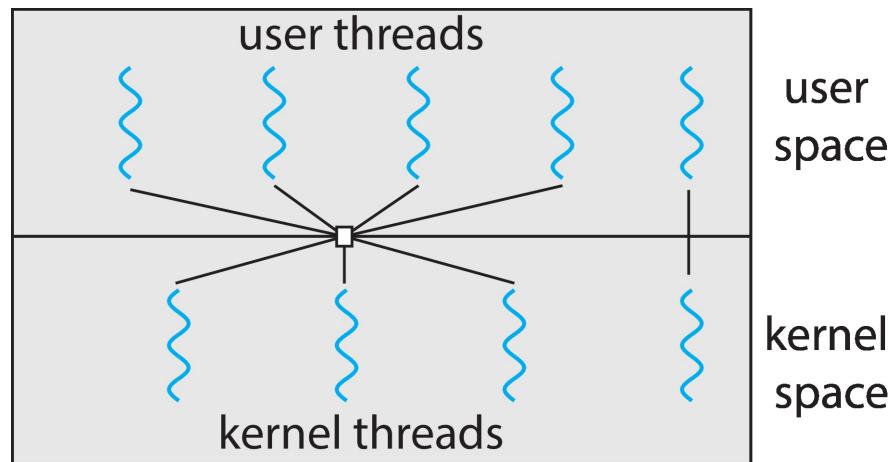
- Allows many user level threads to be mapped to many kernel threads
- Allows the operating system to create a sufficient number of kernel threads
- Windows with the *ThreadFiber* package
- Otherwise not very common





# Two-level Model

- Similar to M:M, except that it allows a user thread to be **bound** to kernel thread





# Thread Libraries

---

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





# Pthreads

---

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





# Pthreads Example

---

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

#include <stdlib.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 */

    /* set the default attributes of the thread */
    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);
}
```





# PThreads Example (Cont.)

---

```
/* The thread will execute 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);
```

---



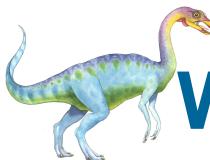


# Windows Multithreaded C Program

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

/* The thread will execute in this function */
DWORD WINAPI Summation(LPVOID Param)
{
    DWORD Upper = *(DWORD*)Param;
    for (DWORD i = 1; i <= Upper; i++)
        Sum += i;
    return 0;
}
```





# Windows Multithreaded C Program (Cont.)

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

    Param = atoi(argv[1]);
    /* 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 */

    /* now wait for the thread to finish */
    WaitForSingleObject(ThreadHandle, INFINITE);

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

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





# 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

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





# Java Threads

## Implementing Runnable interface:

```
class Task implements Runnable  
{  
    public void run() {  
        System.out.println("I am a thread.");  
    }  
}
```

## Creating a thread:

```
Thread worker = new Thread(new Task());  
worker.start();
```

## Waiting on a thread:

```
try {  
    worker.join();  
}  
catch (InterruptedException ie) { }
```





# Java Executor Framework

---

- Rather than explicitly creating threads, Java also allows thread creation around the Executor interface:

```
public interface Executor
{
    void execute(Runnable command);
}
```

- The Executor is used as follows:

```
Executor service = new Executor;
service.execute(new Task());
```





# Java Executor Framework

```
import java.util.concurrent.*;  
  
class Summation implements Callable<Integer>  
{  
    private int upper;  
    public Summation(int upper) {  
        this.upper = upper;  
    }  
  
    /* The thread will execute in this method */  
    public Integer call() {  
        int sum = 0;  
        for (int i = 1; i <= upper; i++)  
            sum += i;  
  
        return new Integer(sum);  
    }  
}
```





# Java Executor Framework (Cont.)

```
public class Driver
{
    public static void main(String[] args) {
        int upper = Integer.parseInt(args[0]);

        ExecutorService pool = Executors.newSingleThreadExecutor();
        Future<Integer> result = pool.submit(new Summation(upper));

        try {
            System.out.println("sum = " + result.get());
        } catch (InterruptedException | ExecutionException ie) { }
    }
}
```





# 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
- Five methods explored
  - Thread Pools
  - Fork-Join
  - OpenMP
  - Grand Central Dispatch
  - Intel Threading Building Blocks





# Thread Pools

---

- Create a number of threads in a pool where they await work
- 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(VOID Param) {  
    /*  
     * this function runs as a separate thread.  
     */  
}
```





# Java Thread Pools

- Three factory methods for creating thread pools in Executors class:

- static ExecutorService newSingleThreadExecutor()
- static ExecutorService newFixedThreadPool(int size)
- static ExecutorService newCachedThreadPool()





# Java Thread Pools (Cont.)

---

```
import java.util.concurrent.*;

public class ThreadPoolExample
{
    public static void main(String[] args) {
        int numTasks = Integer.parseInt(args[0].trim());

        /* Create the thread pool */
        ExecutorService pool = Executors.newCachedThreadPool();

        /* Run each task using a thread in the pool */
        for (int i = 0; i < numTasks; i++)
            pool.execute(new Task());

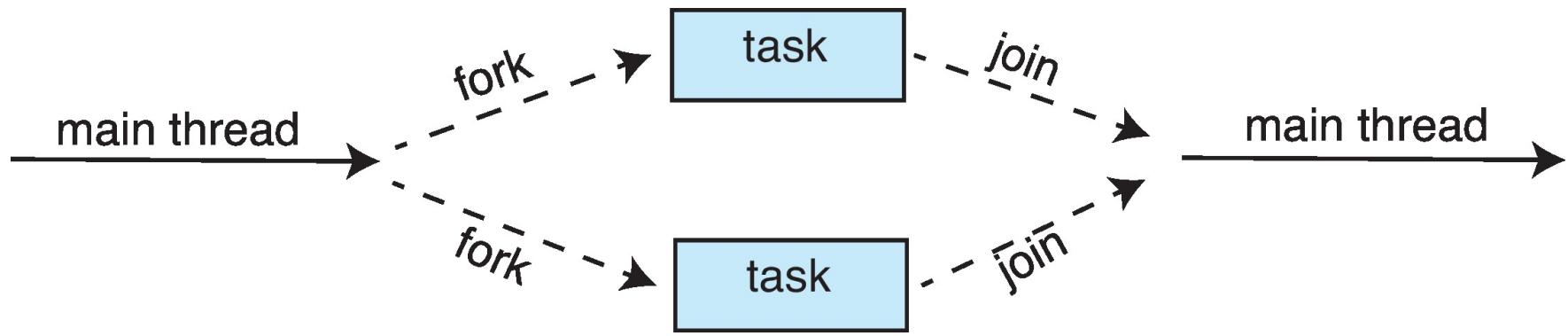
        /* Shut down the pool once all threads have completed */
        pool.shutdown();
    }
}
```





# Fork-Join Parallelism

- Multiple threads (tasks) are **forked**, and then **joined**.





# Fork-Join Parallelism

- General algorithm for fork-join strategy:

```
Task(problem)
    if problem is small enough
        solve the problem directly
    else
        subtask1 = fork(new Task(subset of problem)
        subtask2 = fork(new Task(subset of problem)

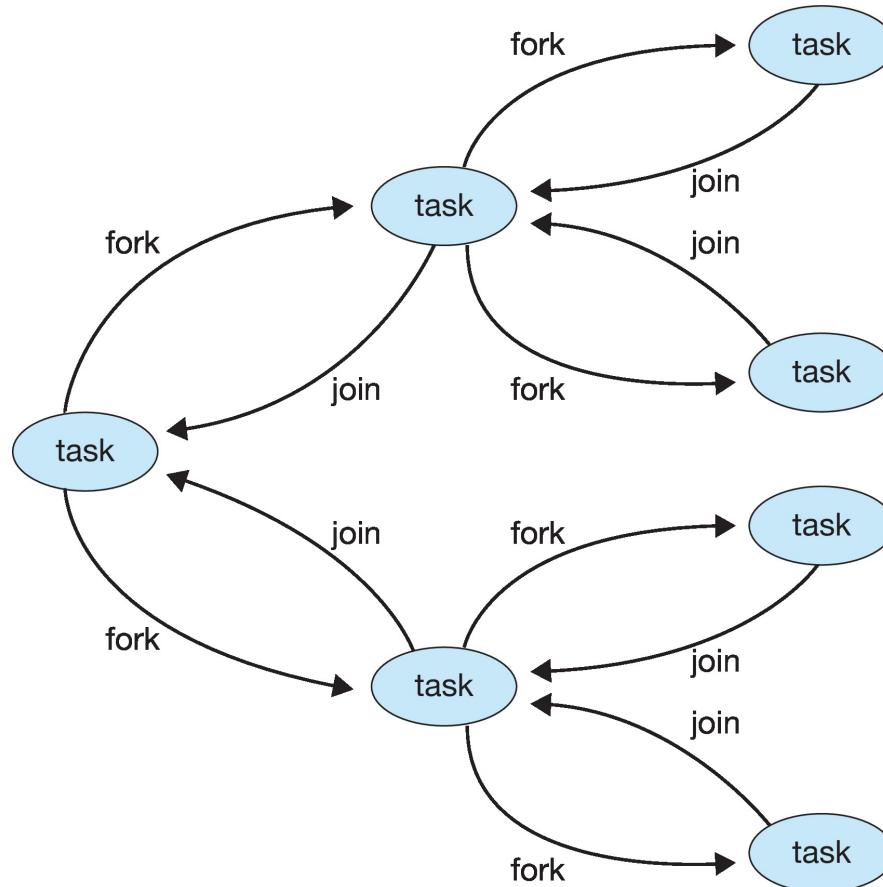
        result1 = join(subtask1)
        result2 = join(subtask2)

    return combined results
```





# Fork-Join Parallelism





# Fork-Join Parallelism in Java

---

```
ForkJoinPool pool = new ForkJoinPool();
// array contains the integers to be summed
int[] array = new int[SIZE];

SumTask task = new SumTask(0, SIZE - 1, array);
int sum = pool.invoke(task);
```





# Fork-Join Parallelism in Java

```
import java.util.concurrent.*;

public class SumTask extends RecursiveTask<Integer>
{
    static final int THRESHOLD = 1000;

    private int begin;
    private int end;
    private int[] array;

    public SumTask(int begin, int end, int[] array) {
        this.begin = begin;
        this.end = end;
        this.array = array;
    }

    protected Integer compute() {
        if (end - begin < THRESHOLD) {
            int sum = 0;
            for (int i = begin; i <= end; i++)
                sum += array[i];

            return sum;
        }
        else {
            int mid = (begin + end) / 2;

            SumTask leftTask = new SumTask(begin, mid, array);
            SumTask rightTask = new SumTask(mid + 1, end, array);

            leftTask.fork();
            rightTask.fork();

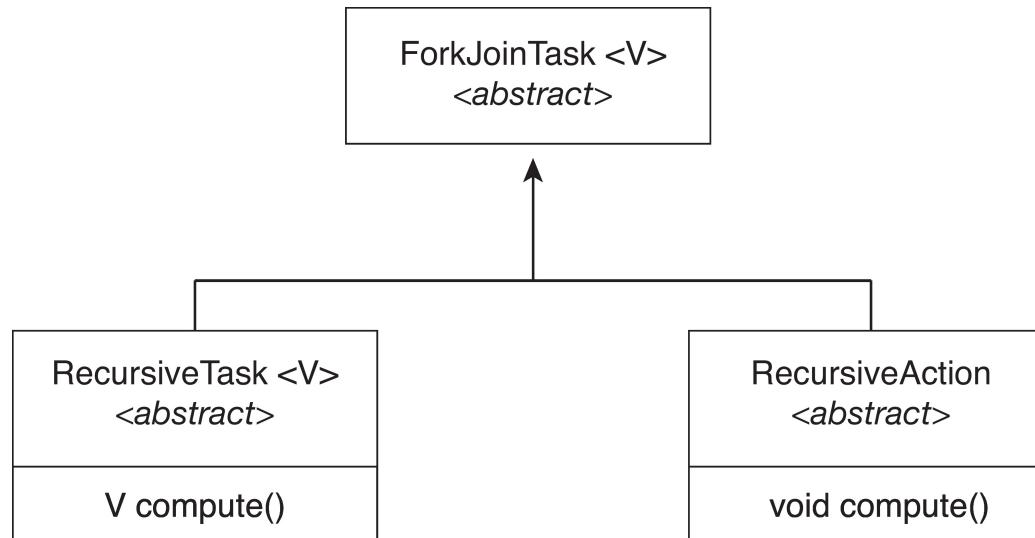
            return rightTask.join() + leftTask.join();
        }
    }
}
```





# Fork-Join Parallelism in Java

- The **ForkJoinTask** is an abstract base class
- **RecursiveTask** and **RecursiveAction** classes extend **ForkJoinTask**
- **RecursiveTask** returns a result (via the return value from the `compute()` method)
- **RecursiveAction** does not return a result





# 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

```
#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;
}
```





- Run the for loop in parallel

```
#pragma omp parallel for
for (i = 0; i < N; i++) {
    c[i] = a[i] + b[i];
}
```





# Grand Central Dispatch

- Apple technology for macOS and iOS operating systems
- Extensions to C, C++ and Objective-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

---

- 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
    - ▶ Four system wide queues divided by quality of service:
      - QOS\_CLASS\_USER\_INTERACTIVE
      - QOS\_CLASS\_USER\_INITIATED
      - QOS\_CLASS\_USER.Utility
      - QOS\_CLASS\_USER\_BACKGROUND





# Grand Central Dispatch

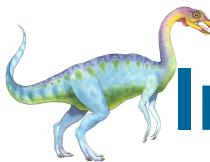
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- For the Swift language a task is defined as a closure – similar to a block, minus the caret
- Closures are submitted to the queue using the `dispatch_async()` function:

```
let queue = dispatch_get_global_queue
    (QOS_CLASS_USER_INITIATED, 0)

dispatch_async(queue, { print("I am a closure.") })
```





# Intel Threading Building Blocks (TBB)

- Template library for designing parallel C++ programs
- A serial version of a simple for loop

```
for (int i = 0; i < n; i++) {  
    apply(v[i]);  
}
```

- The same for loop written using TBB with **parallel\_for** statement:

```
parallel_for (size_t(0), n, [=](size_t i) {apply(v[i]);});
```





# Threading Issues

---

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





# Semantics of fork() and exec()

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





# Signal Handling

- **Signals** are used in UNIX systems to notify a process that a particular event has occurred.
- 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
- 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.)

---

- 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

- Terminating a thread before it has finished
- Thread to be canceled is **target thread**
- Two general approaches:
  - **Asynchronous cancellation** terminates the target thread immediately
  - **Deferred cancellation** allows the target thread to periodically check if it should be cancelled
- 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);

/* wait for the thread to terminate */
pthread_join(tid,NULL);
```





# 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 Cancellation in Java

- Deferred cancellation uses the `interrupt()` method, which sets the interrupted status of a thread.

```
Thread worker;
```

```
    . . .
```

```
/* set the interruption status of the thread */
worker.interrupt()
```

- A thread can then check to see if it has been interrupted:

```
while (!Thread.currentThread().isInterrupted()) {
    . . .
}
```





# Thread-Local Storage

---

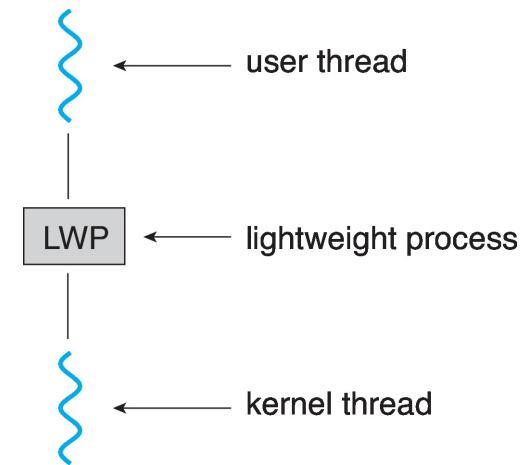
- **Thread-local storage (TLS)** allows each thread to have its own copy of data
- Useful when you do not have control over the thread creation process (i.e., when using a thread pool)
- Different from local variables
  - Local variables visible only during single function invocation
  - TLS visible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





# Scheduler Activations

- Both M:M and Two-level models require communication to maintain the appropriate number of kernel threads allocated to the application
- 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?
- Scheduler activations provide **upcalls** - a communication mechanism from the kernel to the **upcall handler** in the thread library
- This communication allows an application to maintain the correct number kernel threads





# Operating System Examples

---

- Windows Threads
- Linux Threads





# Windows Threads

- Windows API – primary API for Windows applications
- 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 thread





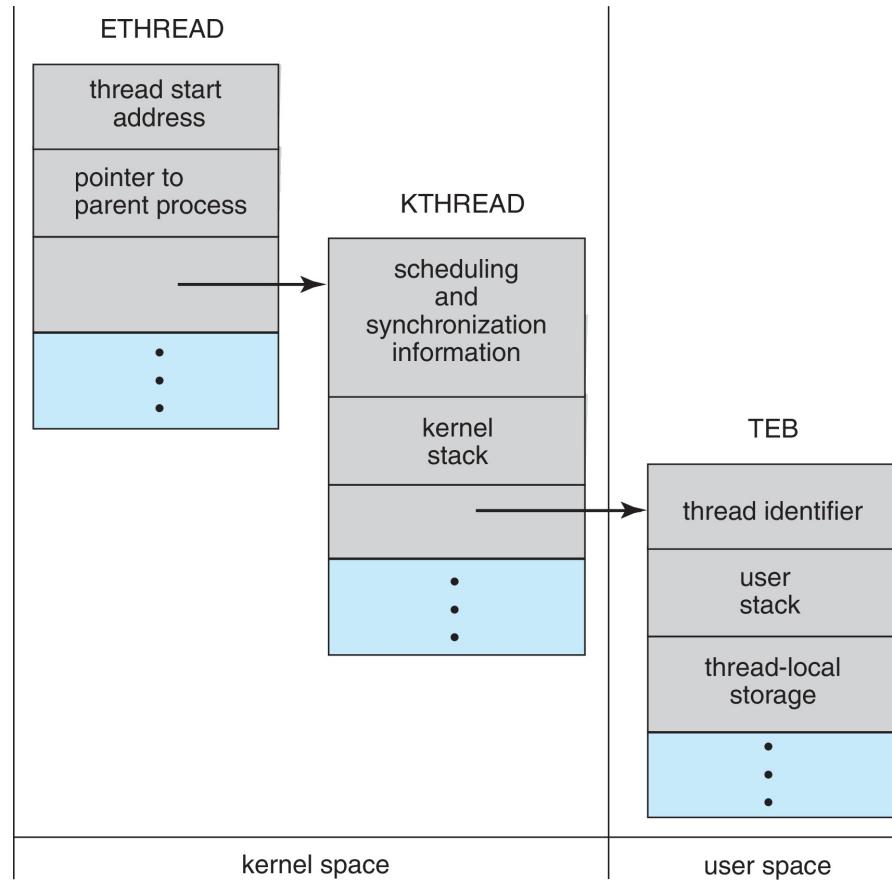
# Windows Threads (Cont.)

- 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

