

Chapter 4: Threads

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Chapter 4: Threads

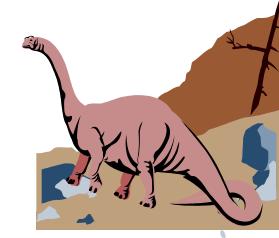
■ Overview

■ Multithreading Models

■ Thread Libraries

■ Threading Issues

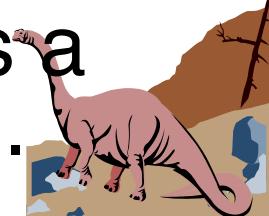
■ Operating System Examples





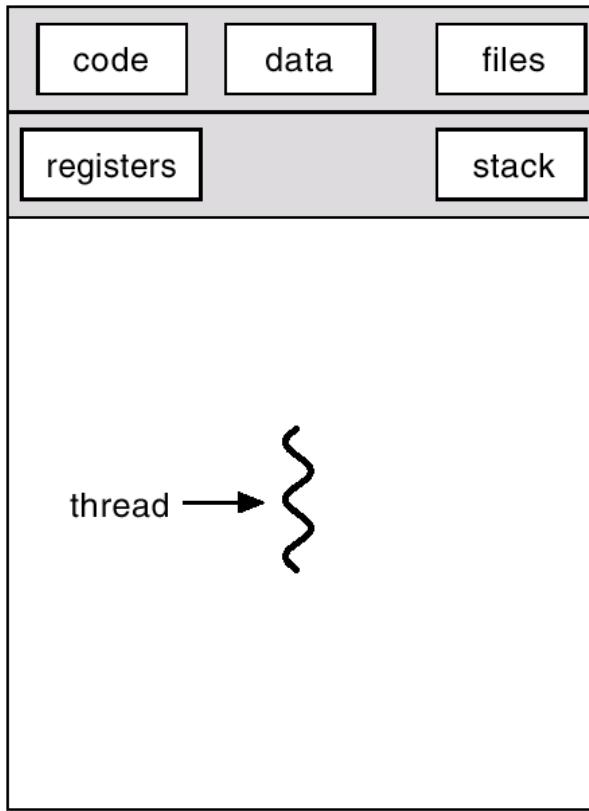
What is a thread?

- A *thread*, also known as *lightweight process* (LWP), is a basic unit of CPU execution.
- A thread has a **thread ID**, a **program counter**, 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.

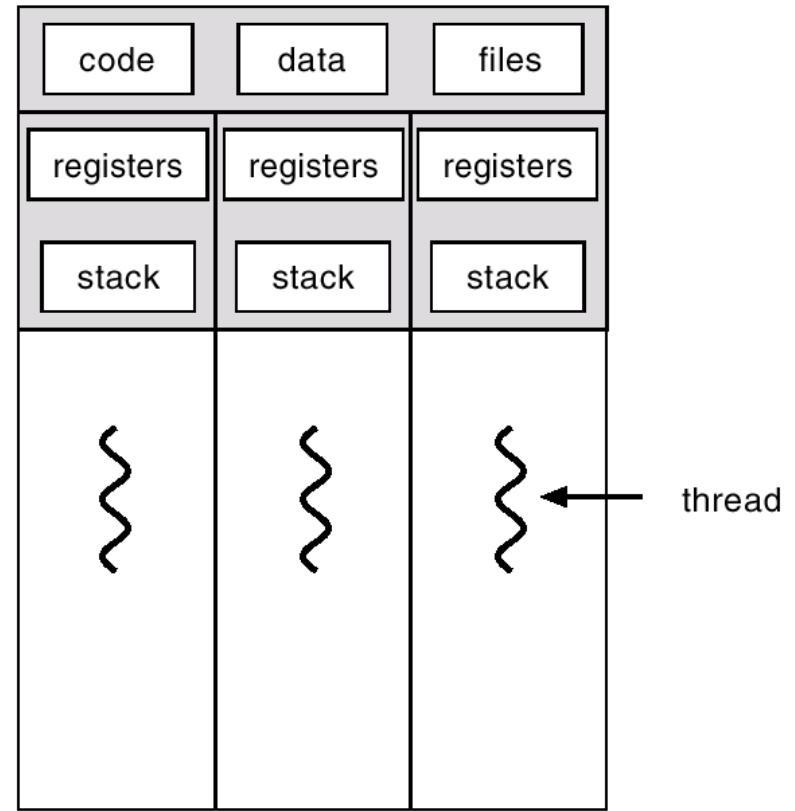




Single and Multithreaded Processes



single-threaded

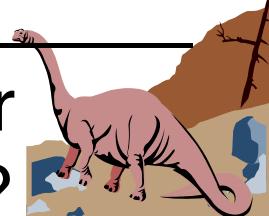


multithreaded

■ How is the heap space shared among threads?

■ Threads in a same process are _____

- tightly coupled or
- loosely coupled?





■ Items shared by all threads in a process

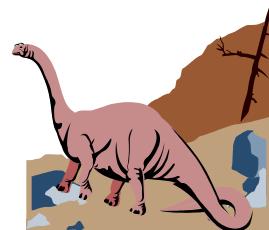
Per process items

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.

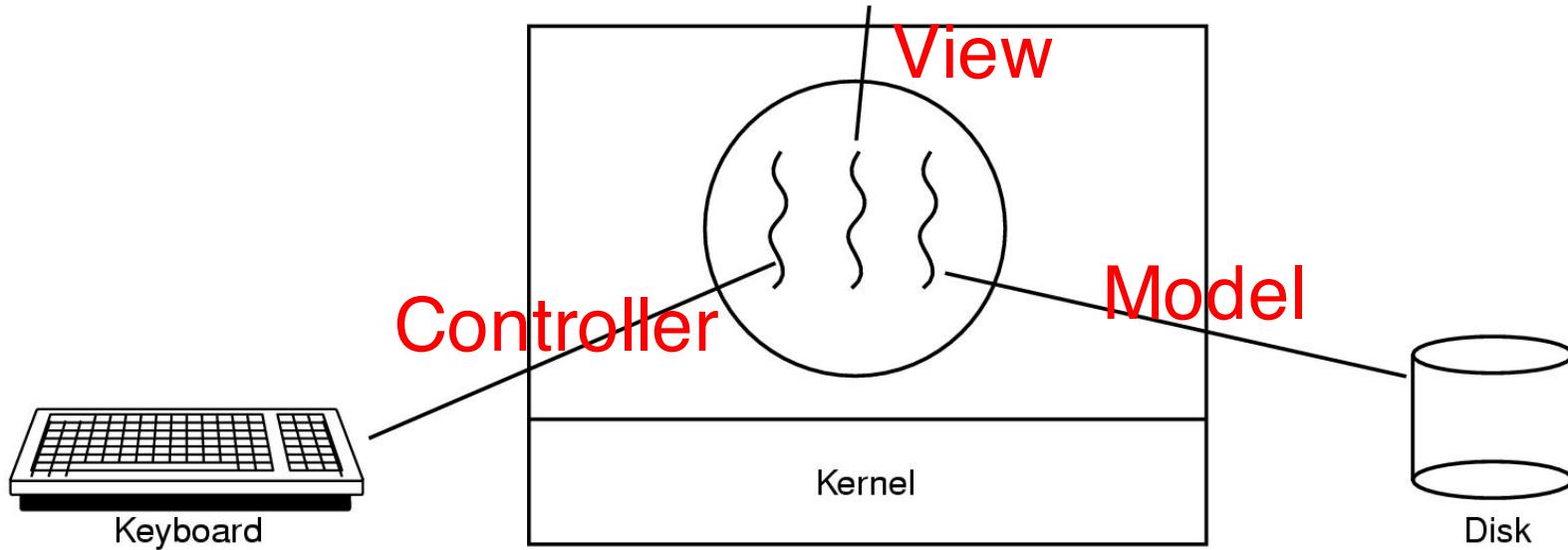
But, in a larger sense, we cannot dedicate, we cannot consecrate, we cannot hallow this ground. The brave men, living and dead,

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.

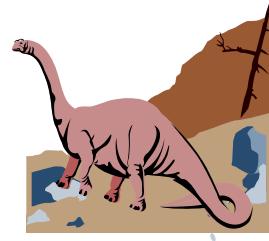
It is for us the living, rather, to be dedicated here to the unfinished work which they who fought here have thus far so nobly advanced. It is rather for us to be here dedicated to the great task remaining before us, that from these honored dead we take increased devotion to that cause for which

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, shall not perish from the earth.

MVC paradigm

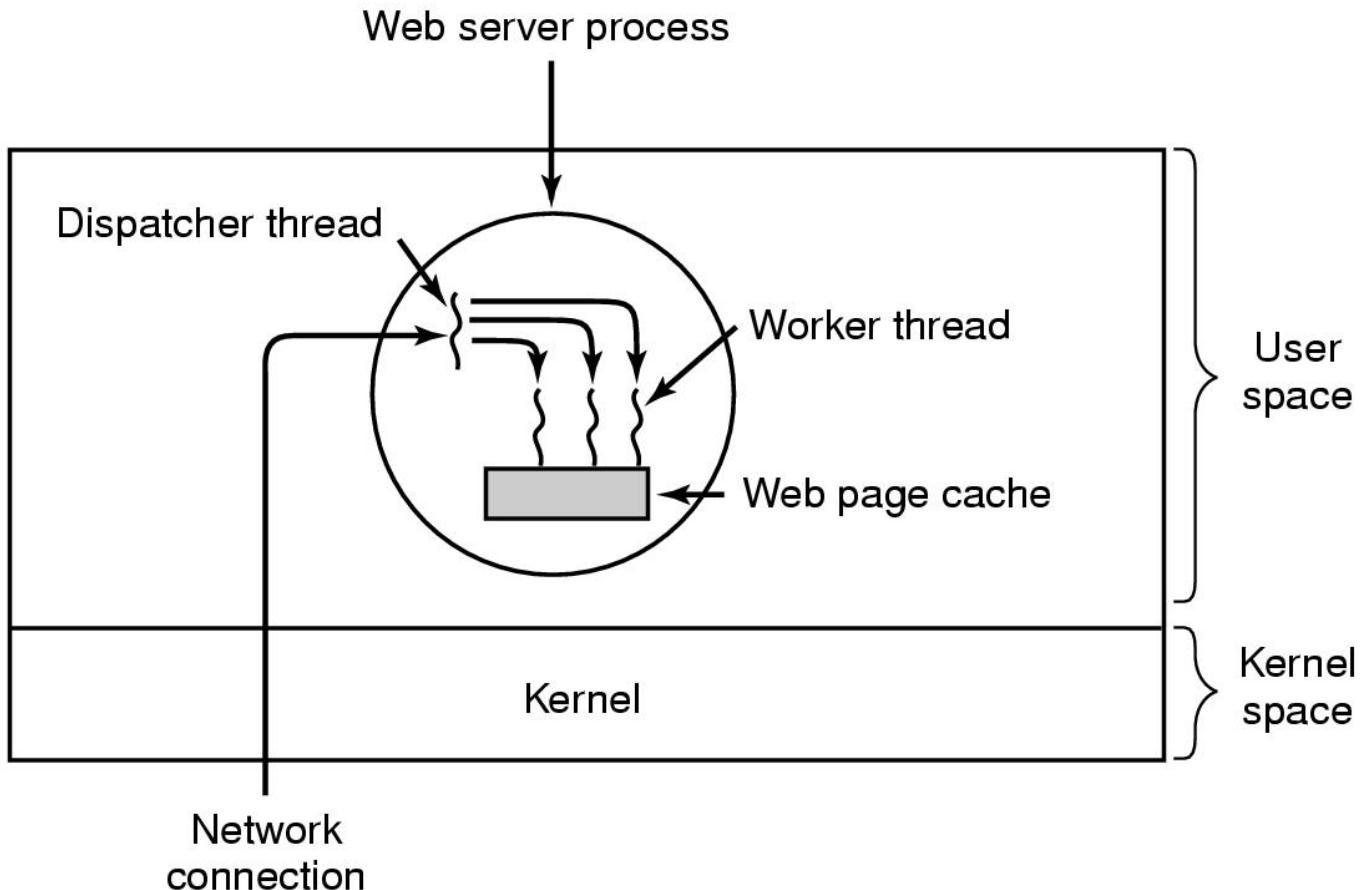


A word processor with three threads

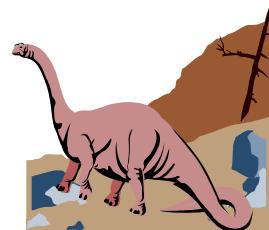




Thread Usage (2)



A multithreaded Web server





Thread Usage (3)

■ Rough outline of code for previous slide

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

Note: A 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



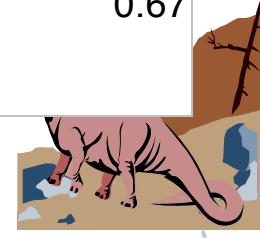


Economy for Creation

■ 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>



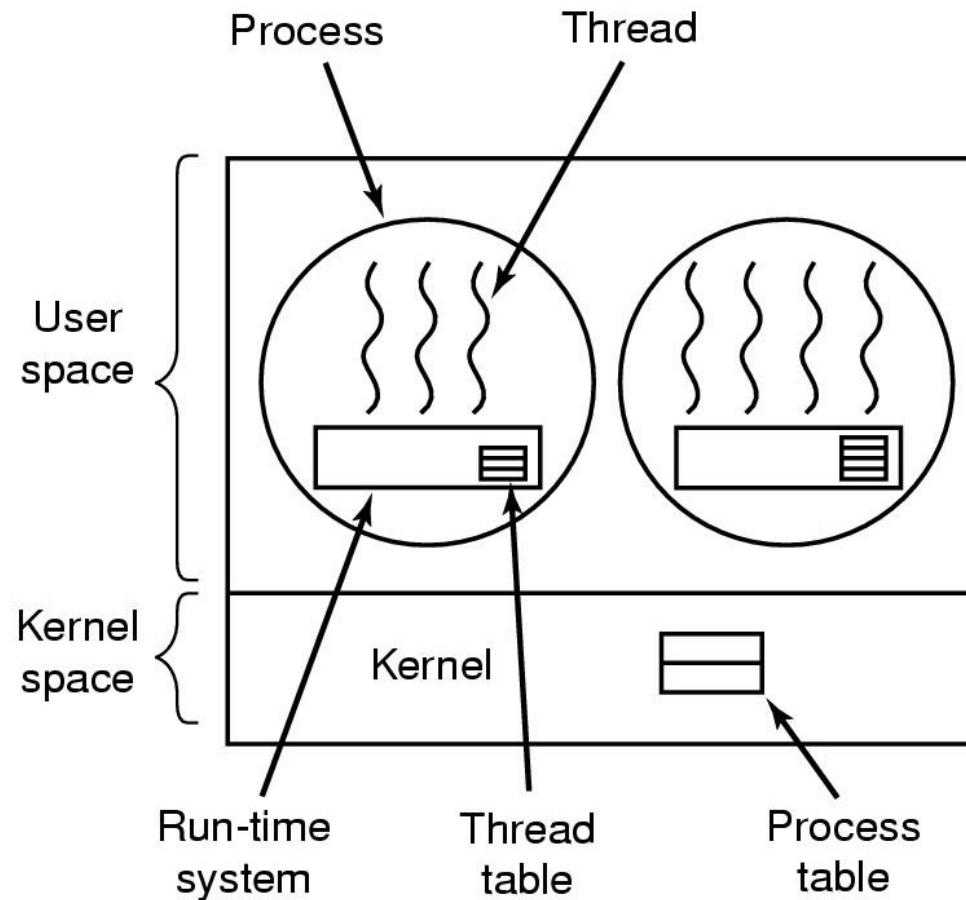


User Threads (Cont.)

- User threads are supported at the **user level**. The kernel **is not aware** of user threads.
- A library provides all support for thread creation, termination, joining, and scheduling.
- There is no kernel intervention, and, hence, 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?



Implementing Threads in User Space



A user-level threads package



Kernel Threads

■ Supported by the Kernel

■ Examples

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



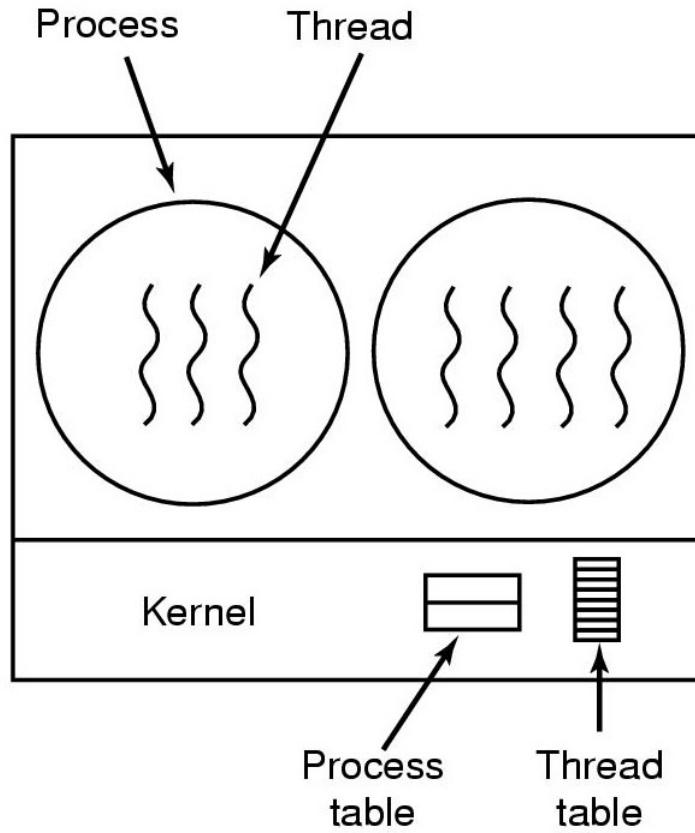


Kernel Threads (Cont.)

- 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

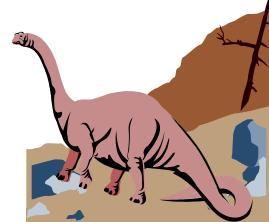


A threads package managed by the kernel
(Note: POSIX *Pthreads* library supports
the creation of kernel threads)



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



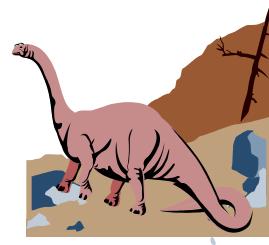


Multithreading Models

■ Many-to-One

■ One-to-One

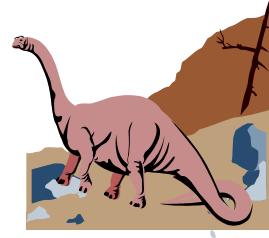
■ Many-to-Many





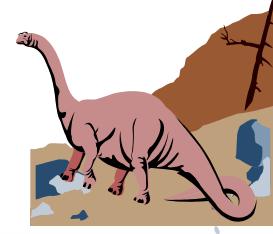
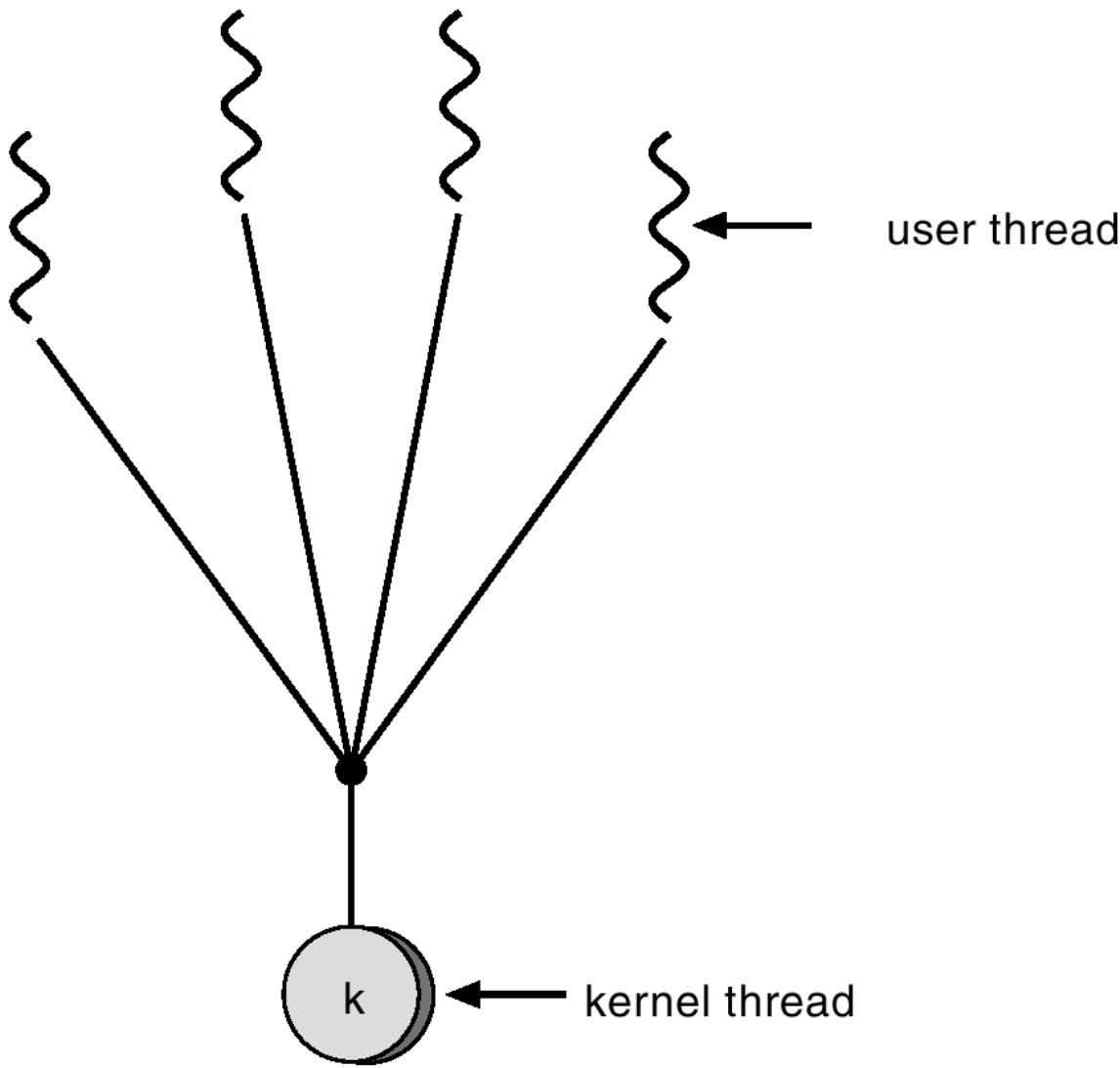
Many-to-One

- Many user-level threads mapped to single kernel thread.
- Used on systems that do not support kernel threads.



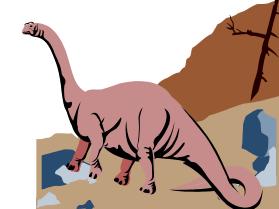
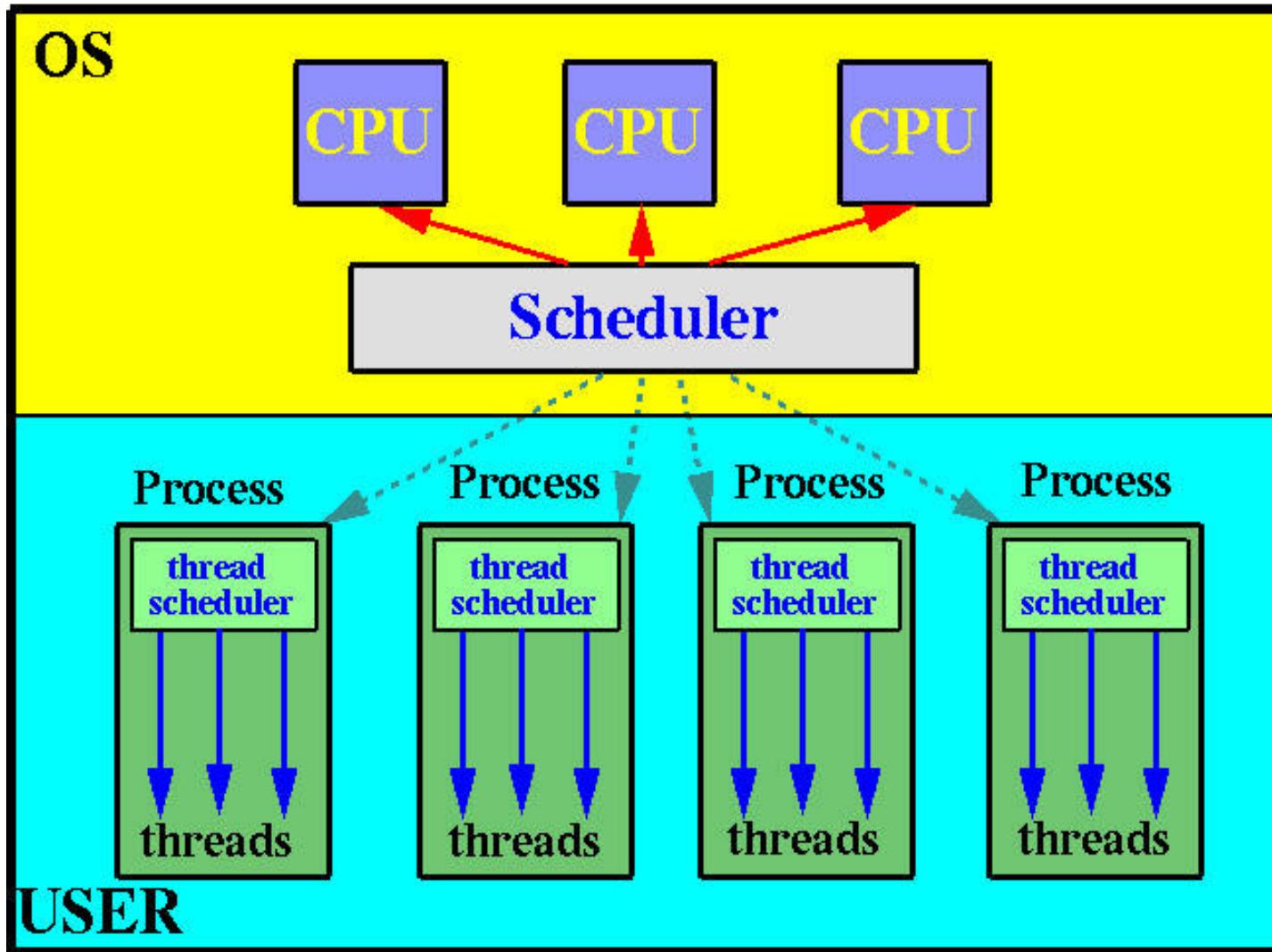


Many-to-One Model





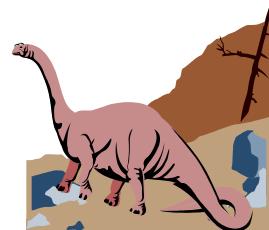
Many-to-One Model (Cont.)





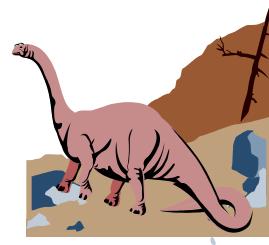
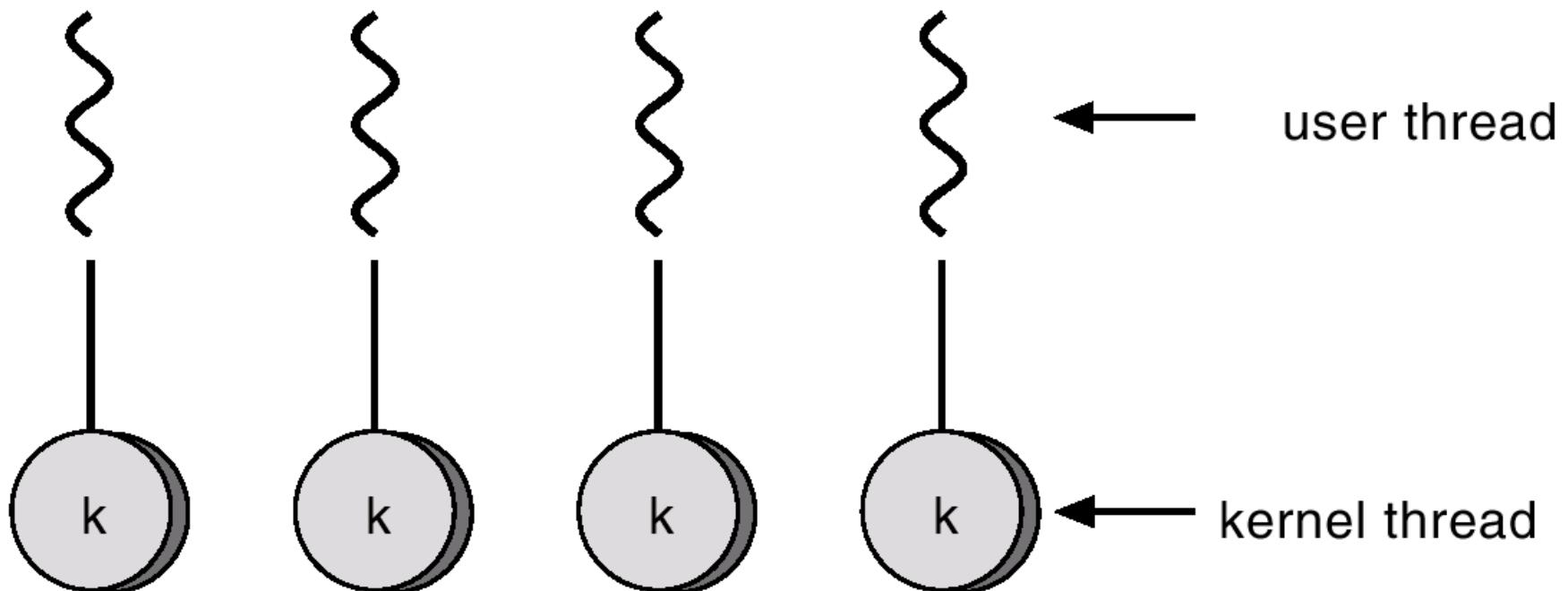
One-to-One

- Each user-level thread maps to kernel thread.
- Examples
 - Windows 95/98/NT/2000
 - OS/2



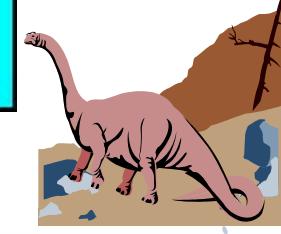
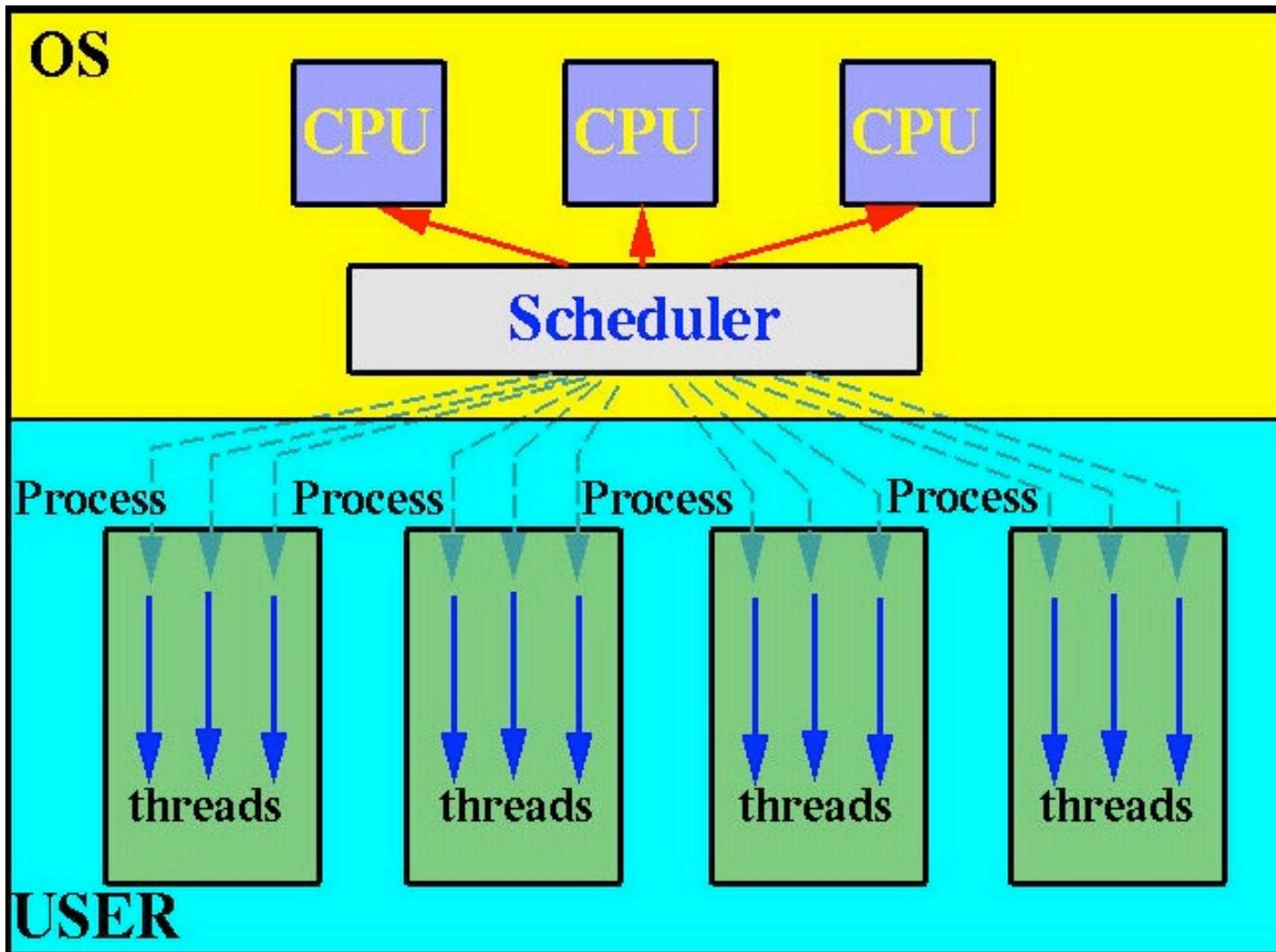


One-to-one Model





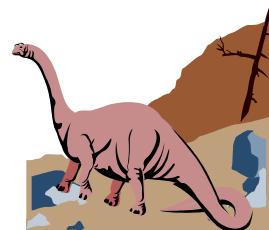
One-to-one Model (Cont.)





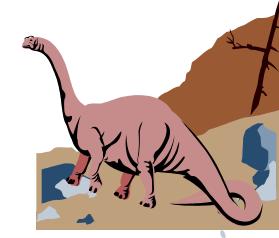
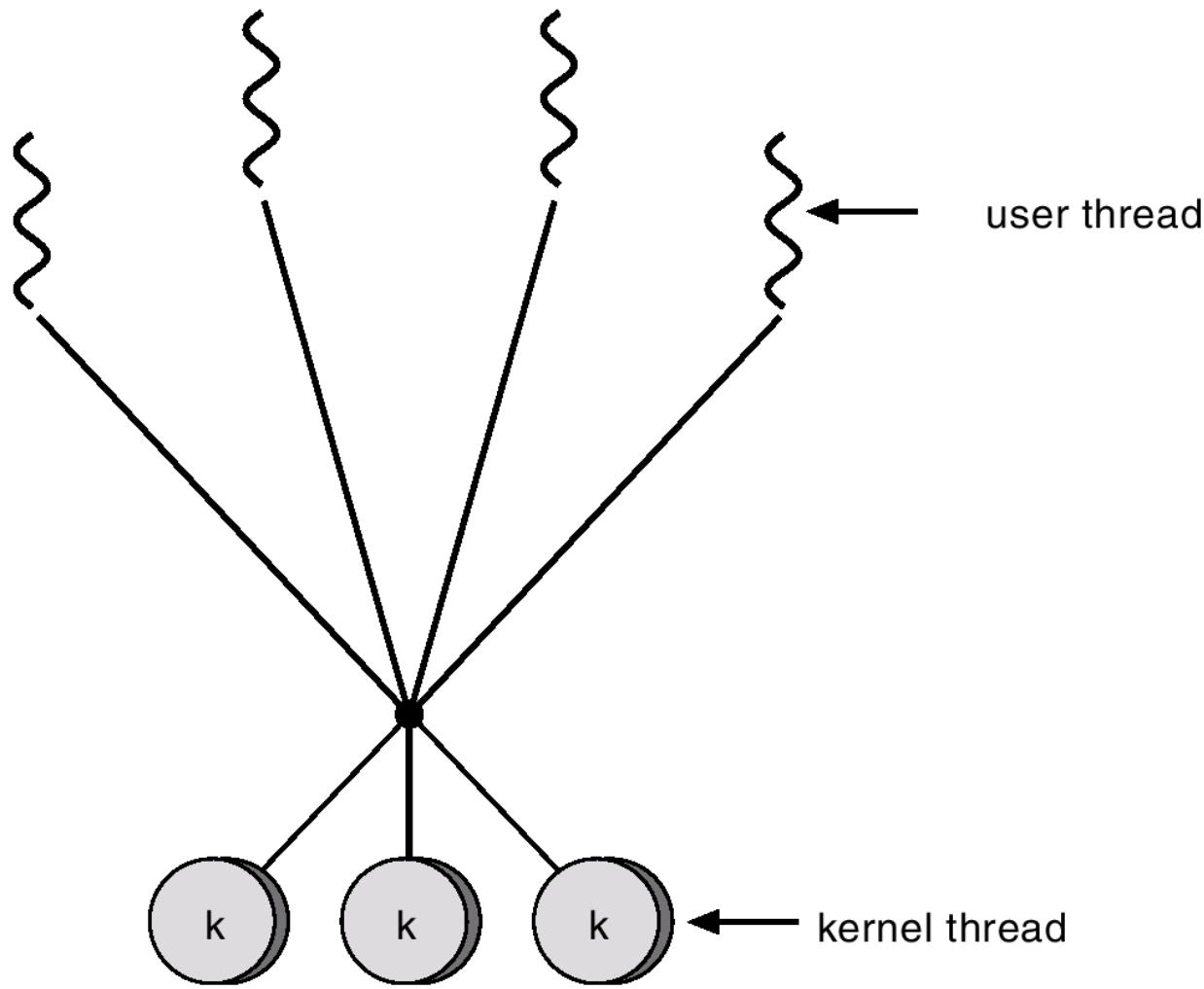
Many-to-Many Model

- Allows many user level threads to be mapped to many kernel threads.
- Allows the operating system to create a sufficient number of kernel threads.
- Solaris 2
- Windows NT/2000 with the *ThreadFiber* package



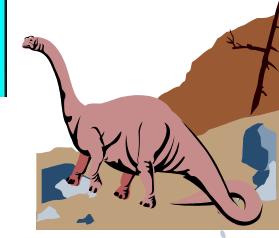
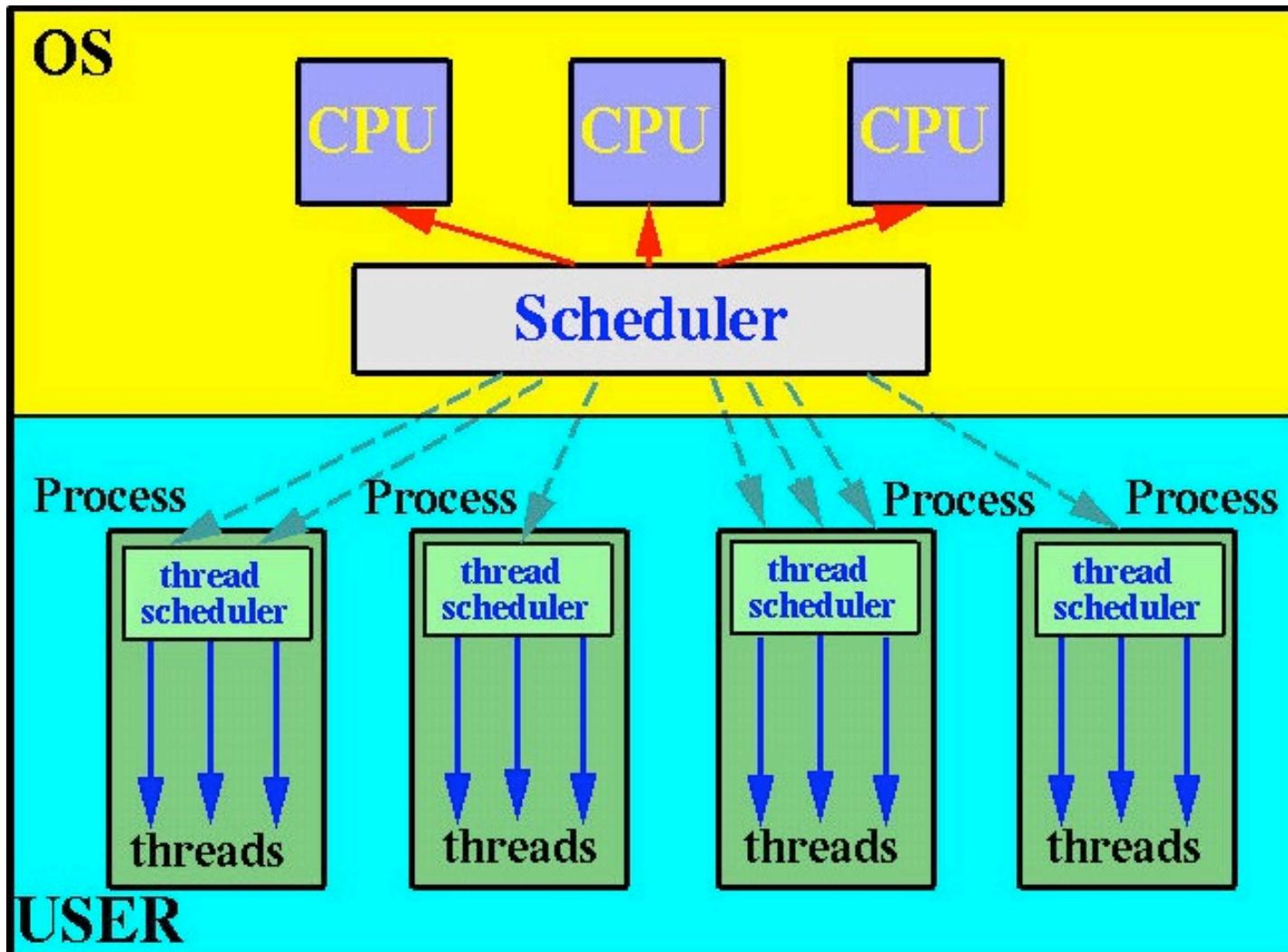


Many-to-Many Model





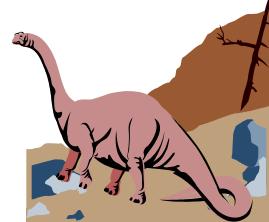
Many-to-Many Model (Cont.)





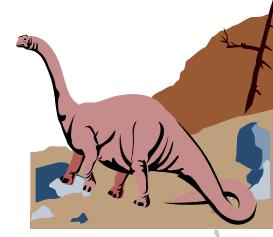
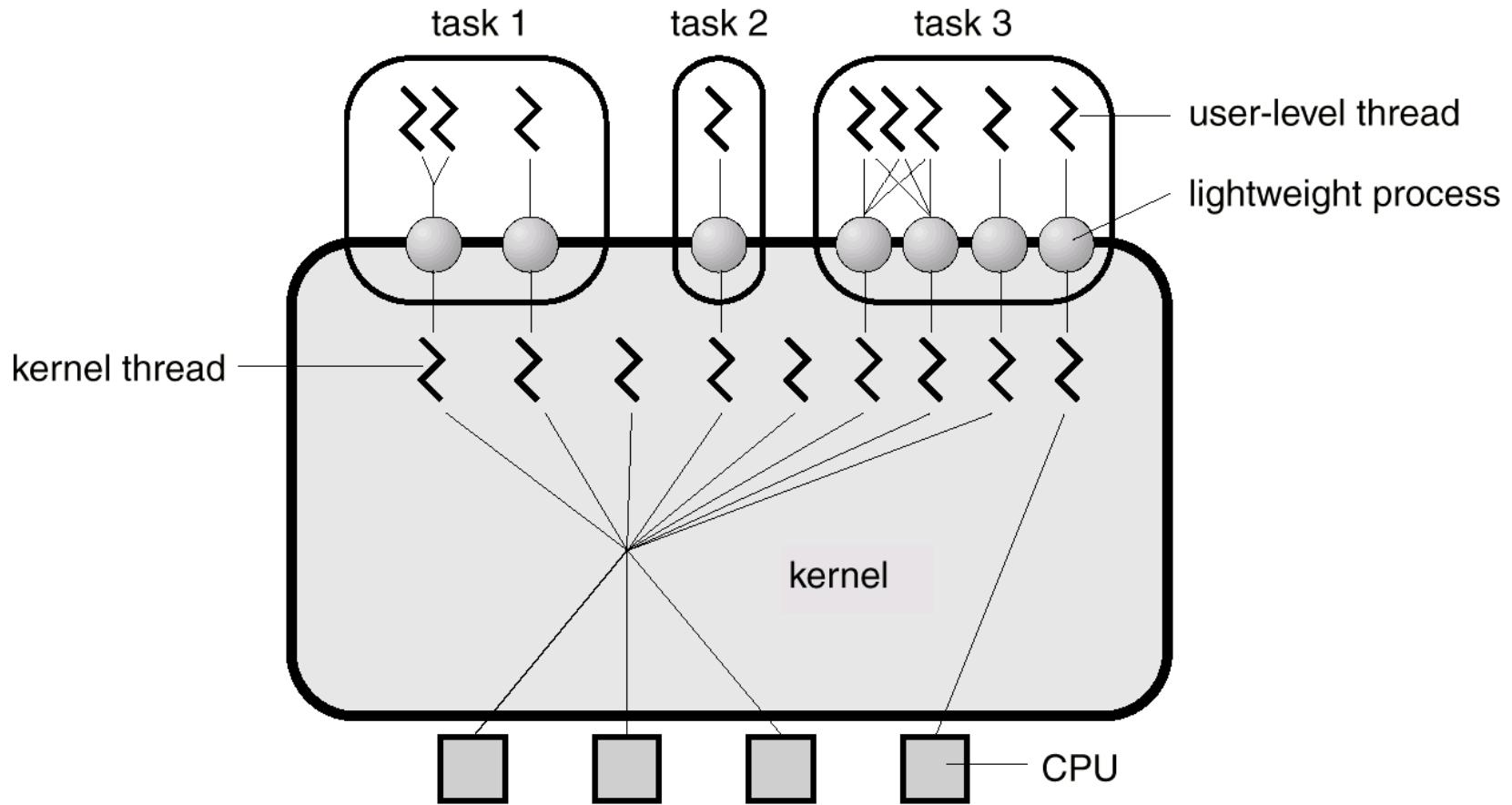
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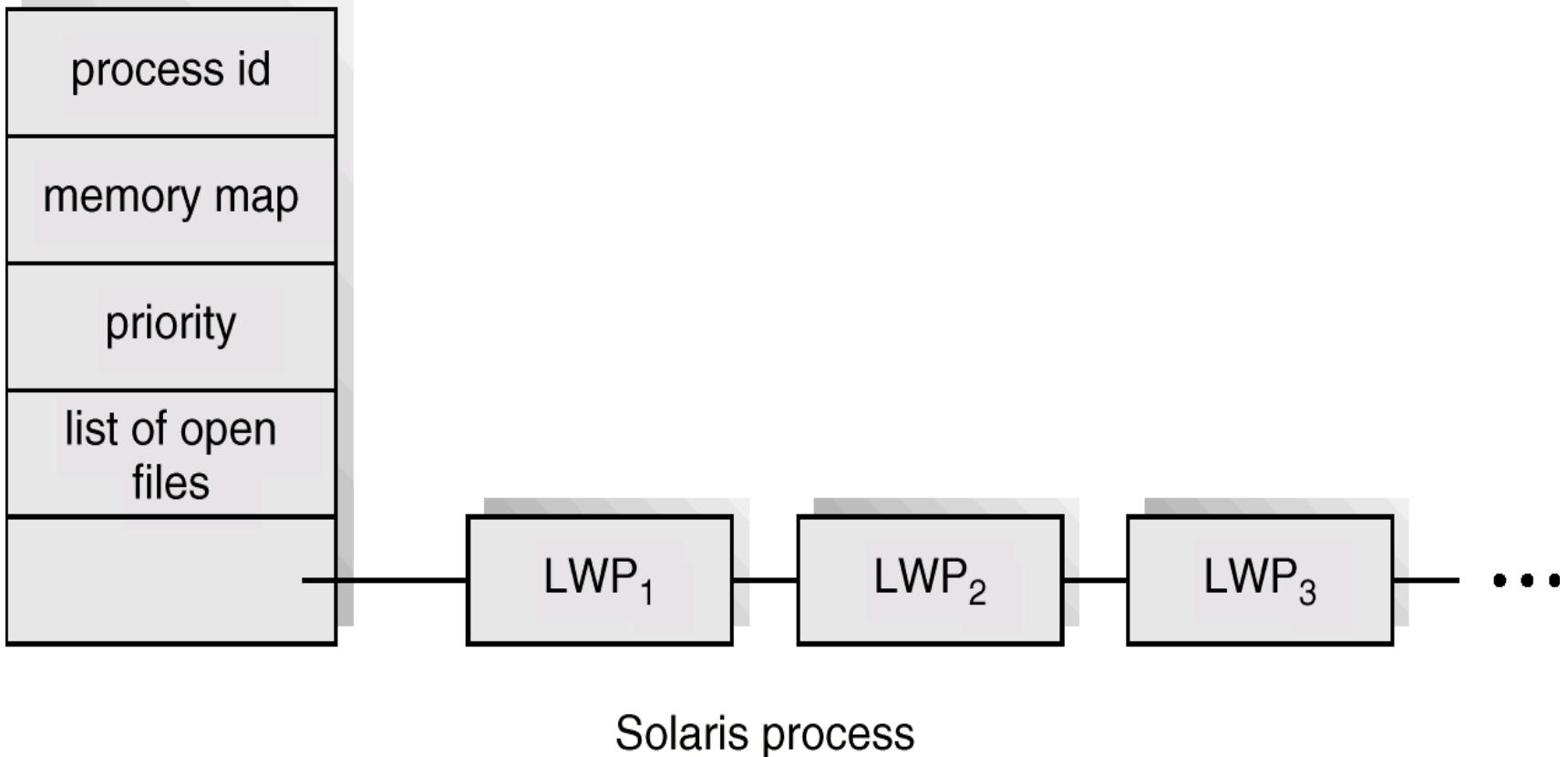


Solaris 2 Threads





Solaris Process





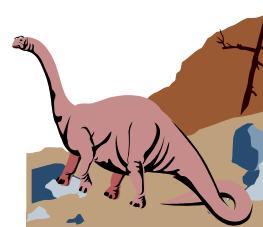
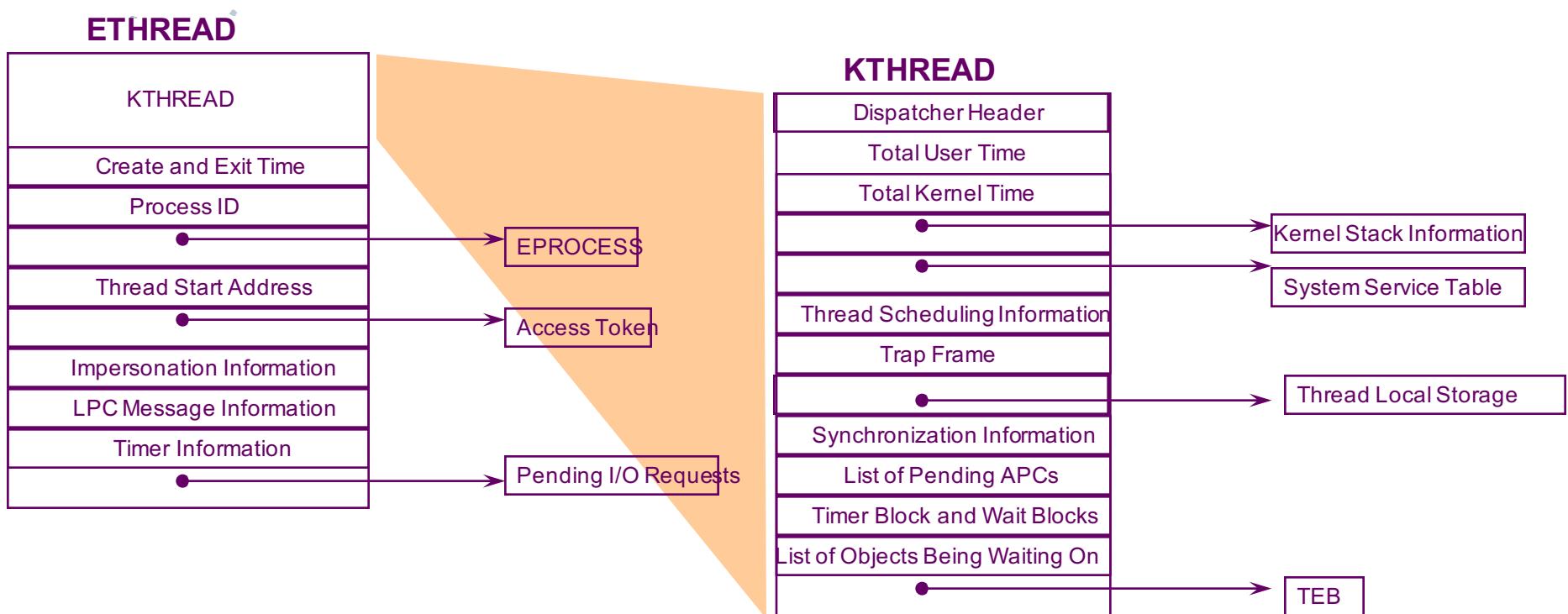
Windows XP Threads

- Implements the one-to-one mapping.
- Each thread contains
 - a thread id
 - register set
 - separate user and kernel stacks
 - private data storage area





Thread Block





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-thread/>



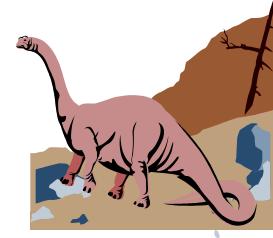


Java Threads

■ Java threads may be created by:

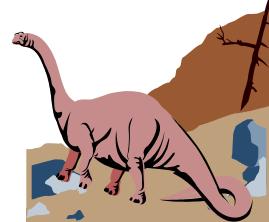
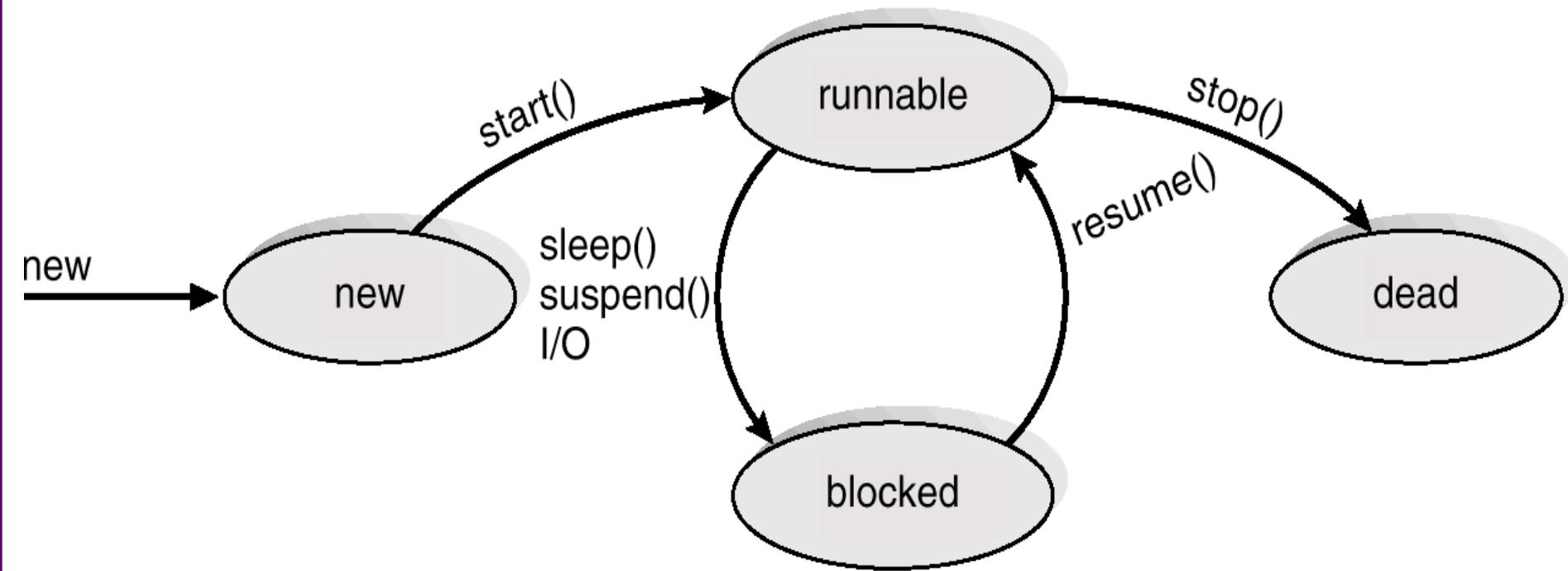
- ◆ Extending Thread class
- ◆ Implementing the Runnable interface

■ Java threads are managed by the JVM.





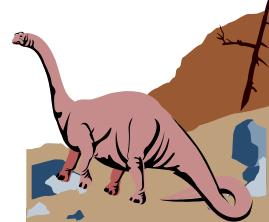
Java Thread States





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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 1×1 threads library, in that threads created by the user are in 1-1 correspondence with schedulable entities (i.e., task) in the kernel

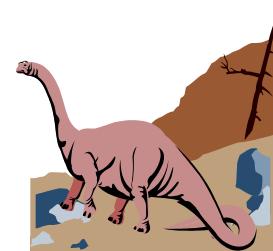




pthread_create

```
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

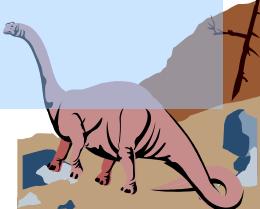
a single argument sent to function

- 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

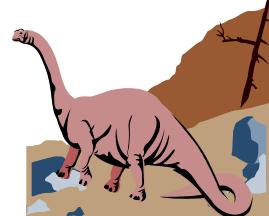
- ◆ joinable and detached

■ threads are joinable by default

- ◆ Resources are kept until *pthread_join*
- ◆ 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

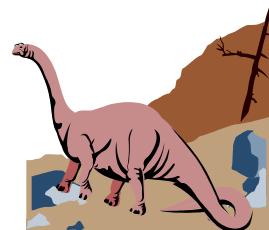
```
int pthread_join(pthread_t *tid, void **val_ptr);
```

- `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 }

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 }
```

Q1: Guess what is the possible output

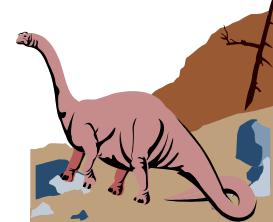


Discussion

- 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
```

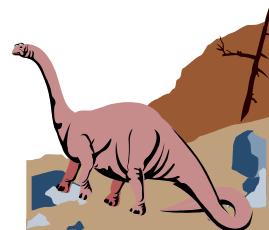
- Now, you may tell the reason





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
interrupt					
	<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
interrupt					
	<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

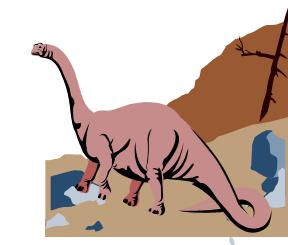
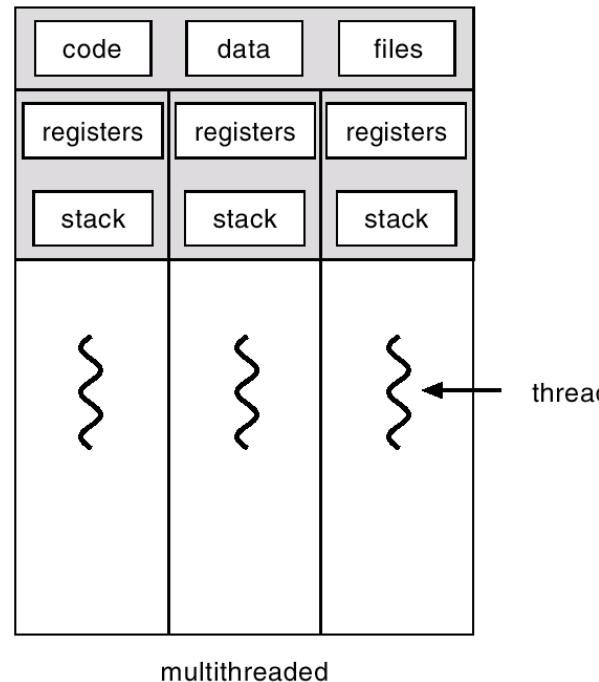
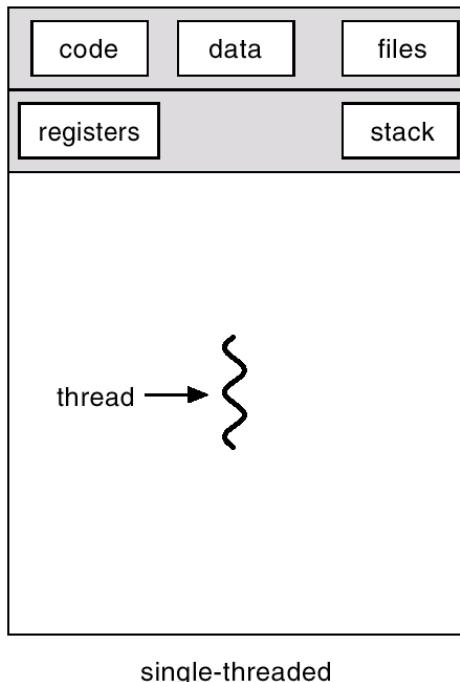
- ◆ The property guarantees that if one thread is executing within the critical section, the others will be prevented from doing so.





Revisit the Threading Model

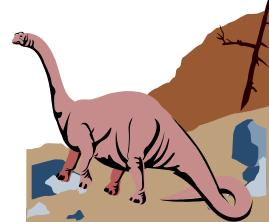
- Stack is a private memory segment of a thread
- “Data” is a public memory segment shared by all threads, which may incur race condition
- Question: What if a thread accesses the data variables on the stack of another thread?





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 !





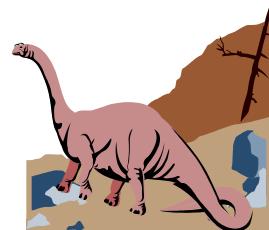
Windows API Thread Termination

```
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**



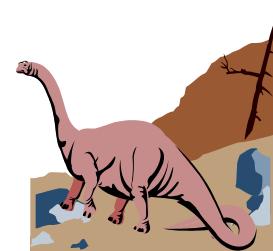


Suspending and Resuming Threads

- 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



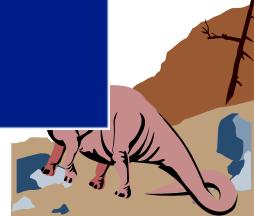


Example: Thread Creation

```
#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);
}
```

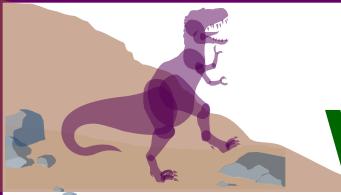




Example Explained

- 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;

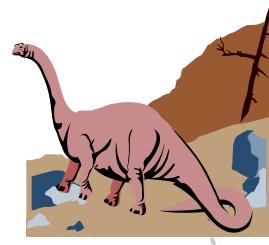
DWORD WINAPI helloFunc(LPVOID arg) {
    printf("Hello Thread\n");
    return 0;
}

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

thrdDone = TRUE;

Not a good idea!

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`

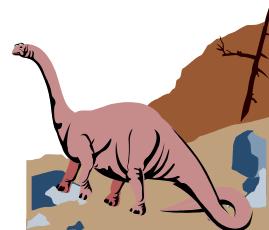
- Return value is first array index found





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



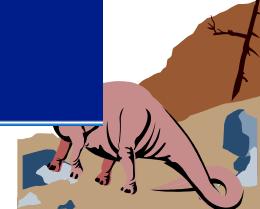


Example: Waiting for multiple threads

```
#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);
}
```





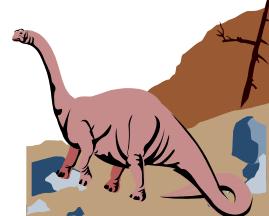
Example: HelloThreads

■ 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
```

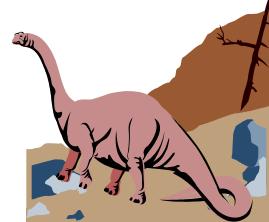




What's Wrong?

```
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);  
}
```

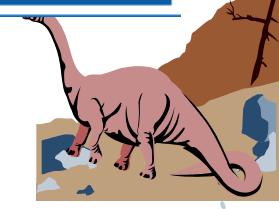
What is printed for myNum?





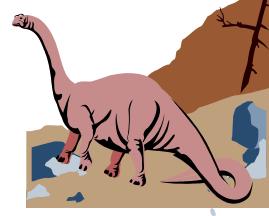
Hello Threads Timeline

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

. . .

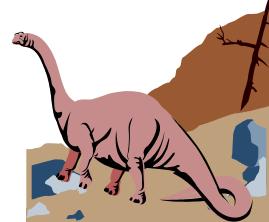
// from main():
for (int i = 0; i < numThreads; i++) {
    tNum[i] = i;
    hThread[i] =
        CreateThread(NULL, 0, threadFunc, &tNum[i],
                    0, NULL);
}
```





Chapter 4: Threads

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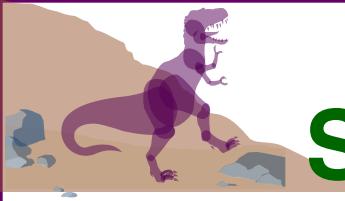




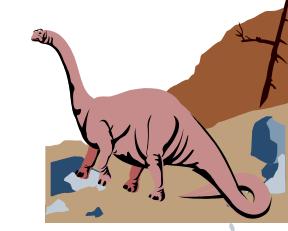
Threading Issues

- Semantics of fork() and exec() system calls.
- Thread cancellation.
- Signal handling
- Thread pools
- Thread specific data
- Scheduler Activations





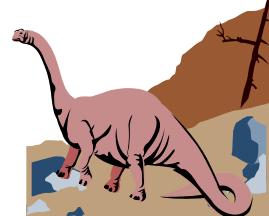
Semantics of fork() and exec()

- 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

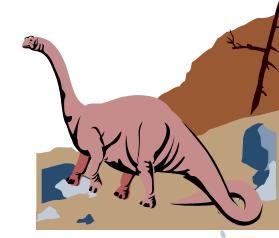
- Terminating a thread before it has finished
- Two general approaches:
 - ◆ **Asynchronous cancellation** terminates the target thread immediately
 - ◆ **Deferred cancellation** allows the target thread to periodically check if it should be cancelled
 - ✓ The point a thread can terminate itself is a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





Thread Cancellation (Cont.)

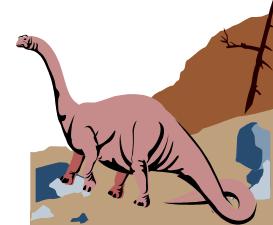
- With **asynchronous cancellation**, if the target thread owns some system-wide resources, the system may not be able to reclaim all resources
- With **deferred cancellation**, the target thread determines the time to terminate itself. Reclaiming resources is not a problem.
- Most systems implement 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

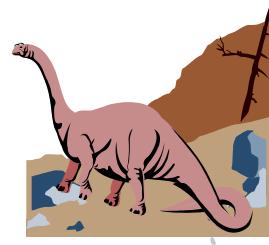




Signal Handling (Cont.)

■ Options:

- ◆ 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





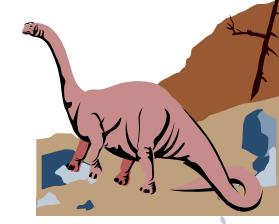
Thread Pools

■ 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





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





Scheduler Activations

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

