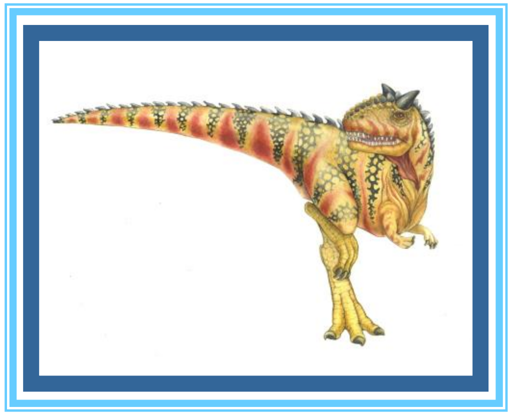
Chapter 4: Threads



Chapter 4: Threads

Objectives

To introduce the notion of a thread—a fundamental unit of CPU utilization that forms the basis of multithreaded computer systems

To discuss the APIs for the Pthreads, Windows, and Java thread libraries

To explore several strategies that provide implicit threading

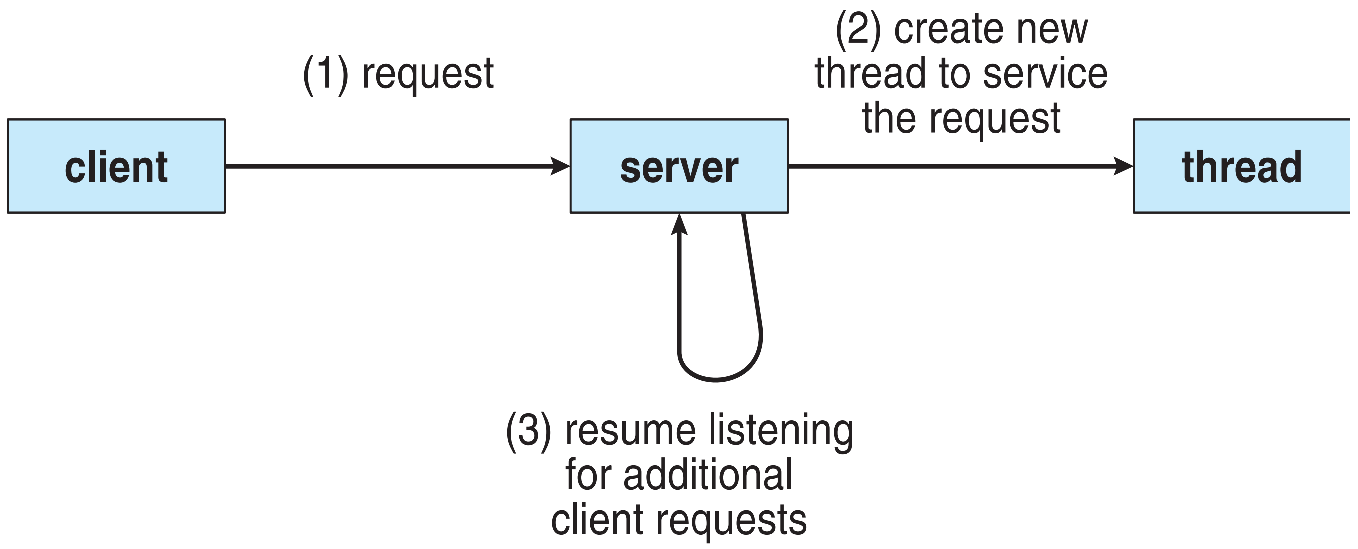
To examine issues related to multithreaded programming

To cover operating system support for threads in Windows and Linux

Motivation

- Most modern applications are multithreaded
- Threads run within application
- Multiple tasks with the application can be implemented by separate threads
  - Update display
  - Fetch data
  - Spell checking
  - Answer a network request
- Process creation is heavy-weight while thread creation is light-weight
- Can simplify code, increase efficiency
- Kernels are generally multithreaded

Multithreaded Server Architecture


(1) request
(2) create new thread to service the request
client
server
thread
(3) resume listening for additional client requests

Benefits

Responsiveness – may allow continued execution if part of process is blocked, especially important for user interfaces

Resource Sharing – threads share resources of process, easier than shared memory or message passing

Economy – cheaper than process creation, thread switching lower overhead than context switching

Scalability – process can take advantage of multiprocessor architectures

Multicore Programming

Multicore or **multiprocessor** systems putting pressure on programmers, challenges include:

- **Dividing activities**
- **Balance**
- **Data splitting**
- **Data dependency**
- **Testing and debugging**

Parallelism implies a system can perform more than one task simultaneously

Concurrency supports more than one task making progress

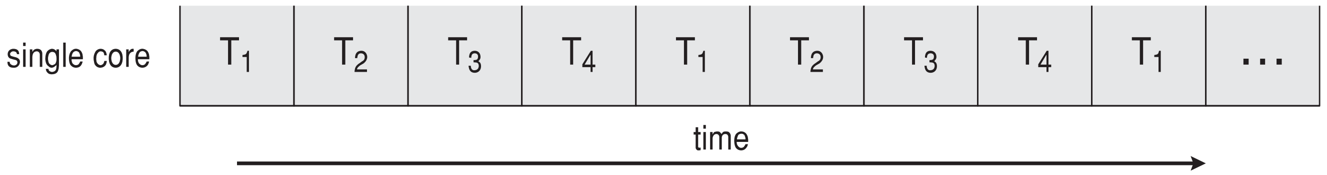
- Single processor / core, scheduler providing concurrency

Multicore Programming (Cont.)

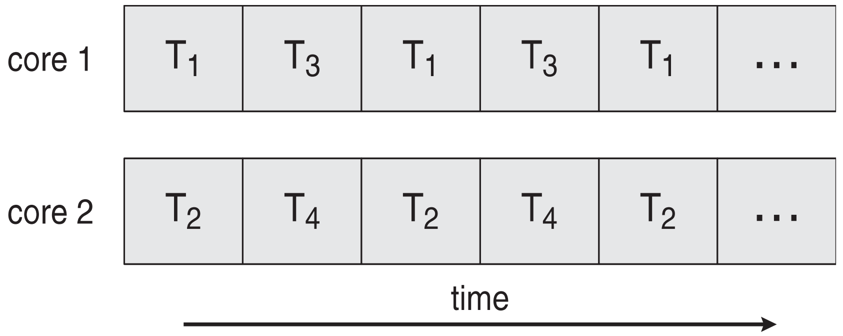
- Types of parallelism
  - **Data parallelism** – distributes subsets of the same data across multiple cores, same operation on each
  - **Task parallelism** – distributing threads across cores, each thread performing unique operation
- As # of threads grows, so does architectural support for threading
  - CPUs have cores as well as ***hardware threads***
  - Consider Oracle SPARC T4 with 8 cores, and 8 hardware threads per core

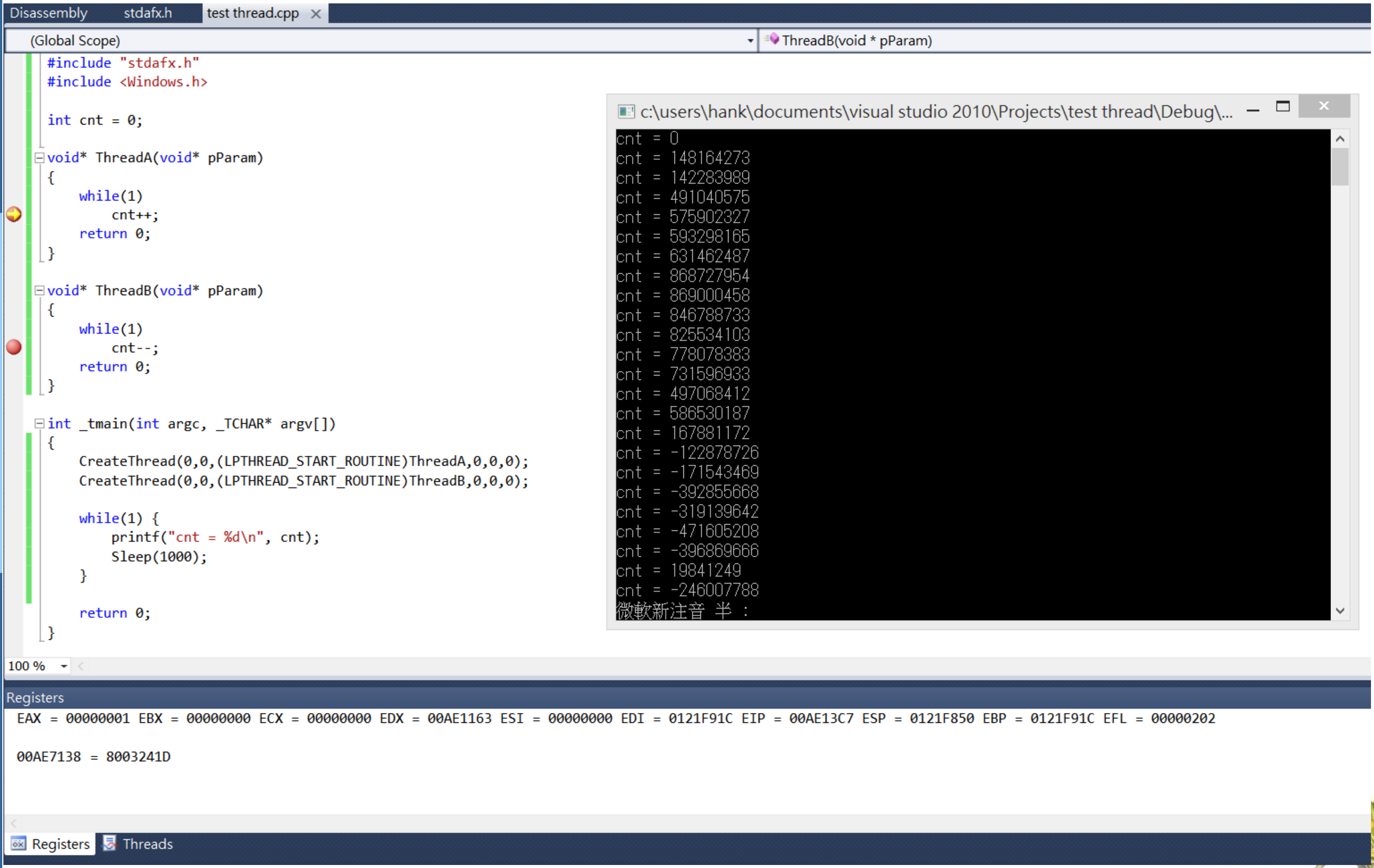
Concurrency vs. Parallelism

Concurrent execution on single-core system:



Parallelism on a multi-core system:



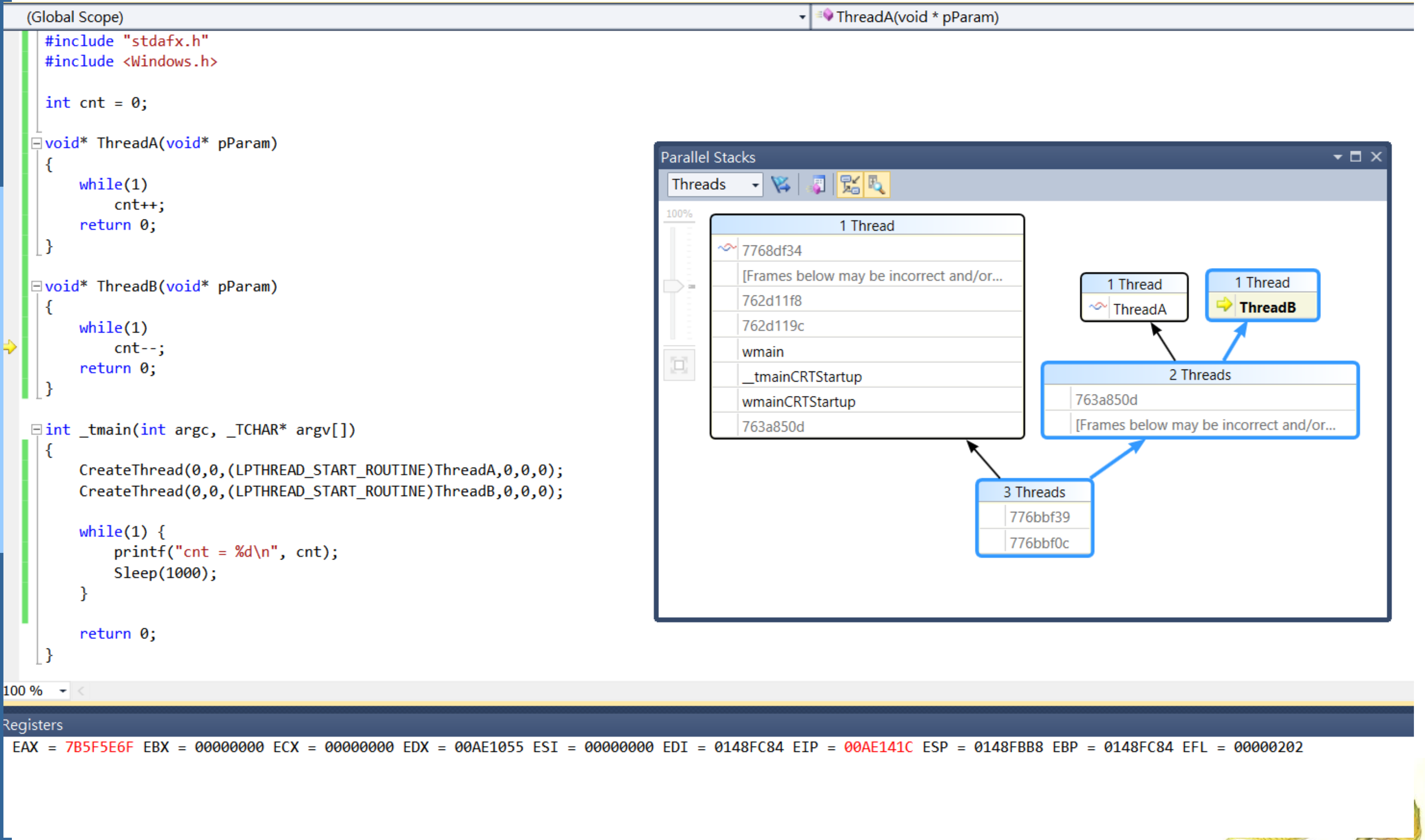


```
#include "stdafx.h"
#include <Windows.h>

int cnt = 0;

void* ThreadA(void* pParam)
{
    while(1)
        cnt++;
    return 0;
}

void* ThreadB(void* pParam)
{
    while(1)
        cnt--;
    return 0;
}

int _tmain(int argc, _TCHAR* argv[])
{
    CreateThread(0,0,(LPTHREAD_START_ROUTINE)ThreadA,0,0,0);
    CreateThread(0,0,(LPTHREAD_START_ROUTINE)ThreadB,0,0,0);

    while(1) {
        printf("cnt = %d\n", cnt);
        Sleep(1000);
    }

    return 0;
}
```

c:\users\hank\documents\visual studio 2010\Projects\test thread\Debug\...

```
cnt = 0
cnt = 148164273
cnt = 142283989
cnt = 491040575
cnt = 575902327
cnt = 593298165
cnt = 631462487
cnt = 868727954
cnt = 869000458
cnt = 846788733
cnt = 825534103
cnt = 778078383
cnt = 731596933
cnt = 497068412
cnt = 586530187
cnt = 167881172
cnt = -122878726
cnt = -171543469
cnt = -392855668
cnt = -319139642
cnt = -471605208
cnt = -396869666
cnt = 19841249
cnt = -246007788
微軟新注音 半 :
```

```
EAX = 00000001 EBX = 00000000 ECX = 00000000 EDX = 00AE1163 ESI = 00000000 EDI = 0121F91C EIP = 00AE13C7 ESP = 0121F850 EBP = 0121F91C EFL = 00000202

00AE7138 = 8003241D
```



```
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#include <Windows.h>

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{
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        cnt++;
    return 0;
}

void* ThreadB(void* pParam)
{
    while(1)
        cnt--;
    return 0;
}

int _tmain(int argc, _TCHAR* argv[])
{
    CreateThread(0,0,(LPTHREAD_START_ROUTINE)ThreadA,0,0,0);
    CreateThread(0,0,(LPTHREAD_START_ROUTINE)ThreadB,0,0,0);

    while(1) {
        printf("cnt = %d\n", cnt);
        Sleep(1000);
    }

    return 0;
}
```
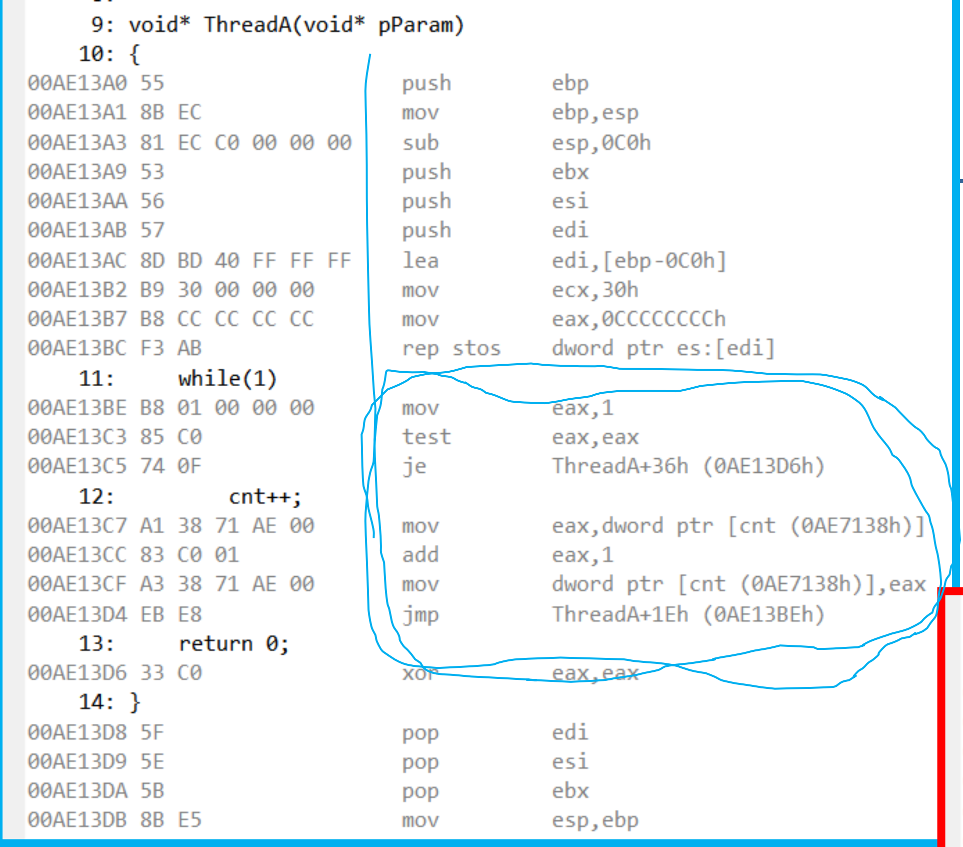
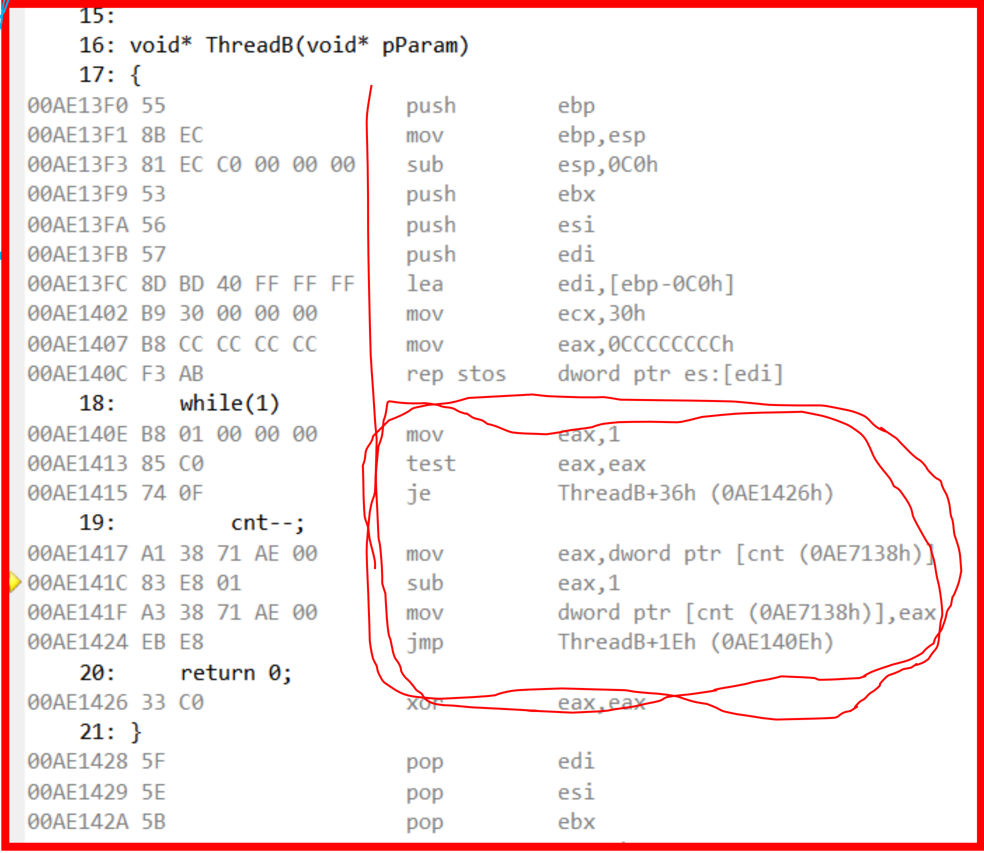

```
EAX = 7B5F5E6F EBX = 00000000 ECX = 00000000 EDX = 00AE1055 ESI = 00000000 EDI = 0148FC84 EIP = 00AE141C ESP = 0148FBB8 EBP = 0148FC84 EFL = 00000202
```

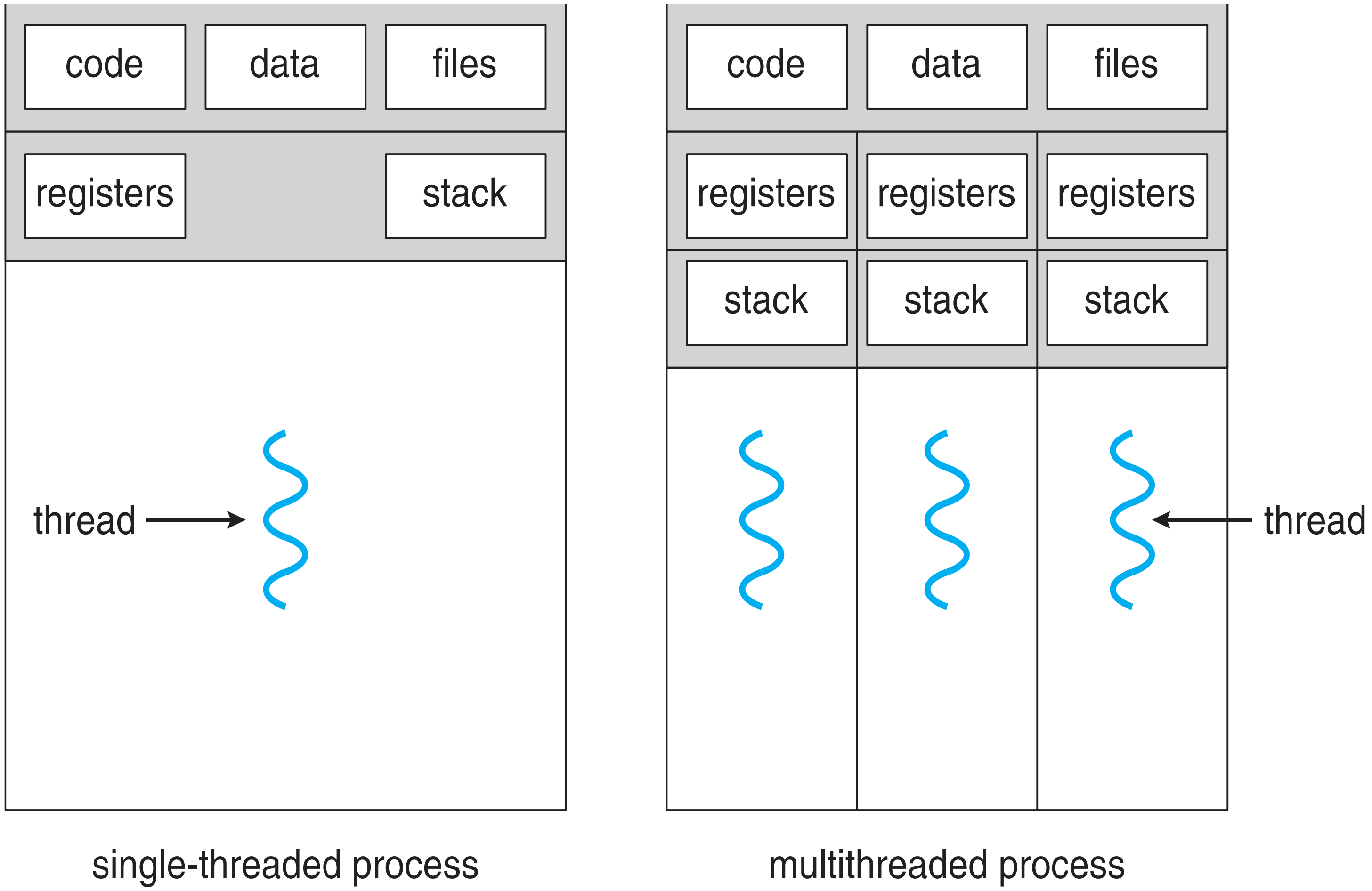


```
    9:  void* ThreadA(void* pParam)
   10:  {
00AE13A0 55                  push        ebp
00AE13A1 8B EC               mov         ebp,esp
00AE13A3 81 EC C0 00 00 00   sub         esp,0C0h
00AE13A9 53                  push        ebx
00AE13AA 56                  push        esi
00AE13AB 57                  push        edi
00AE13AC 8D BD 40 FF FF FF   lea         edi,[ebp-0C0h]
00AE13B2 B9 30 00 00 00      mov         ecx,30h
00AE13B7 B8 CC CC CC CC      mov         eax,0CCCCCCCCh
00AE13BC F3 AB               rep stos    dword ptr es:[edi]
   11:      while(1)
00AE13BE B8 01 00 00 00      mov         eax,1
00AE13C3 85 C0               test        eax,eax
00AE13C5 74 0F               je          ThreadA+36h (0AE13D6h)
   12:          cnt++;
00AE13C7 A1 38 71 AE 00      mov         eax,dword ptr [cnt (0AE7138h)]
00AE13CC 83 C0 01            add         eax,1
00AE13CF A3 38 71 AE 00      mov         dword ptr [cnt (0AE7138h)],eax
00AE13D4 EB E8               jmp         ThreadA+1Eh (0AE13BEh)
   13:      return 0;
00AE13D6 33 C0               xor         eax,eax
   14:  }
00AE13D8 5F                  pop         edi
00AE13D9 5E                  pop         esi
00AE13DA 5B                  pop         ebx
00AE13DB 8B E5               mov         esp,ebp
```



```
   15:
   16:  void* ThreadB(void* pParam)
   17:  {
00AE13F0 55                  push        ebp
00AE13F1 8B EC               mov         ebp,esp
00AE13F3 81 EC C0 00 00 00   sub         esp,0C0h
00AE13F9 53                  push        ebx
00AE13FA 56                  push        esi
00AE13FB 57                  push        edi
00AE13FC 8D BD 40 FF FF FF   lea         edi,[ebp-0C0h]
00AE1402 B9 30 00 00 00      mov         ecx,30h
00AE1407 B8 CC CC CC CC      mov         eax,0CCCCCCCCh
00AE140C F3 AB               rep stos    dword ptr es:[edi]
   18:      while(1)
00AE140E B8 01 00 00 00      mov         eax,1
00AE1413 85 C0               test        eax,eax
00AE1415 74 0F               je          ThreadB+36h (0AE1426h)
   19:          cnt--;
00AE1417 A1 38 71 AE 00      mov         eax,dword ptr [cnt (0AE7138h)]
00AE141C 83 E8 01            sub         eax,1
00AE141F A3 38 71 AE 00      mov         dword ptr [cnt (0AE7138h)],eax
00AE1424 EB E8               jmp         ThreadB+1Eh (0AE140Eh)
   20:      return 0;
00AE1426 33 C0               xor         eax,eax
   21:  }
00AE1428 5F                  pop         edi
00AE1429 5E                  pop         esi
00AE142A 5B                  pop         ebx
```

Single and Multithreaded Processes



Amdahl's Law

Identifies performance gains from adding additional cores to an application that has both serial and parallel components

S is serial portion

N processing cores

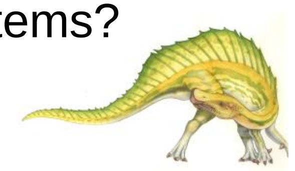
$$speedup \leq \frac{1}{S + \frac{(1-S)}{N}}$$

That is, if application is 75% parallel / 25% serial, moving from 1 to 2 cores results in speedup of 1.6 times

As *N* approaches infinity, speedup approaches 1 / *S*

Serial portion of an application has disproportionate effect on performance gained by adding additional cores

But does the law take into account contemporary multicore systems?



User Threads and Kernel Threads

User threads - management done by user-level threads library

Three primary thread libraries:

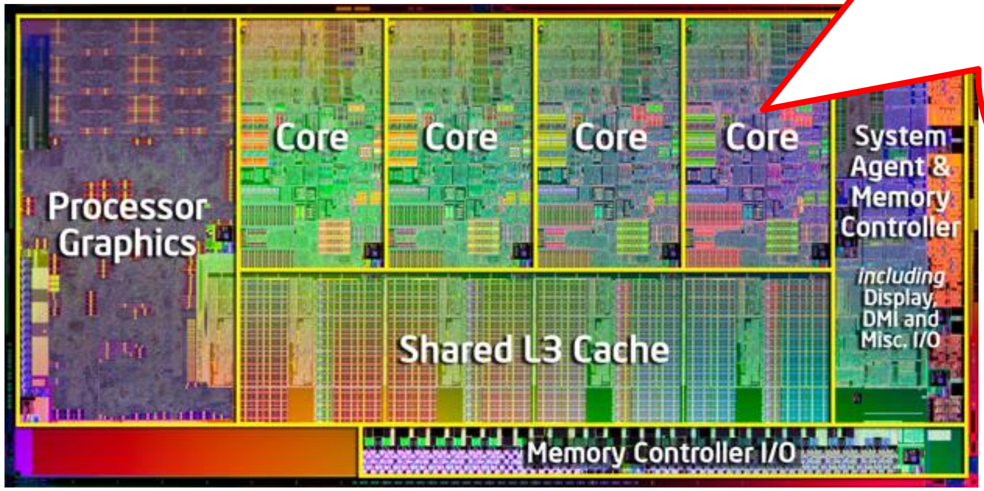
- POSIX **Pthreads**
- Windows threads
- Java threads

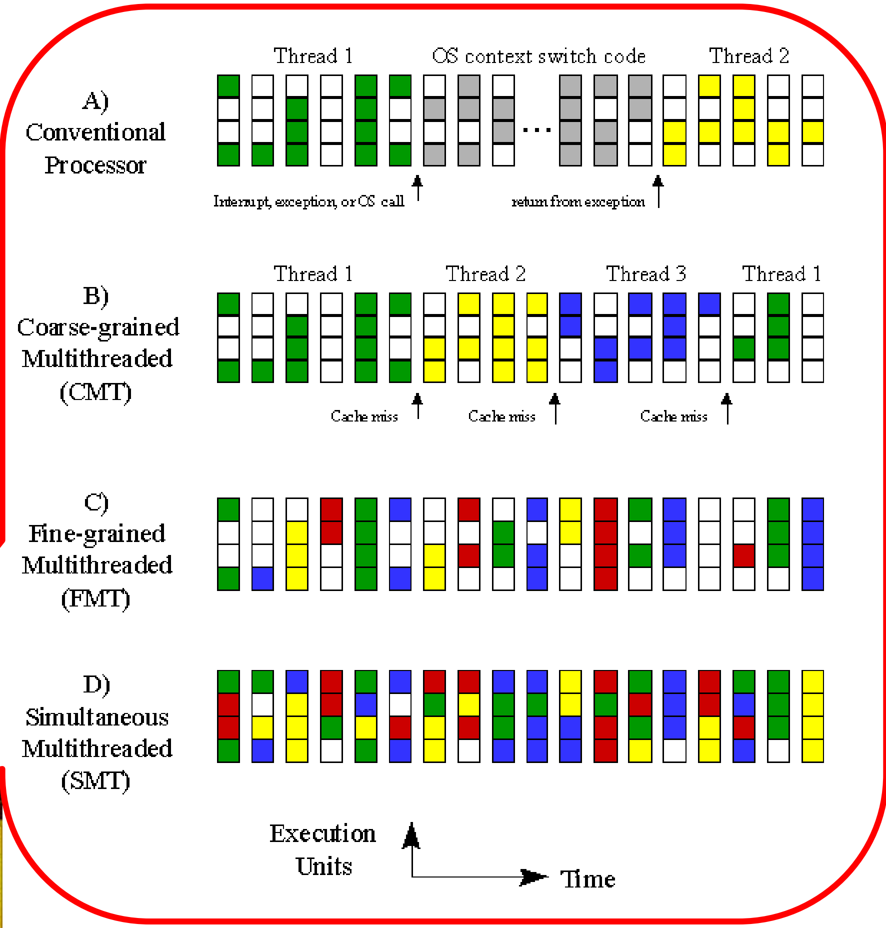
Kernel threads - Supported by the Kernel

Examples – virtually all general purpose operating systems, including:

- Windows
- Solaris
- Linux
- Tru64 UNIX
- Mac OS X

Hardware Threads




A) Conventional Processor
Thread 1
OS context switch code
Thread 2
Interrupt, exception, or OS call
return from exception
B) Coarse-grained Multithreaded (CMT)
Thread 1
Thread 2
Thread 3
Thread 1
Cache miss
Cache miss
Cache miss
C) Fine-grained Multithreaded (FMT)
D) Simultaneous Multithreaded (SMT)
Execution Units
Time

Multithreading Models

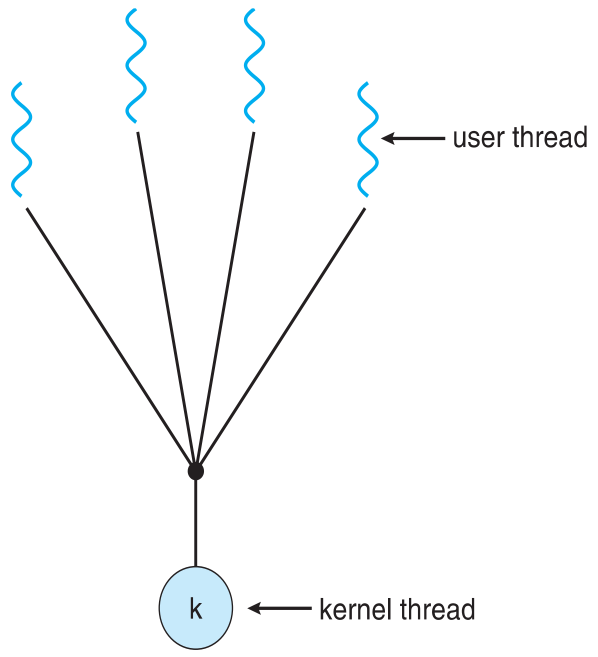
Many-to-One

One-to-One

Many-to-Many

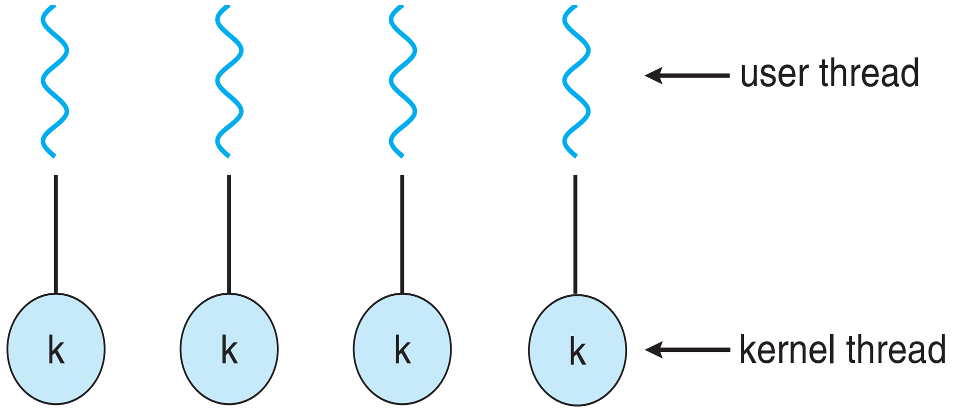
Many-to-One

- Many user-level threads mapped to single kernel thread
- One thread blocking causes all to block
- Multiple threads may not run in parallel on muticore system because only one may be in kernel at a time
- Few systems currently use this model
- Examples:
  - **Solaris Green Threads**
  - **GNU Portable Threads**



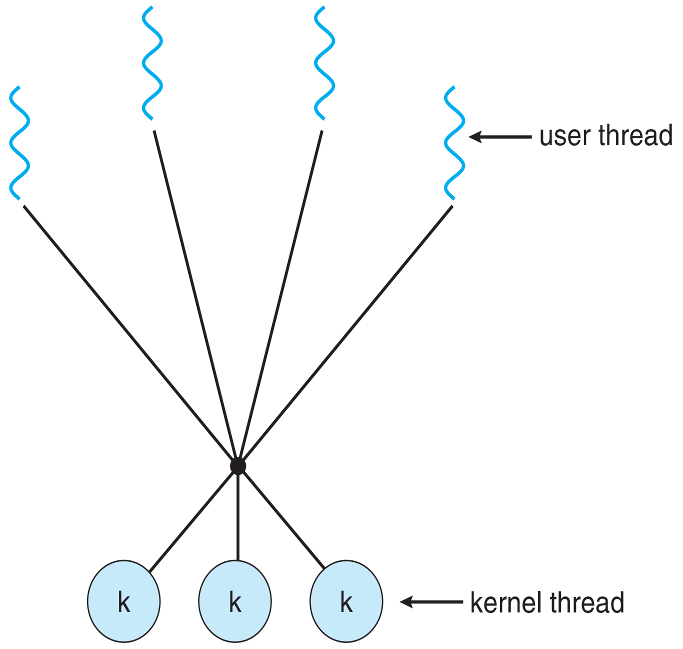
One-to-One

- Each user-level thread maps to kernel thread
- Creating a user-level thread creates a kernel thread
- More concurrency than many-to-one
- Number of threads per process sometimes restricted due to overhead
- Examples
  - Windows
  - Linux
  - Solaris 9 and later



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 prior to version 9
- Windows with the *ThreadFiber* package

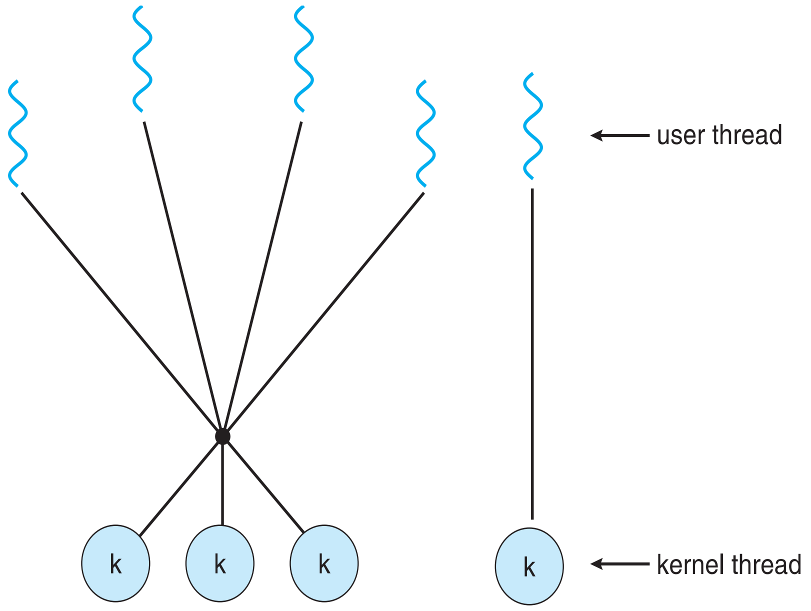


Two-level Model

Similar to M:M, except that it allows a user thread to be **bound** to kernel thread

Examples

- IRIX
- HP-UX
- Tru64 UNIX
- Solaris 8 and earlier



Thread Libraries

- **Thread library** provides programmer with API for creating and managing threads
- Two primary ways of implementing
  - Library entirely in user space
  - Kernel-level library supported by the OS

Pthreads

May be provided either as user-level or kernel-level

A POSIX standard (IEEE 1003.1c) API for thread creation and synchronization

Specification, not ***implementation***

API specifies behavior of the thread library, implementation is up to development of the library

Common in UNIX operating systems (Solaris, Linux, Mac OS X)

Pthreads Example

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

int sum; /* this data is shared by the thread(s) */
void *runner(void *param); /* threads call this function */

int main(int argc, char *argv[])
{
   pthread_t tid; /* the thread identifier */
   pthread_attr_t attr; /* set of thread attributes */

   if (argc != 2) {
      fprintf(stderr,"usage: a.out <integer value>\n");
      return -1;
   }
   if (atoi(argv[1]) < 0) {
      fprintf(stderr,"%d must be >= 0\n",atoi(argv[1]));
      return -1;
   }
```

Pthreads Example (Cont.)

```
   /* get the default attributes */
   pthread_attr_init(&attr);
   /* create the thread */
   pthread_create(&tid,&attr,runner,argv[1]);
   /* wait for the thread to exit */
   pthread_join(tid,NULL);

   printf("sum = %d\n",sum);
}

/* The thread will begin control in this function */
void *runner(void *param)
{
   int i, upper = atoi(param);
   sum = 0;

   for (i = 1; i <= upper; i++)
      sum += i;

   pthread_exit(0);
}
```

Pthreads Code for Joining 10 Threads

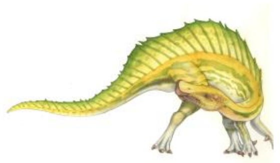
```
#define NUM_THREADS 10

/* an array of threads to be joined upon */
pthread_t workers[NUM_THREADS];

for (int i = 0; i < NUM_THREADS; i++)
   pthread_join(workers[i], NULL);
```

Windows Multithreaded C Program

```
#include <windows.h>
#include <stdio.h>
DWORD Sum; /* data is shared by the thread(s) */

/* the thread runs in this separate function */
DWORD WINAPI Summation(LPVOID Param)
{
   DWORD Upper = *(DWORD*)Param;
   for (DWORD i = 0; i <= Upper; i++)
      Sum += i;
   return 0;
}

int main(int argc, char *argv[])
{
   DWORD ThreadId;
   HANDLE ThreadHandle;
   int Param;

   if (argc != 2) {
      fprintf(stderr,"An integer parameter is required\n");
      return -1;
   }
   Param = atoi(argv[1]);
   if (Param < 0) {
      fprintf(stderr,"An integer >= 0 is required\n");
      return -1;
   }
```

Windows Multithreaded C Program (Cont.)

```
    /* create the thread */
    ThreadHandle = CreateThread(
      NULL, /* default security attributes */
      0, /* default stack size */
      Summation, /* thread function */
      &Param, /* parameter to thread function */
      0, /* default creation flags */
      &ThreadId); /* returns the thread identifier */

    if (ThreadHandle != NULL) {
       /* now wait for the thread to finish */
      WaitForSingleObject(ThreadHandle,INFINITE);

      /* close the thread handle */
      CloseHandle(ThreadHandle);

      printf("sum = %d\n",Sum);
    }
}
```



Java Threads

Java threads are managed by the JVM

Typically implemented using the threads model provided by underlying OS

Java threads may be created by:

```
public interface Runnable
{
    public abstract void run();
}
```

Extending Thread class

Implementing the Runnable interface

Java Multithreaded Program

```
class Sum
{
  private int sum;

  public int getSum() {
   return sum;
  }

  public void setSum(int sum) {
   this.sum = sum;
  }
}

class Summation implements Runnable
{
  private int upper;
  private Sum sumValue;

  public Summation(int upper, Sum sumValue) {
   this.upper = upper;
   this.sumValue = sumValue;
  }

  public void run() {
   int sum = 0;
   for (int i = 0; i <= upper; i++)
      sum += i;
   sumValue.setSum(sum);
  }
}
```

Java Multithreaded Program (Cont.)

```
public class Driver
{
   public static void main(String[] args) {
     if (args.length > 0) {
       if (Integer.parseInt(args[0]) < 0)
        System.err.println(args[0] + " must be >= 0.");
       else {
        Sum sumObject = new Sum();
        int upper = Integer.parseInt(args[0]);
        Thread thrd = new Thread(new Summation(upper, sumObject));
        thrd.start();
        try {
           thrd.join();
           System.out.println
                    ("The sum of "+upper+" is "+sumObject.getSum());
       } catch (InterruptedException ie) { }
       }
     }
     else
       System.err.println("Usage: Summation <integer value>"); }
}
```

Implicit Threading

- Growing in popularity as numbers of threads increase, program correctness more difficult with explicit threads
- Creation and management of threads done by compilers and run-time libraries rather than programmers
- Three methods explored
  - Thread Pools
  - OpenMP
  - Grand Central Dispatch
- Other methods include Microsoft Threading Building Blocks (TBB), **`java.util.concurrent`** package

Thread Pools

- Create a number of threads 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
  - Separating task to be performed from mechanics of creating task allows different strategies for running task
    - i.e.Tasks could be scheduled to run periodically
- Windows API supports thread pools:

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

OpenMP

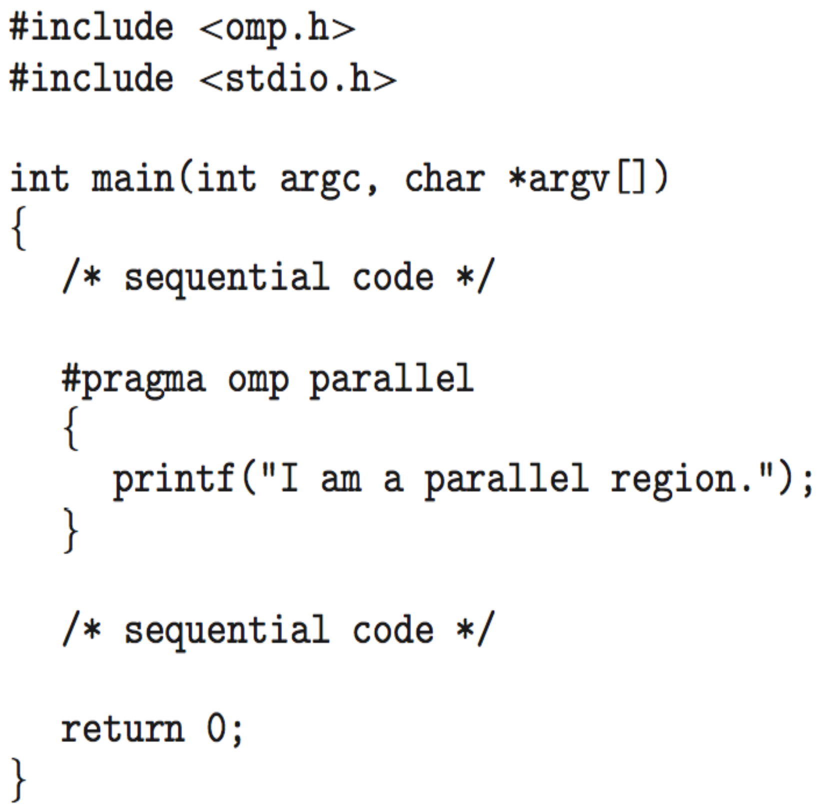
- Set of compiler directives and an API for C, C++, FORTRAN
- Provides support for parallel programming in shared-memory environments
- Identifies **parallel regions** – blocks of code that can run in parallel

`#pragma omp parallel`

Create as many threads as there are cores

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

Run for loop in parallel



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

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

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

   /* sequential code */

   return 0;
}
```

Grand Central Dispatch

- Apple technology for Mac OS X and iOS operating systems
- Extensions to C, C++ languages, API, and run-time library
- Allows identification of parallel sections
- Manages most of the details of threading
- Block is in “^{ }” - `^{ printf("I am a block"); }`
- Blocks placed in dispatch queue
  - Assigned to available thread in thread pool when removed from queue

Grand Central Dispatch

Two types of dispatch queues:

- serial – blocks removed in FIFO order, queue is per process, called **main queue**
  - Programmers can create additional serial queues within program
- concurrent – removed in FIFO order but several may be removed at a time
  - Three system wide queues with priorities low, default, high

```
dispatch_queue_t queue = dispatch_get_global_queue
   (DISPATCH_QUEUE_PRIORITY_DEFAULT, 0);

dispatch_async(queue, ^{ printf("I am a block."); });
```

Threading Issues

- Semantics of **fork()** and **exec()** system calls
- Signal handling
  - Synchronous and asynchronous
- Thread cancellation of target thread
  - Asynchronous or deferred
- Thread-local storage
- Scheduler Activations

Semantics of fork() and exec()

Does **`fork()`** duplicate only the calling thread or all threads?

Some UNIXes have two versions of fork

`exec()` usually works as normal – replace the running process including all threads

Signal Handling

- **Signals** are used in UNIX systems to notify a process that a particular event has occurred.
- A **signal handler** is used to process signals
  1. Signal is generated by particular event
  2. Signal is delivered to a process
  3. Signal is handled by one of two signal handlers:
     1. default
     2. user-defined
- Every signal has **default handler** that kernel runs when handling signal
  - **User-defined signal handler** can override default
  - For single-threaded, signal delivered to process

Signal Handling (Cont.)

- Where should a signal be delivered for multi-threaded?
  - Deliver the signal to the thread to which the signal applies
  - Deliver the signal to every thread in the process
  - Deliver the signal to certain threads in the process
  - Assign a specific thread to receive all signals for the process

- http://devarea.com/linux-handling-signals-in-a-multithreaded-application/#.XI-nEygzaF4

Thread Cancellation

Terminating a thread before it has finished

Thread to be canceled is **target thread**

Two general approaches:

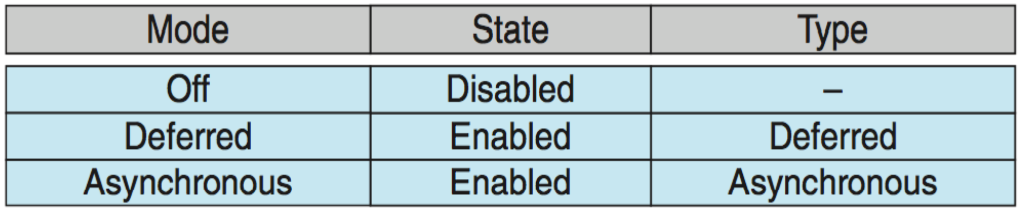
- **Asynchronous cancellation** terminates the target thread immediately
- **Deferred cancellation** allows the target thread to periodically check if it should be cancelled

Pthread code to create and cancel a thread:

```
pthread_t tid;

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

. . .

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

Thread Cancellation (Cont.)

Invoking thread cancellation requests cancellation, but actual cancellation depends on thread state



Mode	State	Type
Off	Disabled	–
Deferred	Enabled	Deferred
Asynchronous	Enabled	Asynchronous

If thread has cancellation disabled, cancellation remains pending until thread enables it

Default type is deferred

- Cancellation only occurs when thread reaches **cancellation point**
  - I.e. **`pthread_testcancel()`**
  - Then **cleanup handler** is invoked

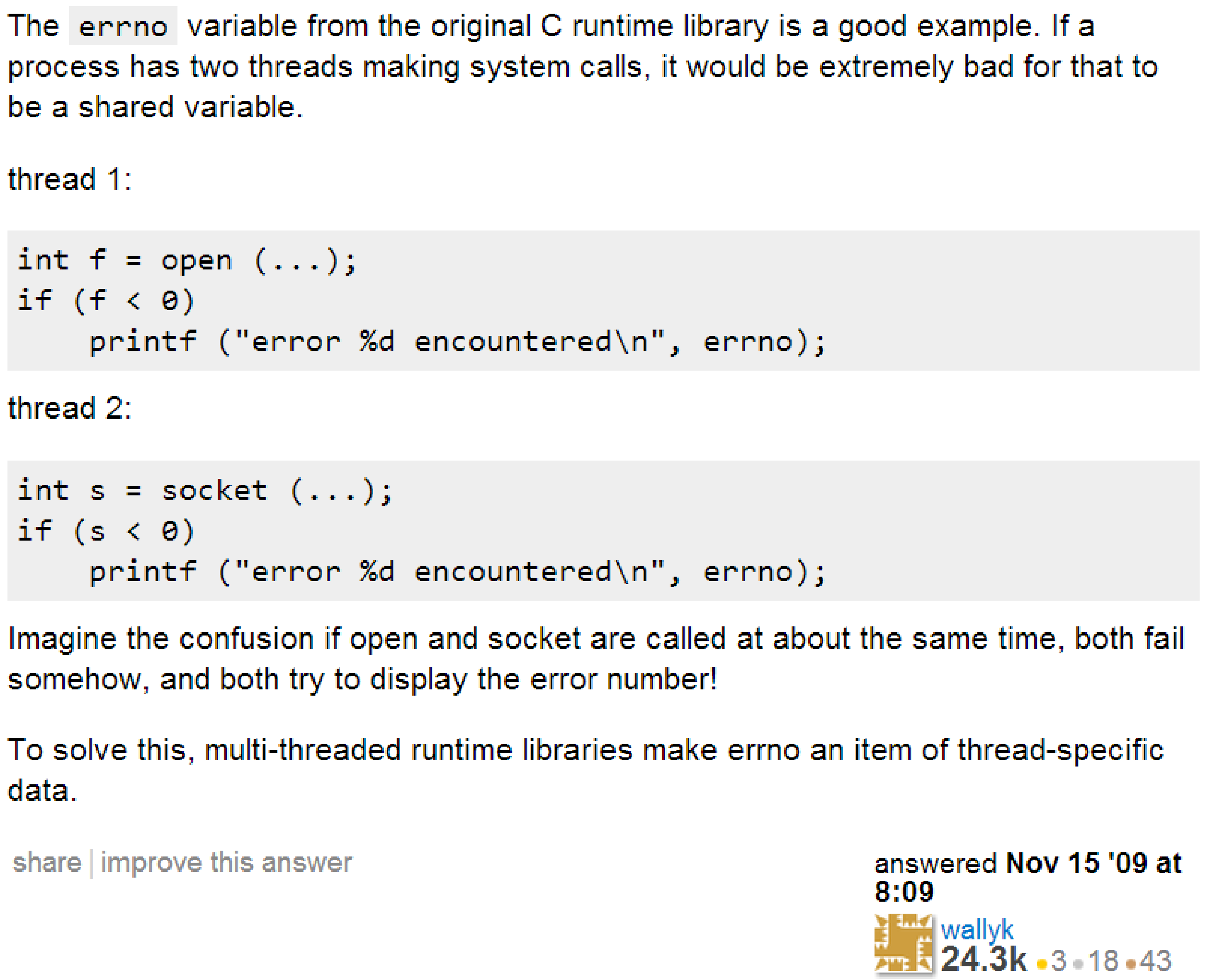
On Linux systems, thread cancellation is handled through signals

https://blog.csdn.net/sun_ashe/article/details/84561375

Thread-Local Storage

- **Thread-local storage** (**TLS**) allows each thread to have its own copy of data
- Useful when you do not have control over the thread creation process (i.e., when using a thread pool)
- Different from local variables
  - Local variables visible only during single function invocation
  - TLS visible across function invocations
- Similar to **`static`** data
  - TLS is unique to each thread

Thread Specific Data



The `errno` variable from the original C runtime library is a good example. If a process has two threads making system calls, it would be extremely bad for that to be a shared variable.

thread 1:

```
int f = open (...);
if (f < 0)
    printf ("error %d encountered\n", errno);
```

thread 2:

```
int s = socket (...);
if (s < 0)
    printf ("error %d encountered\n", errno);
```

Imagine the confusion if open and socket are called at about the same time, both fail somehow, and both try to display the error number!

To solve this, multi-threaded runtime libraries make errno an item of thread-specific data.

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answered **Nov 15 '09 at 8:09**

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pthread_setspecific()

Function

assign thread-specific data to key

SYNOPSIS

SYNOPSIS

```
#include <pthread.h>

int pthread_setspecific(pthread_key_t key, const void *value);
```

DESCRIPTION

The `pthread_setspecific()` function associates a thread-specific data value with a key obtained via a previous call to `pthread_key_create()`. Different threads may bind different values to the same key. These values are typically pointers to blocks of dynamically allocated memory that have been reserved for use by the calling thread.

The effect of calling `pthread_setspecific()` with a key value not obtained from `pthread_key_create()` or after the key has been deleted with `pthread_key_delete()` is undefined.

PARAMETERS

key
: Is the thread-specific data key to which data is assigned.

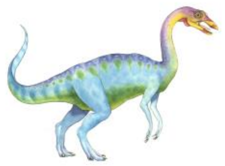
value
: Is the thread-specific data value to store.

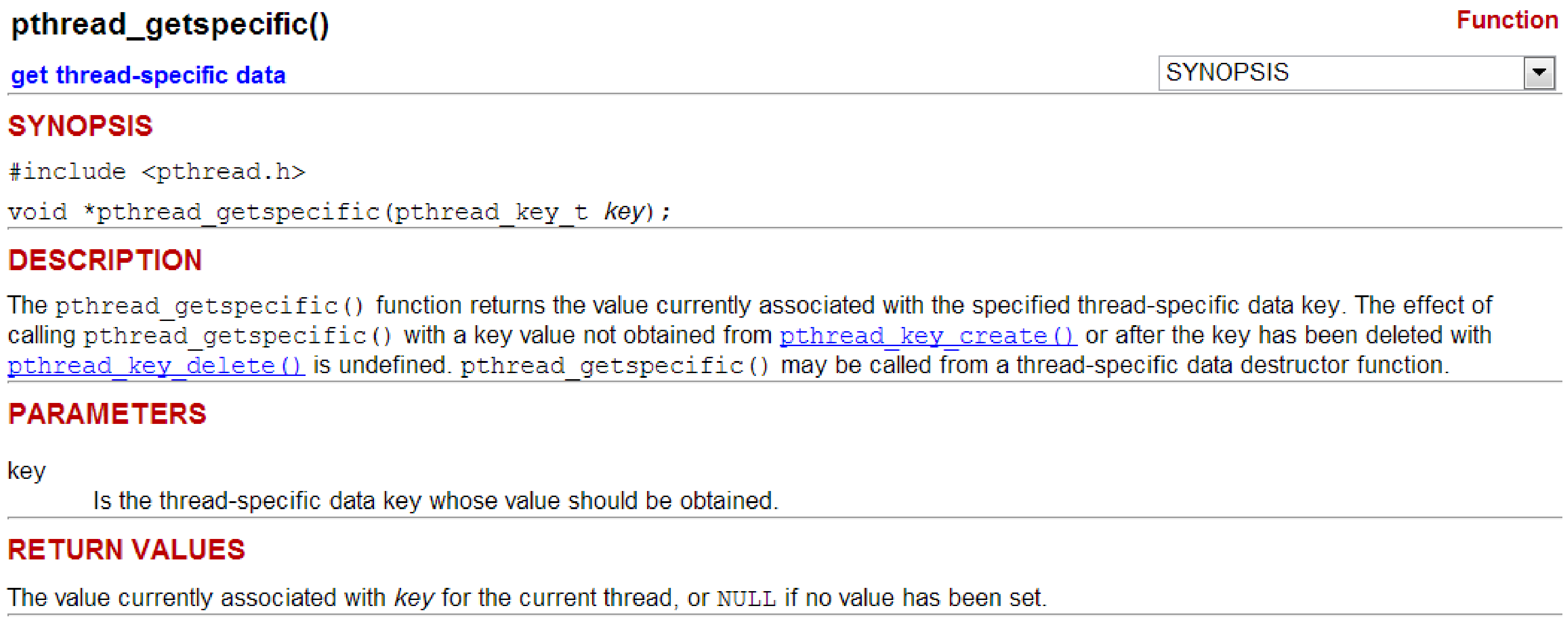
RETURN VALUES

On success, `pthread_setspecific()` returns 0. On error, one of the following values is returned:

`EINVAL`
: *key* is not a valid thread-specific data key.

`ENOMEM`
: Insufficient memory exists to associate the value with the key.





pthread_getspecific() **Function**

get thread-specific data

SYNOPSIS

```
#include <pthread.h>
void *pthread_getspecific(pthread_key_t key);
```

DESCRIPTION

The `pthread_getspecific()` function returns the value currently associated with the specified thread-specific data key. The effect of calling `pthread_getspecific()` with a key value not obtained from `pthread_key_create()` or after the key has been deleted with `pthread_key_delete()` is undefined. `pthread_getspecific()` may be called from a thread-specific data destructor function.

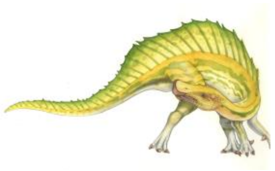
PARAMETERS

key

Is the thread-specific data key whose value should be obtained.

RETURN VALUES

The value currently associated with *key* for the current thread, or `NULL` if no value has been set.



Language-specific implementation

[edit]

Apart from relying on programmers to call the appropriate API functions, it is also possible to extend the programming language to support TLS.

C++

[edit]

C++11 introduces the `thread_local`[1] keyword which can be used in the following cases

- Namespace level (global) variables
- File static variables
- Function static variables
- Static member variables

How about local variables?

Aside from that, various C++ compiler implementations provide specific ways to declare thread-local variables:

- Solaris Studio C/C++, IBM XL C/C++, GNU C and Intel C/C++ (Linux systems) use the syntax:

```
__thread int number;
```

- Visual C++[2], Intel C/C++ (Windows systems), C++Builder, and Digital Mars C++ use the syntax:

```
__declspec(thread) int number;
```

- C++Builder also supports the syntax:

```
int __thread number;
```

On Windows versions before Vista and Server 2008, `__declspec(thread)` works in DLLs only when those DLLs are bound to the executable, and will *not* work for those loaded with *LoadLibrary()* (a protection fault or data corruption may occur).[3]

Scheduler Activations

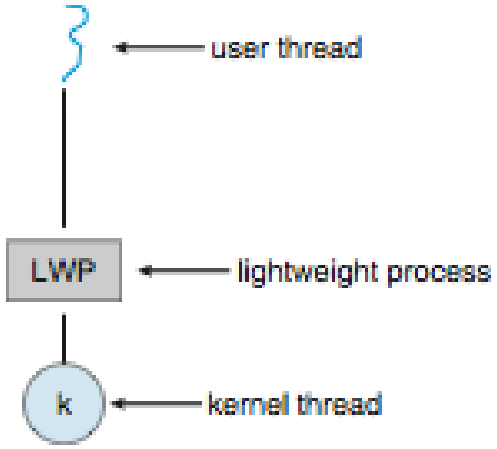
Both M:M and Two-level models require communication to maintain the appropriate number of kernel threads allocated to the application

Typically use an intermediate data structure between user and kernel threads – **lightweight process** (**LWP**)

- Appears to be a virtual processor on which process can schedule user thread to run
- Each LWP attached to kernel thread
- How many LWPs to create?

Scheduler activations provide **upcalls** - a communication mechanism from the kernel to the **upcall handler** in the thread library

This communication allows an application to maintain the correct number kernel threads



Operating System Examples

Windows Threads

Linux Threads

Windows Threads

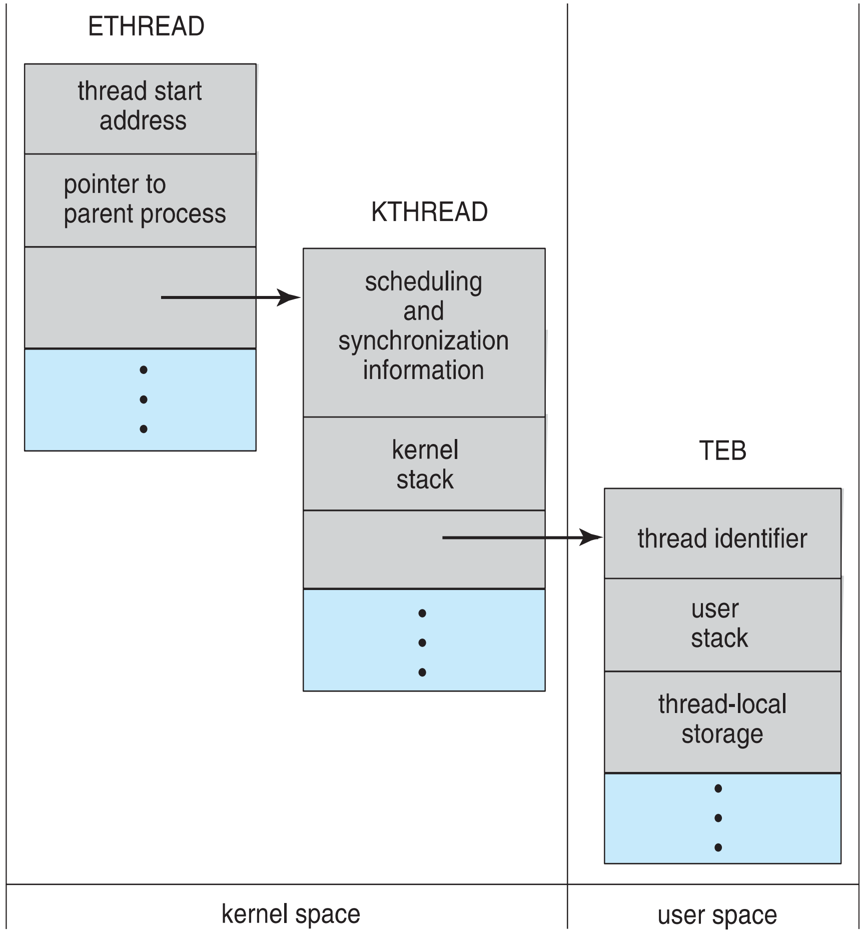
- Windows implements the Windows API – primary API for Win 98, Win NT, Win 2000, Win XP, and Win 7
- Implements the one-to-one mapping, kernel-level
- Each thread contains
  - A thread id
  - Register set representing state of processor
  - Separate user and kernel stacks for when thread runs in user mode or kernel mode
  - Private data storage area used by run-time libraries and dynamic link libraries (DLLs)
- The register set, stacks, and private storage area are known as the **context** of the thread

Windows Threads (Cont.)

The primary data structures of a thread include:

- ETHREAD (executive thread block) – includes pointer to process to which thread belongs and to KTHREAD, in kernel space
- KTHREAD (kernel thread block) – scheduling and synchronization info, kernel-mode stack, pointer to TEB, in kernel space
- TEB (thread environment block) – thread id, user-mode stack, thread-local storage, in user space

Windows Threads Data Structures



Linux Threads

Linux refers to them as ***tasks*** rather than ***threads***

Thread creation is done through **`clone()`** system call

`clone()` allows a child task to share the address space of the parent task (process)

- Flags control behavior

flag	meaning
`CLONE_FS`	File-system information is shared.
`CLONE_VM`	The same memory space is shared.
`CLONE_SIGHAND`	Signal handlers are shared.
`CLONE_FILES`	The set of open files is shared.

`struct task_struct` points to process data structures (shared or unique)

End of Chapter 4