

Chapter 4: Threads

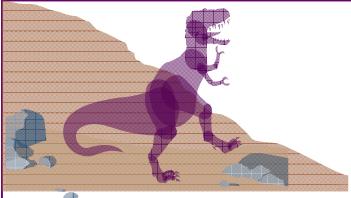
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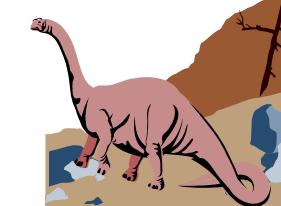
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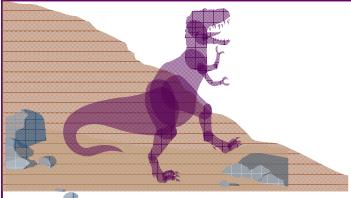
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Chapter 4: Threads

- Overview
- Multithreading Models
- Thread Libraries
- Threading Issues
- Operating System Examples





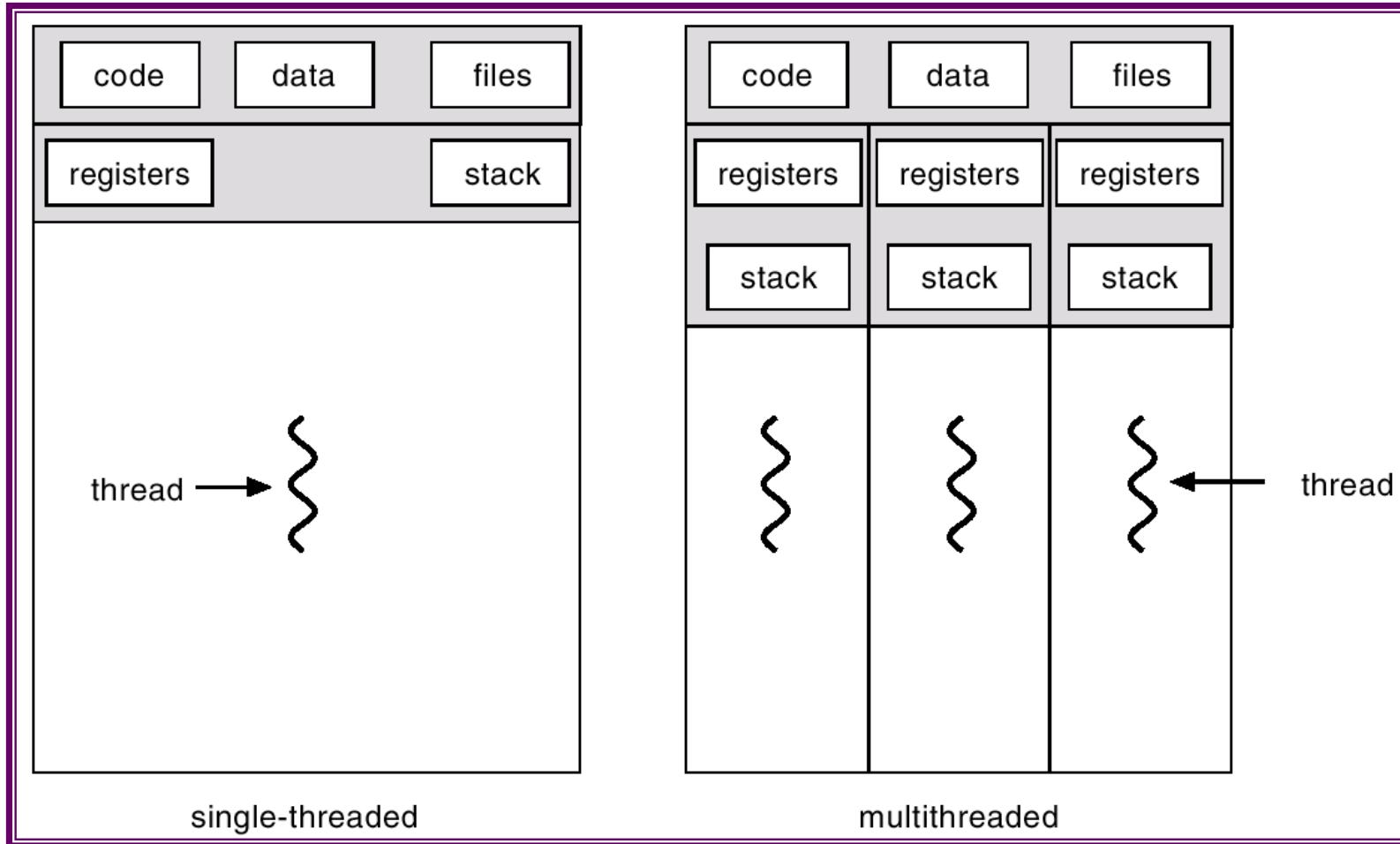
What is a thread?

- 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.



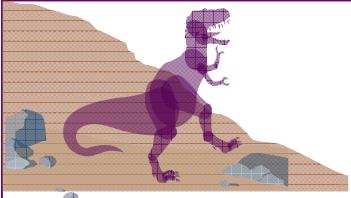


Single and Multithreaded Processes



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





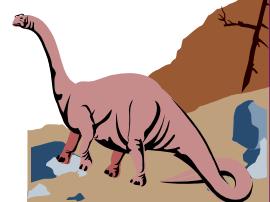
Per process items

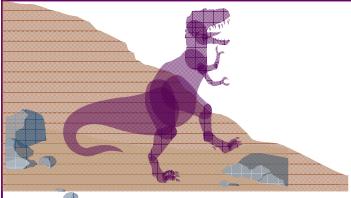
Address space
Global variables
Open files
Child processes
Pending alarms
Signals and signal handlers
Accounting information

Per thread items

Program counter
Registers
Stack
State

- Items shared by all threads in a process
- Items private to each thread





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

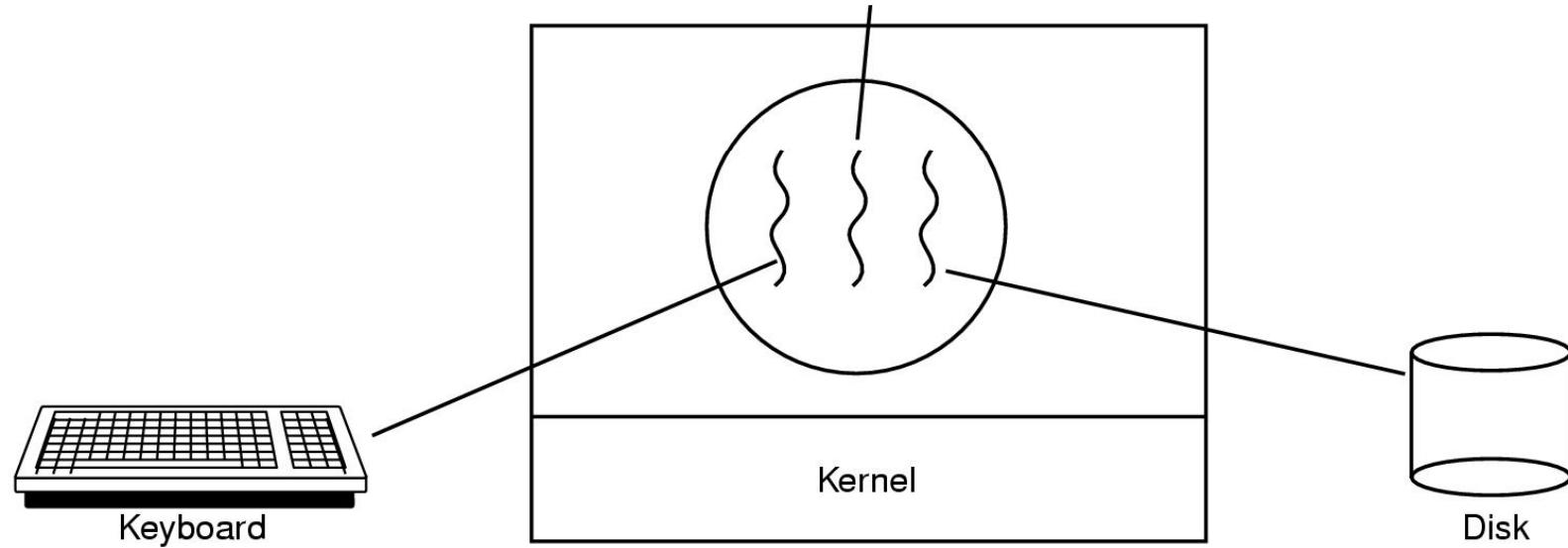
lives that this nation might live. It is altogether fitting and proper that we should do this.

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

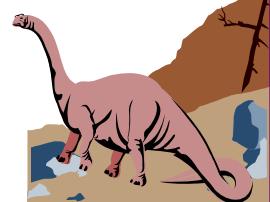
who struggled here have consecrated it, far above our poor power to add or detract. The world will little note, nor long remember, what we say here, but it can never forget what they did here.

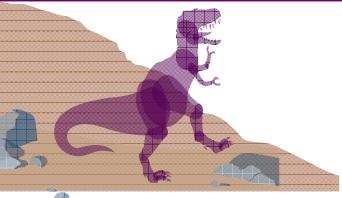
It is for us the living, rather, to be dedicated to the great task remaining before us, that from these honored dead we take increased devotion to that cause for which

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

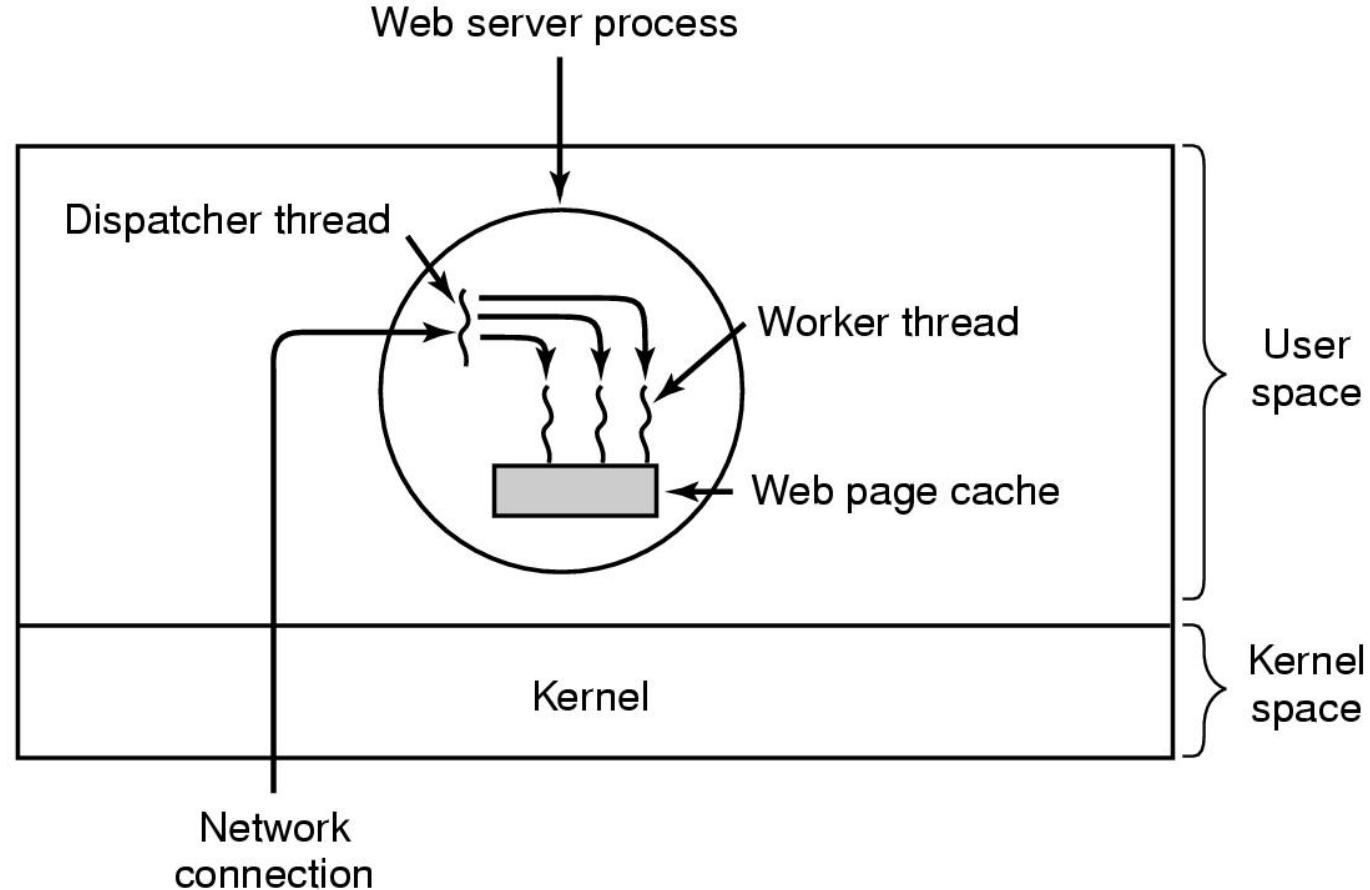


A word processor with three threads

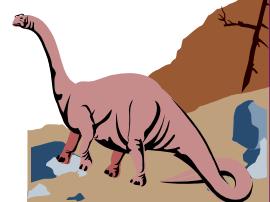


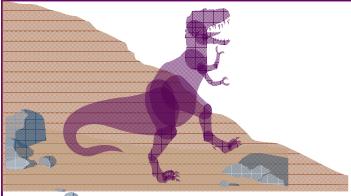


Thread Usage (2)



A multithreaded Web server





Thread Usage (3)

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

(a)

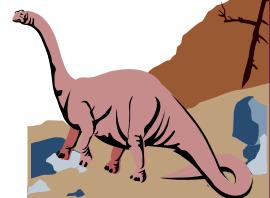
```
while (TRUE) {  
    wait_for_work(&buf)  
    look_for_page_in_cache(&buf, &page);  
    if (page_not_in_cache(&page)  
        read_page_from_disk(&buf, &page);  
    return_page(&page);  
}
```

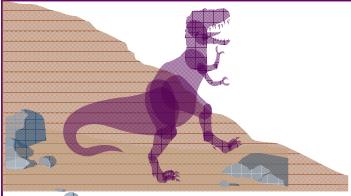
(b)

■ Rough outline of code for previous slide

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

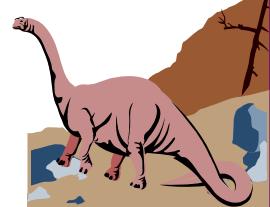
Note: A Event-Driven Framework

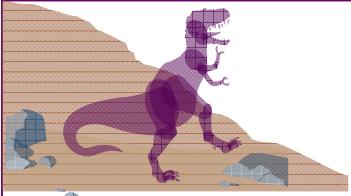




Benefits

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



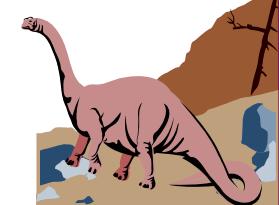


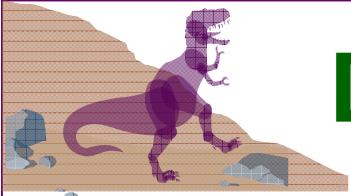
Benefits (cont.)

■ Process fork() vs. pthread_create()

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

<http://www.cnblogs.com/mywolrd/archive/2009/02/04/1930708.html>

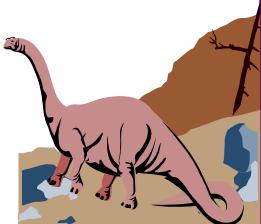


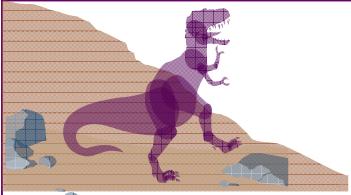


Different Ways to Implement Concurrency

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

Lower
Cost in
Context
Switching

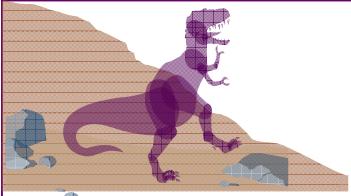




User Threads

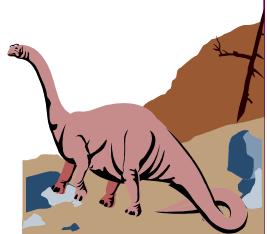
- Thread management done by user-level threads library
 - ◆ Context switching of threads in the same process is done in user mode
- Examples
 - **POSIX *Pthreads***
 - *Mach C-threads*
 - *Solaris Ul-threads*

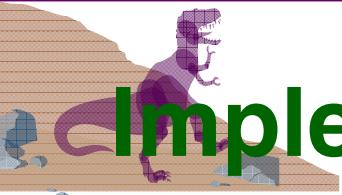




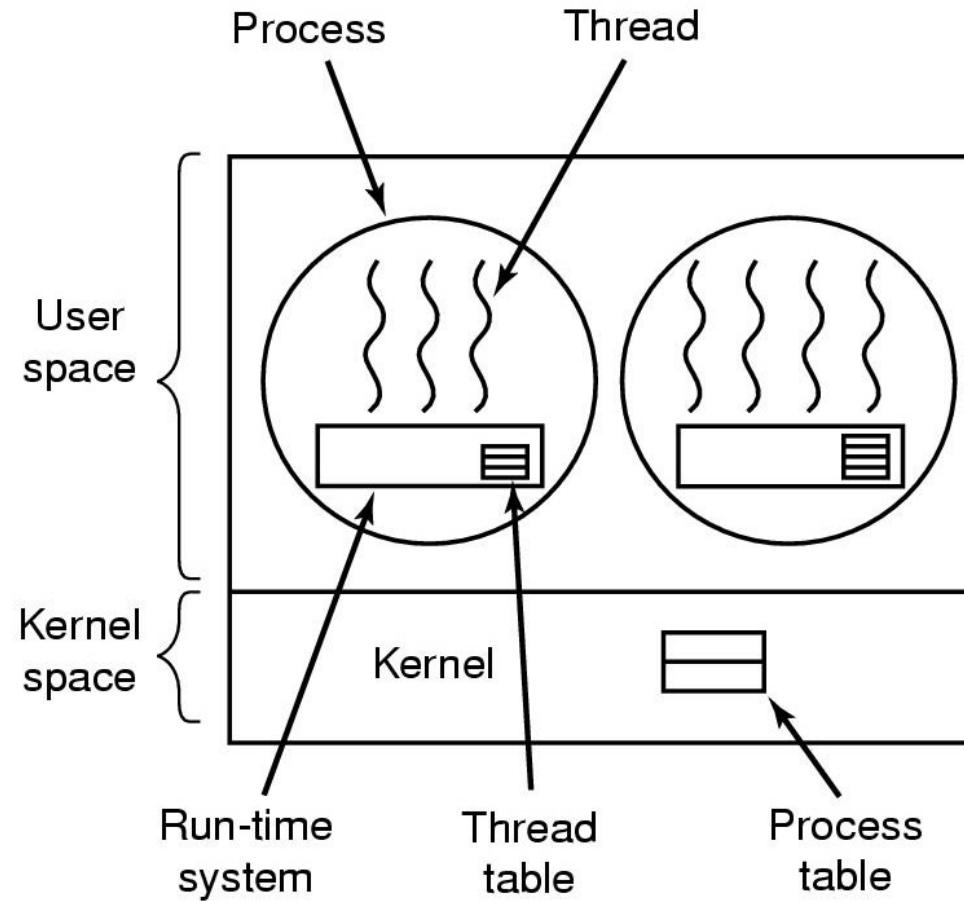
User Threads (Cont.)

- 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.
- Can be mitigated by asynchronous I/O.



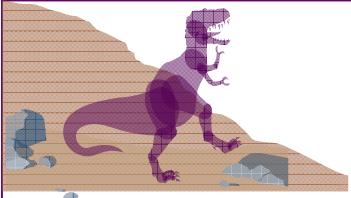


Implementing Threads in User Space



A user-level threads package



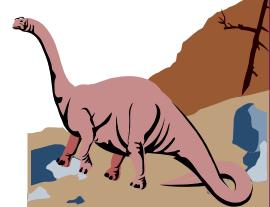


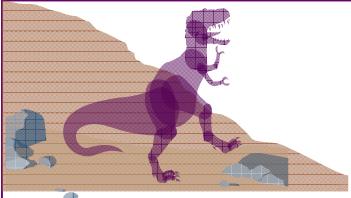
Kernel Threads

- Supported by the Kernel

- Examples

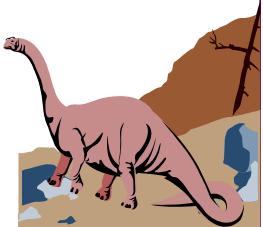
- Windows 95/98/NT/2000
- Solaris
- Tru64 UNIX
- BeOS
- Linux

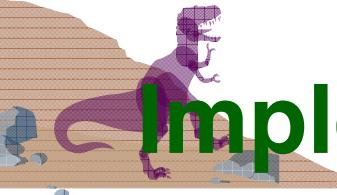




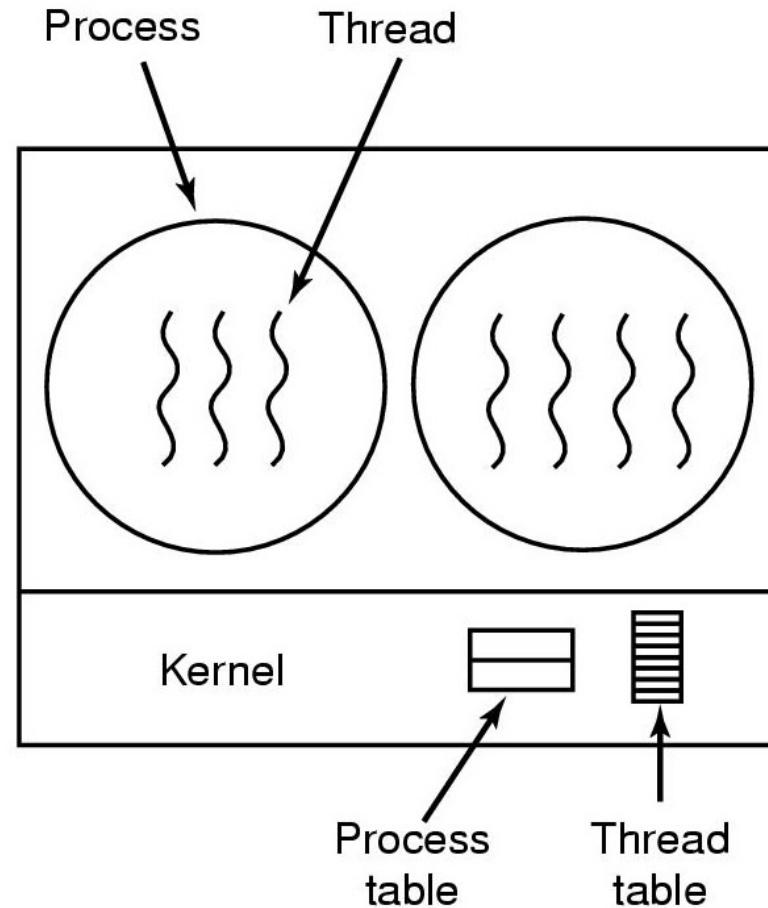
Kernel Threads (Cont.)

- 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

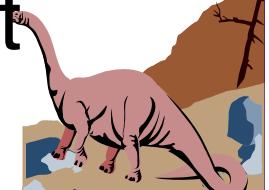


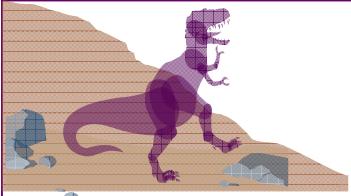


Implementing Threads in the Kernel



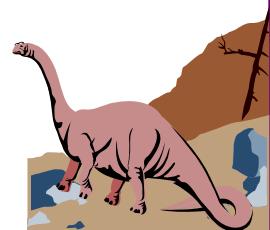
A threads package managed by the kernel
(Note: POSIX *Pthreads* library support
also the creation of kernel threads)

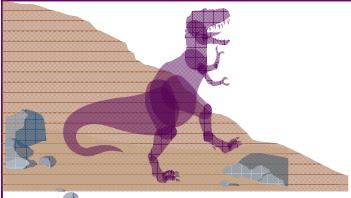




Chapter 4: Threads

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

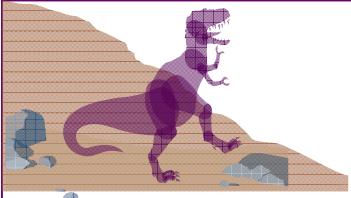




Multithreading Models

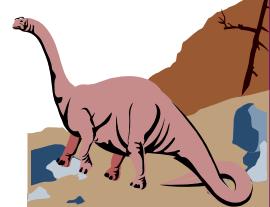
- Many-to-One
- One-to-One
- Many-to-Many

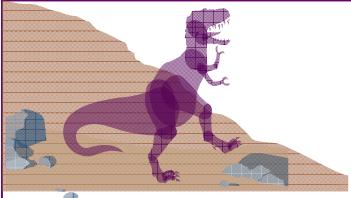




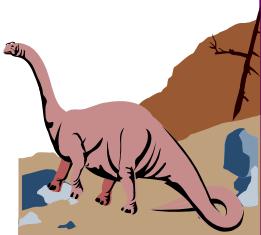
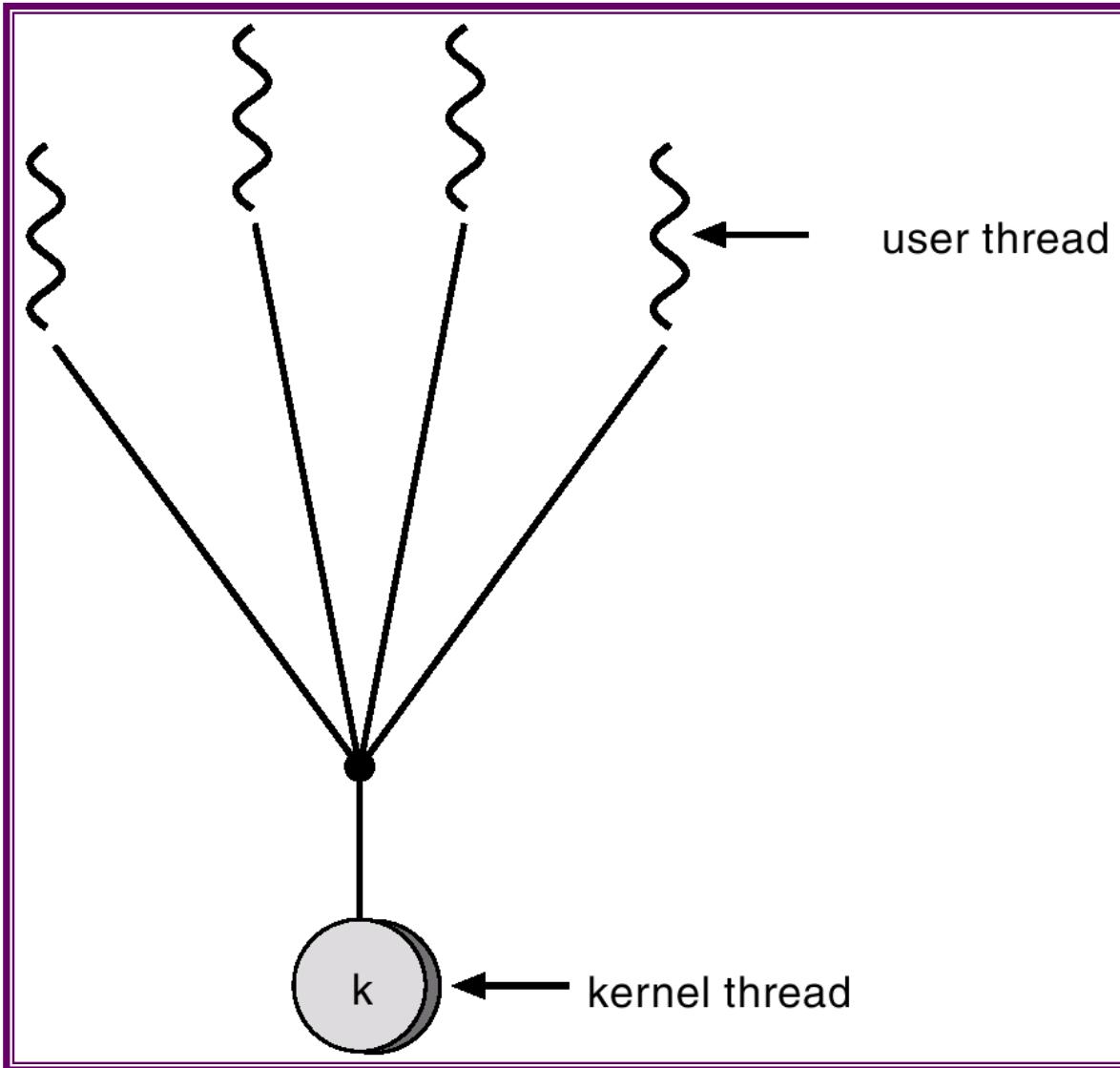
Many-to-One

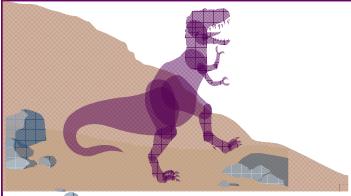
- Many user-level threads mapped to single kernel thread.
- Used on systems that do not support kernel threads.



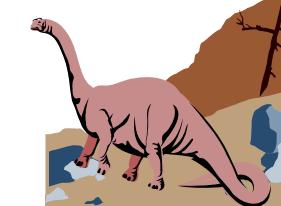
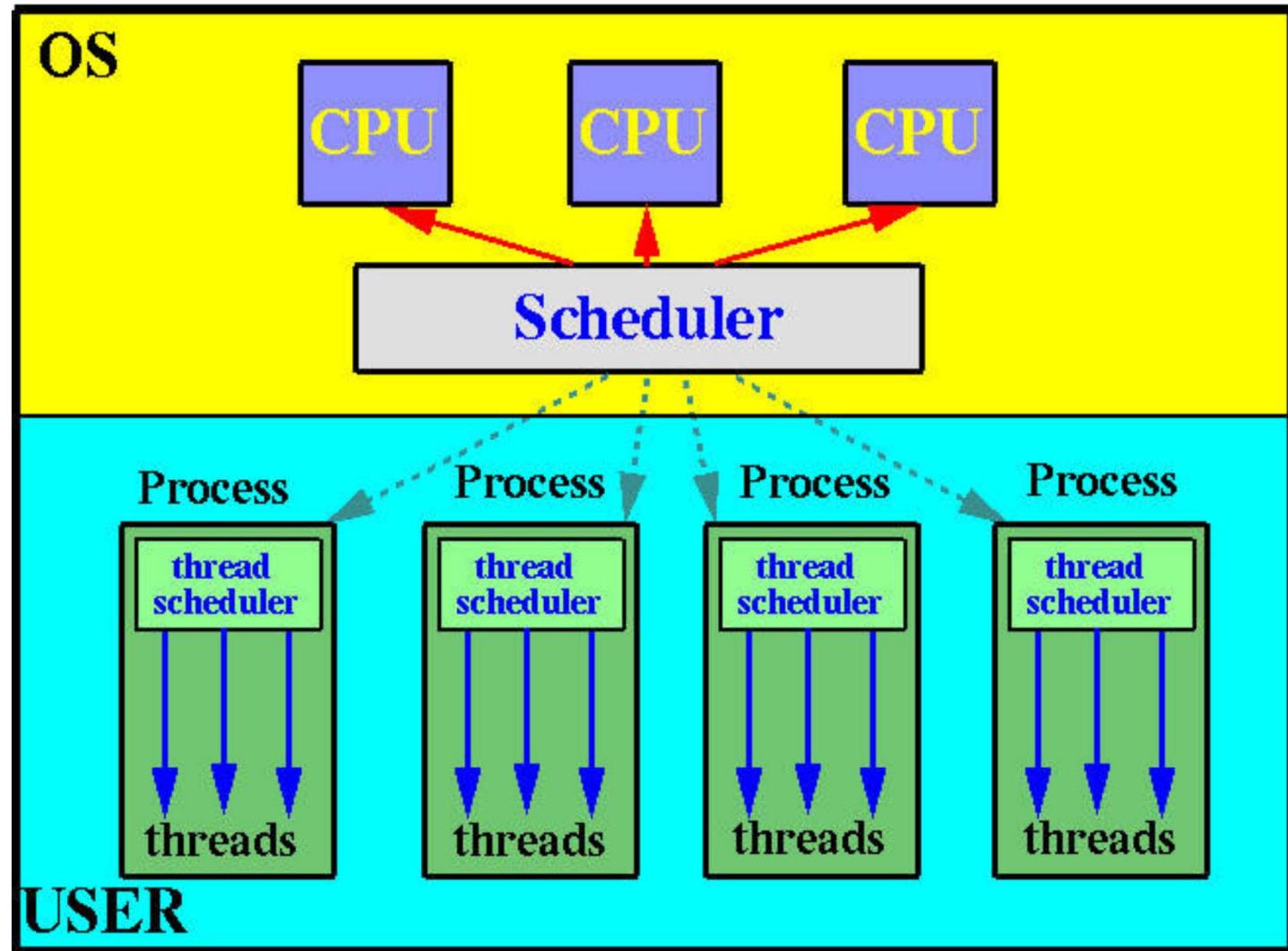


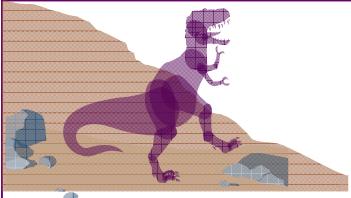
Many-to-One Model





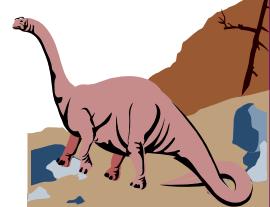
Many-to-One Model (Cont.)

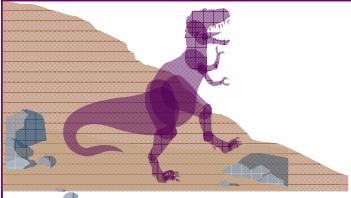




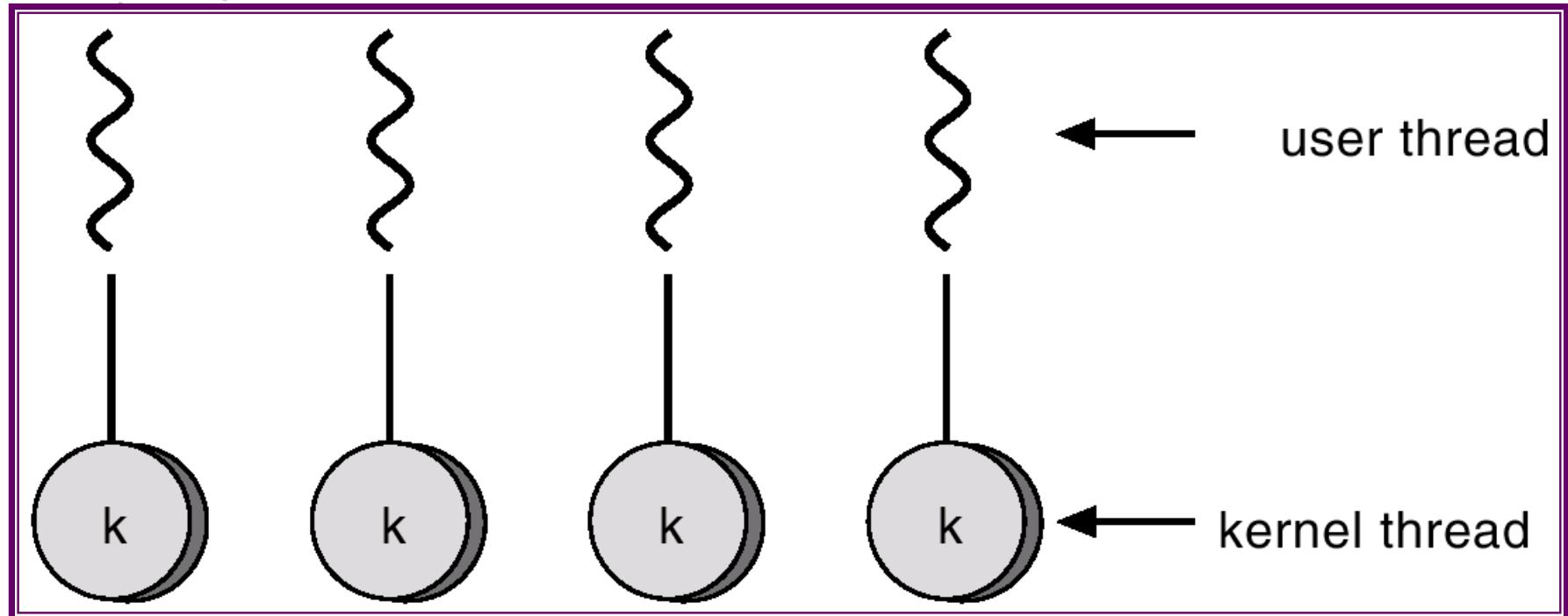
One-to-One

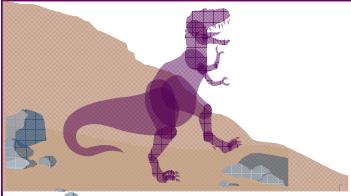
- Each user-level thread maps to kernel thread.
- Examples
 - Windows 95/98/NT/2000
 - OS/2



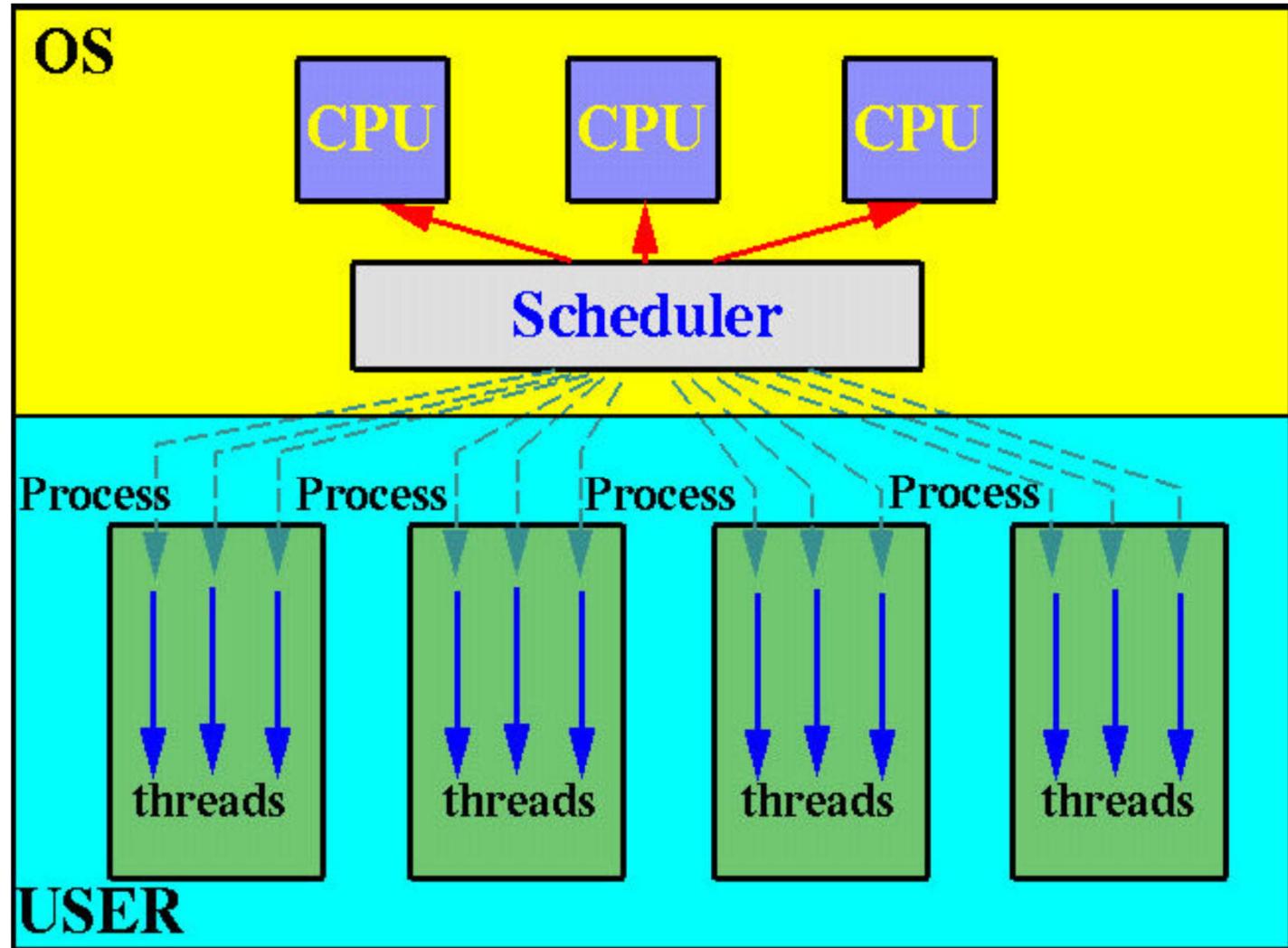


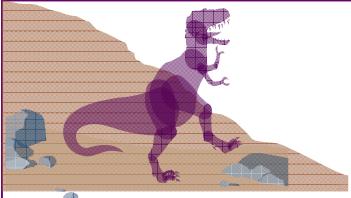
One-to-one Model





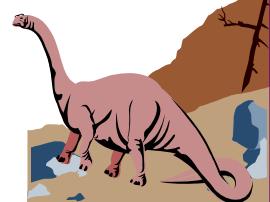
One-to-one Model (Cont.)

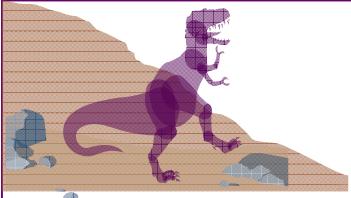




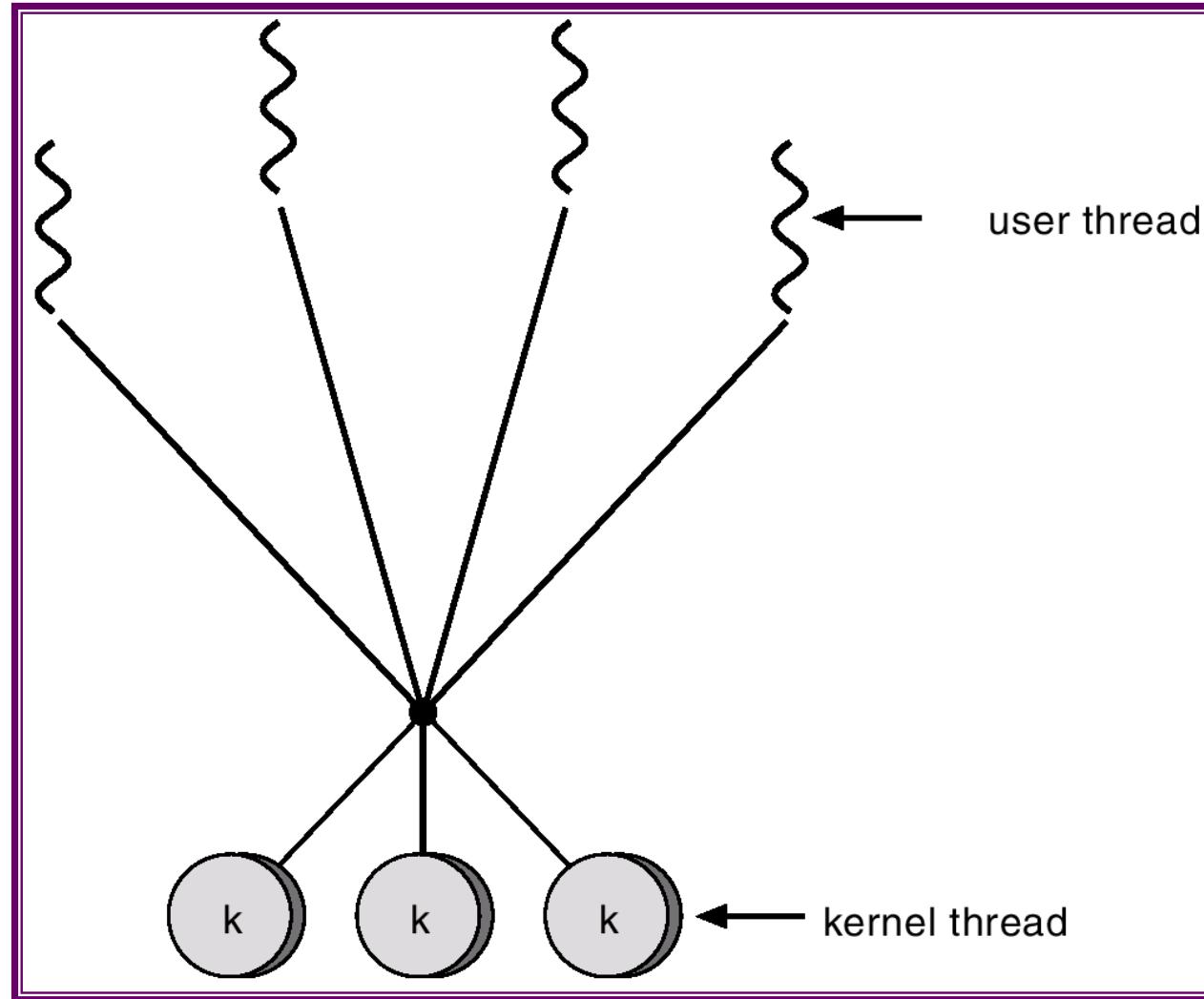
Many-to-Many Model

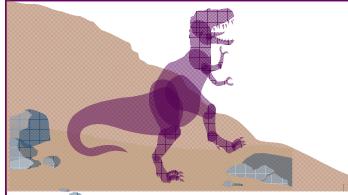
- Allows many user level threads to be mapped to many kernel threads.
- Allows the operating system to create a sufficient number of kernel threads.
- Solaris 2
- Windows NT/2000 with the *ThreadFiber* package



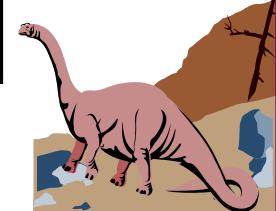
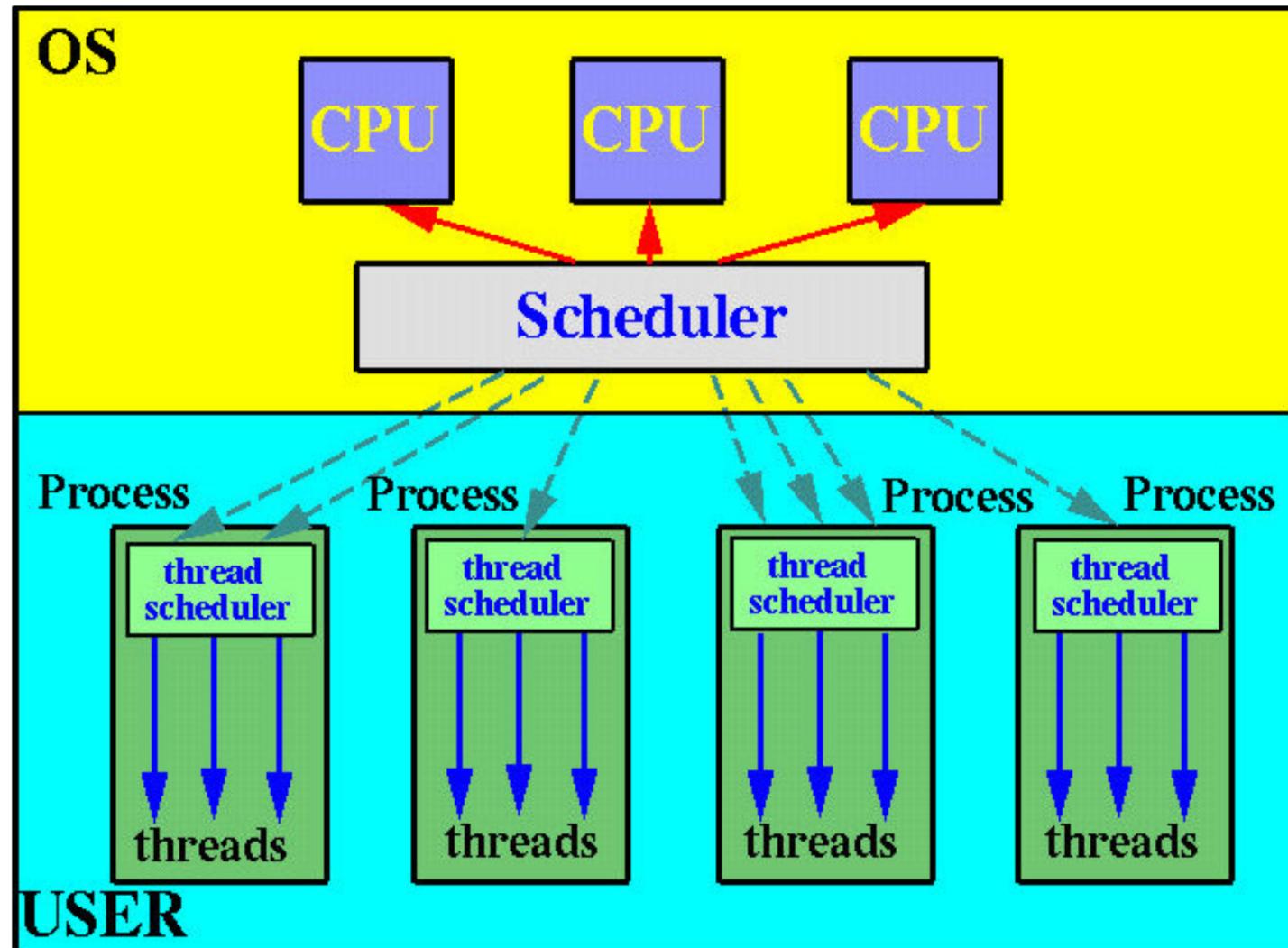


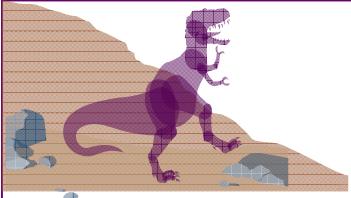
Many-to-Many Model





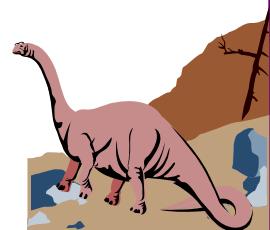
Many-to-Many Model (Cont.)

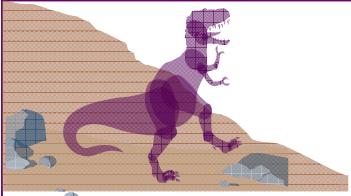




Chapter 4: Threads

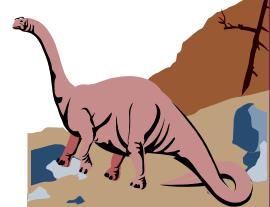
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- Windows Threads API
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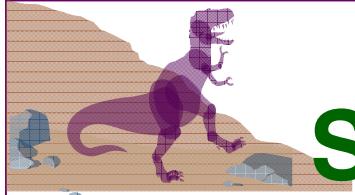




Threading Issues

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

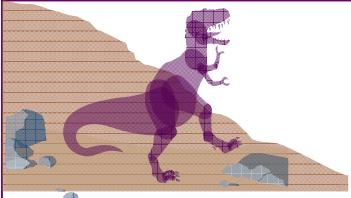




Semantics of fork() and exec()

- 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

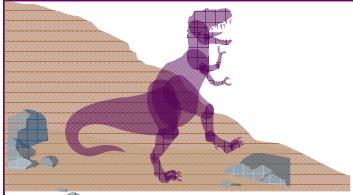




Thread Cancellation

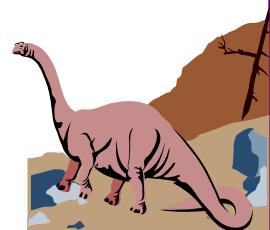
- Terminating a thread before it has finished
- Two general approaches:
 - ◆ **Asynchronous cancellation** terminates the target thread immediately
 - ◆ **Deferred cancellation** allows the target thread to periodically check if it should be cancelled
 - ✓ The point a thread can terminate itself is a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

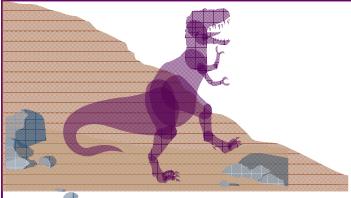




Thread Cancellation (Cont.)

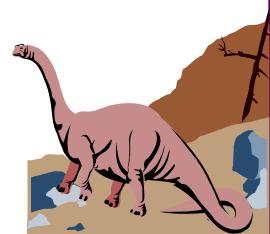
- With **asynchronous cancellation**, if the target thread owns some system-wide resources, the system may not be able to reclaim all resources
- With **deferred cancellation**, the target thread determines the time to terminate itself. Reclaiming resources is not a problem.
- Most systems implement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

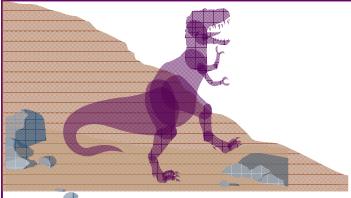




Signal Handling

- **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



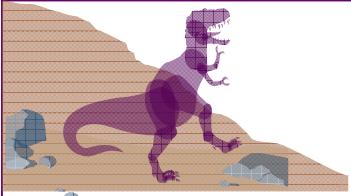


Signal Handling (Cont.)

■ 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

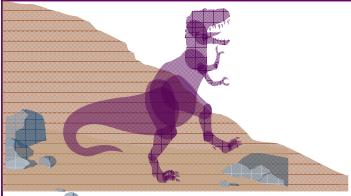




Thread Pools

- 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

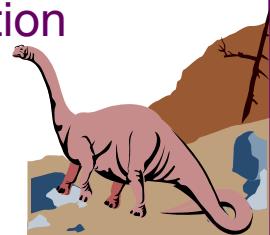


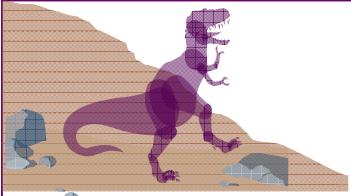


Thread Specific Data

- 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

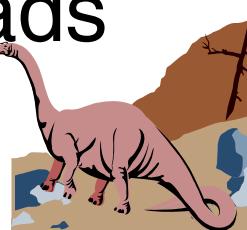
https://en.wikipedia.org/wiki/Thread-local_storage#Pthreads_implementation

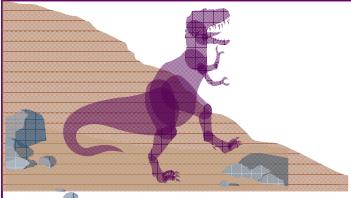




Scheduler Activations

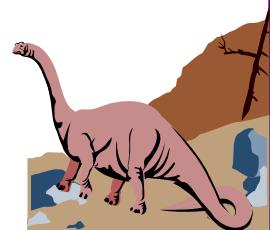
- Both M:M and Two-level models require communication to maintain the appropriate number of kernel threads allocated to the application
- Scheduler activations provide **upcalls** - a communication mechanism from the kernel to the thread library
- This communication allows an application to maintain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

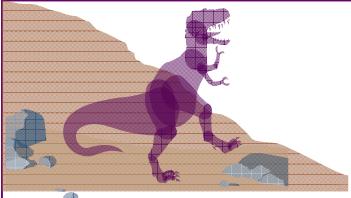




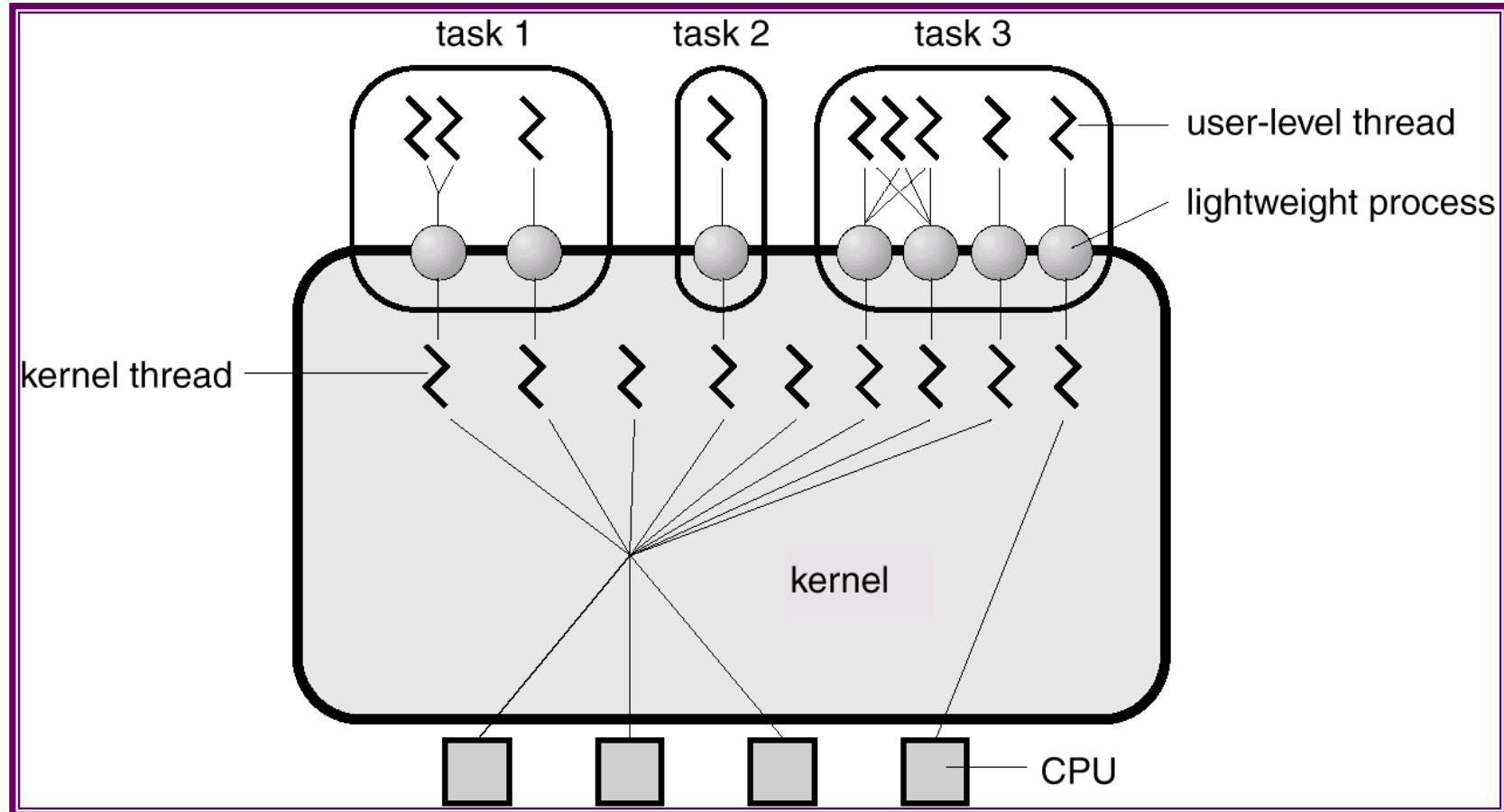
Chapter 4: Threads

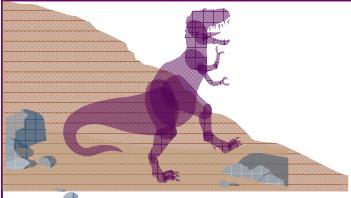
- Overview
- Multithreading Models
- Threading Issues
- Windows XP Threads
- Linux Threads
- Java Threads
- Windows Threads API
- Pthreads



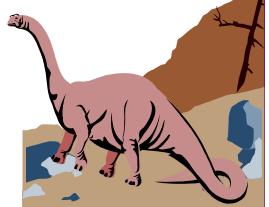
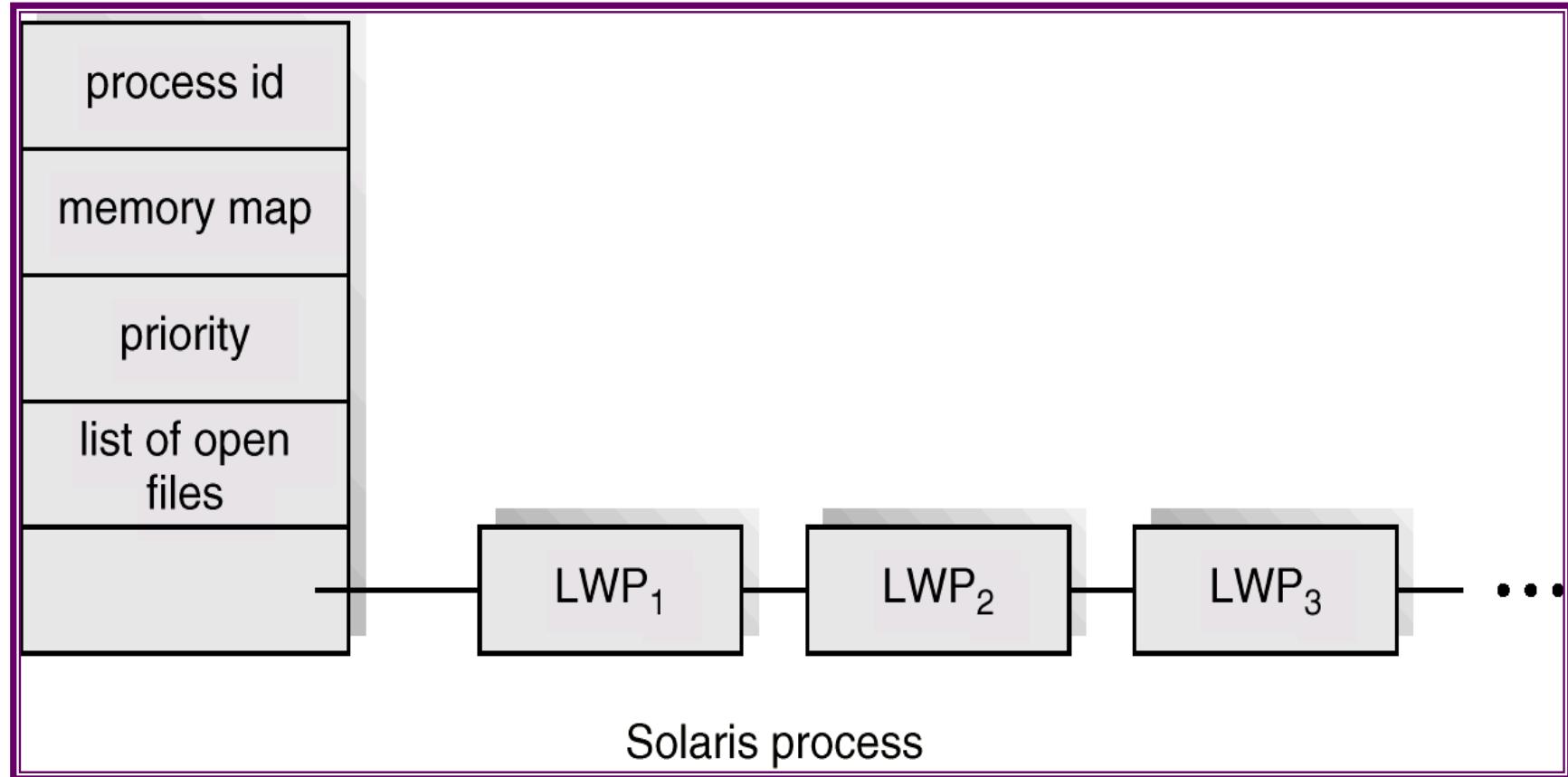


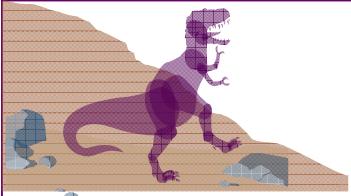
Solaris 2 Threads





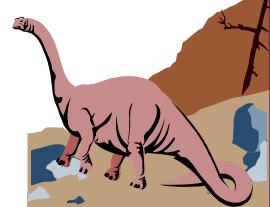
Solaris Process

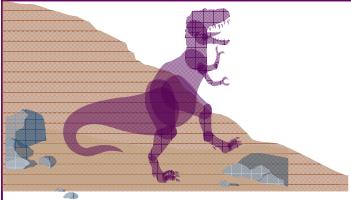




Windows XP Threads

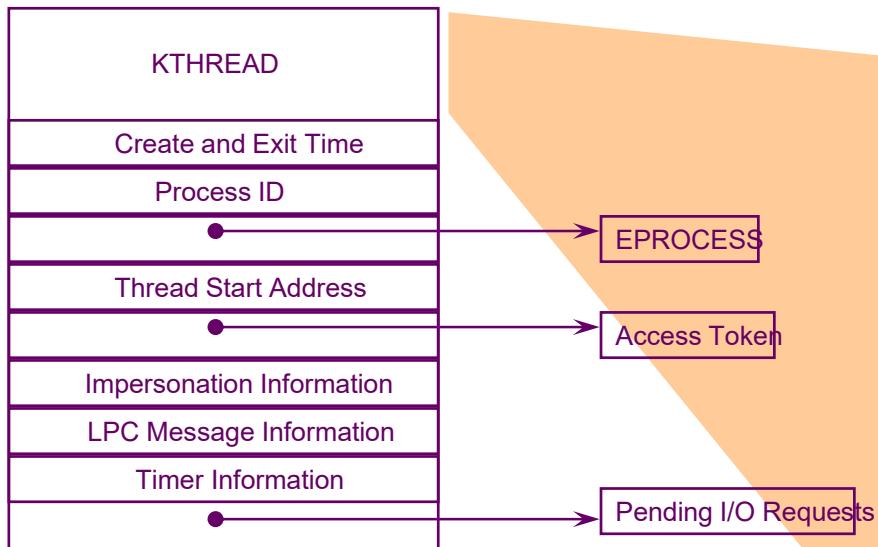
- Implements the one-to-one mapping.
- Each thread contains
 - a thread id
 - register set
 - separate user and kernel stacks
 - private data storage area



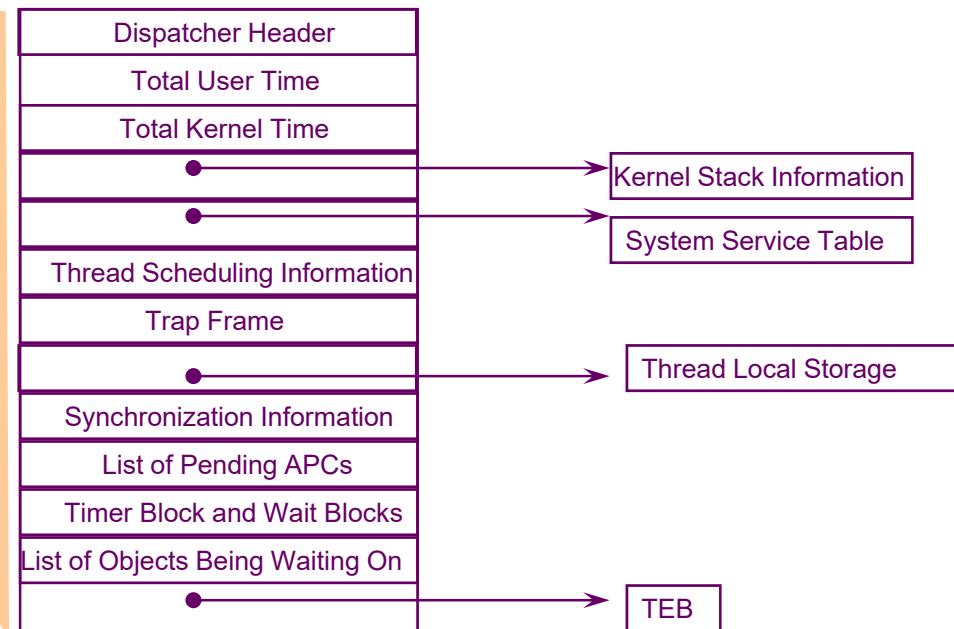


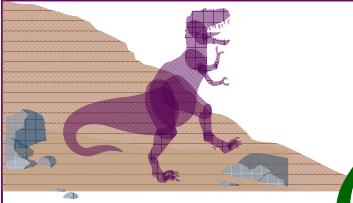
Thread Block

ETHREAD



KTHREAD

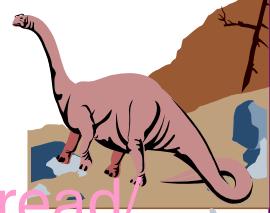


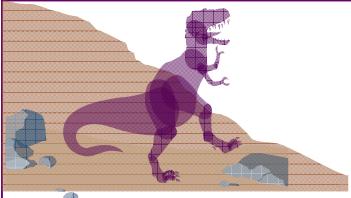


Linux Threads (not POSIX pthreads Library)

- 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>

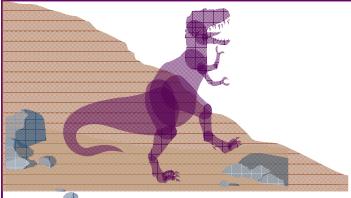




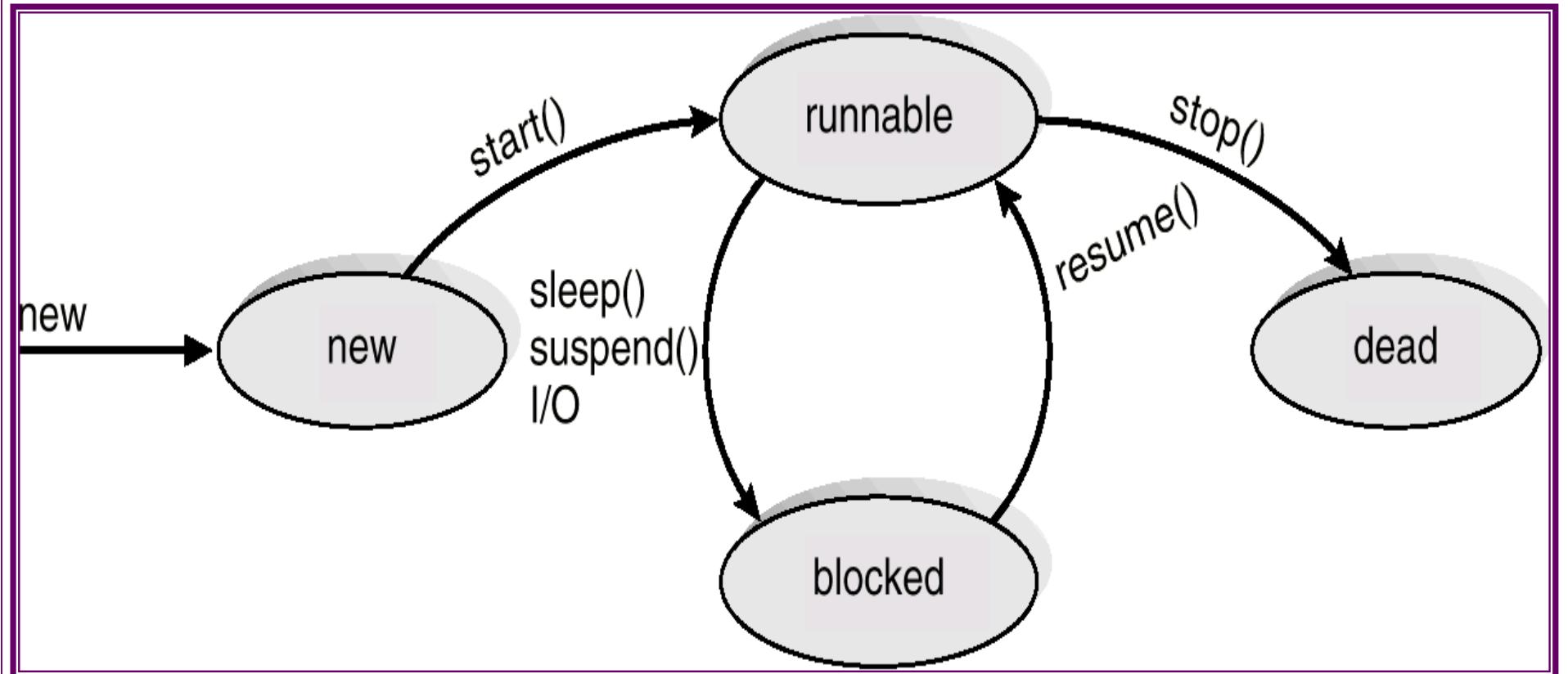
Java Threads

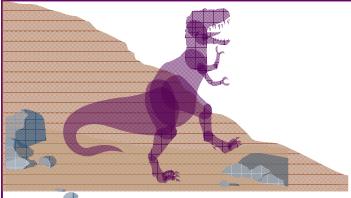
- Java threads may be created by:
 - ◆ Extending Thread class
 - ◆ Implementing the Runnable interface
- Java threads are managed by the JVM.





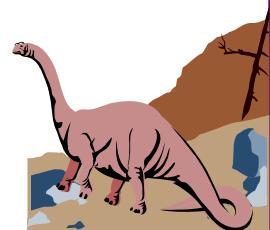
Java Thread States

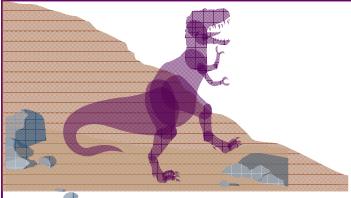




Chapter 4: Threads

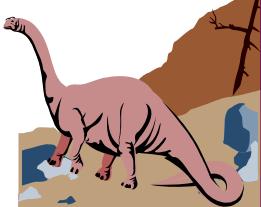
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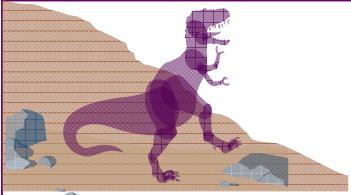




Pthreads

- 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.
- Common in UNIX operating systems.

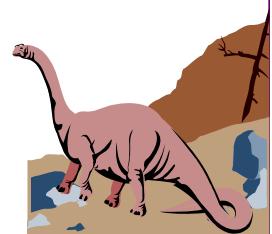


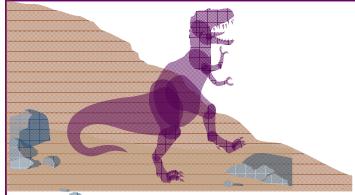


pthread_create

```
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**





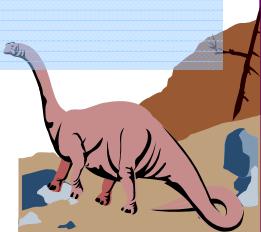
`pthread_create` explained

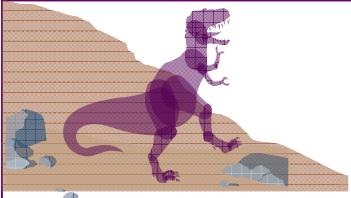
spawn a thread running the function
thread handle returned via `pthread_t` structure

- specify `NULL` to use default attributes
- single argument sent to function
- If no argument to function, specify `NULL`
- check error codes!

EAGAIN – insufficient resources to create thread

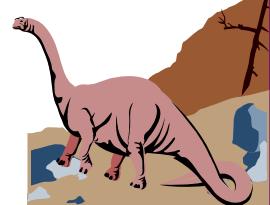
EINVAL – invalid attribute

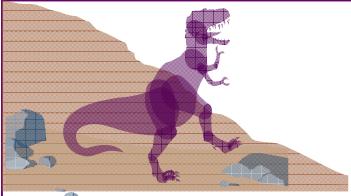




Threads states

- 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*

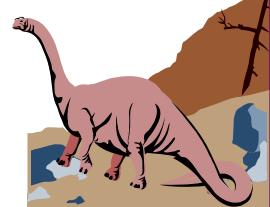


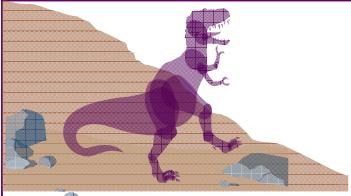


Waiting for a thread

```
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

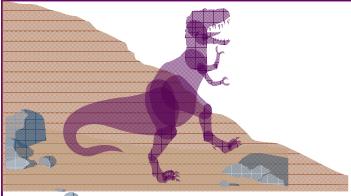
exit value is returned from joined thread

- Type returned is (void *)
- use NULL if no return value expected

ESRCH – thread not found

EINVAL – thread not joinable





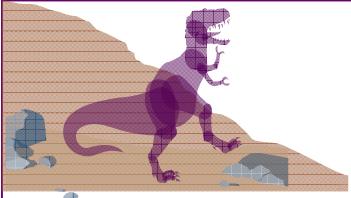
Example: Multiple threads

```
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>

void *print_msg_function( void *ptr );

main()
{
    pthread_t thread1, thread2;
    const char *msg1 = "Thread 1";
    const char *msg2 = "Thread 2";
    int iret1, iret2;
```





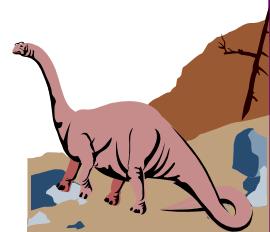
Example: Multiple threads

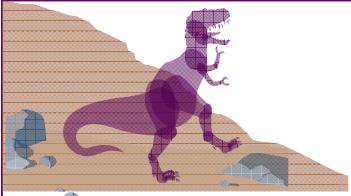
```
iret1 = pthread_create( &thread1, NULL,
                        print_msg_function, (void*) msg1);

if(iret1) {
    fprintf(stderr,"Error - pthread_create() return code:
%d\n",iret1);
    exit(EXIT_FAILURE);
}

iret2 = pthread_create( &thread2, NULL,
                        print_msg_function, (void*) msg2);

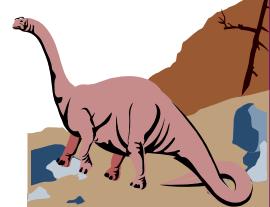
if(iret2) {
    fprintf(stderr,"Error - pthread_create() return code:
%d\n",iret2);
    exit(EXIT_FAILURE);
}
```

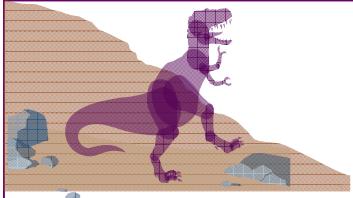




Example: Multiple threads

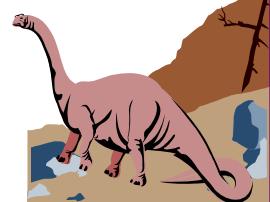
```
printf("pthread_create() for thread 1 returns:  
%d\n",iret1);  
printf("pthread_create() for thread 2 returns:  
%d\n",iret2);  
  
pthread_join( thread1, NULL);  
pthread_join( thread2, NULL);  
printf("main thread exit");  
exit(EXIT_SUCCESS);  
}  
  
void *print_msg_function( void *ptr ) {  
    char *msg;  
    msg = (char *) ptr;  
    printf("%s \n", msg);  
}
```

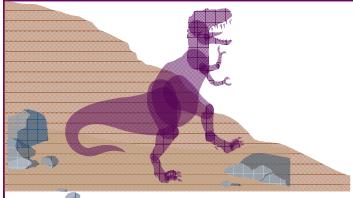




Example: Multiple threads

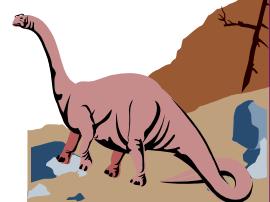
Main Thread	Thread1	Thread2
<code>pthread_create(&thread1);</code>		
<code>pthread_create(&thread2);</code>		
<code>printf("pthread_create() for thread 1");</code>		
<code>printf("pthread_create() for thread 2");</code>		
	<code>printf("Thread 1 \n");</code>	
		<code>printf("Thread 2 \n");</code>
<code>pthread_join(thread1);</code>		
<code>pthread_join(thread2);</code>		
<code>printf("main thread exit");</code>		

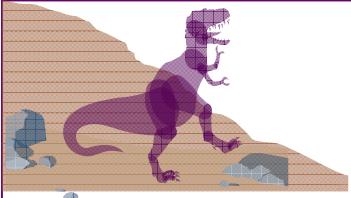




Example: Multiple threads

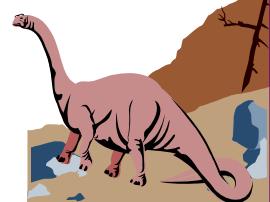
Main Thread	Thread1	Thread2
<code>pthread_create(&thread1);</code>		
	<code>printf("Thread 1 \n");</code>	
<code>pthread_create(&thread2);</code>		
<code>printf("pthread_create() for thread 1");</code>		
<code>printf("pthread_create() for thread 2");</code>		
		<code>printf("Thread 2 \n");</code>
<code>pthread_join(thread1);</code>		
<code>pthread_join(thread2);</code>		
<code>printf("main thread exit");</code>		

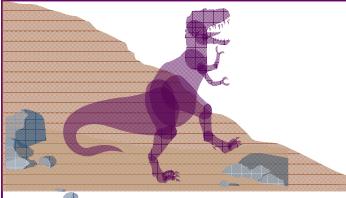




Example: Multiple threads

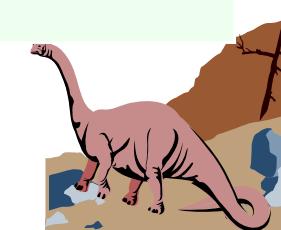
Main Thread	Thread1	Thread2
<code>pthread_create(&thread1);</code>		
<code>pthread_create(&thread2);</code>		
		<code>printf("Thread 2 \n");</code>
<code>printf("pthread_create() for thread 1");</code>		
<code>printf("pthread_create() for thread 2");</code>		
	<code>printf("Thread 1 \n");</code>	
<code>pthread_join(thread1);</code>		
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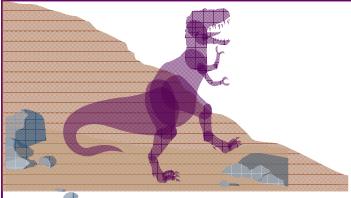




Example: Multiple threads

Main Thread	Thread1	Thread2
<code>pthread_create(&thread1);</code>		
<code>pthread_create(&thread2);</code>		
		<code>printf("Thread 2 \n");</code>
	<code>printf("Thread 1 \n");</code>	
<code>printf("pthread_create() for thread 1");</code>		
<code>printf("pthread_create() for thread 2");</code>		
<code>pthread_join(thread1);</code>		
<code>pthread_join(thread2);</code> <code>printf("main thread exit");</code>		

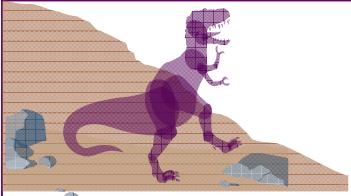




Thread Termination

- `void pthread_exit(void *status);`
 - ◆ terminate the current thread
- `int pthread_cancel(pthread_t thread);`
 - ◆ the thread to be cancelled may:
 - ✓ ignore the request
 - ✓ terminated immediately (Asynchronous cancellation)
 - ✓ deferred terminated (Deferred cancellation)
- `int pthread_kill(pthread_t thread, int sig);`

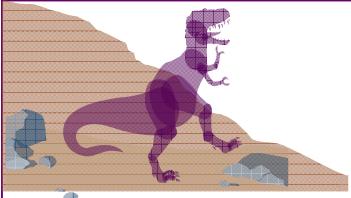




Deferred Cancellation

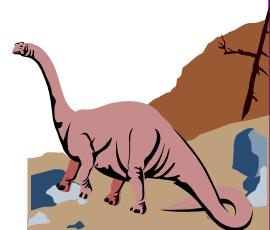
- `int pthread_setcancelstate(int state, int *oldstate);`
 - ◆ set the calling thread's cancelability stat
 - ◆ `PTHREAD_CANCEL_ENABLE`
 - ◆ `PTHREAD_CANCEL_DISABLE`
- `int pthread_setcanceltype(int type, int *oldtype)`
 - ◆ `PTHREAD_CANCEL_ASYNCHROUS`
 - ◆ `PTHREAD_CANCEL_DEFERRED`
- `void pthread_testcancel(void);`
 - ◆ create a cancellation point in the calling thread.

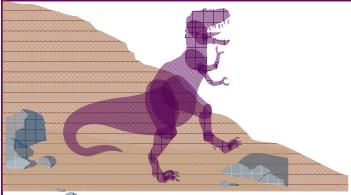




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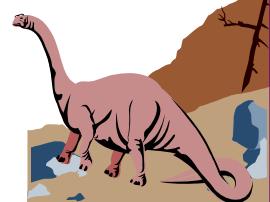


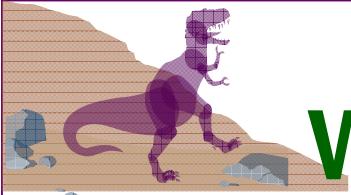


Windows Thread APIs

- CreateThread
- ExitThread
- TerminateThread
- GetExitCodeThread

- GetCurrentThreadId - returns global ID
- GetCurrentThread - returns handle
- SuspendThread/ResumeThread
- GetThreadTimes





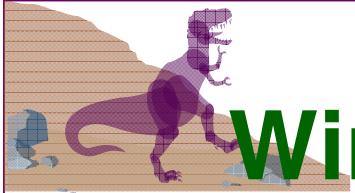
Windows API Thread Creation

```
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-NUL pointer !





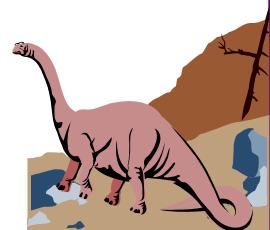
Windows API Thread Termination

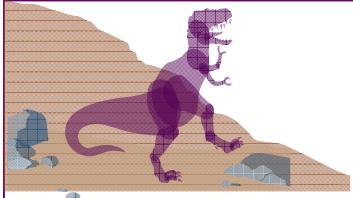
```
VOID ExitThread( DWORD devExitCode )
```

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

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

- Returns exit code or STILL_ACTIVE



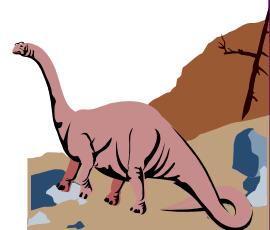


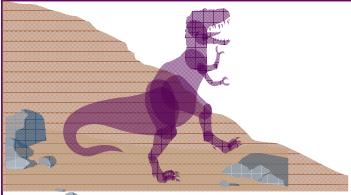
Suspending and Resuming Threads

- 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

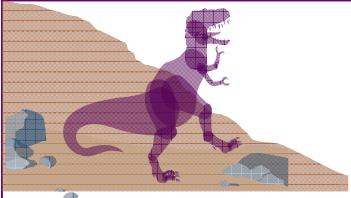
```
#include <stdio.h>
#include <windows.h>

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

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

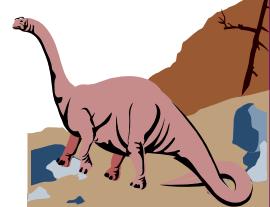
What's Wrong?

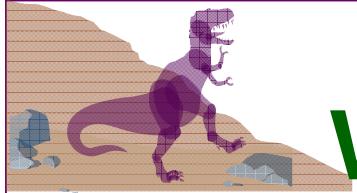




Example Explained

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





Waiting for Windows* Thread

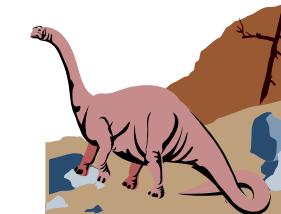
```
#include <stdio.h>
#include <windows.h>
BOOL thrdDone = FALSE;

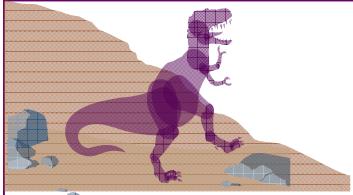
DWORD WINAPI helloFunc(LPVOID arg) {
    printf("Hello Thread\n");
    return 0;
}

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

thrdDone = TRUE;

Not a good idea!





Waiting for a Thread

Wait for one object (thread)

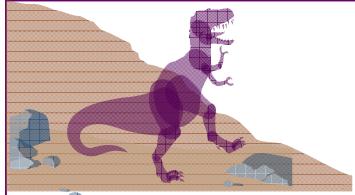
```
DWORD WaitForSingleObject(  
    HANDLE hHandle,  
    DWORD dwMilliseconds );
```

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

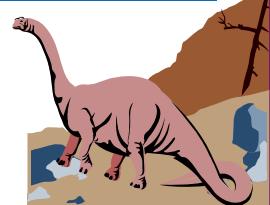
Wait for up to 64 objects (threads)

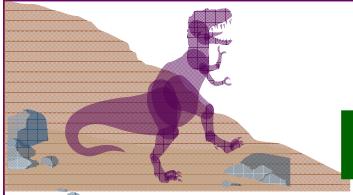
```
DWORD WaitForMultipleObjects(  
    DWORD nCount,  
    CONST HANDLE *lpHandles, // array  
    BOOL fWaitAll, // wait for one or all  
    DWORD dwMilliseconds)
```

Wait for all: **fWaitAll==TRUE**

Wait for any: **fWaitAll==FALSE**

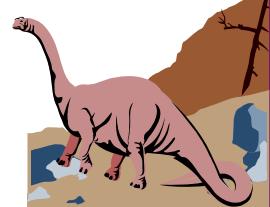
- Return value is first array index found

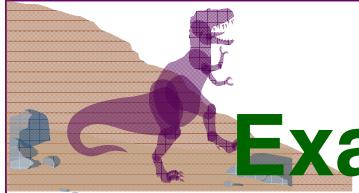




Notes on WaitFor* Functions

- 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





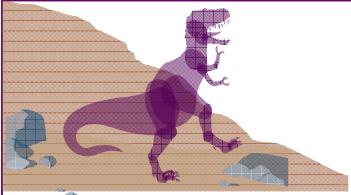
Example: Waiting for multiple threads

```
#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);
}
```



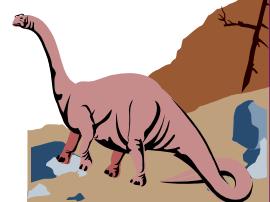


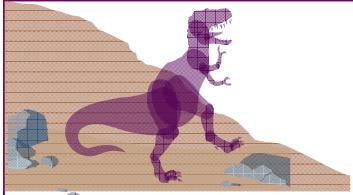
Example: HelloThreads

- 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
```



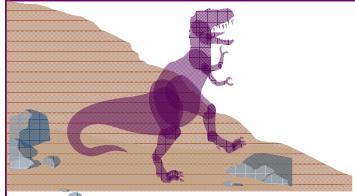


What's Wrong?

```
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?

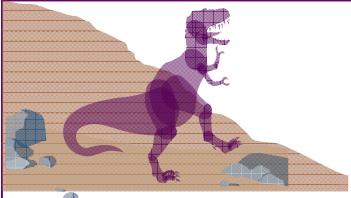




Hello Threads Timeline

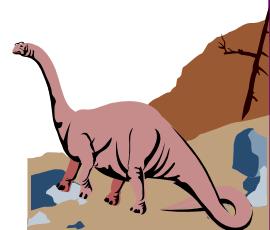
<i>Time</i>	<i>main</i>	<i>Thread 0</i>	<i>Thread 1</i>
T ₀	i = 0	---	----
T ₁	create(&i)	---	---
T ₂	i++ (i == 1)	launch	---
T ₃	create(&i)	p = pArg	---
T ₄	i++ (i == 2)	myNum = *p myNum = 2	launch
T ₅	wait	print(2)	p = pArg
T ₆	wait	exit	myNum = *p myNum = 2

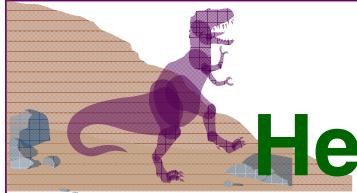




Race Conditions

- 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);
}
```

