

# **Chapter 4: Threads**

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# Chapter 4: Threads

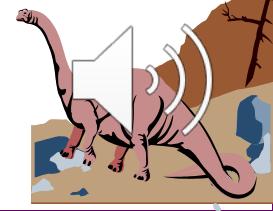
## ■ Overview

## ■ Multithreading Models

## ■ Thread Libraries

## ■ Threading Issues

## ■ Operating System Examples





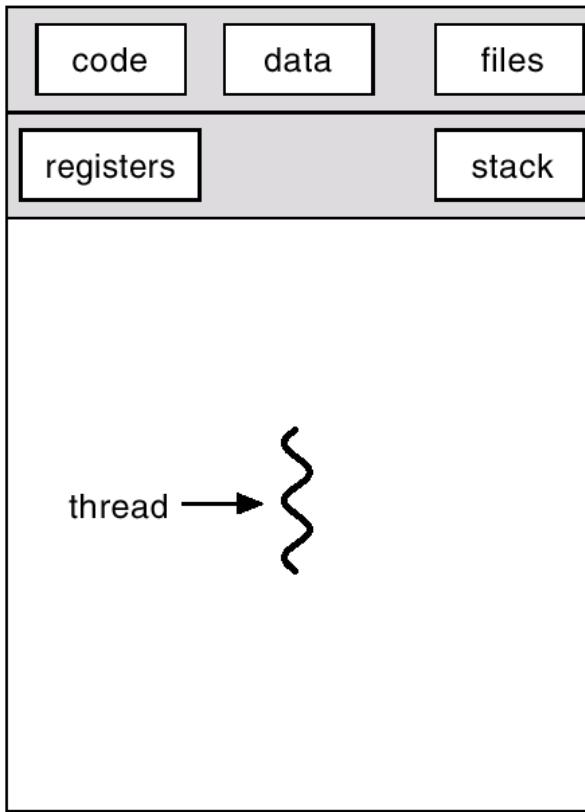
# What is a thread?

- A *thread*, also known as *lightweight process* (LWP), is a basic unit of CPU execution.
- A thread has a **thread ID**, a **program counter (instruction pointer)**, a **register set**, and a **stack**. Thus, it is similar to a process has.
- However, a thread **shares** with other threads in the **same** process its code section, data section, and other OS resources (e.g., files and signals).
- A process, or **heavyweight process**, has a *single* thread of control after its creation.

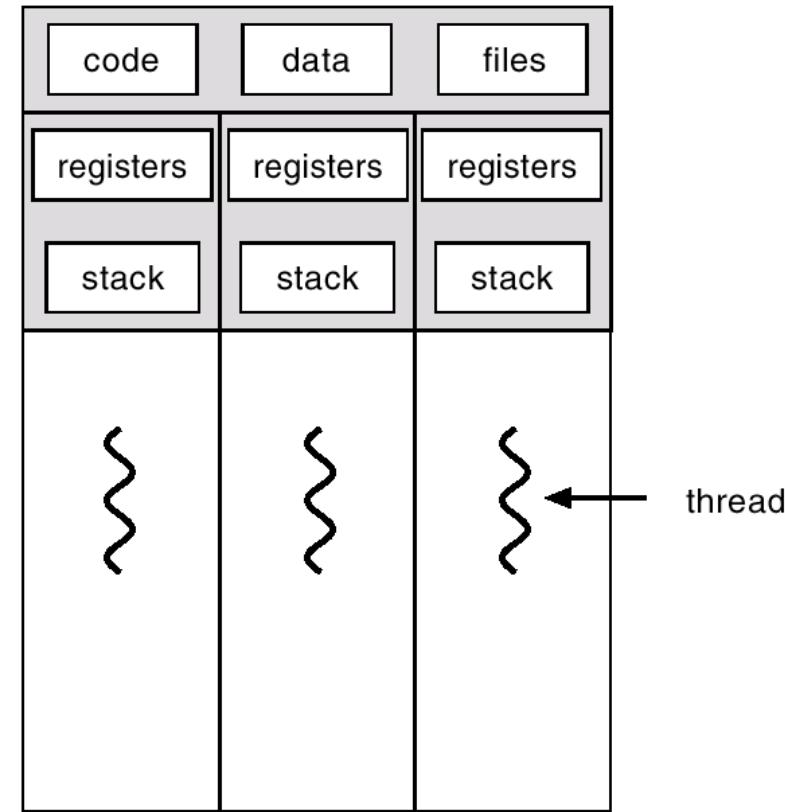




# Single and Multithreaded Processes



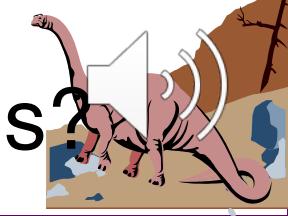
single-threaded



multithreaded

- Threads in a same process are \_\_\_\_\_
  - tightly coupled or
  - loosely coupled?

- How is the heap space shared among threads?





## ■ Items shared by all threads in a process

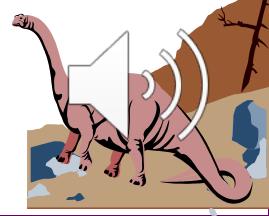
### **Per process items**

Address space  
Global variables  
Open files  
Child processes  
Pending alarms  
Signals and signal handlers  
Accounting information

## ■ Items private to each thread

### **Per thread items**

Program counter  
Registers  
Stack  
State





# Thread Usage (1)

Four score and seven years ago, our fathers brought forth upon this continent a new nation, conceived in liberty, and dedicated to the proposition that all men are created equal. Now we are engaged in a great civil war, testing whether that

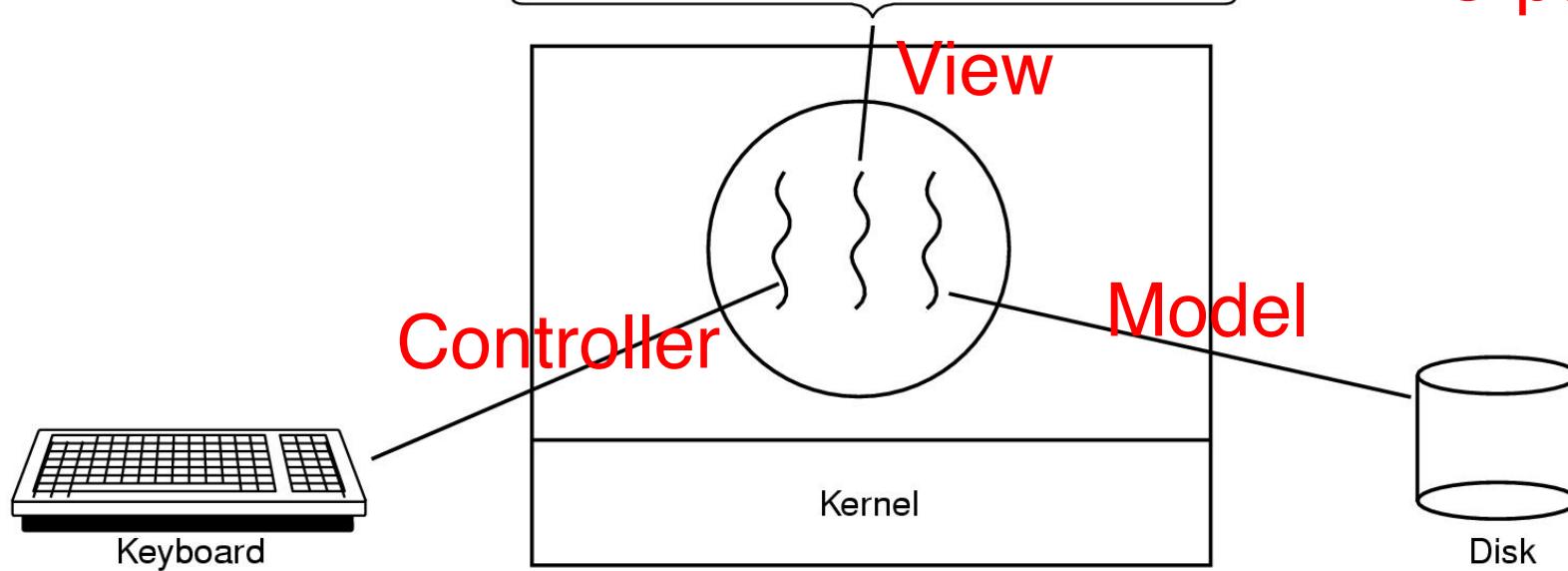
nation, or any nation so conceived and so dedicated, can long endure. We are met on a great battlefield of that war.

We have come to dedicate a portion of that field as a final resting place for those who here gave their lives that this nation might live. It is altogether fitting and proper that we should do this.

But, in a larger sense, we cannot dedicate, we cannot consecrate, we cannot hallow this ground. The brave men, living and dead,

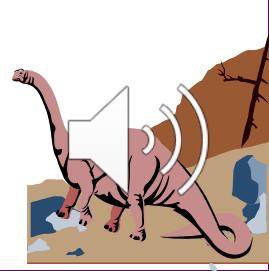
who struggled here have consecrated it, far above our poor power to add or detract. The world will little note, nor long remember, what we say here, but it can never forget what they did here. It is for us the living, rather, to be dedicated here to the unfinished work which they who fought here have thus far so nobly advanced. It is rather for us to be here dedicated to the great task remaining before us, that from these honored dead we take increased devotion to that cause for which

they gave the last full measure of devotion, that we here highly resolve that these dead shall not have died in vain that this nation, under God, shall have a new birth of freedom and that government of the people, by the people, for the people,



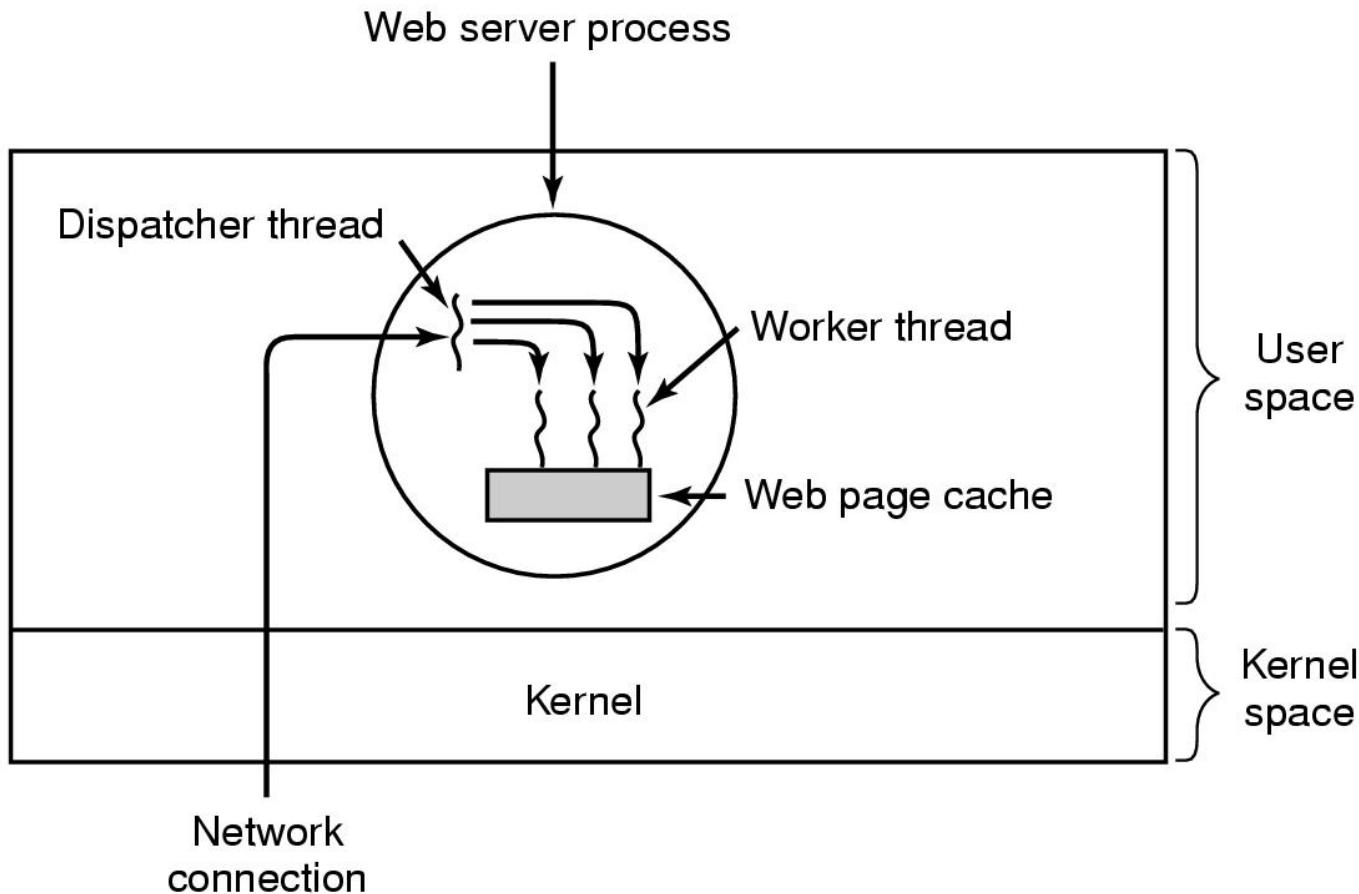
MVC paradigm

A word processor with three threads

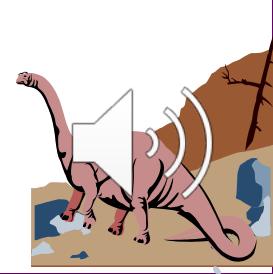




# Thread Usage (2)



## A multithreaded Web server





# Thread Usage (3)

■ Rough outline of code for previous slide

- (a) Dispatcher thread
- (b) Worker thread

Note: An Event-Driven Framework

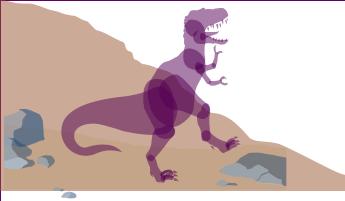
```
while (TRUE) {  
    get_next_request(&buf);  
    handoff_work(&buf);  
}
```

(a)

```
while (TRUE) {  
    wait_for_work(&buf)  
    look_for_page_in_cache(&buf, &page);  
    if (page_not_in_cache(&page))  
        read_page_from_disk(&buf, &page);  
    return_page(&page);  
}
```

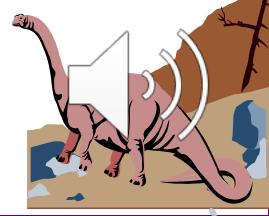
(b)





# Benefits

- Responsiveness
- Resource Sharing
- Economy
- Utilization of MP Architectures

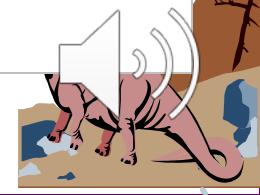




# Economy for Creation

- Compare timing of fork() and pthread\_create()
  - ◆ Timings reflect 50,000 process/thread creations, were performed with the time utility, and units are in seconds, no optimization flags.

Platform	fork()			pthread_create()		
	real	user	sys	real	user	sys
AMD 2.4 GHz Opteron (8cpus/node)	41.07	60.08	9.01	0.66	0.19	0.43
IBM 1.9 GHz POWER5 p5-575 (8cpus/node)	64.24	30.78	27.68	1.75	0.69	1.10
IBM 1.5 GHz POWER4 (8cpus/node)	104.05	48.64	47.21	2.01	1.00	1.52
INTEL 2.4 GHz Xeon (2 cpus/node)	54.95	1.54	20.78	1.64	0.67	0.90
INTEL 1.4 GHz Itanium2 (4 cpus/node)	54.54	1.07	22.22	2.03	1.26	0.67

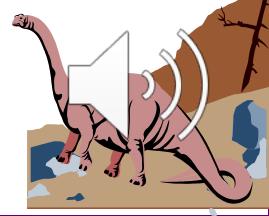




# Economy for Context Switching

- Process (notes: Process Control Block in OS Kernel)
- Light-weight Process and Kernel Threads
- User Threads

Lower Cost in Creation and Context Switching





# User Threads

## ■ Thread management done by user-level threads library

- ◆ Context switching of threads in the same process is done in user mode

## ■ Examples

- **POSIX *Pthreads*** (see scope parameter of `pthread_create`: `PTHREAD_SCOPE_PROCESS` or `PTHREAD_SCOPE_SYSTEM`)
- Mach *C-threads*
- Solaris UI-*threads*

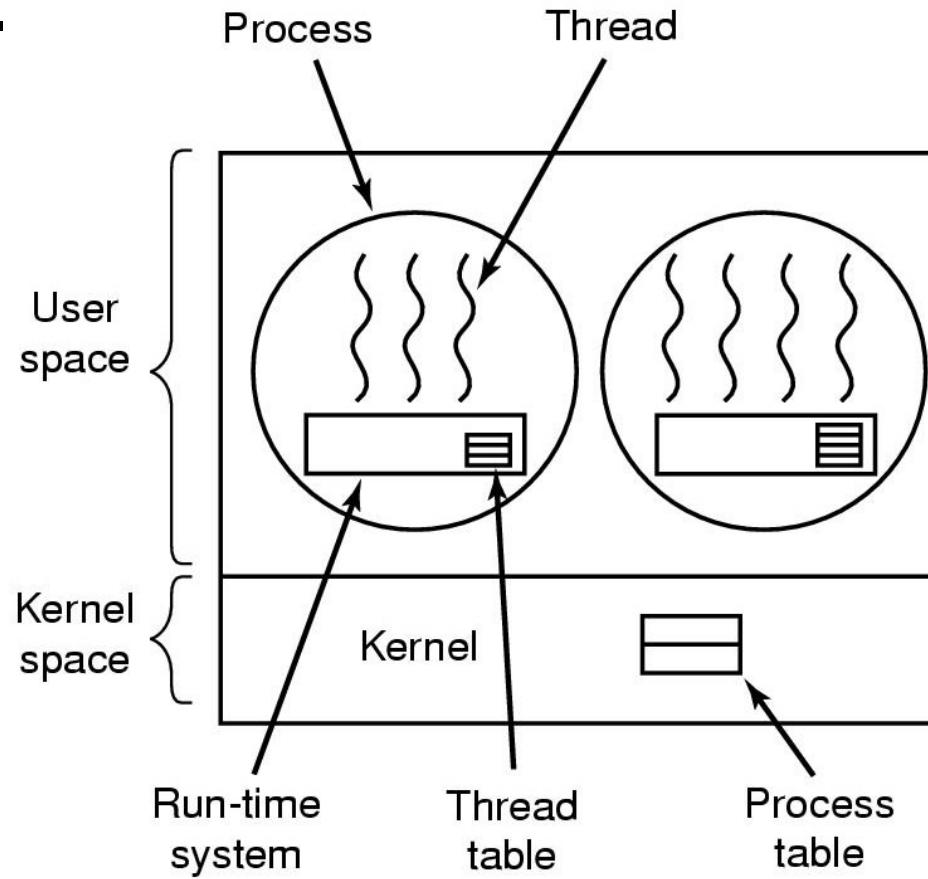
<http://www.yolinux.com/TUTORIALS/LinuxTutorialPosixThreads.html#CREATIONTERMINATION>



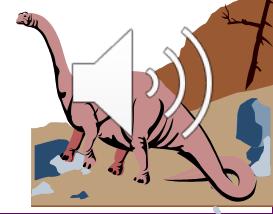


# User Threads (Cont.)

- A user-level thread library provides all support for thread creation, termination, joining, and scheduling.



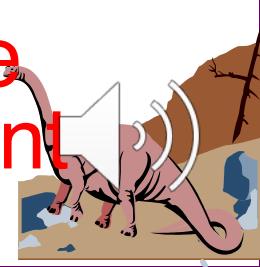
A user-level threads package





# Pros and Cons of User Threads

- User threads are supported at the **user level**. The kernel **is not aware** of user threads.
- Because there is no kernel intervention, user threads are usually **more efficient**.
- Unfortunately, since the kernel only recognizes the containing process (of the threads), ***if one thread is blocked, each other threads of the same process are also blocked*** since the containing process is blocked.
- Question: Can two user threads in a same process run simultaneously on two different CPU cores?



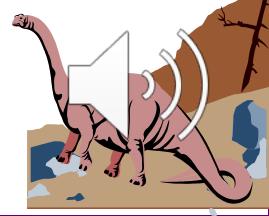


# Kernel Threads

## ■ Supported by the Kernel

## ■ Examples

- Windows 95/98/NT/2000
- Solaris
- Tru64 UNIX
- BeOS
- Linux and POSIX Thread





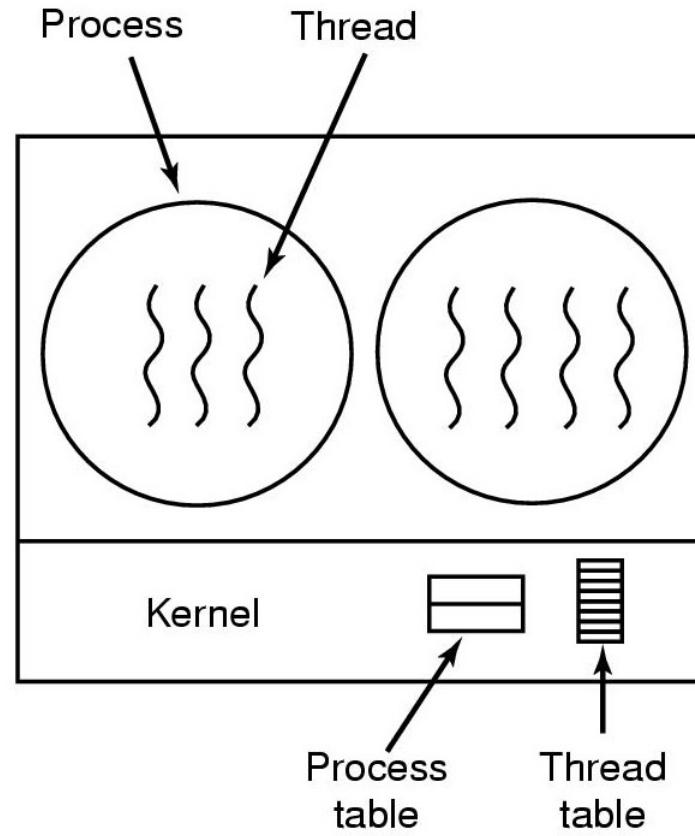
# Kernel Threads (Cont.)

- Kernel threads are directly supported by the kernel. The kernel does thread creation, termination, joining, and scheduling in kernel space.
- Kernel threads are usually **slower** than the user threads.
- However, *blocking one thread will not cause other threads of the same process to block*. The kernel simply runs other threads.
- In a multiprocessor environment, the kernel can schedule threads on different processors

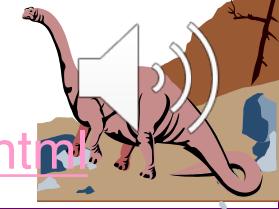




# Implementing Threads in the Kernel



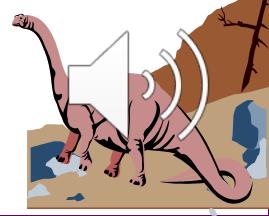
A threads package managed by the kernel  
(Note: POSIX *Pthreads* library supports  
the creation of kernel threads)

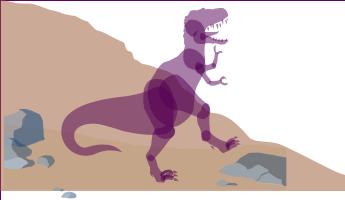




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- Multithreading Models
- Threading Issues
- Windows XP Threads
- Linux Threads
- Java Threads
- Pthreads
- Windows Threads API



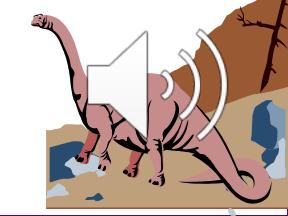


# Multithreading Models

■ Many-to-One

■ One-to-One

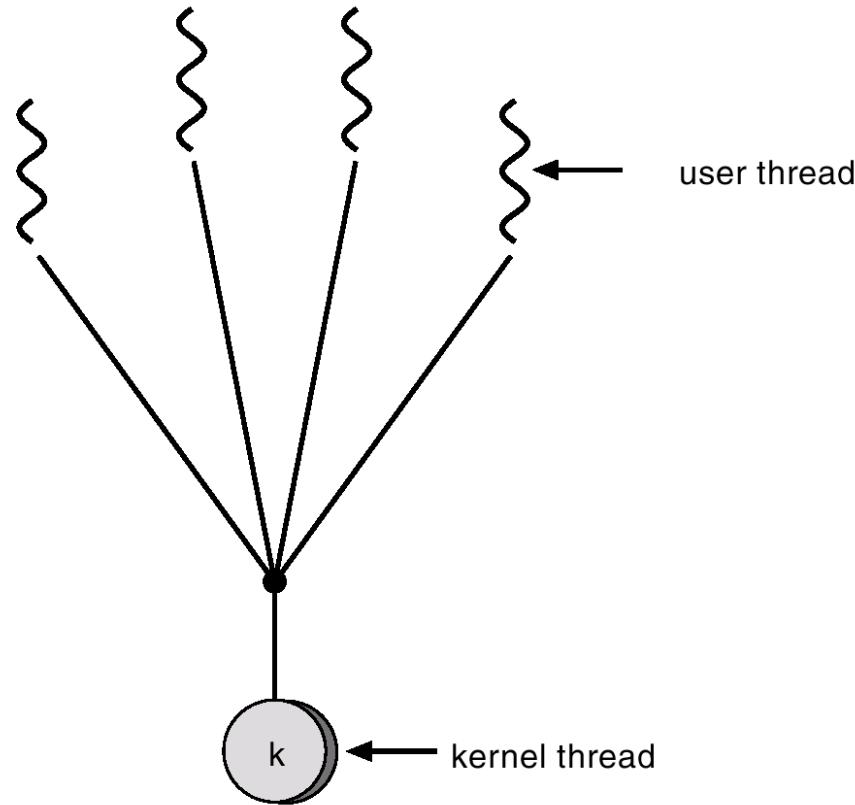
■ Many-to-Many





# Many-to-One

- Many user-level threads mapped to a single kernel thread.

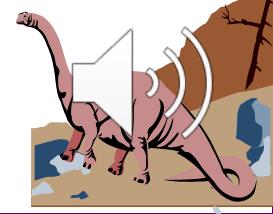
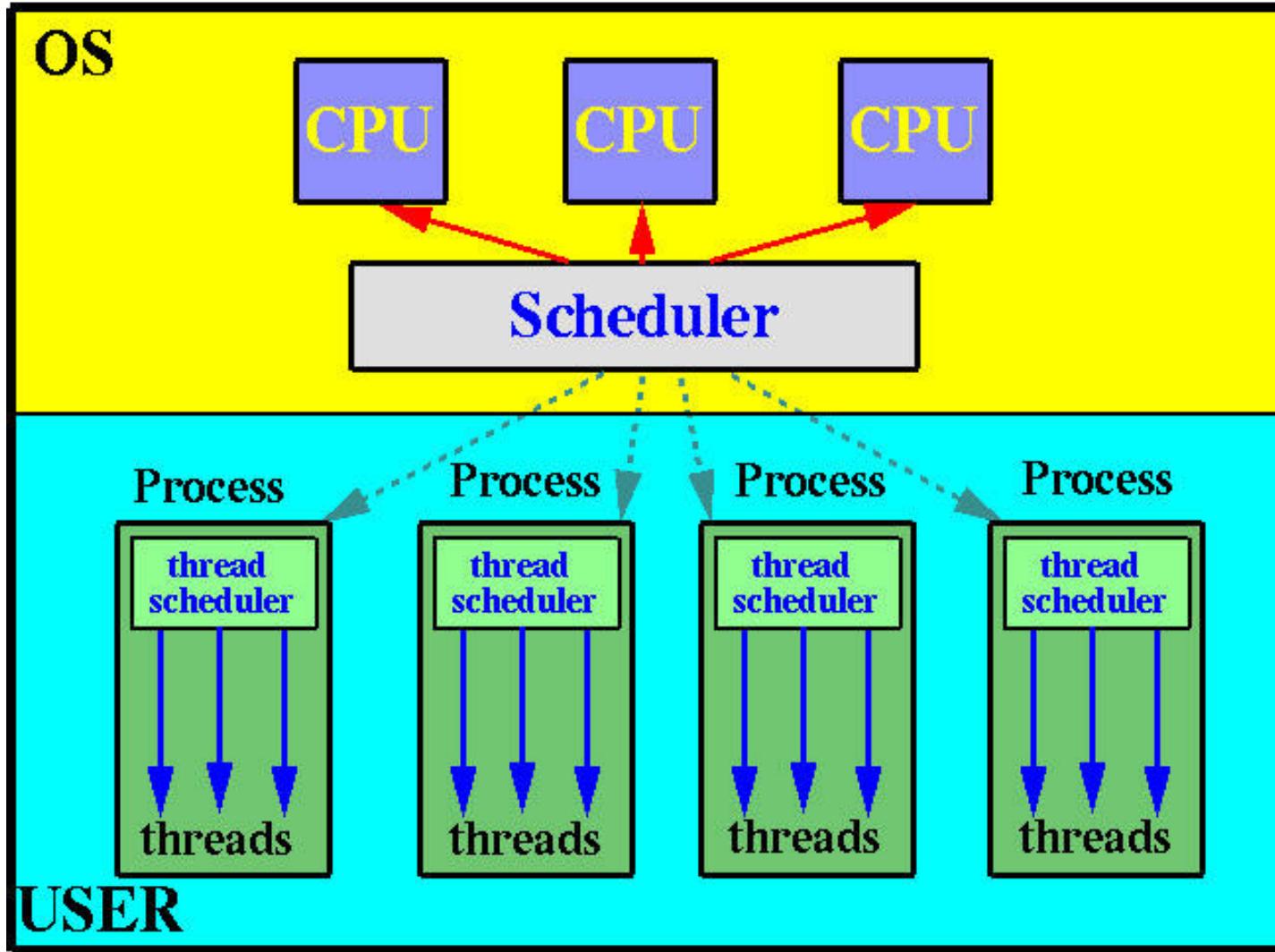


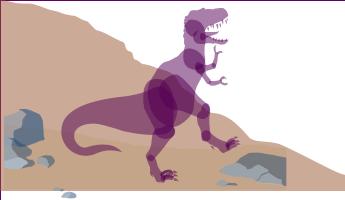
- Used on systems that do not support kernel threads.





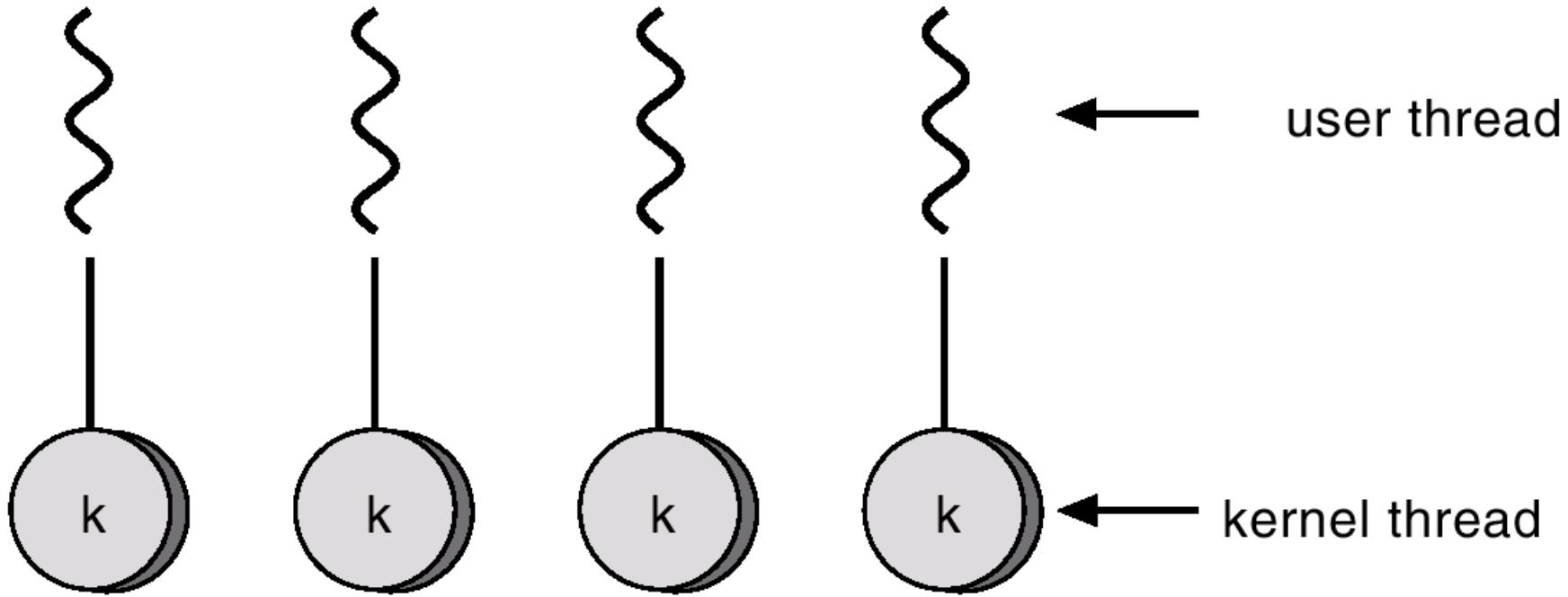
# Many-to-One Model (Cont.)





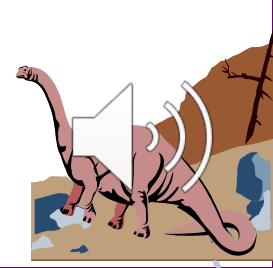
# One-to-One

- Each user-level thread maps to kernel thread



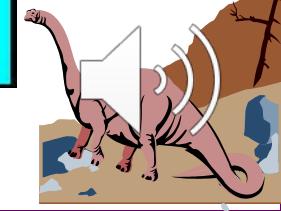
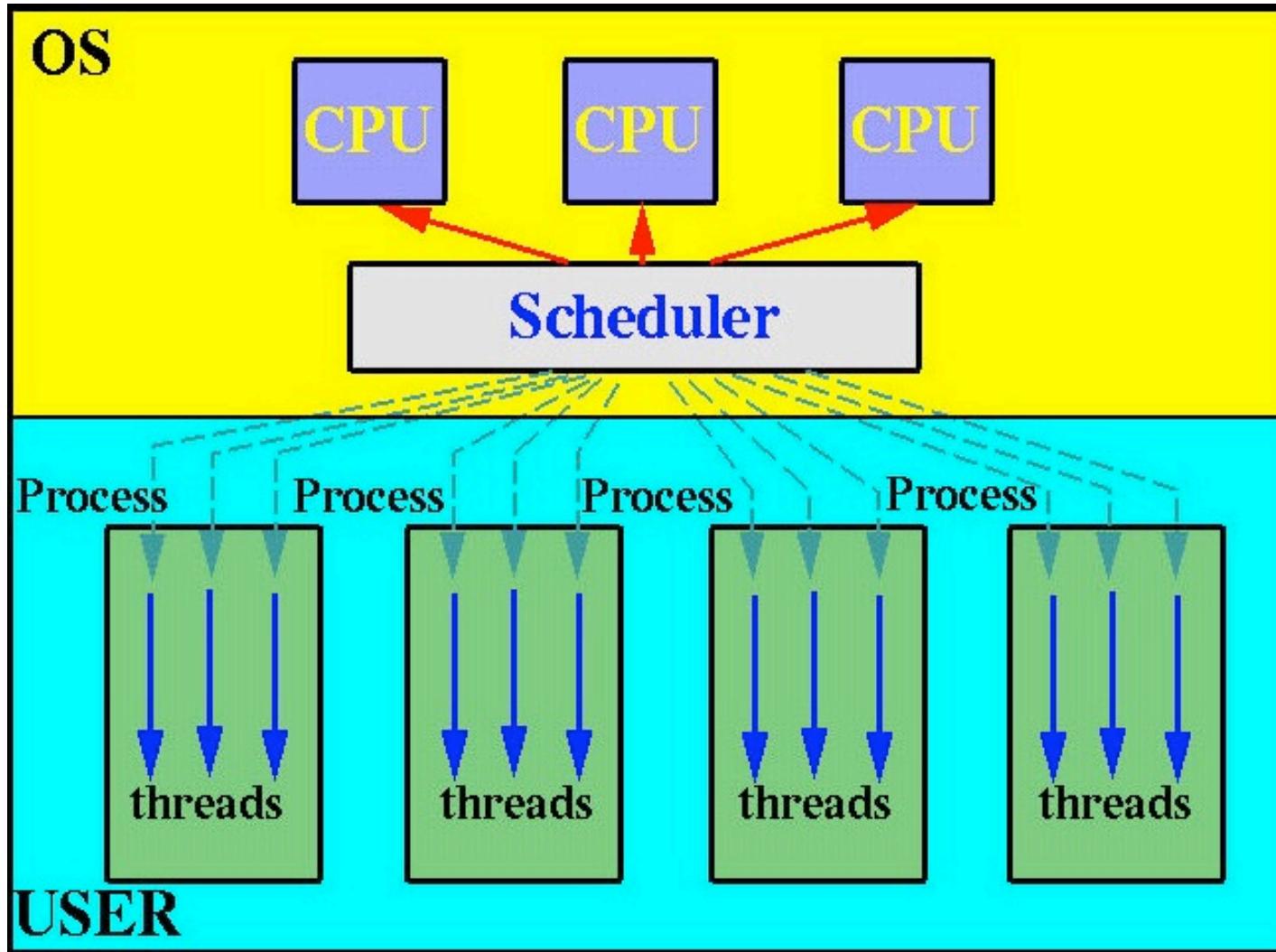
- Examples

- Windows 95/98/NT/2000
- OS/2





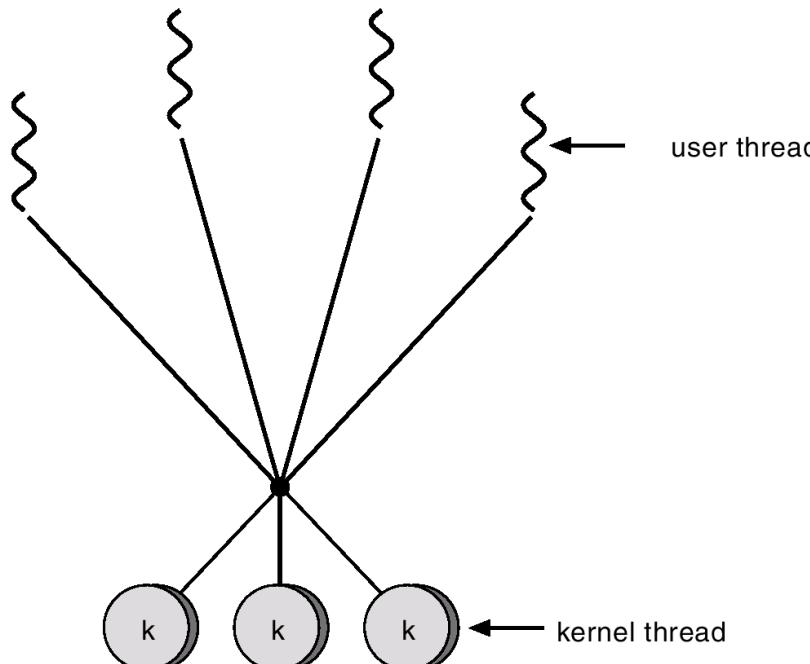
# One-to-one Model (Cont.)





# 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.

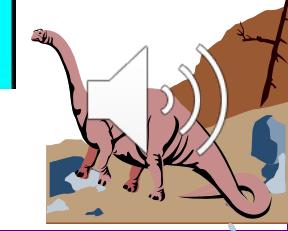
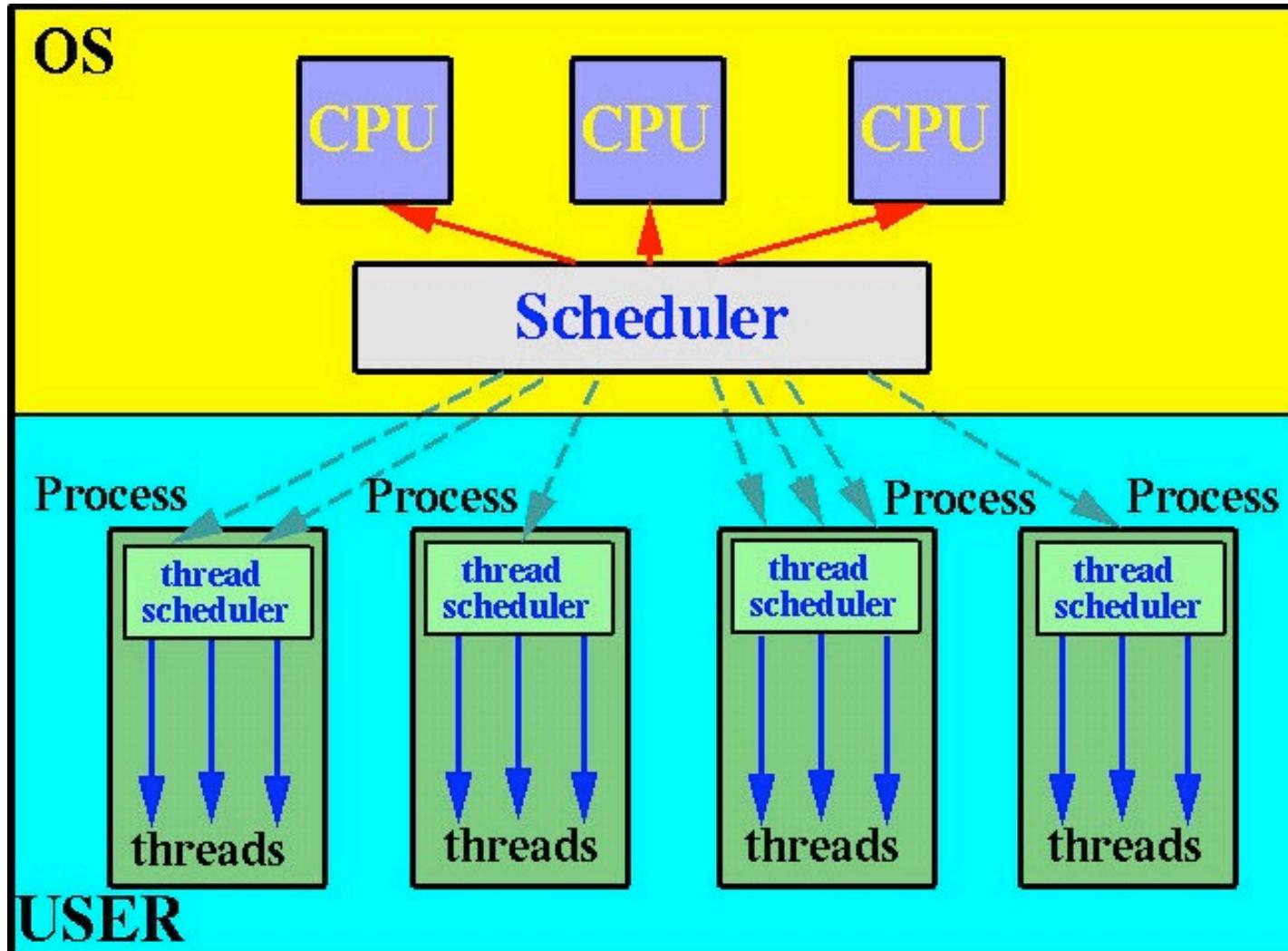


- Windows NT/2000 with *ThreadFiber* package
- Solaris 2





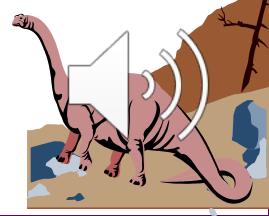
# Many-to-Many Model (Cont.)





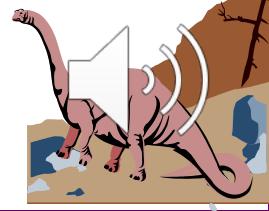
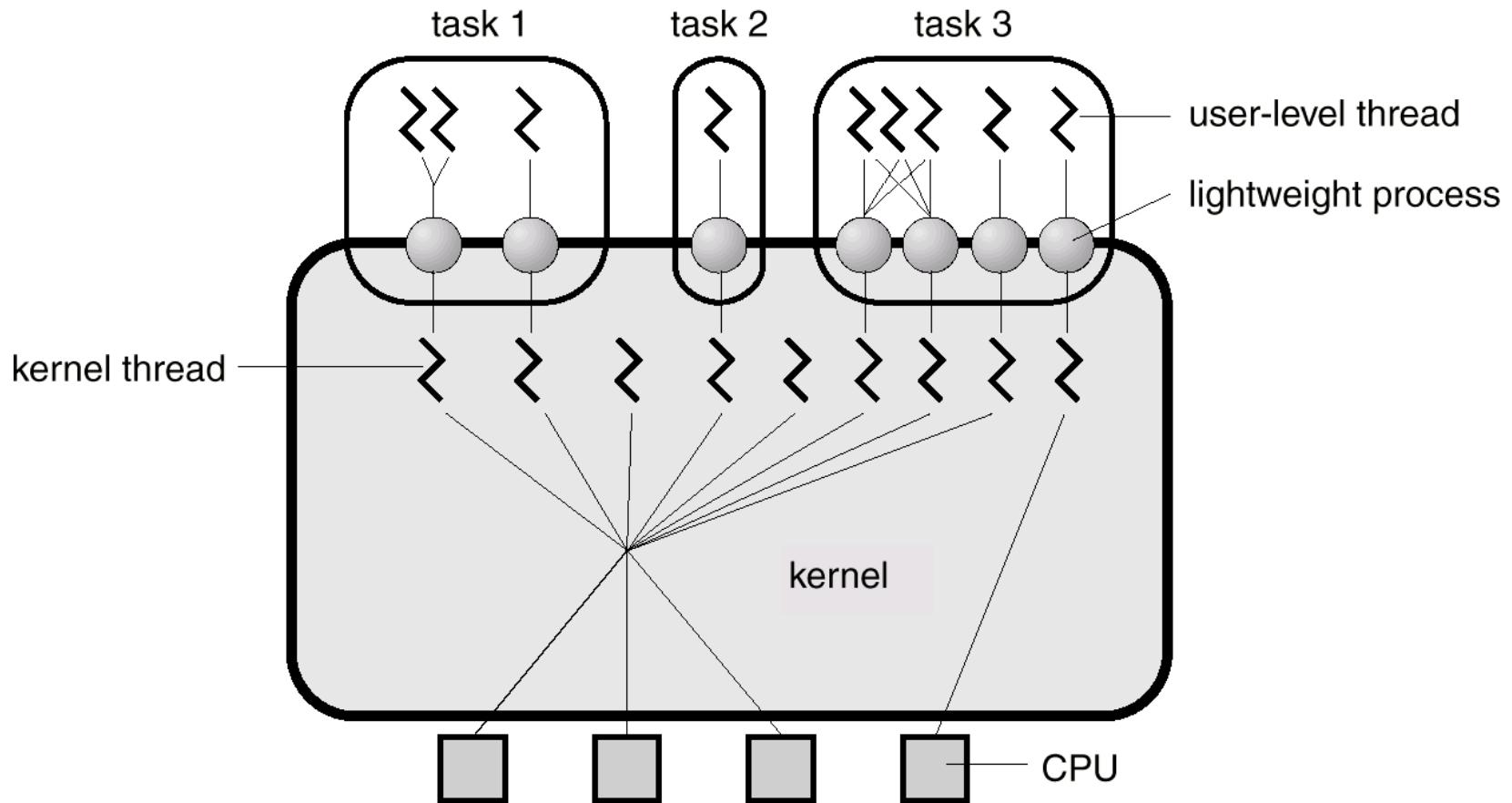
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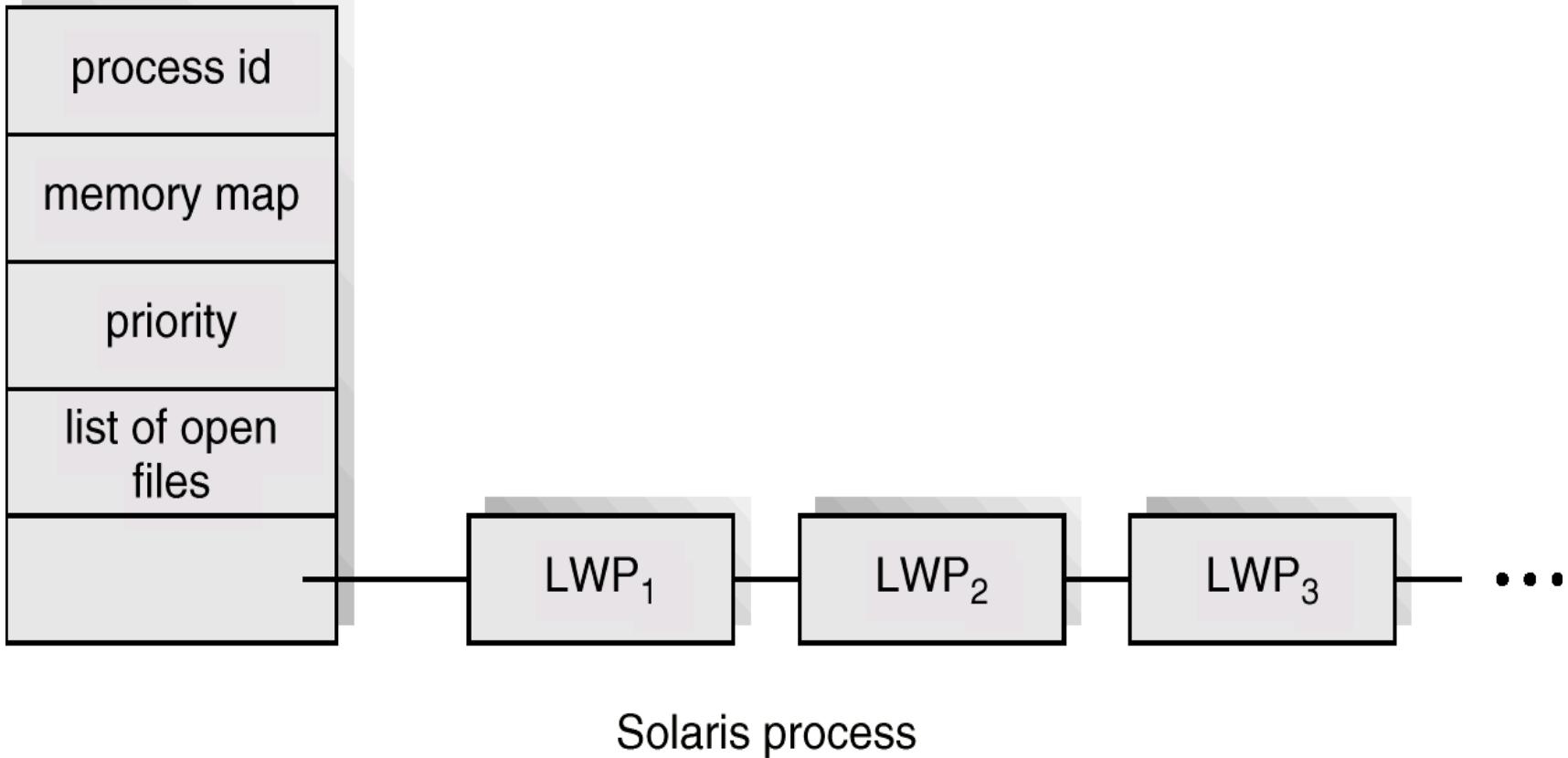


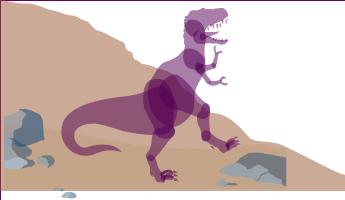
# Solaris 2 Threads





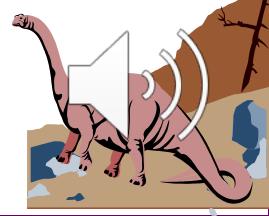
# Solaris Process





# Windows XP Threads

- Implements the one-to-one mapping.
- Each thread has a corresponding thread control block in kernel, which contains
  - a thread id
  - register set
  - separate user and kernel stacks
  - private data storage area



# Thread Block

ETHREAD

KTHREAD
Create and Exit Time
Process ID
Thread Start Address
Impersonation Information
LPC Message Information
Timer Information

EPROCESS

Access Token

Pending I/O Requests

KTHREAD

Dispatcher Header
Total User Time
Total Kernel Time
Thread Scheduling Information
Trap Frame
Synchronization Information
List of Pending APCs
Timer Block and Wait Blocks
List of Objects Being Waiting On

Kernel Stack Information

System Service Table

Thread Local Storage

TEB

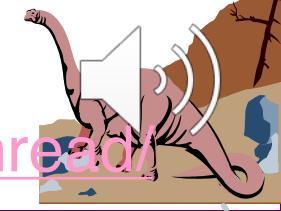


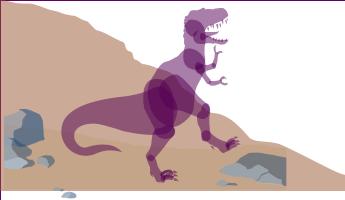
# Linux Threads (not POSIX pthreads Library)

- 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)
- What is the difference between fork() and clone()?

<http://linux.die.net/man/2/clone>

<http://www.ibm.com/developerworks/cn/linux/kernel/l-threads/>



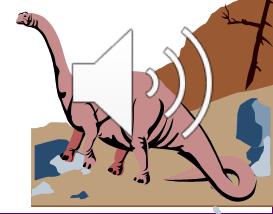


# Java Threads

■ Java threads may be created by:

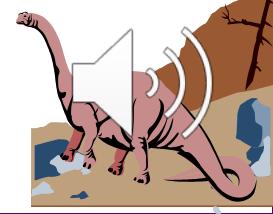
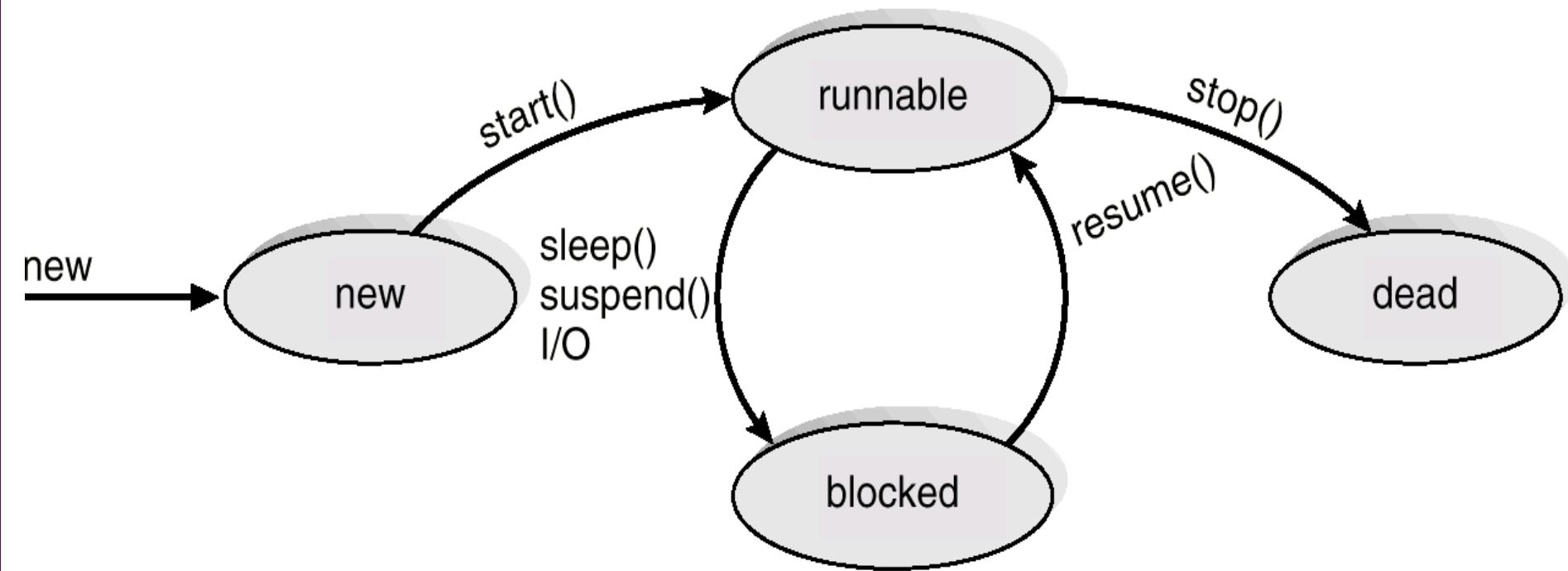
- ◆ Extending Thread class
- ◆ Implementing the Runnable interface

■ Java threads are managed by the JVM.





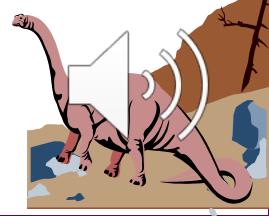
# Java Thread States





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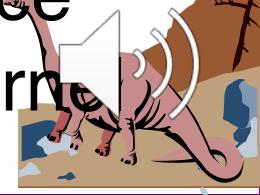


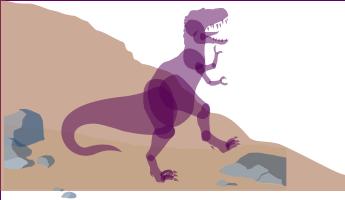
# PThreads

- a POSIX standard (IEEE 1003.1c) API for thread creation and synchronization.
  - ◆ API specifies behavior of the thread library,
  - ◆ Implementation is up to development of the library

**POSIX 1003.1 Commands :** <http://www.unix.com/man-page-posix-repository.php>

- Common in UNIX operating systems.
- Implemented over Linux operating system by Native POSIX Thread Library (NPTL)
  - ◆ NPTL is a  $1 \times 1$  threads library, in that threads created by the user are in 1-1 correspondence with schedulable entities (i.e., task) in the kernel.

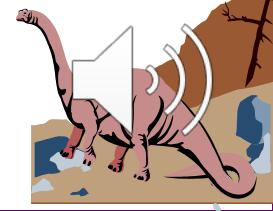


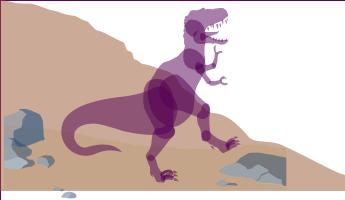


# pthread\_create

```
int pthread_create(pthread_t * tid, const pthread_attr_t * attr, void *(*function) (void *), void *arg);
```

- **pthread\_t \* tid**
  - ◆ handle or ID of created thread
- **const pthread\_attr\_t \*attr**
  - ◆ attributes of thread to be created
- **void \*(\*function) (void \*)**
  - ◆ function to be mapped to thread
- **void \*arg**
  - ◆ single argument to function
- **Integer return value for error code**





# pthread\_create explained

spawn a thread running the function ;  
thread handle returned via pthread\_t structure

- specify *NULL* to use default attributes

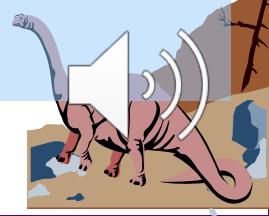
a single argument sent to function

- If no argument to function, specify *NULL*

check error codes!

**EAGAIN – insufficient resources to create thread**

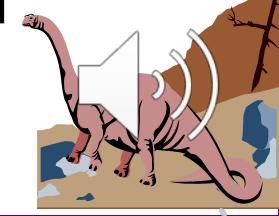
**EINVAL – invalid attribute**





# Threads states

- pthread threads have two states
  - ◆ joinable and detached
- threads are joinable by default
  - ◆ Resources are kept until *pthread\_join*.
  - ◆ When a joinable thread terminates, some of the thread resources are kept allocated, and released only when another thread performs *pthread\_join* on that thread.
  - ◆ can be reset with attribute or API call
- detached thread can not be joined
  - ◆ resources can be reclaimed at termination
  - ◆ cannot reset to be *joinable*





# Waiting for a thread

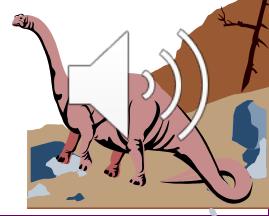
```
int pthread_join(pthread_t *tid, void **val_ptr);
```

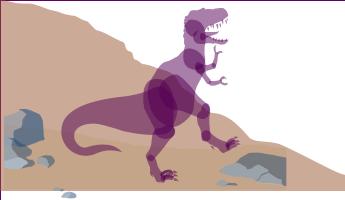
- `pthread_t *tid`

- ◆ handle of joinable thread

- `void **val_ptr`

- ◆ exit value returned by joined thread





# **pthread\_join explained**

calling thread waits for the thread with handle tid to terminate

- only one thread can be joined

- thread must be joinable

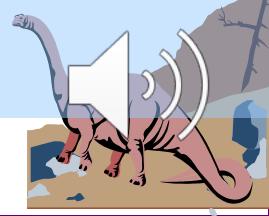
exit value is returned from joined thread

- Type returned is (void \*)

- use NULL if no return value expected

**ESRCH –thread not found**

**EINVAL – thread not joinable**



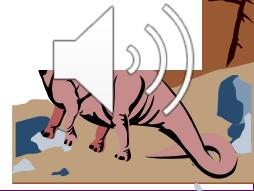


# Example 1

```
1 #include <stdio.h>
2 #include <assert.h>
3 #include <pthread.h>
4
5 void *mythread(void *arg) {
6     printf("%s\n", (char *) arg);
7     return NULL;
8 }
9
10 int
11 main(int argc, char *argv[]) {
12     pthread_t p1, p2;
13     int rc;
14     printf("main: begin\n");
15     rc = pthread_create(&p1, NULL, mythread, "A"); assert(rc == 0);
16     rc = pthread_create(&p2, NULL, mythread, "B"); assert(rc == 0);
17     // join waits for the threads to finish
18     rc = pthread_join(p1, NULL); assert(rc == 0);
19     rc = pthread_join(p2, NULL); assert(rc == 0);
20     printf("main: end\n");
21     return 0;
22 }
```

Q1: Guess what are the possible outputs?

Q2: What if we remove the two Pthread\_join() function calls?  
Note: the termination of main thread will cause the automatic termination of children threads





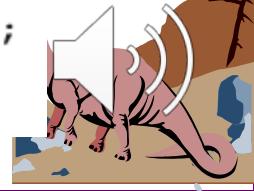
# Example 2

```
volatile int counter = 0; // shared global variable
```

```
14 void *
15 mythread(void *arg)
16 {
17     printf("%s: begin\n", (char *) arg);
18     int i;
19     for (i = 0; i < 1e7; i++) {
20         counter = counter + 1;
21     }
22     printf("%s: done\n", (char *) arg);
23     return NULL;
24 }
```

Q1: Guess what is the possible output

```
32 int
33 main(int argc, char *argv[])
34 {
35     pthread_t p1, p2;
36     printf("main: begin (counter = %d)\n", counter);
37     Pthread_create(&p1, NULL, mythread, "A");
38     Pthread_create(&p2, NULL, mythread, "B");
39
40     // join waits for the threads to finish
41     Pthread_join(p1, NULL);
42     Pthread_join(p2, NULL);
43     printf("main: done with both (counter = %d)\n", counter);
44     return 0;
45 }
```



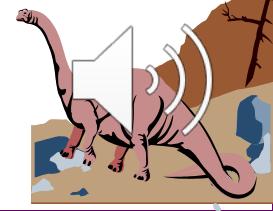


# Discussion

- Why not deterministic?
- The Heart Of The Problem: Uncontrolled Scheduling
- What happens when executing “counter = counter + 1;” ?
- Understand the code sequence that the compiler generates for the update to counter.

```
        mov 0x8049a1c, %eax
        add $0x1, %eax
        mov %eax, 0x8049a1c
```

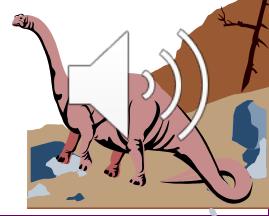
- Now, you may tell the reason





# Uncontrolled Scheduling

OS	Thread 1	Thread 2	(after instruction)		
			PC	%eax	counter
	<i>before critical section</i>		100	0	50
	mov 0x8049a1c, %eax		105	50	50
	add \$0x1, %eax		108	51	50
<b>interrupt</b>					
	<i>save T1's state</i>				
	<i>restore T2's state</i>		100	0	50
		mov 0x8049a1c, %eax	105	50	50
		add \$0x1, %eax	108	51	50
		mov %eax, 0x8049a1c	113	51	51
<b>interrupt</b>					
	<i>save T2's state</i>				
	<i>restore T1's state</i>		108	51	51
		mov %eax, 0x8049a1c	113	51	51





# Uncontrolled Scheduling

## Race condition

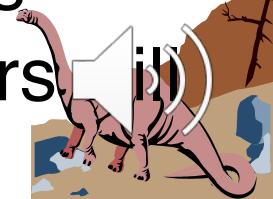
- ◆ Several processes (threads) access and manipulate the same data concurrently and the outcome of the execution depends on the particular order in which the access takes place.
- ◆ Result indeterminate.

## Critical section

- ◆ Multiple threads executing a segment of code, which can result in a race condition.

## What we want: Mutual exclusion

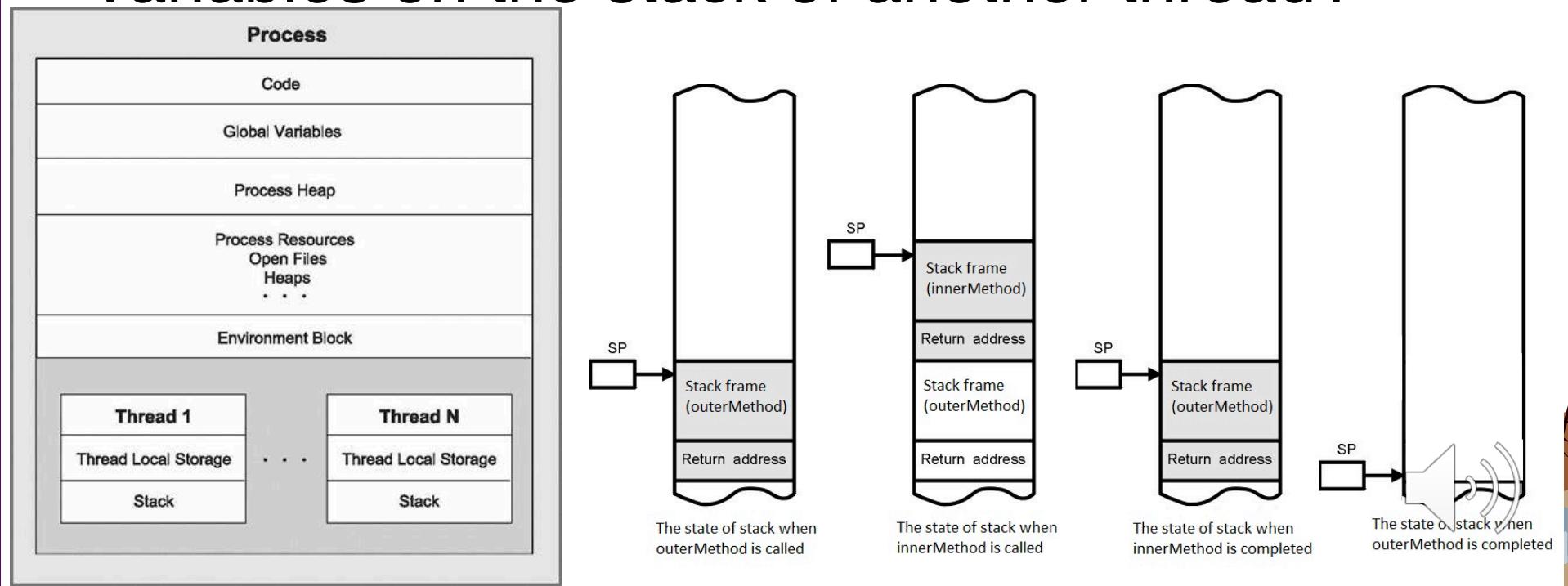
- ◆ The property guarantees that if one thread is executing within the critical section, the others be prevented from doing so.





# Revisit the Threading Model

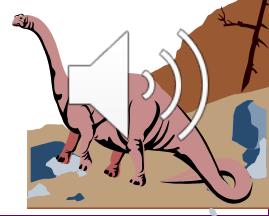
- “Data” is a public memory segment shared by all threads, which may incur race condition
- Stack is a private memory segment of a thread
- Question: What if a thread accesses the data variables on the stack of another thread?





# Chapter 4: Threads

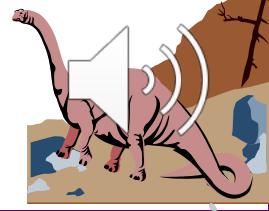
- Overview
- Multithreading Models
- Threading Issues
- Windows XP Threads
- Linux Threads
- Java Threads
- Pthreads
- Windows Thread APIs





# Windows Thread APIs

- CreateThread
- ExitThread
- TerminateThread
- GetExitCodeThread
  
- GetCurrentThreadId - returns global ID
- GetCurrentThread - returns handle
- SuspendThread/ResumeThread
- GetThreadTimes



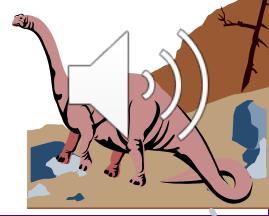


# Windows API Thread Creation

```
HANDLE CreateThread (
    LPSECURITY_ATTRIBUTES lpsa,
    DWORD cbStack,
    LPTHREAD_START_ROUTINE lpStartAddr,
    LPVOID lpvThreadParm,
    DWORD fdwCreate,
    LPDWORD lpIDThread)
```

cbStack == 0: thread's stack size defaults to primary thread's size

- lpstartAddr points to function declared as  
**DWORD WINAPI ThreadFunc(LPVOID)**
- lpvThreadParm is 32-bit argument
- lpIDThread points to DWORD that receives thread ID  
non-NULL pointer !





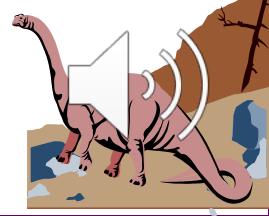
# Windows API Thread Termination

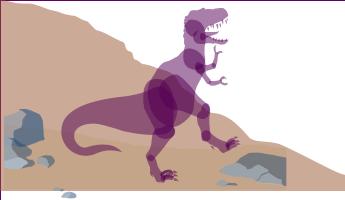
```
VOID ExitThread( DWORD devExitCode )
```

- When the last thread in a process terminates, the process itself terminates

```
BOOL GetExitCodeThread (  
    HANDLE hThread, LPDWORD lpdwExitCode)
```

- Returns exit code or **STILL\_ACTIVE**



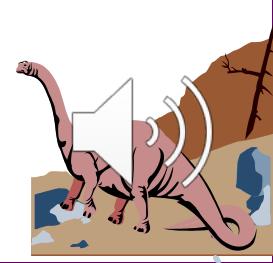


# Suspending and Resuming Threads

- Each thread has suspend count
- Can only execute if suspend count == 0
- Thread can be created in suspended state

```
DWORD ResumeThread (HANDLE hThread)  
DWORD SuspendThread(HANDLE hThread)
```

- Both functions return suspend count or  
0xFFFFFFFF on failure



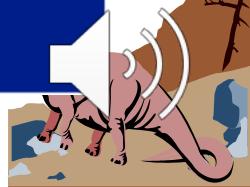
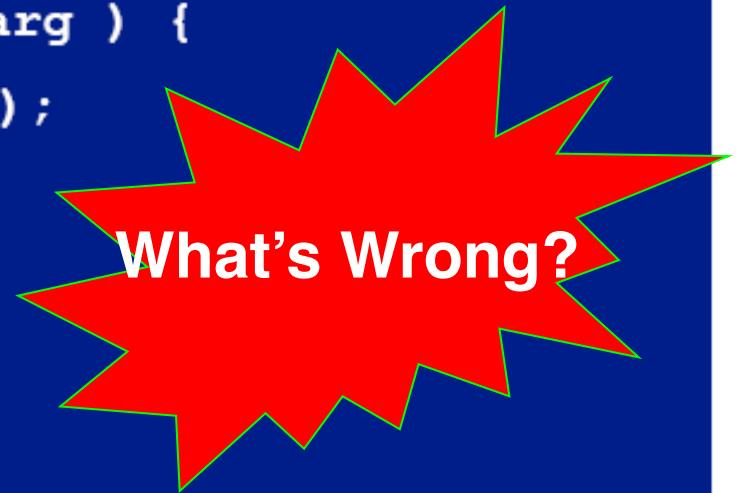


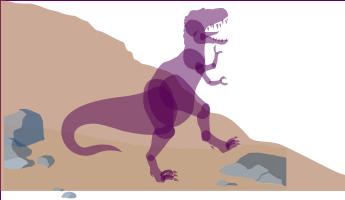
# Example: Thread Creation

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

DWORD WINAPI helloFunc(LPVOID arg) {
    printf("Hello Thread\n");
    return 0;
}

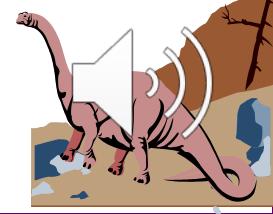
main() {
    HANDLE hThread =
        CreateThread(NULL, 0, helloFunc,
                    NULL, 0, NULL);
}
```





# Example Explained

- Main thread is process
- When process goes, all threads go
- Need some methods of waiting for a thread to finish





# Waiting for Windows\* Thread

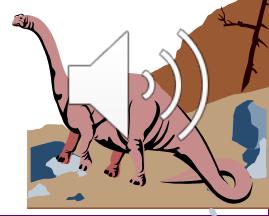
```
#include <stdio.h>
#include <windows.h>
BOOL thrdDone = FALSE;

DWORD WINAPI helloFunc(LPVOID arg) {
    printf("Hello Thread\n");
    return 0;
}

main() {
    HANDLE hThrea
    CreateThread(
        NULL, 0, NULL );
    while (!thrdDone);
}
```

**Not a good idea!**

A callout bubble points from the line `return 0;` to the text `thrdDone = TRUE;`. Another callout bubble points from the line `CreateThread(` to the text `Not a good idea!`. A third callout bubble points from the line `while (!thrdDone);` to the text `while (!thrdDone);`.





# Waiting for a Thread

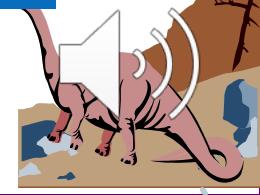
Wait for one object (thread)

```
DWORD WaitForSingleObject(  
    HANDLE hHandle,  
    DWORD dwMilliseconds );
```

Calling thread waits (blocks) until

- Time expires
  - Return code used to indicate this
- Thread exits (handle is signaled)
  - Use **INFINITE** to wait until thread termination

Does not use CPU cycles





# Waiting for Many Threads

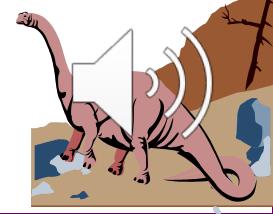
Wait for up to 64 objects (threads)

```
DWORD WaitForMultipleObjects(  
    DWORD nCount,  
    CONST HANDLE *lpHandles, // array  
    BOOL fWaitAll, // wait for one or all  
    DWORD dwMilliseconds)
```

Wait for all: `fWaitAll==TRUE`

Wait for any: `fWaitAll==FALSE`

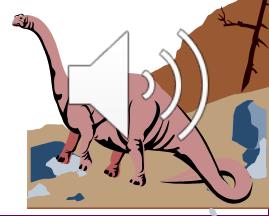
- Return value is first array index found





# Notes on WaitFor\* Functions

- Handle as parameter
- Used for different types of objects
- Kernel objects have two states
  - ◆ Signaled
  - ◆ Non-signaled
- Behavior is defined by object referred to by handle
  - ◆ Thread: signaled means terminated



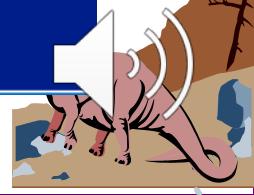


# Example: Waiting for multiple threads

```
#include <stdio.h>
#include <windows.h>
const int numThreads = 4;

DWORD WINAPI helloFunc(LPVOID arg) {
    printf("Hello Thread\n");
    return 0; }

main() {
    HANDLE hThread[numThreads];
    for (int i = 0; i < numThreads; i++)
        hThread[i] =
            CreateThread(NULL, 0, helloFunc, NULL, 0, NULL);
    WaitForMultipleObjects(numThreads, hThread,
                          TRUE, INFINITE);
}
```





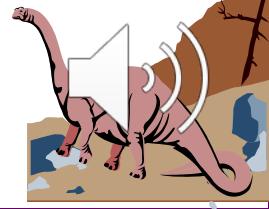
# Example: HelloThreads

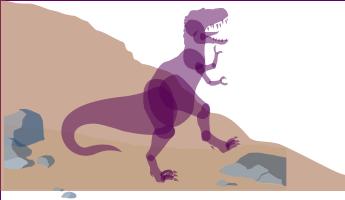
## ■ Modify the previous example code to print out

- ◆ appropriate “Hello Thread” message
- ◆ Unique thread number
  - ✓ use for-loop variable of CreateThread loop

## ■ Sample output:

```
Hello from Thread #0  
  
Hello from Thread #1  
  
Hello from Thread #2  
  
Hello from Thread #3
```

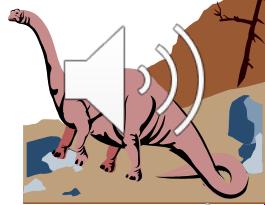




# What's Wrong?

```
DWORD WINAPI threadFunc(LPVOID pArg) {  
    int* p = (int*)pArg;  
    int myNum = *p;  
    printf("Thread number %d\n", myNum);  
}  
.  
.  
.  
// from main():  
for (int i = 0; i < numThreads; i++) {  
    hThread[i] =  
        CreateThread(NULL, 0, threadFunc, &i, 0, NULL);  
}
```

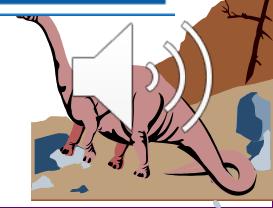
What is printed for myNum?





# Hello Threads Timeline

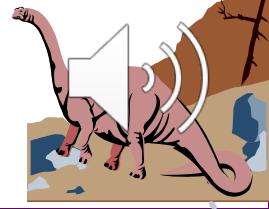
<i>Time</i>	<i>main</i>	<i>Thread 0</i>	<i>Thread 1</i>
T <sub>0</sub>	i = 0	---	----
T <sub>1</sub>	create(&i)	---	---
T <sub>2</sub>	i++ (i == 1)	launch	---
T <sub>3</sub>	create(&i)	p = pArg	---
T <sub>4</sub>	i++ (i == 2)	myNum = *p myNum = 2	launch
T <sub>5</sub>	wait	print(2)	p = pArg
T <sub>6</sub>	wait	exit	myNum = *p myNum = 2

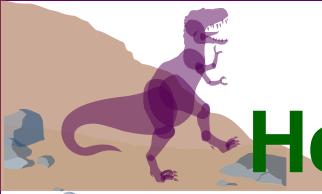




# Race Conditions

- Concurrent access of same variable by multiple threads
  - ◆ Read/Write conflict
  - ◆ Write/Write conflict
- Most common error in concurrent programs
- May not be apparent at all times
- How to avoid data races?
  - ◆ Local storage
  - ◆ Control shared access with critical regions



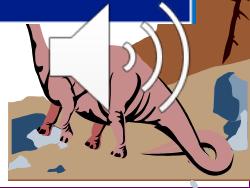


# Hello Thread: Local Storage solution

```
DWORD WINAPI threadFunc(LPVOID pArg)
{
    int myNum = *((int*)pArg);
    printf( "Thread number %d\n", myNum);
}

. . .

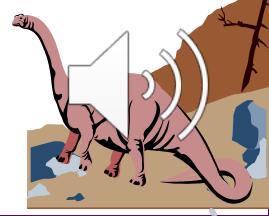
// from main():
for (int i = 0; i < numThreads; i++) {
    tNum[i] = i;
    hThread[i] =
        CreateThread(NULL, 0, threadFunc, &tNum[i],
                    0, NULL);
}
```

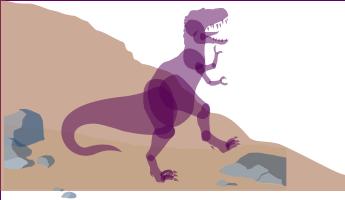




# Chapter 4: Threads

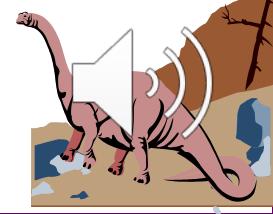
- Overview
- Multithreading Models
- Threading Issues
- Windows XP Threads
- Linux Threads
- Java Threads
- Pthreads
- Windows Threads API

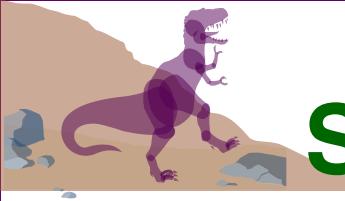




# Threading Issues

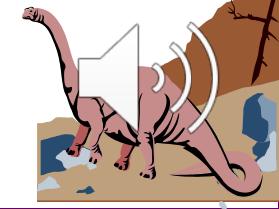
1. Semantics of fork() and exec() system calls.
2. Thread cancellation.
3. Signal handling
4. Thread pools
5. Thread specific data
6. Scheduler Activations

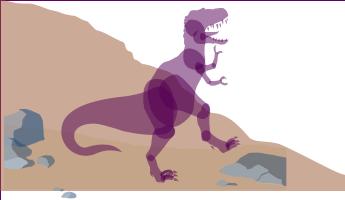




# Semantics of fork() and exec()

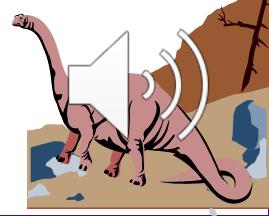
- Does **fork()** duplicate only the calling thread or all threads?
- In a Pthreads-compliant implementation, the **fork()** call always creates a new child process with a single thread, regardless of how many threads its parent may have had at the time of the call.
- Furthermore, the child's thread is a replica of the thread in the parent that called **fork**





# Thread Cancellation

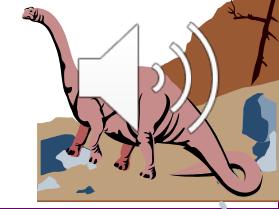
- Terminating a thread before it has finished
- Two general approaches:
  - ◆ **Asynchronous cancellation** terminates the target thread immediately
  - ◆ **Deferred cancellation** allows the target thread to periodically check if it should be cancelled
    - ✓ The point a thread can terminate itself is a **cancellation point**.





# Thread Cancellation (Cont.)

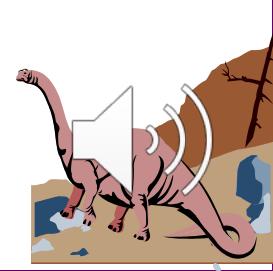
- With **asynchronous cancellation**, if the target thread owns some system-wide resources, the system may not be able to reclaim all resources
- With **deferred cancellation**, the target thread determines the time to terminate itself. Reclaiming resources is not a problem.
- Most systems implement asynchronous cancellation for processes (e.g., use the **kill** system call) and threads.
- **Pthread** supports **deferred cancellation**.





# Signal Handling

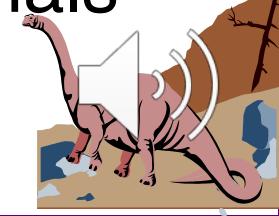
- **Signals** are used in UNIX systems to notify a process that a particular event has occurred
- All signals follow the same pattern:
  1. Signal is generated by particular event
  2. Signal is delivered to a process
  3. Signal is handled
- A **signal handler** is used to process signals





# Signal Handling (Cont.)

- How to handle a signal when its target process has multiple threads?
- Options:
  1. Deliver the signal to the thread to which the signal applies
  2. Deliver the signal to every thread in the process
  3. Deliver the signal to certain threads in the process
  4. Assign a specific thread to receive all signals for the process





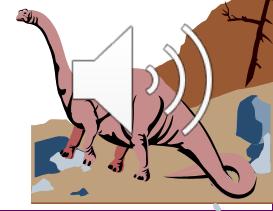
# Thread Pools

■ 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

[https://en.wikipedia.org/wiki/Thread\\_pool](https://en.wikipedia.org/wiki/Thread_pool)

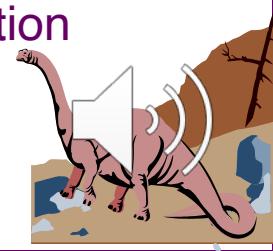




# Thread Specific Data

- 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)
- Pthreads library supports thread specific data

[https://en.wikipedia.org/wiki/Thread-local\\_storage#Pthreads\\_implementation](https://en.wikipedia.org/wiki/Thread-local_storage#Pthreads_implementation)

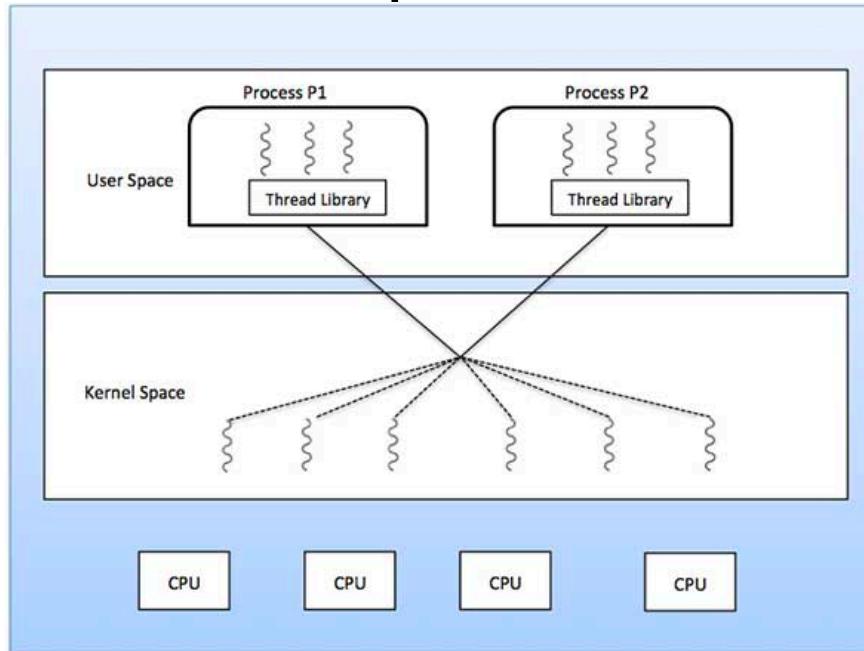




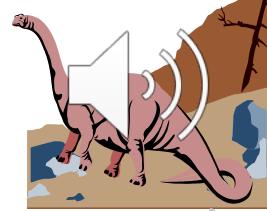
# Thread Scheduler Activations

■ **Background:** Server-version operating systems often use many-to-many and two-level thread models

- ◆ The thread library needs to maintain the appropriate number of kernel threads allocated to the process
- ◆ Requires kernel-user space communication to do it



ity





# Thread Scheduler Activations

- ◆ Scheduler activations provide **upcalls**: a communication mechanism from the kernel to the user-mode thread lib
- ◆ When the kernel knows a thread has blocked/resumed, it notifies the process' run-time system about this event
- ◆ This communication allows an application to maintain the correct number of available kernel threads

