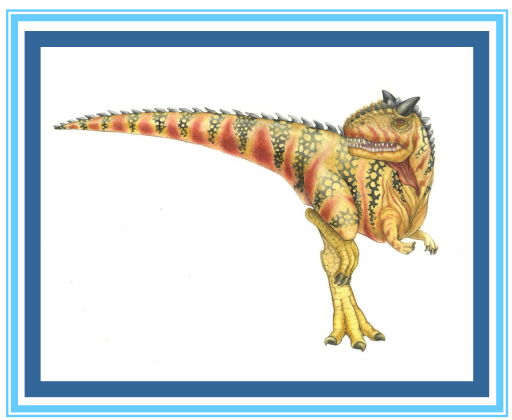
Lecture 4: Threads



Lecture 4: Threads

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

Objectives

- To Introduce Notion of a Thread—a Fundamental Unit of CPU Utilization that Forms Basis of Multithreaded Computer Systems
- To Discuss APIs for Pthreads, Windows, and Java Thread Libraries
- To Explore Several Strategies that Provide Implicit Threading
- To Examine Issues Related to Multithreaded Programming
- To Cover OS Support for Threads in Windows and Linux

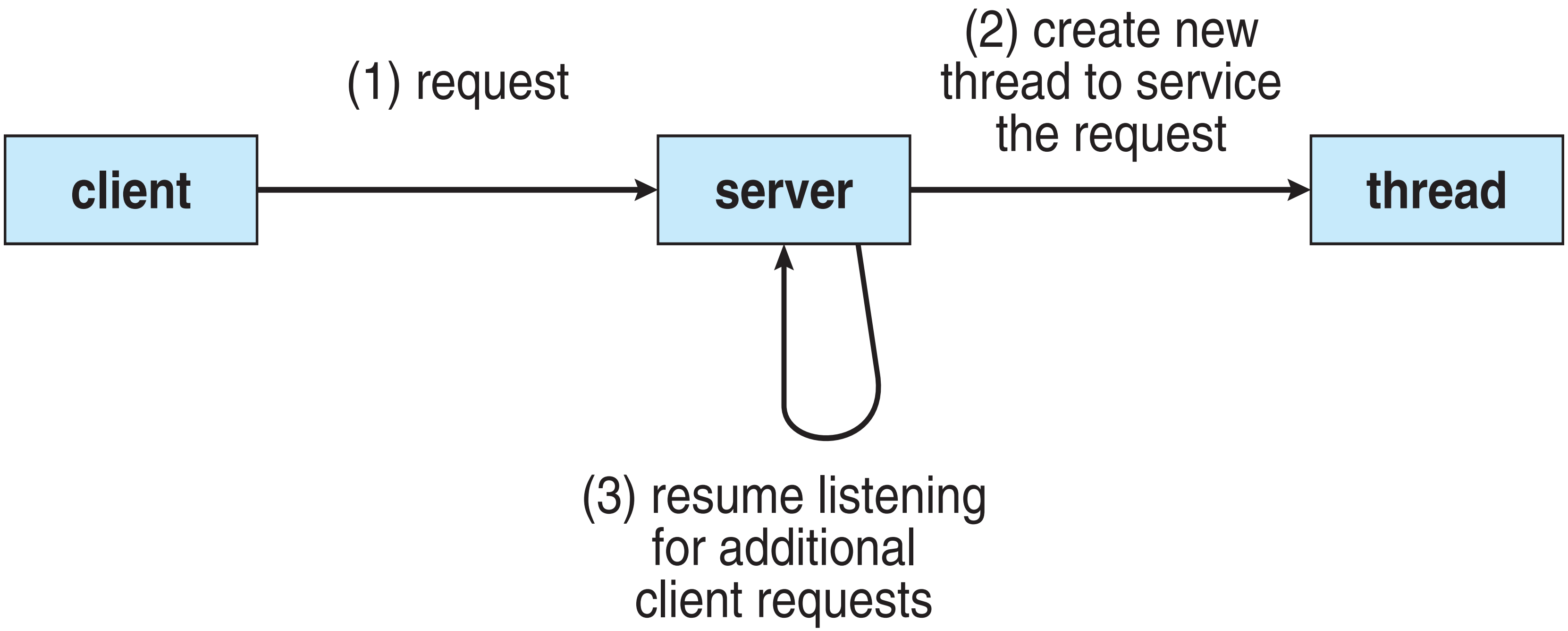
Motivation

- Many Parts of a Typical Application can be Run in Parallel (in Different Threads)
- Example 1: Web Browser
  - Thread A: display images
  - Thread B: retrieve data from network
- Example 2: Word Processor
  - Thread A: displaying graphics
  - Thread B: responding to keystrokes by user
  - Thread C: spell & grammar check in background

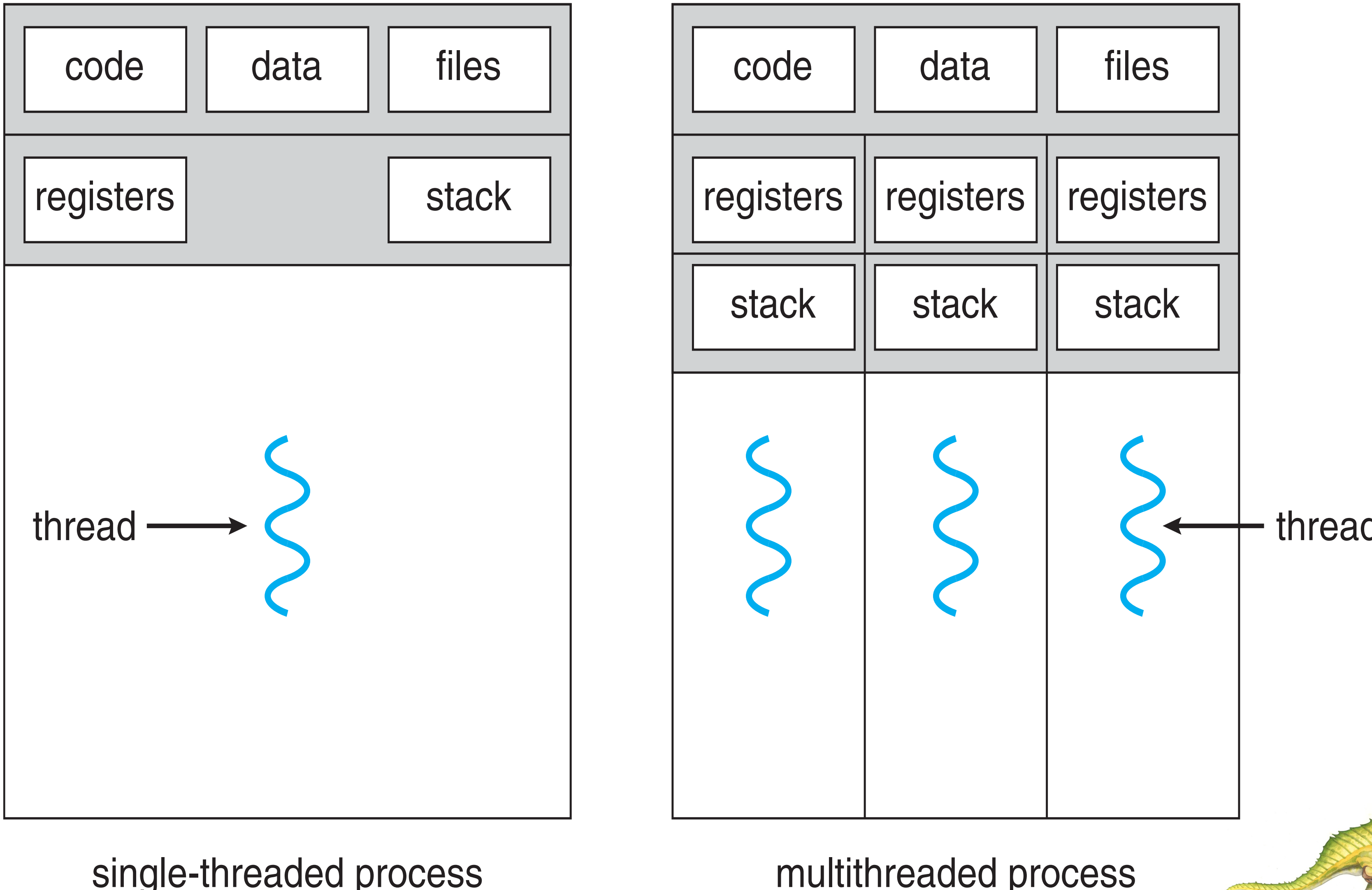
Motivation (cont.)

- Example 3: Matrix Multiplication (1000x1000)
  - Can have up to 1M parallel threads of execution
- Example 4: Remote Procedure Calls (RPCs)
- Example 5: when a process need an I/O
- Possible Solution: Creating Child Processes
  - Allows multiple flows of execution ☺
  - Time-consuming ☹
  - Resource consumptive ☹
- Fact:
  - Child Process will Perform Same Task as Parent Process ➔ Why to Incur such Overheads?

Multithreaded Server Architecture



Single and Multithreaded Processes



Multi-Threading in OS Kernels

- Most OSes are Multi-Threaded
  - Each thread performs a specific task
- Example
  - A thread to manage I/O type A
  - A thread to manage memory
  - A thread for interrupt handling

Benefits of Multi-Threading

- **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
  - Solaris: process creation 30X slower, context switching 5X slower
- **Scalability –** process can take advantage of multiprocessor architectures

Threads vs. Processes

- Processes typically Independent
  - Threads exist as subsets of a process
- Processes Carry Much more State Info
  - Threads of a process share process state as well as memory and other resources
- Processes have Separate Address Spaces
  - Threads share their address space
- Processes Interact Only through IPC
- Processes Much Slower Context Switch Time
- Processes Much Slower Creation Time

Multicore Programming

- **Multicore** or **Multiprocessor** Systems Putting Pressure on Programmers
- Programming Challenges Include:
  - **Dividing activities**
  - **Balance**
  - **Data splitting**
  - **Data dependency**
  - **Testing and debugging**

Multicore Programming (cont.)

- ***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
  - Possible to have concurrency without parallelism

Concurrency vs. Parallelism

- **Concurrent Exec. on a Single-Core System:**

single core	T_1	T_2	T_3	T_4	T_1	T_2	T_3	T_4	T_1	…

time →

- **Parallelism on a Multi-Core System:**

core 1	T_1	T_3	T_1	T_3	T_1	…
core 2	T_2	T_4	T_2	T_4	T_2	…

time →

Amdahl's Law

- Imagine an Application has both Serial and Parallel Components
- *S* is Serial Portion
- *N* Processing Cores

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

- Sample Program: 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*

Multicore Programming (cont.)

- **Before Advent of Multi-core Systems**
  - CPU schedulers designed to provide illusion of parallelisms (not actual parallelism)
  - Processes were running concurrently (but not in parallel)
- **As # of Threads Grows, so Does Architectural Support for Threading**
  - CPUs have cores as well as ***HW threads***
    - HW support such as multiple sets of RFs and PCs
  - Consider Oracle SPARC T4 with 8 cores, and 8 hardware threads per core

User Threads and Kernel Threads

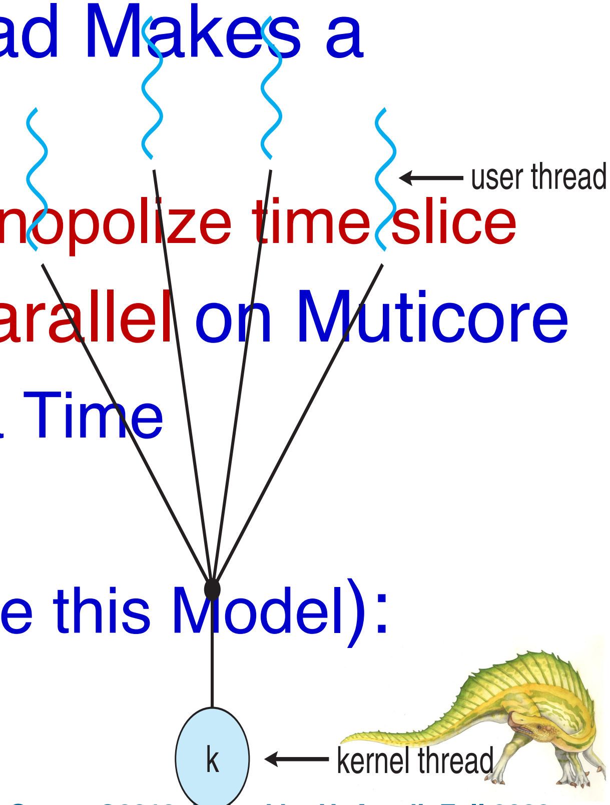
- **Kernel Threads**
  - Supported and managed directly by OS
- **User Threads**
  - Management done by user-level threads library
  - Supported above kernel and managed without kernel support
    - Kernel is unaware of them unless they are mapped to kernel threads
  - Context switching very fast (no interaction with kernel)
- **Note:** Ultimately, a Relationship Must Exist between User threads and Kernel threads

Multithreading Models

- Many-to-One (N:1)
  - All application-level threads maps to a single kernel-level scheduled entity
- One-to-One (1:1)
  - Threads created by user are in 1-1 correspondence with schedulable entities in kernel (Some say, no user-level thread)
- Many-to-Many (M:N)
  - Maps M number of application-level threads to N number of kernel entities

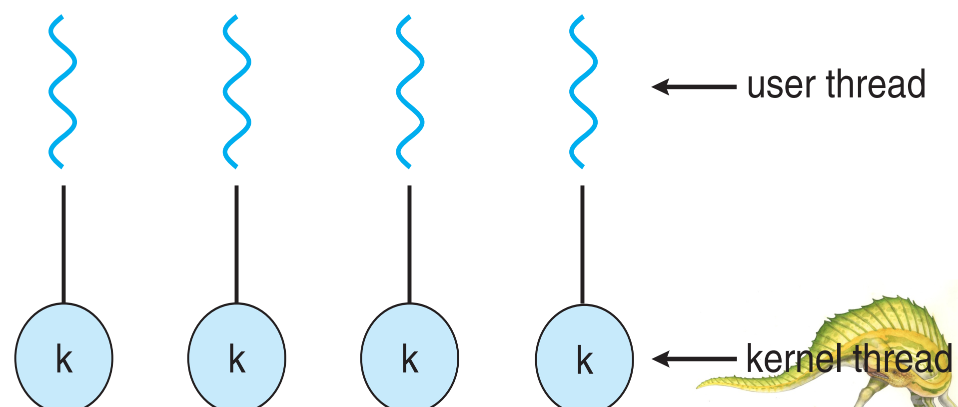
Many-to-One

- Many User-Level Threads Mapped to Single Kernel Thread
- Thread management Done by thread library in user space → fast & efficient
- Entire Process Will Block if a thread Makes a Blocking System Call
  - Alternatively, a single thread can monopolize time slice
- Multiple Threads may not Run in Parallel on Muticore
  - Since only one may be in Kernel at a Time
  - Does not benefit from multi cores
- Examples (Few Systems Currently use this Model):
  - **Solaris Green Threads**
  - **GNU Portable Threads**



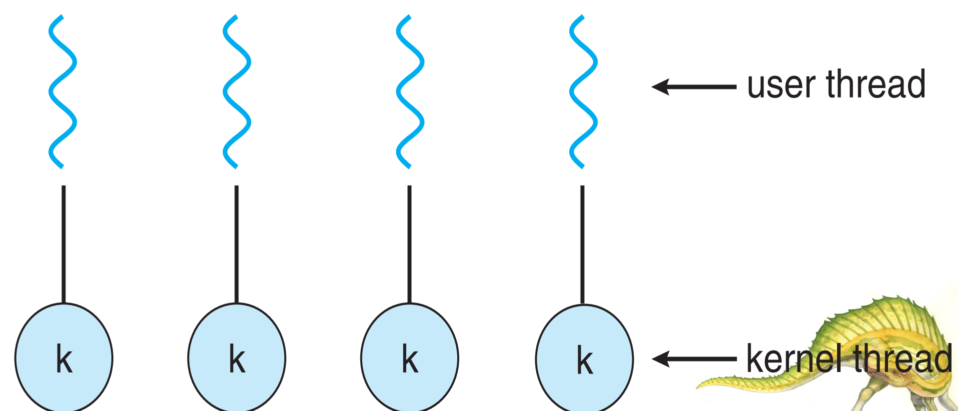
One-to-One

- Each User-Level Thread Maps to Kernel Thread
- Creating a User-Level Thread Creates a Kernel Thread
- More Concurrency than Many-to-One
  - Allows another thread to run when a thread makes a blocking system call
- Examples
  - Windows, Linux
  - Solaris 9 and later



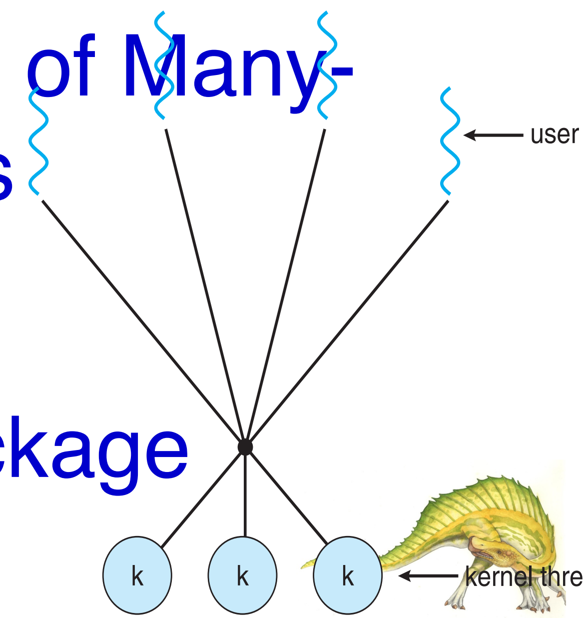
One-to-One (cont.)

- Main Drawback
  - Creating a user thread requires creating corresponding kernel thread
  - ➔ Overhead of creating kernel threads can burden performance of an application
  - Solution: most implementations of this model restrict number of threads supported by system



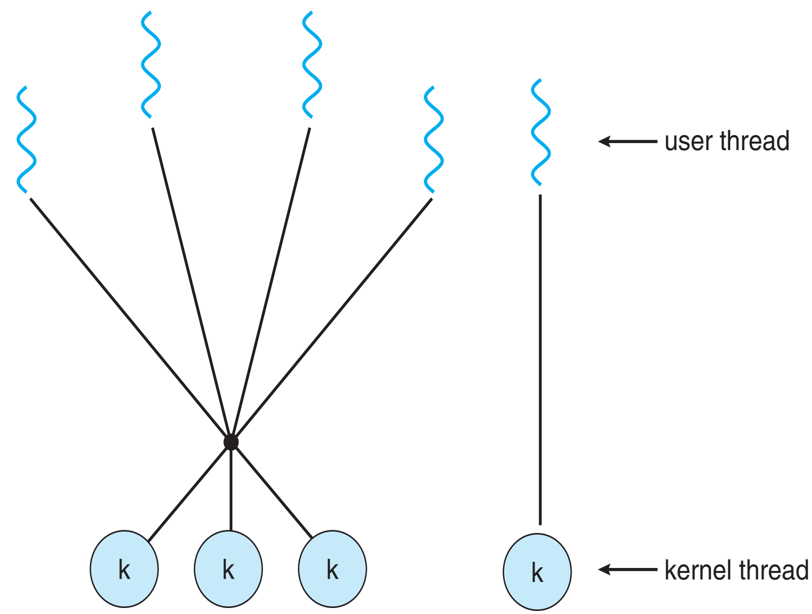
Many-to-Many Model

- Multiplexes Many User Level Threads to be Mapped to Smaller or Equal Number of Kernel Threads
- Allows OS to Create a Sufficient Number of Kernel Threads
- Tries to Address Shortcomings of Many-to-one and One-to-One Models
- Solaris prior to version 9
- Windows with *ThreadFiber* package



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



Processes, User Threads, Kernel Threads

- Process
  - Isolated with its own virtual address space
  - Contains process data like file handles
  - Lots of overhead
  - Every process has at least one kernel thread
- Kernel Threads
  - Shared virtual address space
  - Contains running state data
  - Less overhead
  - From OS's point of view, this is what is scheduled to run on a CPU

Processes, User Threads, Kernel Threads

- User Threads
  - Shared virtual address space, contains running state data
  - Kernel unaware
  - Even less overhead

Trade-Offs

- Processes
  - Secure and isolated ☺
  - Kernel aware ☺
  - Creating a new process (address space!) brings lots of overhead ☹

Trade-Offs (cont.)

- Kernel Threads
  - No need to create a new address space ☺
  - No need to change address space in context switch ☺
  - Kernel aware ☺
  - Still need to enter kernel to context switch ☹
- User Threads
  - No new address space, no need to change address space ☺
  - No need to enter kernel to switch ☺
  - Kernel is unaware; No multiprocessing; I/O blocks all user threads; ☹

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 OS

Thread Libraries (cont.)

- Library Entirely in User Space
  - With no kernel support
  - All code/data structures in user space
  - Invoking a function in API results in a local function call in user space not a system call
- Kernel-Level Library Supported by OS
  - Code and data structures for library exist in kernel space
  - Invoking a function in API → system call

Thread Libraries (cont.)

- Three Main Thread Libraries in Use
- POSIX Pthreads Library
  - Thread extension of POSIX standard
  - May be provided as either a user- or kernel-level
- Win32 Thread Library
  - Kernel-level library
- Java Thread API
  - Allows threads to be created & managed directly in Java programs
  - Implemented using a thread library of host system since JVM runs on top of host system

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 Thread Library, Implementation is up to Development of Library
- Common in UNIX OS (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

```c
#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

- Java Threads Managed by JVM
- Typically Implemented using Threads Model provided by Underlying OS
- Each Java Program consists of at Least One Single Thread

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

- 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
- Two Methods explored (Reading Assignment)
  - OpenMP
  - Grand Central Dispatch

Threading Issues

- Semantics of **fork()** and **exec()** system calls
- Signal Handling
  - Synchronous and asynchronous
- Thread Cancellation of Target Thread
  - Asynchronous or deferred
- Scheduler Activations

Semantics of fork() and exec()

- Does `fork()` Duplicate only Calling Thread or all Threads?
  - Some UNIXes have two versions of fork
- What about `exec?`
  - Usually works as normal
  - Replaces running process including all threads

Signal Handling

- **Signals** Used in UNIX to Notify a Process that a Particular Event has Occurred
- **Signal Handler** Used to Deal with 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:
     - default
     - user-defined

Signal Handling (cont.)

- 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 signal to thread to which signal applies
  - Deliver signal to every thread in process
  - Deliver signal to certain threads in process
  - Assign a specific thread to receive all signals for process

Thread Pools

- Create a Number of Threads in a Pool where they Await Work

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

- Advantages:
  - Usually slightly faster to service a request with an existing thread than create a new thread
  - Allows number of threads in application(s) to be bound to size of pool
- Windows API supports thread pools

Thread Cancellation

- Terminating a Thread before it has finished
- Thread to be Canceled is **Target Thread**
- Two General Approaches
  - **Asynchronous cancellation** terminates target thread immediately
  - **Deferred can** periodically ch
- Pthread Code

```
pthread_t tid;

/* create the thread */
pthread_create(&tid, 0, worker, NULL);

. . .

/* cancel the thread */
pthread_cancel(tid);
```

Thread Cancellation (Cont.)

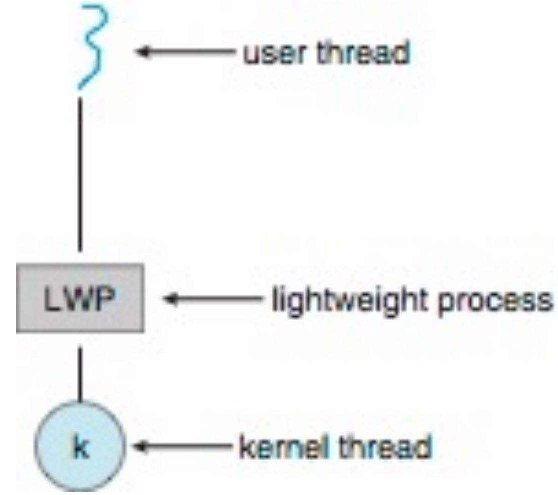
- Invoking Thread Cancellation Requests Cancellation, but Actual Cancellation Depends on Thread State

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, thread cancellation handled through signals

Scheduler Activations

- M:M/Two-Level Models Require communication to maintain appropriate number of kernel threads allocated to application



- **LightWeight Process (LWP)**
  - Typically use an intermediate data structure between user and kernel threads
  - 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?

Operating System Examples

- Reading Assignments
  - Windows threads
  - Linux threads
  - Upcalls

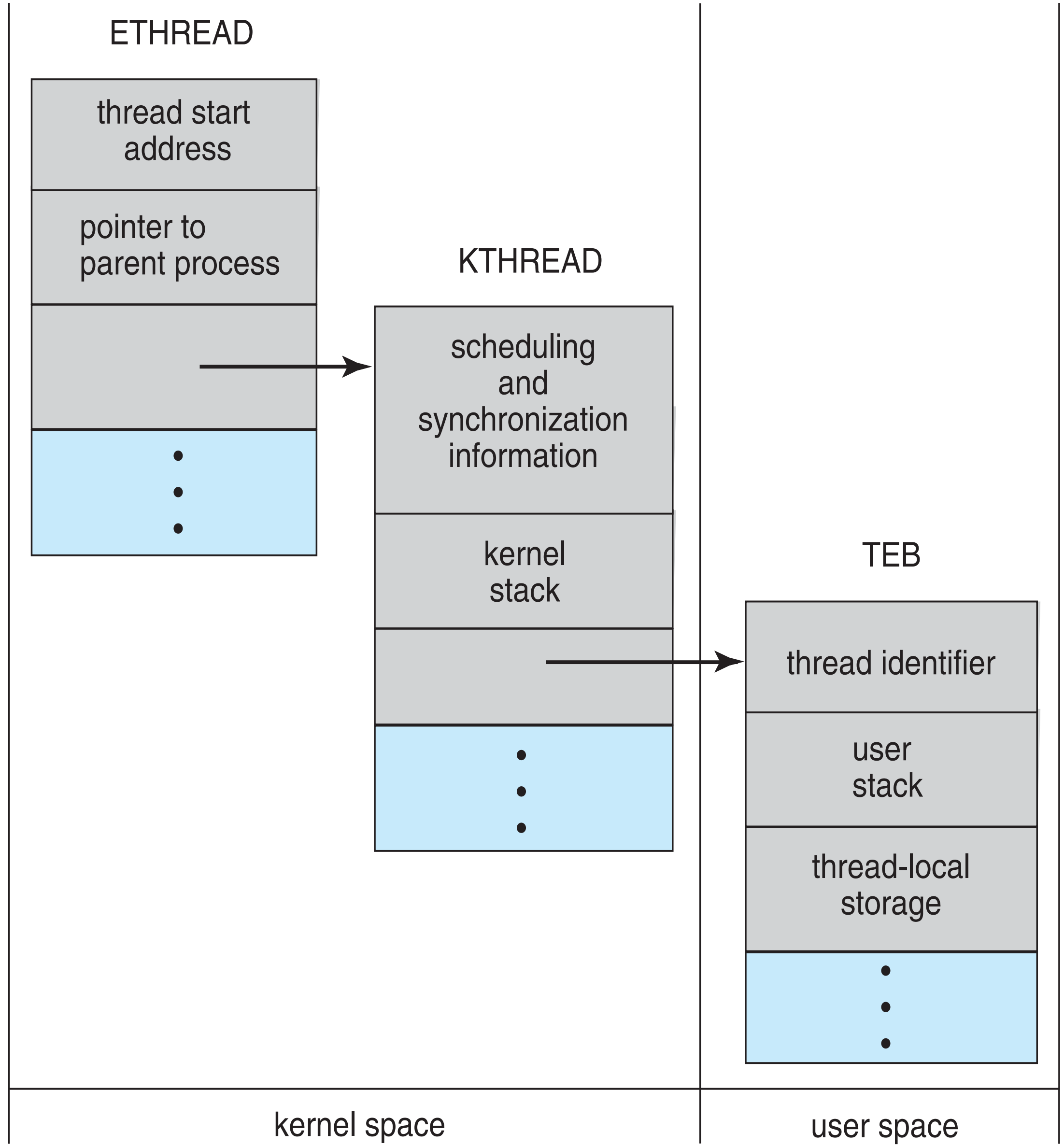
Windows Threads

- Windows implements Windows API
  - Primary API for Win98, WinNT, Win2000, WinXP, Win7
- Implements 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)
- **Context of Thread**: register set, stacks, and private storage area

Windows Threads (Cont.)

- 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

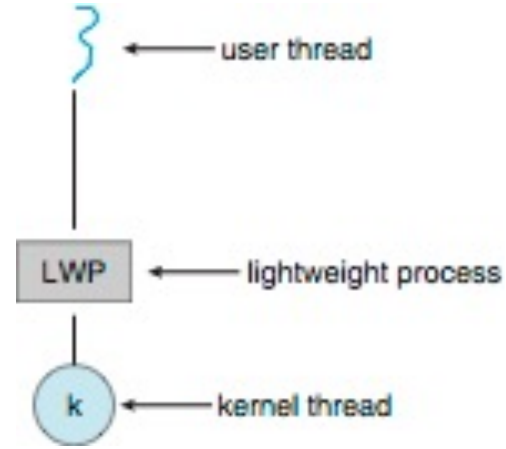


Linux Threads

- Linux refers to them as ***tasks*** rather than ***threads***
- Thread creation using **`clone()`** system call
- **`clone()`** allows a child task to share address space of parent task (process)
  - Flags control behavior
- **`struct task_struct`** points to process data structures (shared or unique)

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.

Scheduler Activations (cont.)



- Scheduler Activations Provides **upcalls**
  - A communication mechanism from kernel to **upcall handler** in thread library
  - This communication allows an application to maintain correct number kernel threads

End of Lecture 4