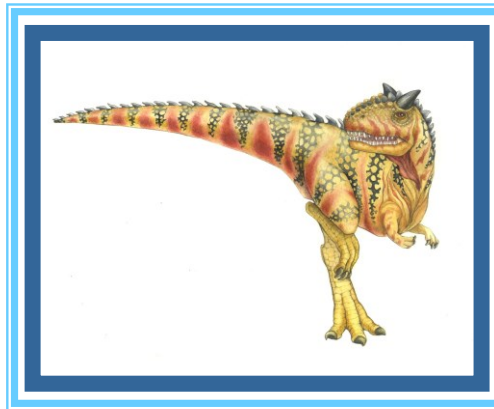


Chapter 4: Threads & Concurrency





Outline

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





Objectives

- 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





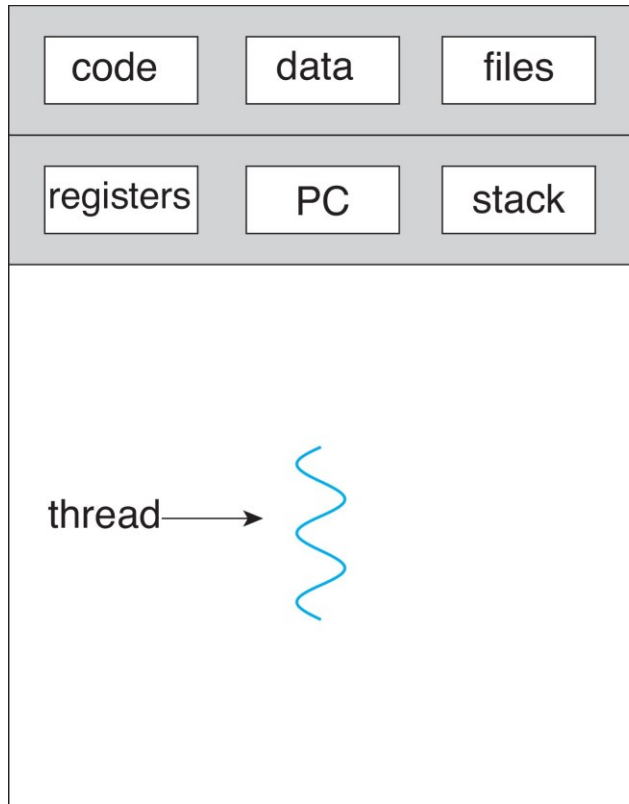
Motivation

- Most modern applications are multithreaded
- Threads run within application
- Multiple tasks with 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

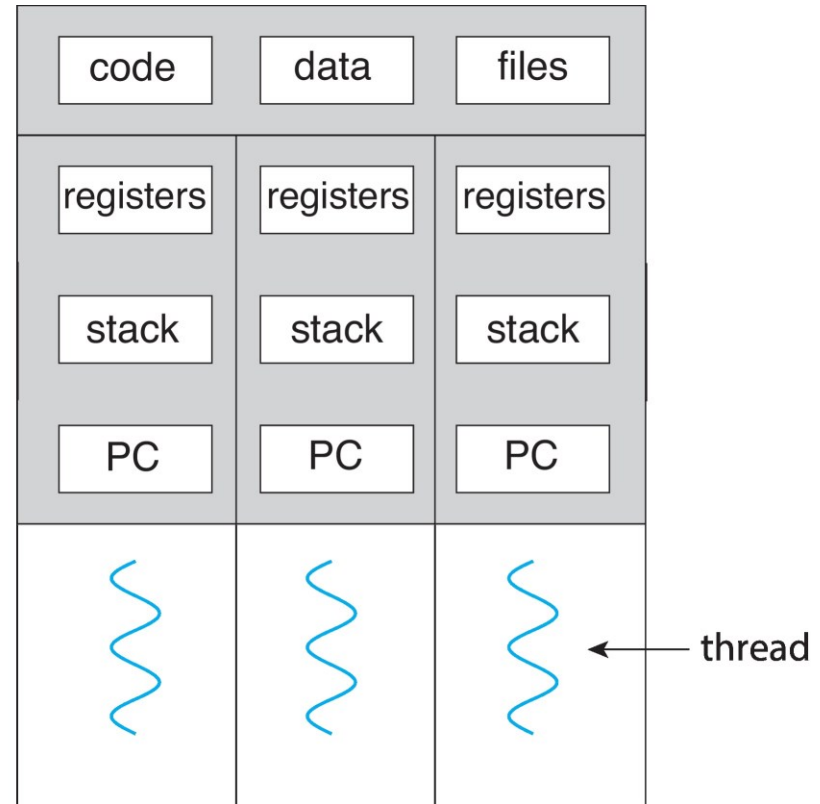




Single and Multithreaded Processes



single-threaded process

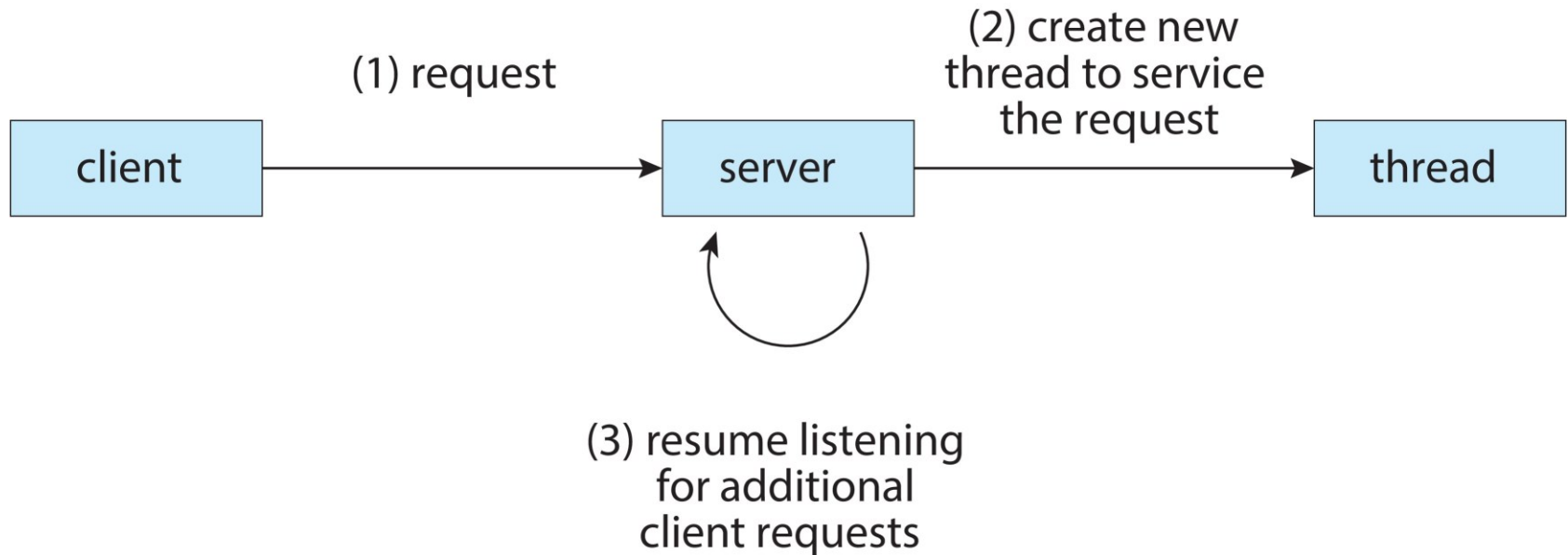


multithreaded process





Multithreaded Server Architecture





Benefits

- **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

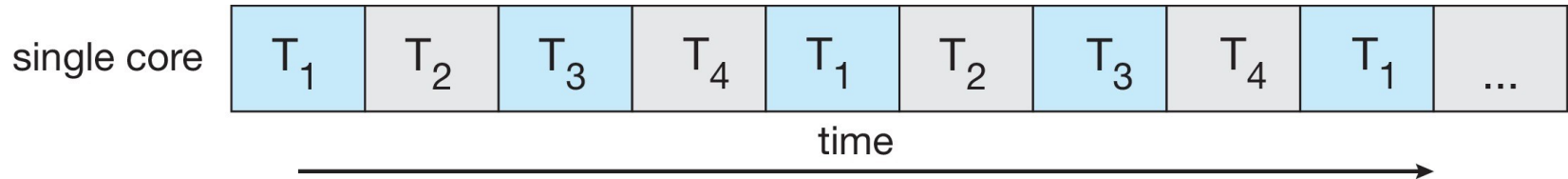
- **Multicore** or **multiprocessor** systems puts pressure on programmers, challenges include:
 - **Dividing activities**
 - **Balance**
 - **Data splitting**
 - **Data dependency**
 - **Testing and debugging**
- **Parallelism** implies a system can perform more than one task simultaneously
- **Concurrency**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



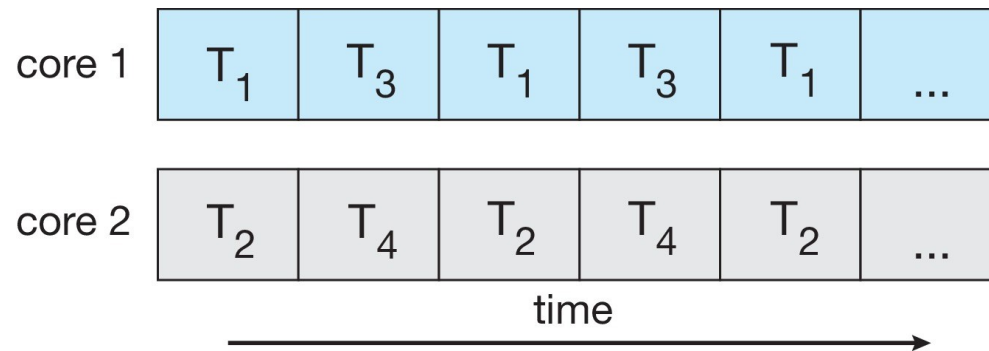


Concurrency vs. Parallelism

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



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





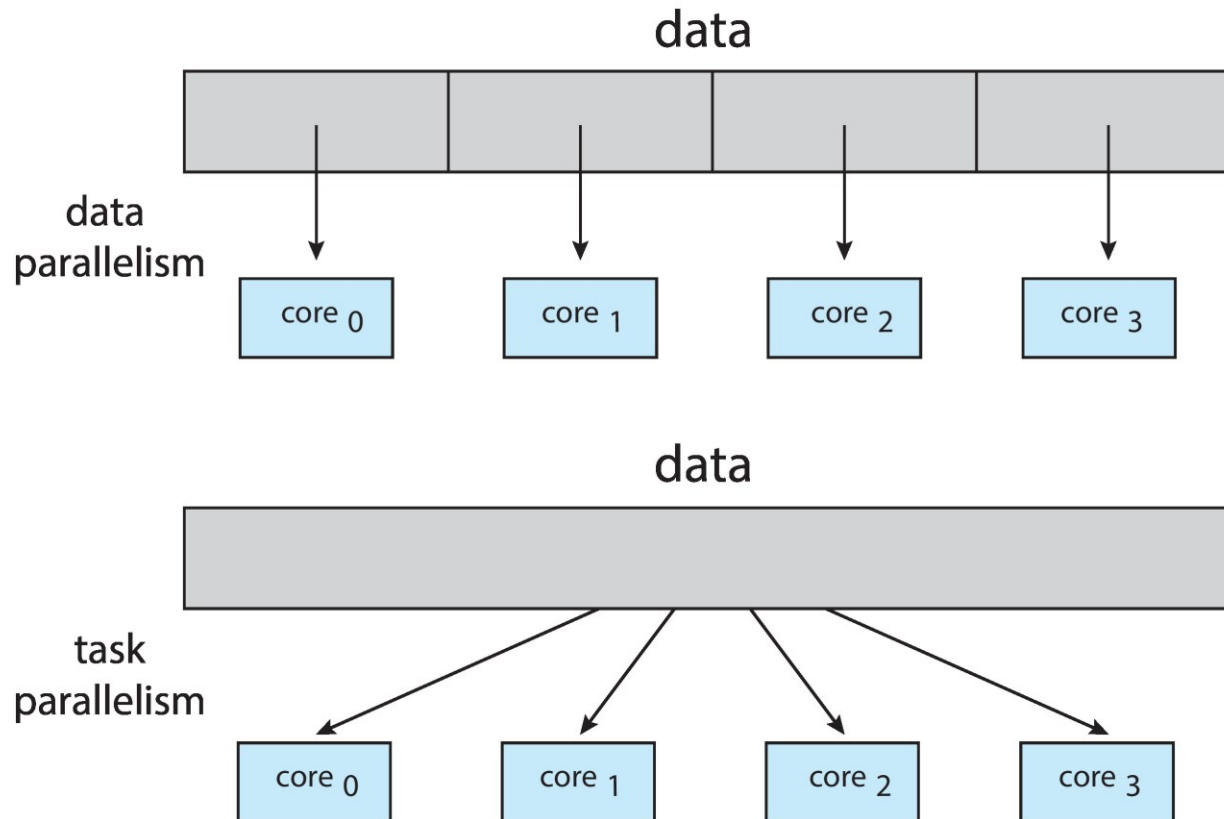
Multicore Programming

- 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 $1 / S$

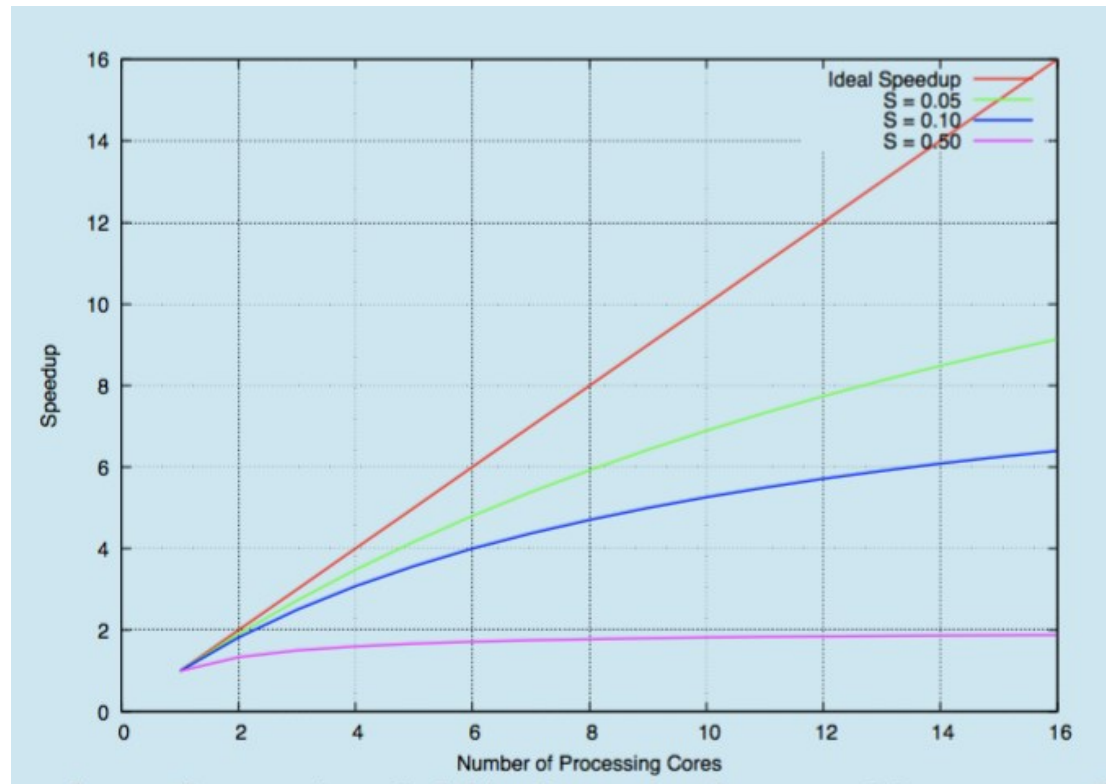
Serial portion of an application has disproportionate effect on performance gained by adding additional cores

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





Amdahl's Law





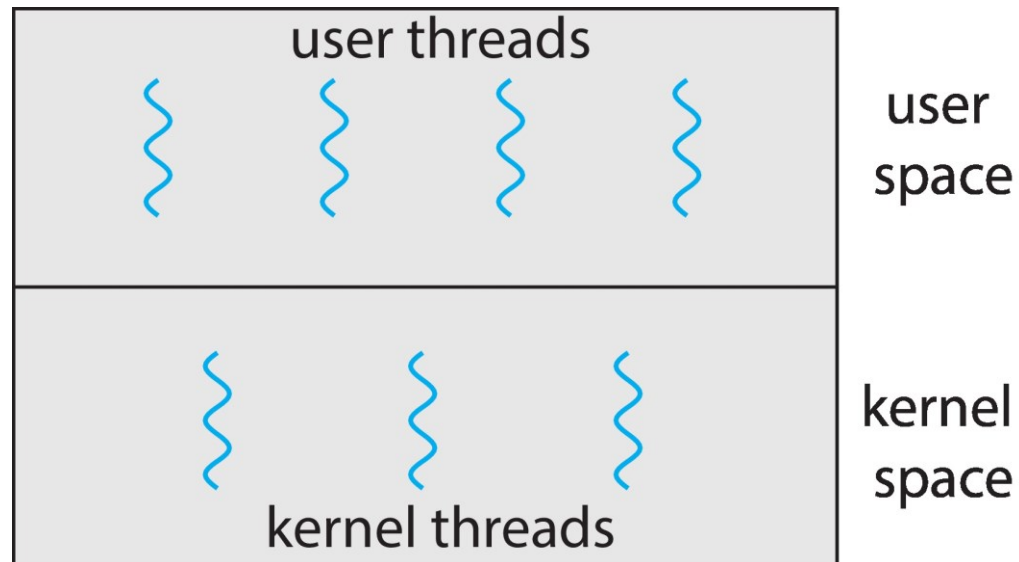
User Threads and Kernel Threads

- **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

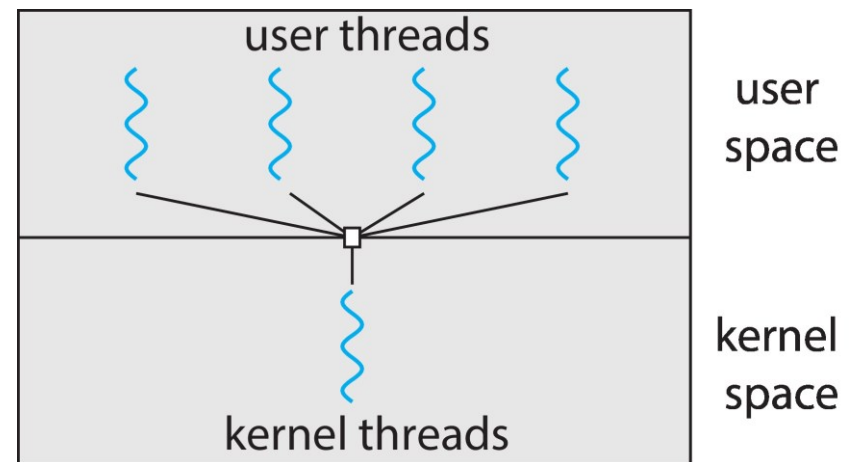
- Many-to-One
- One-to-One
- Many-to-Many





Many-to-One

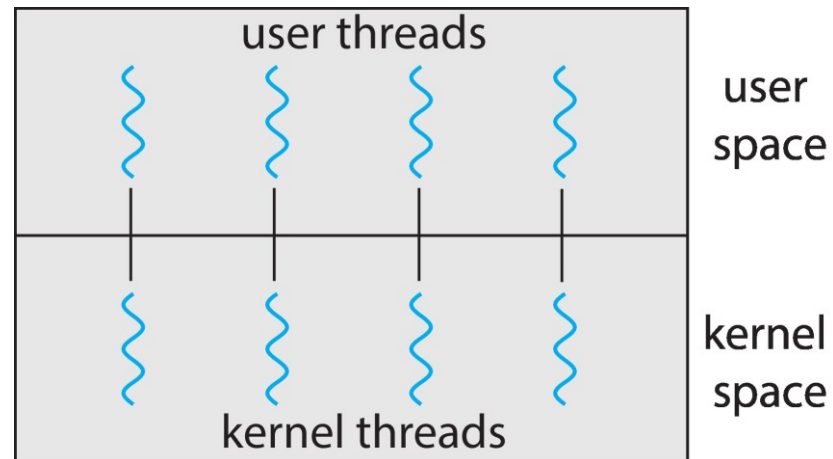
- Many user-level threads mapped to single kernel thread
- One thread blocking causes all to block
- Multiple threads may not run in parallel on multicore system because only one may be in kernel at a time
- Few systems currently use this model
- Examples:
 - **Solaris Green Threads**
 - **GNU Portable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





One-to-One

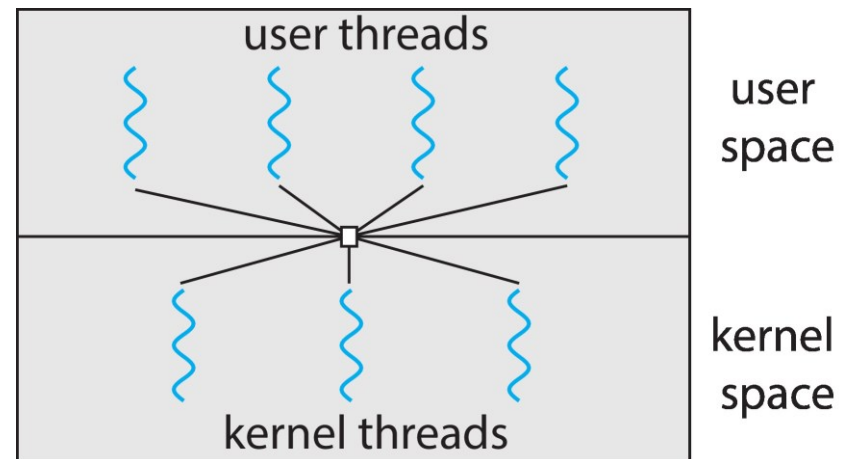
- Each user-level thread maps to kernel thread
- Creating a user-level thread creates a kernel thread
- More concurrency than many-to-one
- Number of threads per process sometimes restricted due to overhead
- Examples
 - Windows
 - Linux





Many-to-Many Model

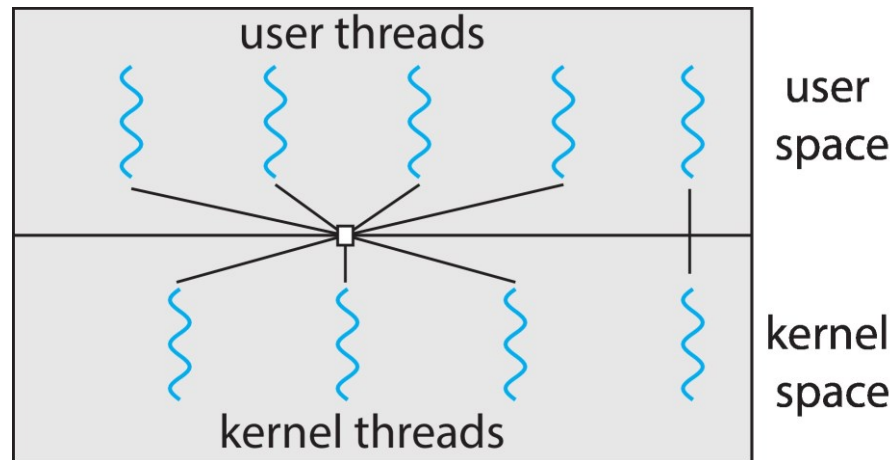
- Allows many user level threads to be mapped to many kernel threads
- Allows the operating system to create a sufficient number of kernel threads
- Windows with the *ThreadFiber* package
- Otherwise not very common





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();
}
```

- Standard practice is to implement Runnable 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(AVOID 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());

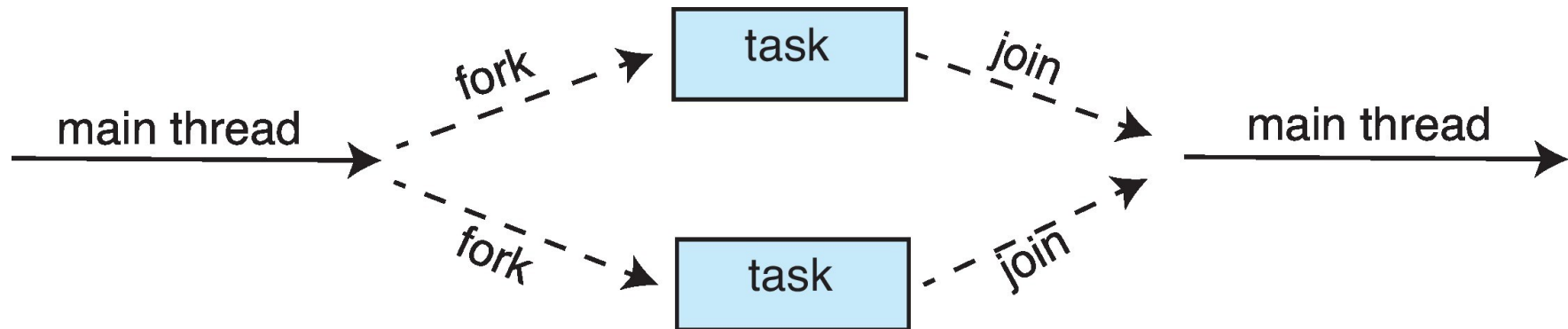
        /* Shut down the pool once all threads have completed */
        pool.shutdown();
    }
}
```





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))

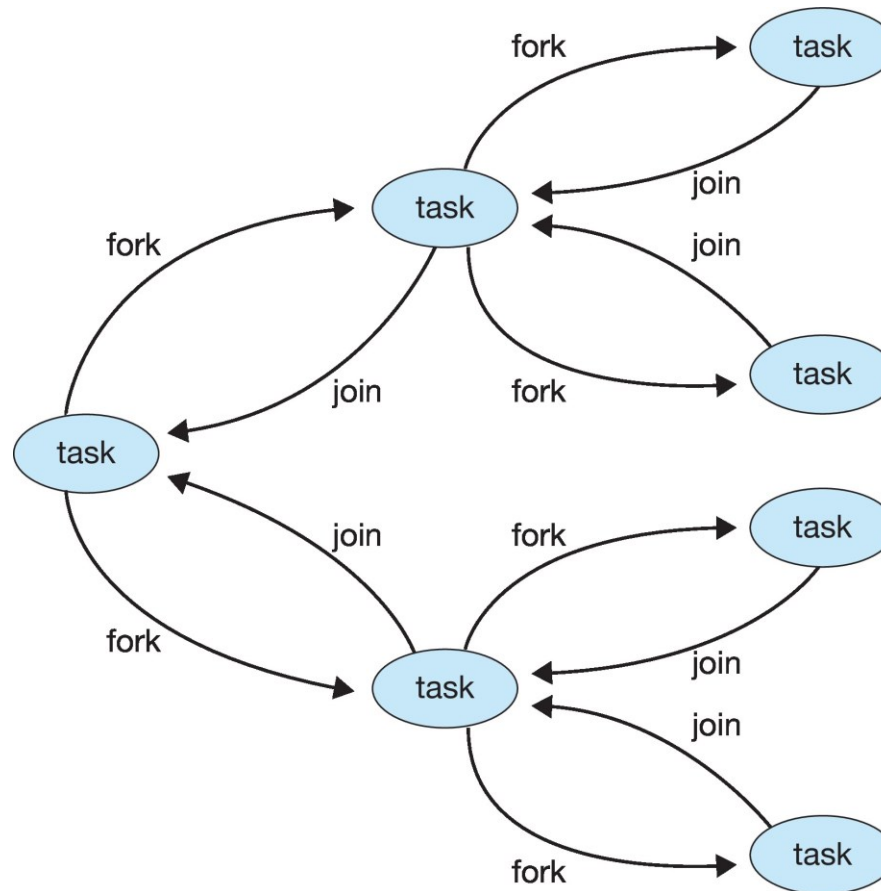
    result1 = join(subtask1)
    result2 = join(subtask2)

    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();

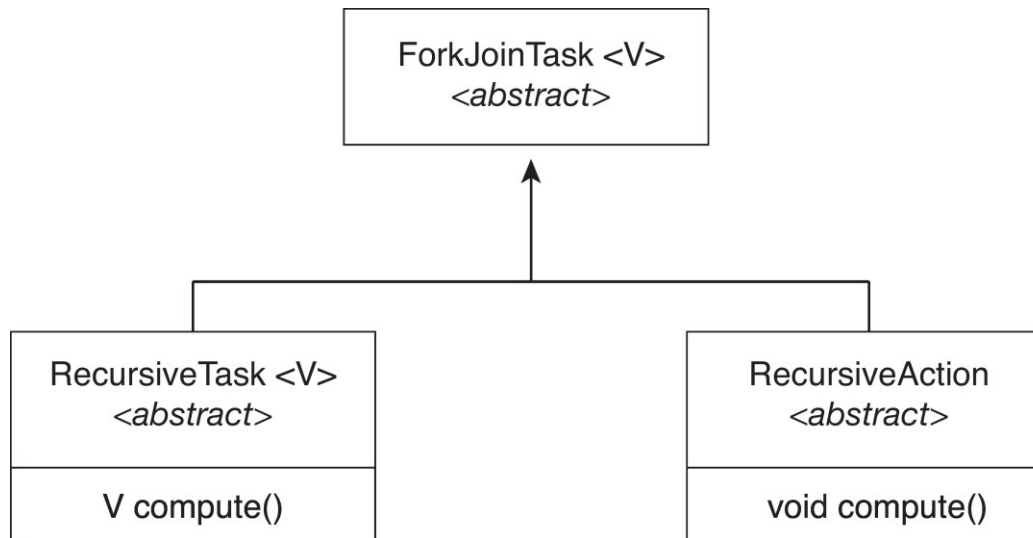
            return rightTask.join() + leftTask.join();
        }
    }
}
```





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

- 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

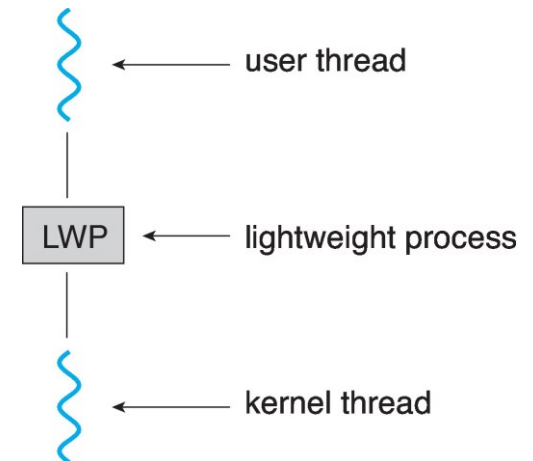
- **Thread-local storage (TLS)** allows each thread to have its own copy of data
- Useful when you do not have control over the thread creation process (i.e., when using a thread pool)
- Different from local variables
 - Local variables visible only during single function invocation
 - TLS visible across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





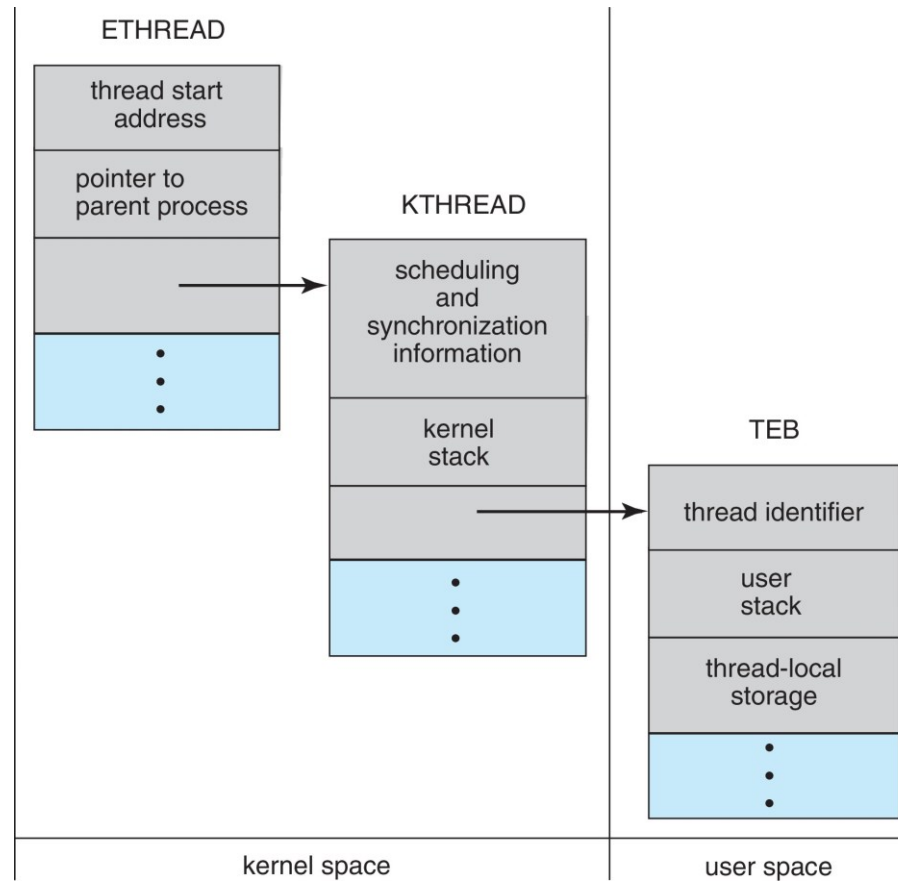
Windows Threads (Cont.)

- 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

