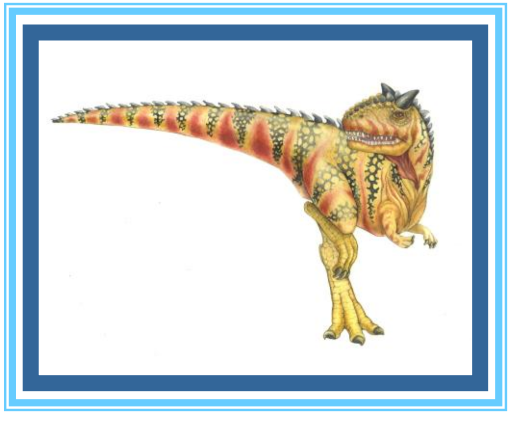
Chapter 4: Threads



Chapter 4: Threads

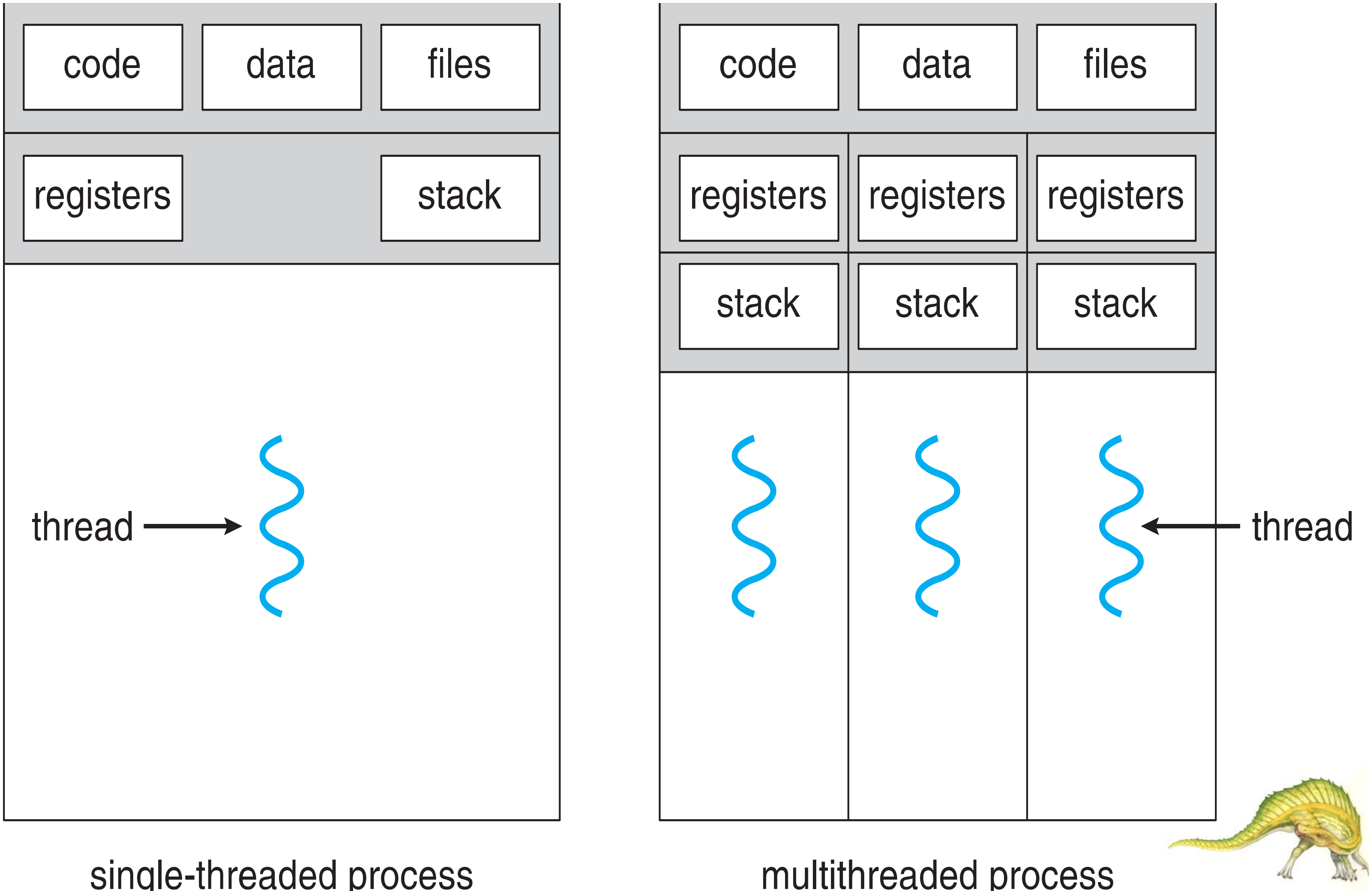
- Overview
- Multicore Programming
- Multithreading Models
- Thread Libraries
- Implicit Threading
- Threading Issues
- Operating System Examples

Objectives

- ***Thread*** of a process: basic unit of CPU utilization and is composed of a:
  - Thread ID
  - Program counter: register EIP
  - Register set
  - Stack
  - And ***it hares with other threads of the same process***, the
    - Code segment
    - Data segment
    - OS resources: open files, signals, … etc

- To discuss the APIs for the Pthreads, Windows, and Java thread libraries
- To explore several strategies that provide implicit threading
- To examine issues related to multithreaded programming
- To cover operating system support for threads in Windows and Linux

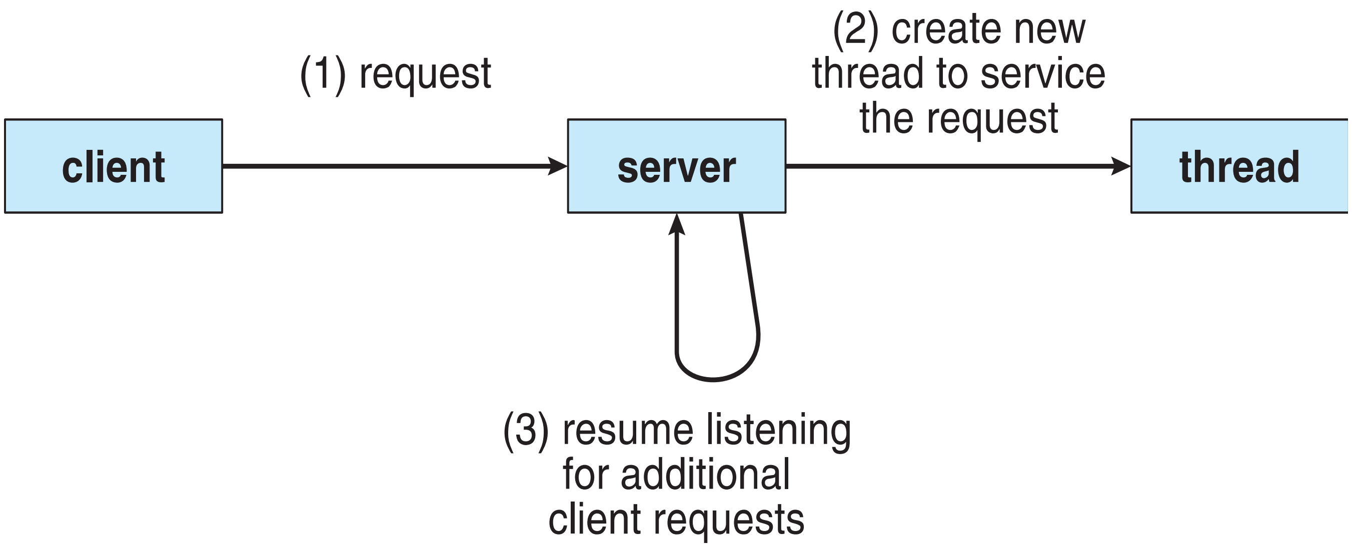
Single and Multithreaded Processes



Motivation

- Most modern applications and computers 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
  - For applications performing ***multiple similar*** tasks
    - It is costly to create a process for each task
  - Ex: web server serving multiple clients requesting the same service
    - Create a separate thread for each service
- Multithreaded programs: can simplify code, increase efficiency.
- Kernels are generally multithreaded. Interrupt handling, device management, etc

Multithreaded Server Architecture



Benefits

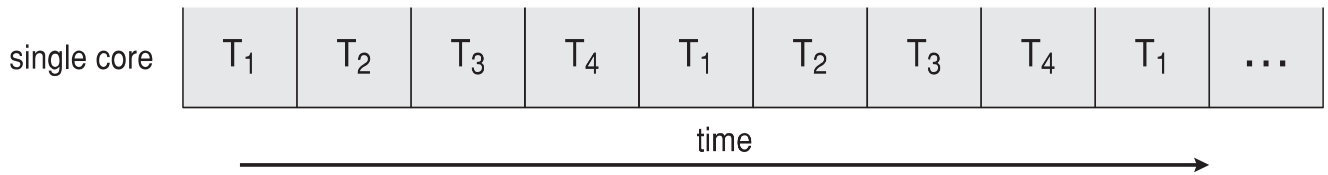
- **Responsiveness**
  - may allow continued execution if part (i.e. thread) of a process is time-consuming, especially important for user interfaces. User needs not wait
- **Resource Sharing**
  - threads share resources of process, easier than shared-memory or message-passing. Since programmer need not explicitly code for communication between threads (shared-memory or message-passing codes, in Chap-3)
- **Economy**
  - cheaper than process creation, thread switching has lower overhead than context switching. See figure on Page-4: thread share most of process's PCB
- **Scalability**
  - process can take advantage of multiprocessor architectures. Threads can run in parallel on different processing cores. See figure on Page-4 again

Multicore Programming

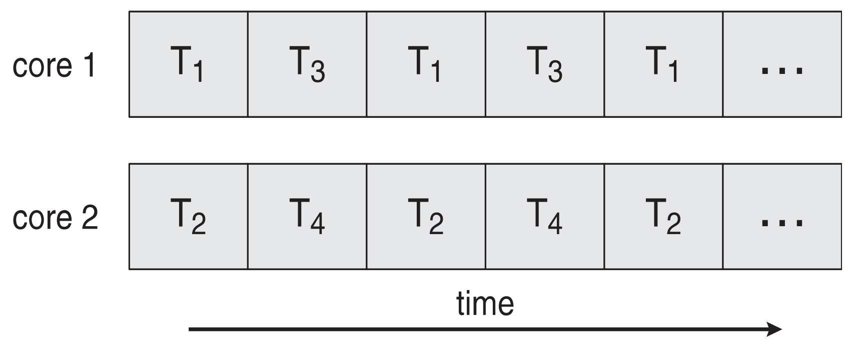
- **Multicore** or **multiprocessor** systems putting pressure on programmers. OS designers must write CPU scheduling algorithms that use multiple cores. App programmers must design multithreaded programs. Challenges include:
  - **Identifying tasks**: What are the separate independent threads ?
  - **Balance**: How to divide the work (set of tasks) fairly among CPU cores ?
  - **Data splitting**: How to divide the data fairly among CPU cores ?
  - **Data dependency**: What do to when there is dependency between threads ?
  - **Testing and debugging**: Correct parallel/concurrent/multithreaded program?
- Multithreaded programming provides a mechanism for ***more efficient use of multiple cores and improved concurrency***. New software design paradigm ?
- ***Parallelism*** implies a system can perform more than one task simultaneously
- ***Concurrency*** supports more than one task making progress
  - Single processor / core. CPU scheduler providing concurrency

Concurrency vs. Parallelism

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



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



Multicore Programming

- **Types of parallelism** (and concurrencies)
  - **Data parallelism** – distributes subsets of the same data across multiple cores, same operation on each
    - Ex: summing elements of a length-*N* array: 1-core vs 2-core system
  - **Task parallelism** – distributing threads across cores, each thread performing unique operation. Different threads may use same data or distinct data
    - Ex: sorting and summing a length-*N* array: 1-core vs 2-core system
  - **Hybrid Data-and-Task parallelism** in practice –
    - Ex: sorting and summing a length-*N* array: 1-core, 2-core or 4-core system
- As # of threads grows, so does architectural support for threading
  - CPUs have cores as well as ***hardware threads***
  - Modern Intel CPUs have two hardware threads, i.e. supports 2 threads/core
  - Oracle SPARC T4 CPU has 8 cores, with 8 hardware threads per core

User Threads and Kernel Threads

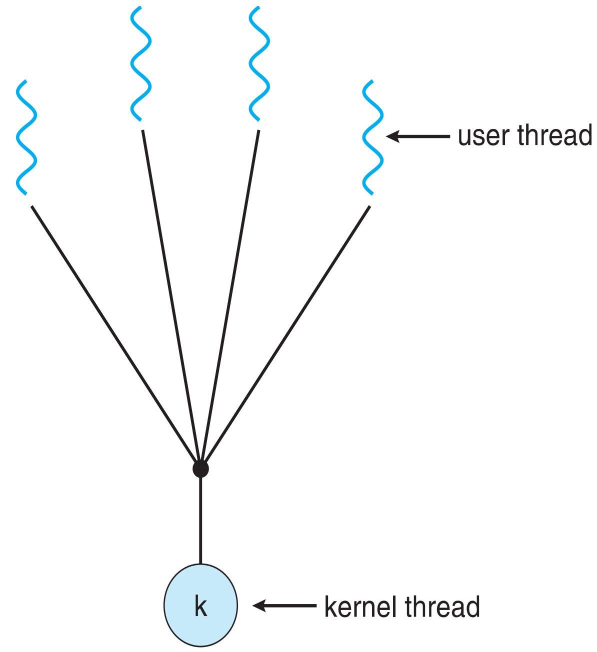
- Support for threads either at user level or kernel level
- **User threads** - management done by user-level threads library
    - Supports thread **programming**: creating and managing program threads
  - Three primary thread libraries: (threads are managed without kernel support)
    - POSIX **Pthreads**
    - Windows threads
    - Java threads
- **Kernel threads** - Supported by the Kernel.
    - Managed directly by the OS
  - Examples – virtually all general purpose operating systems, including:
    - Windows
    - Solaris
    - Linux
    - Tru64 UNIX
    - Mac OS X

Multithreading Models

- A relationship must exist between user threads and kernel threads
  - Many-to-One
    - Many user-level threads mapped to a single kernel thread
  - One-to-One
    - Each user-level thread maps to one kernel thread
  - Many-to-Many
    - Allows many user-level threads to be mapped to many kernel threads

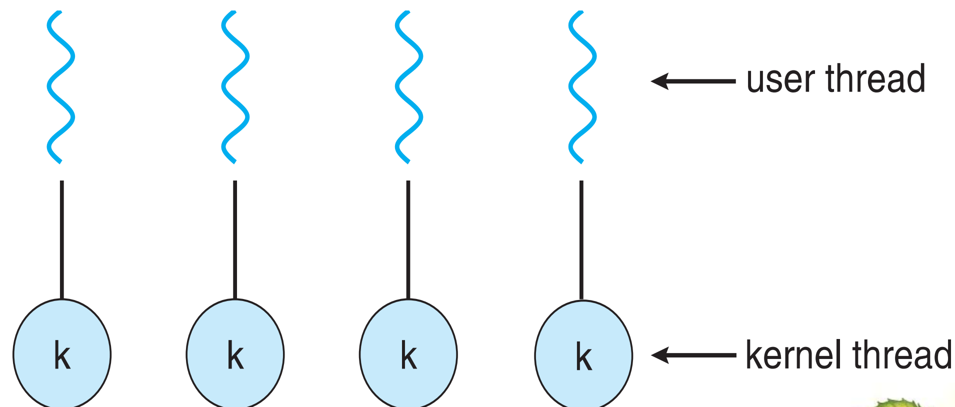
Many-to-One

- Many user-level threads mapped to single kernel thread
  - Efficiently managed by the thread library
- One thread blocking causes all to block
  - If the thread makes a blocking system-call
- Multiple threads are unable to run in parallel on multicore system because only one thread can be in kernel at a time
  - Does not benefit from multiple cores
- Few systems currently use this model
- Examples of many-to-one models:
  - **Solaris Green Threads** (adopted in early versions of Java thread library)
  - **GNU Portable Threads**



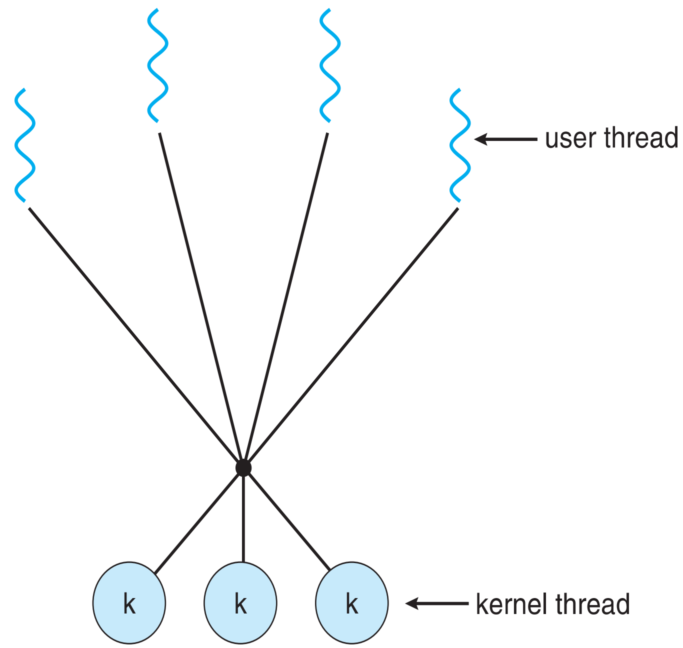
One-to-One

- Each user-level thread maps to one kernel thread
- Problem: creating a user thread requires creating the corresponding kernel thread
  - Thread ***creations*** burden the performance of an application; ***an overhead***
- Provides more concurrency than many-to-one model ***in case a thread has blocked***, and allows multiple threads to run in parallel on multiple CPU systems
- Number of threads per process sometimes restricted due to overhead
- Examples of one-to-one models
  - Windows
  - Linux
  - Solaris 9 and later



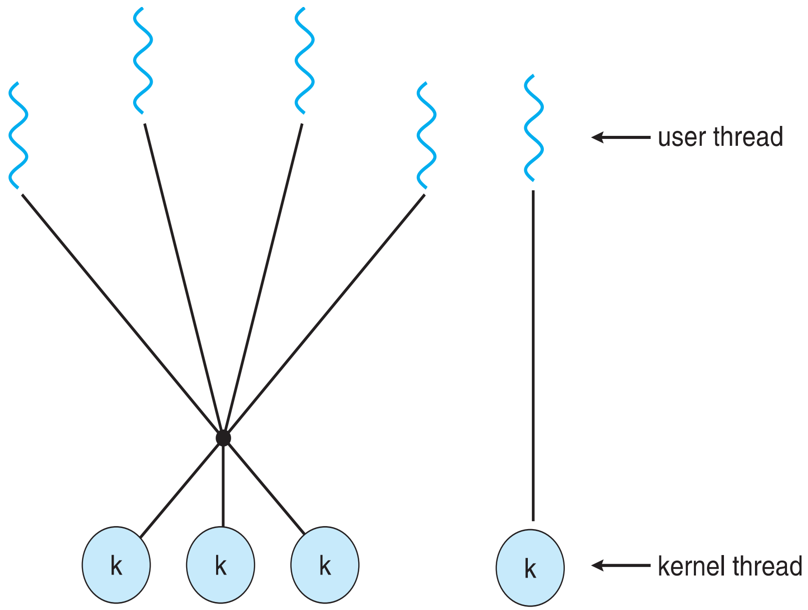
Many-to-Many Model

- Allows *m* user-level threads to be mapped to *n* kernel threads; $n \leq m$
- User can create as many user threads as wished
- Allows the operating system to create a sufficient number of kernel threads to be allocated to applications
- Does not have the problems of other models
- Solaris prior to version 9
- Windows with the *ThreadFiber* package



Two-level Model

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



Thread Libraries

- **Thread library** provides programmer with API for creating and managing threads
- Two primary ways of implementing
  - Thread library is entirely in user space with no kernel support
    - Codes and data structures for thread library are available to the user
    - Thread library functions are ***not*** system-calls
  - Kernel-level thread library is supported directly by the OS
    - Codes and data structures for thread library are ***not*** available to the user
    - Thread library functions are system-calls to the kernel

POSIX Pthreads

- A POSIX standard (IEEE 1003.1c) API for thread creation and synchronization
- Threads extensions of POSIX may be provided either as user-level or kernel-level
- ***Specification***, not ***implementation***
- API specifies behavior of the thread library, implementation is up to development of the library. OS designers implement Pthreads specification in any way they wish
- 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

```
   /* 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

- Java threads are managed by the JVM
- Typically implemented using the threads model provided by underlying OS
- 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

- Growing in popularity as numbers of threads increase, program correctness more difficult with explicit threads
  - Debugging an application containing 1000s of threads ?
- **Solution = *Implicit Threading***: Let compilers and runtime libraries create and manage threads rather than programmers and applications developers
- Three methods explored
  - Thread Pools
  - OpenMP
  - Grand Central Dispatch
- Other methods include Microsoft Threading Building Blocks (TBB), **`java.util.concurrent`** package

Thread Pools

- Create a number of threads at process startup in a pool where they await work
- Advantages:
  - Usually slightly faster to service a request with an existing thread than create a new thread. A threas returns to pool once it completes servicing a request
  - Allows the number of threads in the application(s) to be bound to the size of the pool. Limits the number of threads that exist at any one point
  - 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 or after a time delay
- Windows thread pool API supports thread pools:

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

OpenMP

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

```
#pragma omp parallel
```

Create as many threads as there are cores

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

Run for_loop in parallel

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

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

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

   /* sequential code */

   return 0;
}
```

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*** specified by “^{ }” - `^{ printf("I am a block"); }`
  - Block = self-contained unit of work identified by the programmer as above
- Blocks placed in a dispatch queue
  - Assigned to available thread in thread pool when removed from queue

Grand Central Dispatch

- GCD schedules by placing them blocks on dispatch queue. Two types of 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 concurrent 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."); });
```

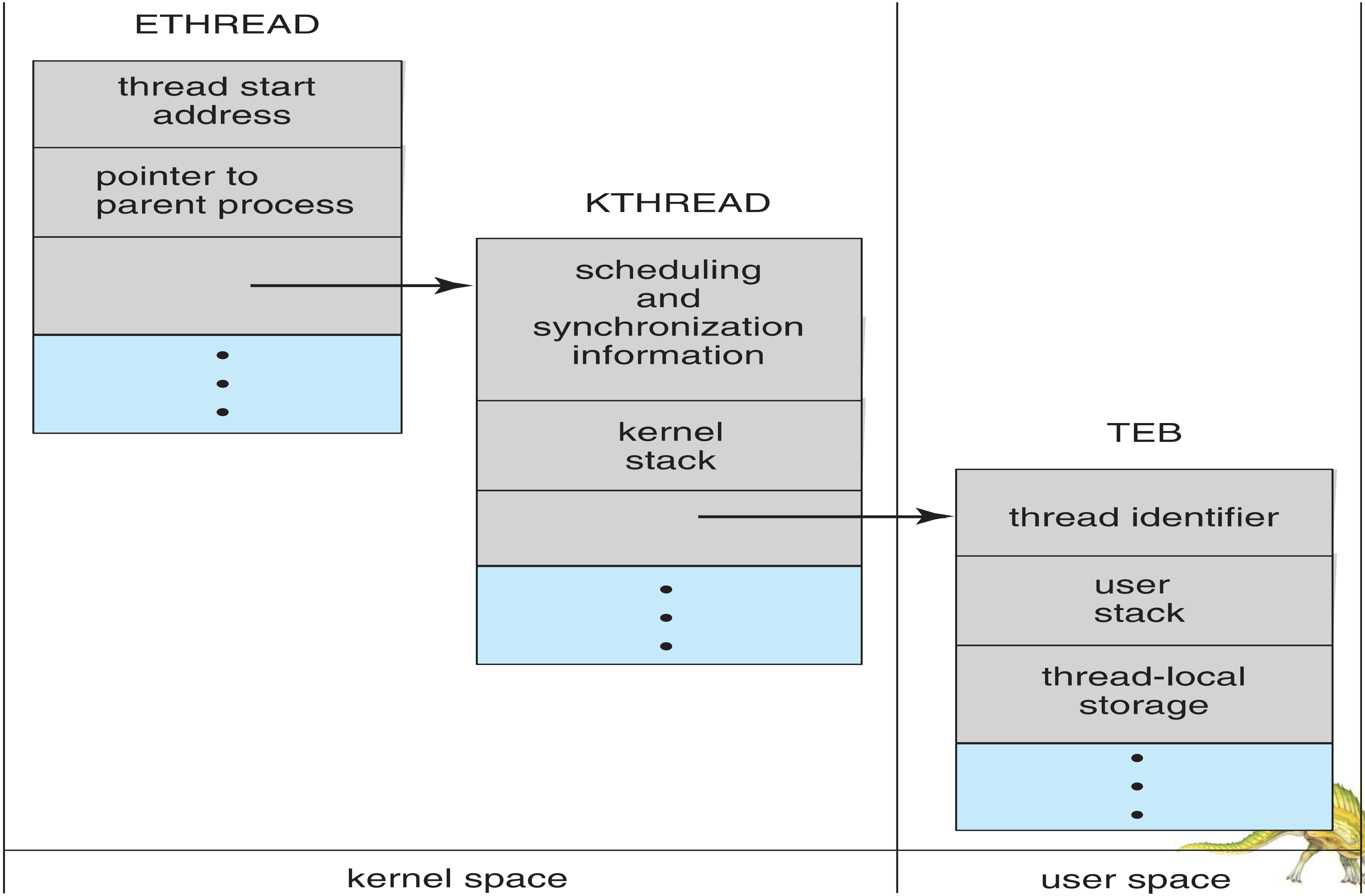
Operating System Examples
Windows Threads

- Windows implements the Windows API – primary API for Win 98, Win NT, Win 2000, Win XP, and Win 7
- Implements the one-to-one mapping, kernel-level
  - App run as separate processes, each process may contain many threads
- Each thread contains
  - A thread id
  - Register set representing state of processor
  - Separate user and kernel stacks; for threads running in user 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

- The primary data structures of a thread include:
  - ETHREAD (executive thread block) – includes: pointer to process to which thread belongs, and address of routine in which the tread starts control, and pointer to KTHREAD; exists in kernel space only
  - KTHREAD (kernel thread block) – includes: scheduling and synchronization info, kernel-mode stack, pointer to TEB; exists in kernel space only
  - TEB (thread environment block) – includes: thread id, user-mode stack, thread-local storage; exists in user space only

Windows Threads Data Structures



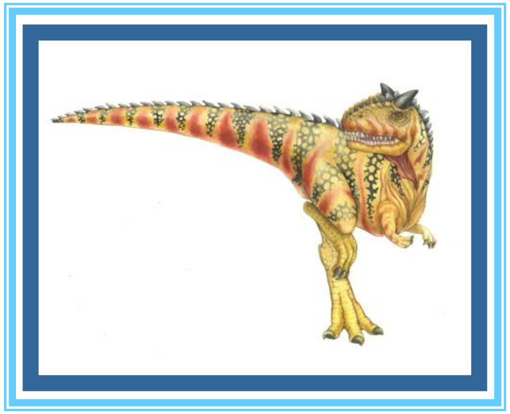
Operating System Examples
Linux Threads

- 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: determine what and how much to share

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



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

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

- 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?

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);
```

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

- **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