Chapter 4:

Threads & Concurrency

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

Objectives

- Identify the basic components of a thread, and contrast threads and processes
- Describe the major benefits and significant challenges of designing multithreaded processes
- Illustrate different approaches to implicit threading, including thread pools, fork-join, OpenMP and Grand Central Dispatch
- Describe how the Windows and Linux operating systems represent threads
- Design multithreaded applications using the Pthreads, Java, and Windows threading APIs

4.1 Overview

A thread is a basic unit of CPU utilization; it comprises a thread ID, a program counter, a register set, and a stack.

Most modern applications are multithreaded

Threads run within application

Multiple tasks with the application can be implemented by separate threads

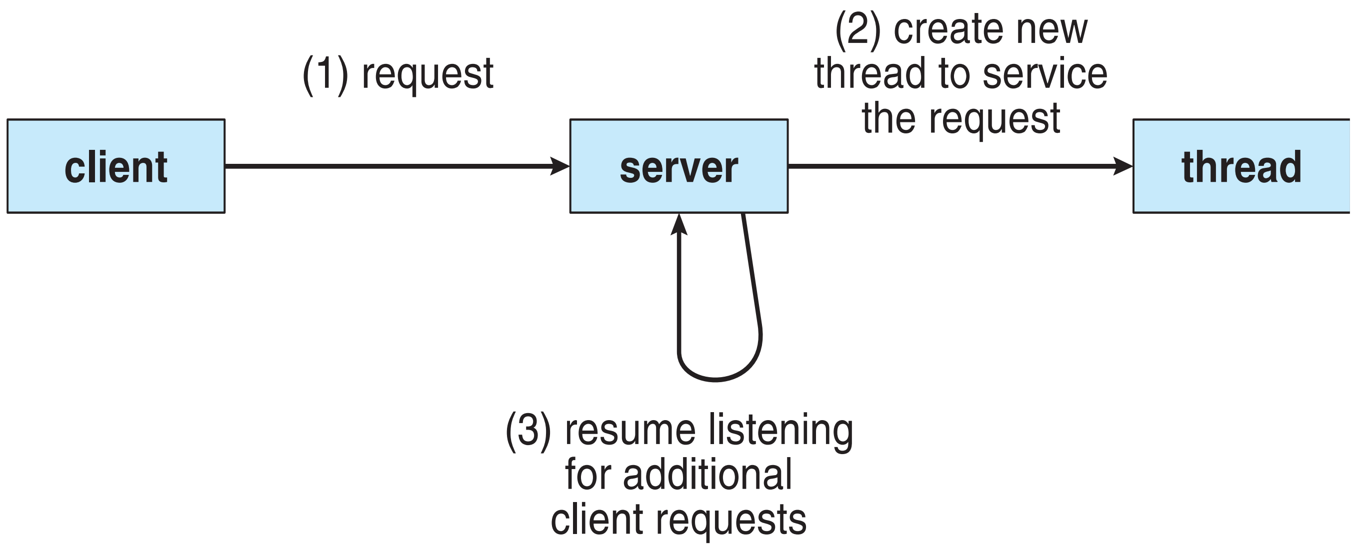
- Update display
- Fetch data
- Spell checking
- Answer a network request

Process creation is heavy-weight while thread creation is light-weight

Can simplify code, increase efficiency

Kernels are generally multithreaded

Multithreaded Server Architecture



Remote procedure call

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

4.2 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 (different) operation

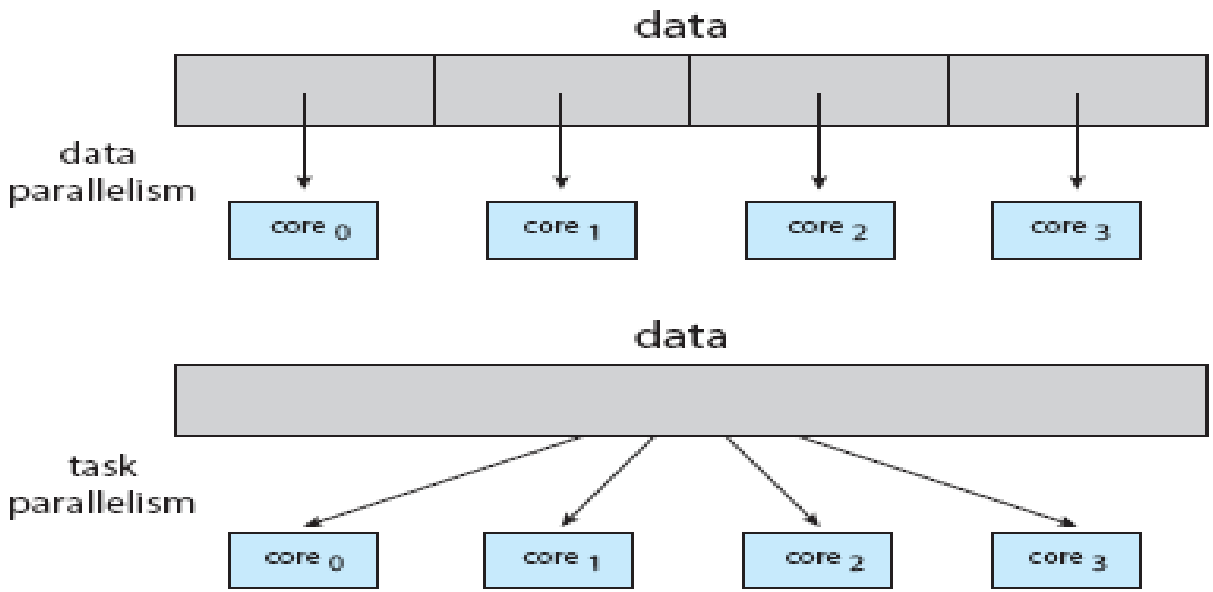


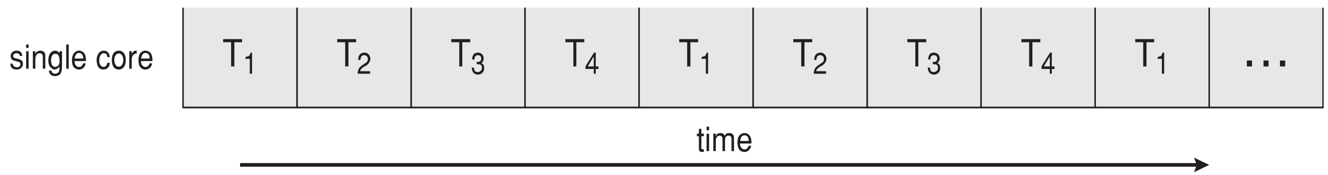
Figure 4.5 Data and task parallelism.

Multicore Programming (Cont.)

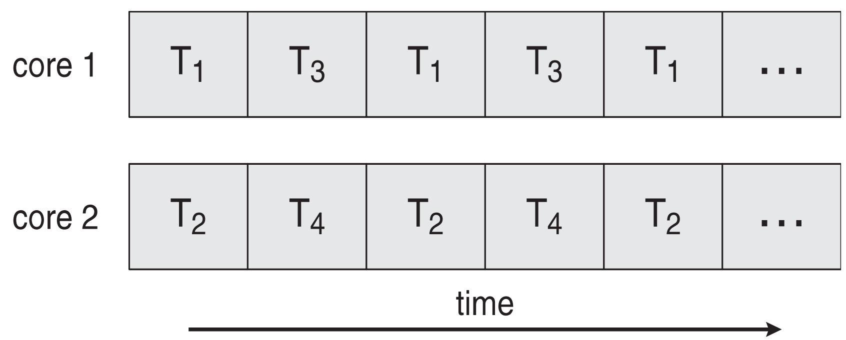
- As # of threads grows, so does architectural support for threading
  - CPUs have cores as well as ***hardware threads***
  - Consider Oracle SPARC T4 with 8 cores, and 8 hardware threads per core

Concurrency vs. Parallelism

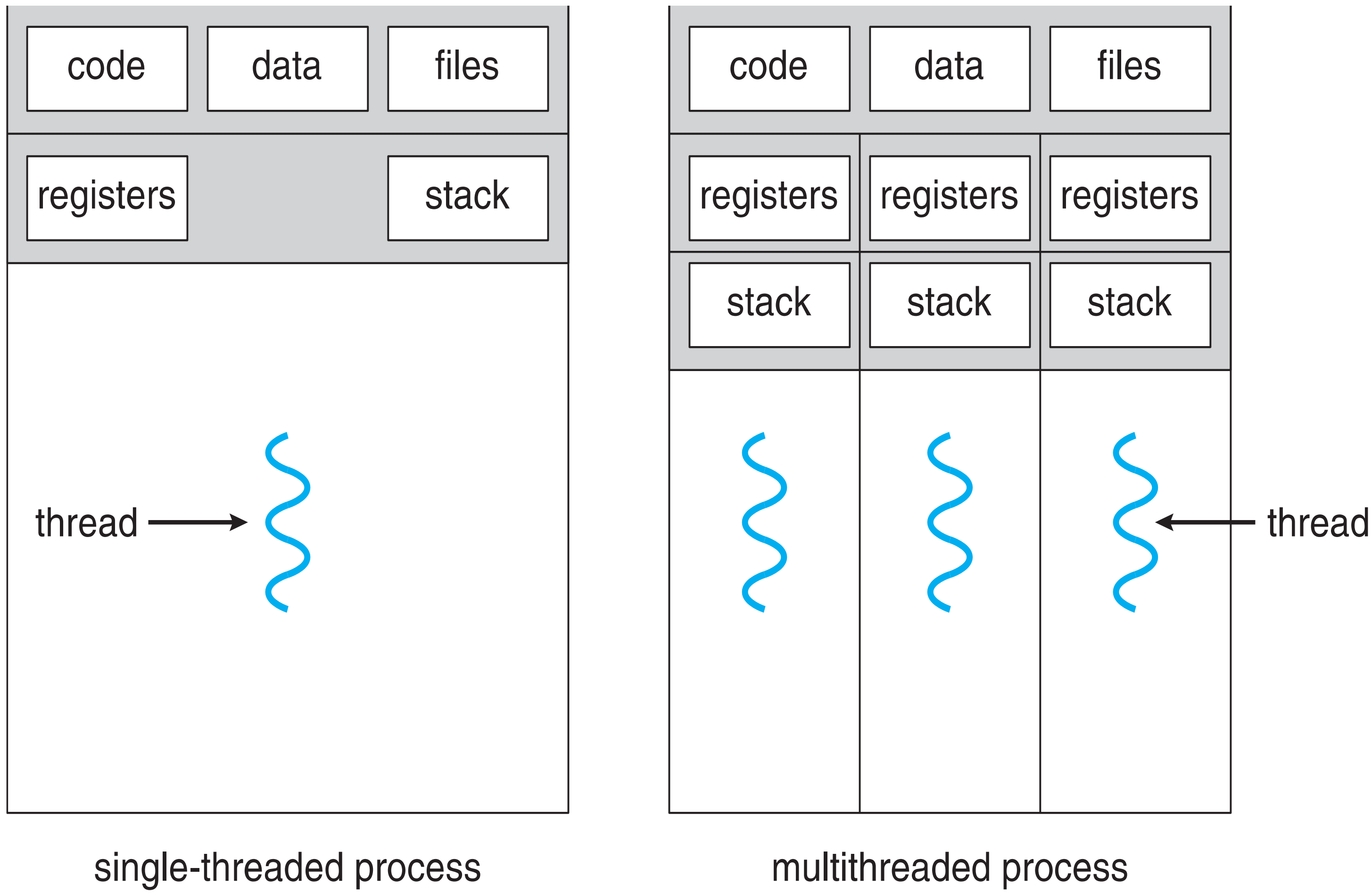
Concurrent execution on single-core system:



Parallelism on a multi-core system:



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

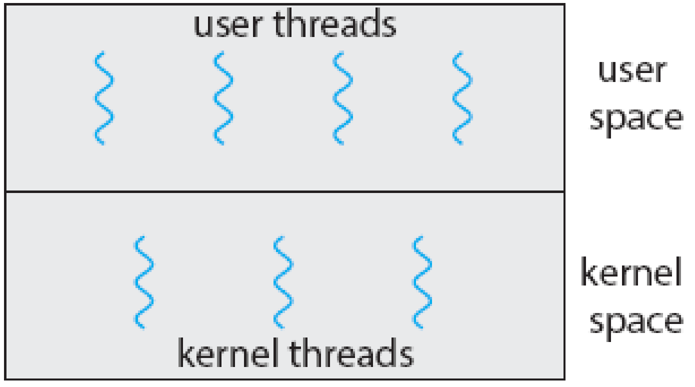


Figure 4.6 User and kernel threads.

4.3 Multithreading Models

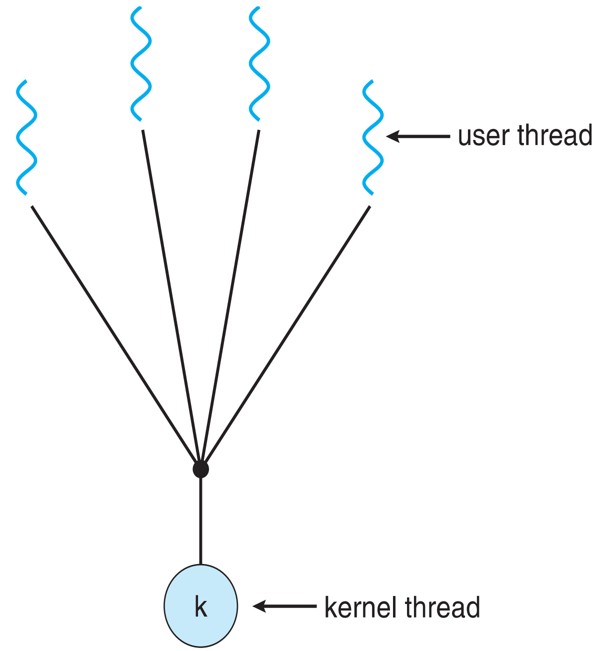
Many-to-One

One-to-One

Many-to-Many

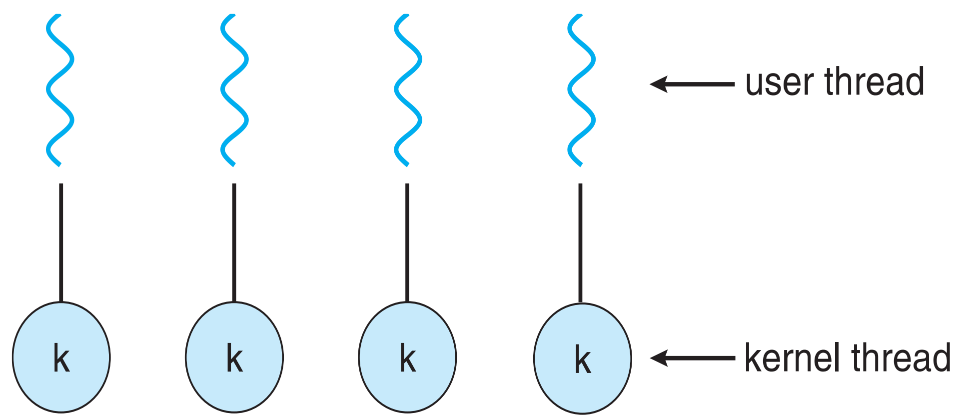
Many-to-One

- 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**



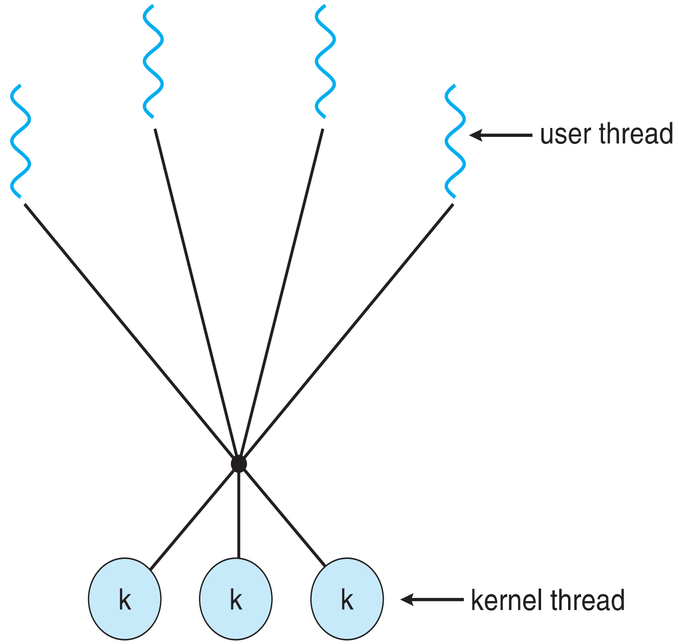
One-to-One

- 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
- Most operating system use this model
- 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
- It is difficult to implement
- Solaris prior to version 9
- Windows with the *ThreadFiber* package

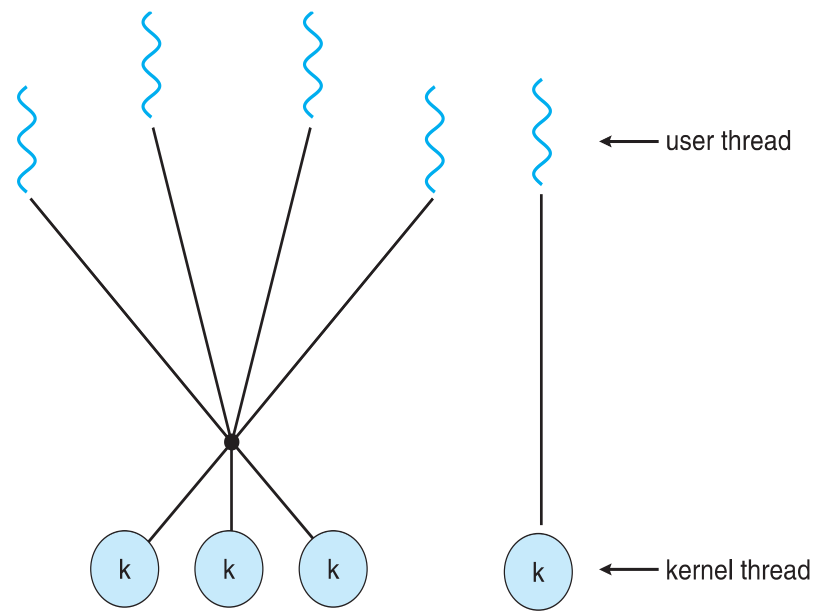


Two-level Model

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



4.4 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 (system call to 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);
}
```

Figure 4.9 Multithreaded C program using the Pthreads API.

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);
```

Figure 4.10 Pthread code for joining ten threads.

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:

- Extending Thread class (derived from Thread class)
- Implementing the Runnable interface

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

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>"); }
}
```

4.5 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

Four methods explored

- Thread Pools
- Fork Join
- OpenMP
- Grand Central Dispatch (GCD)

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 the task to be performed from mechanics of creating the task allows us to use 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.
    */
}
```

Fork Join

A library manages the number of threads that are created and is also responsible for assigning tasks to threads

In some way, the fork-join model is a synchronous version of thread pools in which a library determines the actual number of threads to create

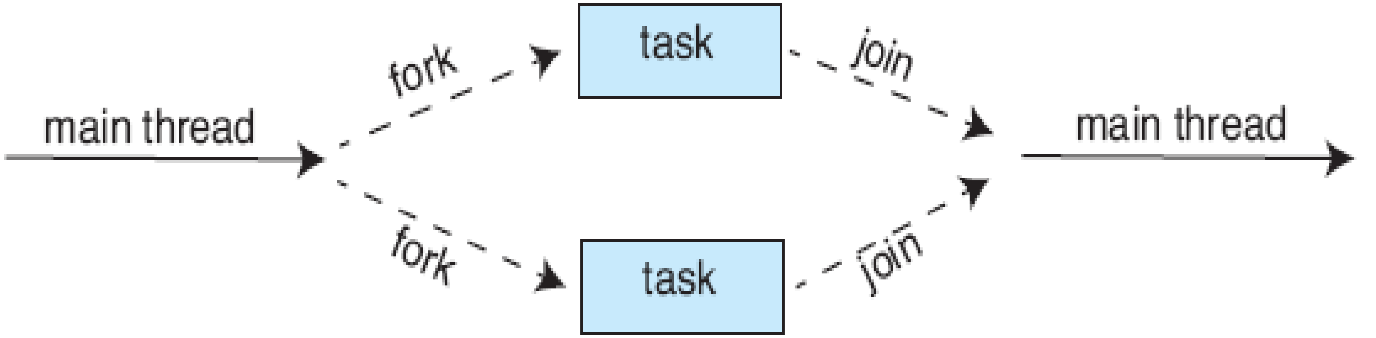


Figure 4.16 Fork-join parallelism.

Fork Join

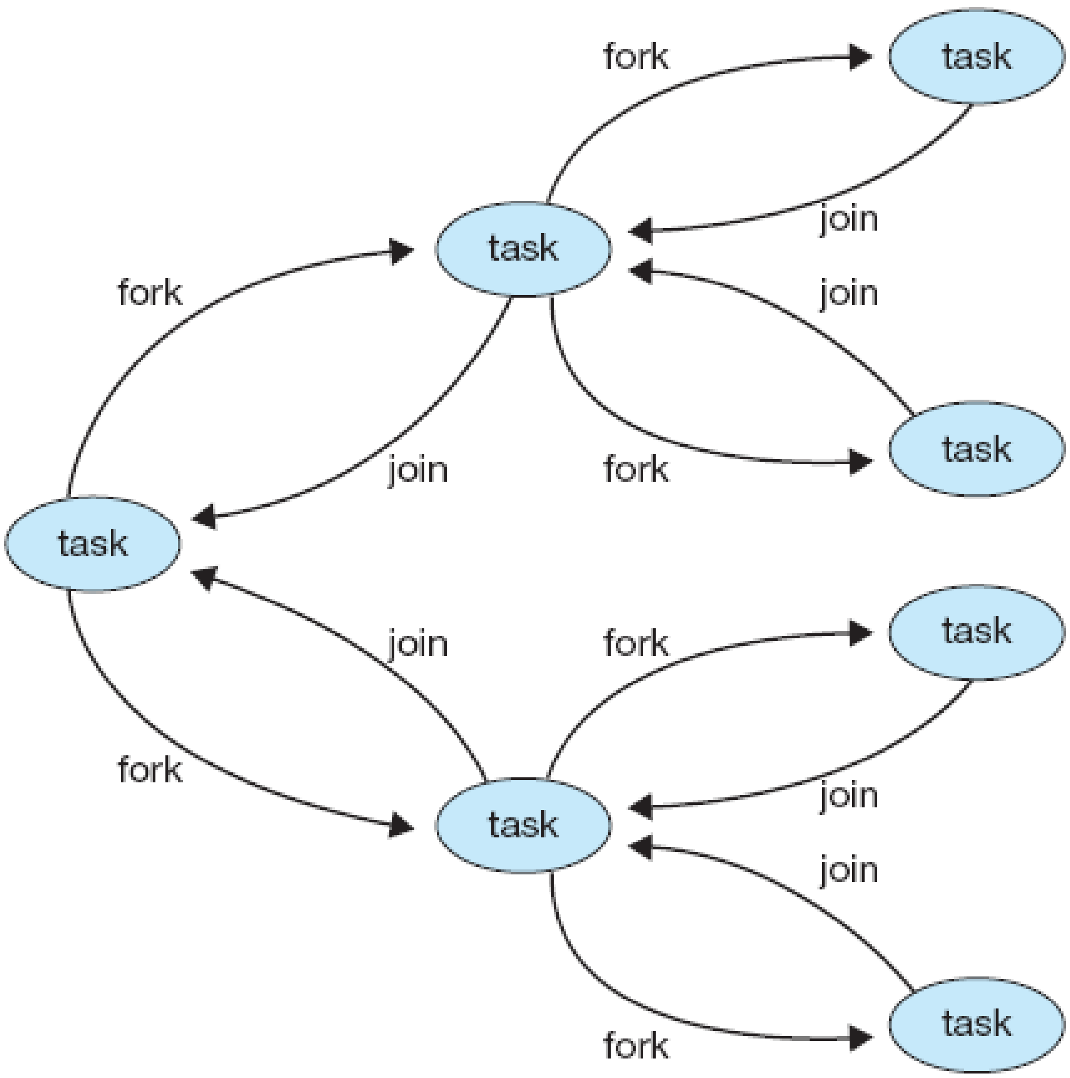


Figure 4.17 Fork-join in Java.

Fork Join

```
ForkJoinPool pool = new ForkJoinPool();
// array contains the integers to be summed
int[] array = new int[SIZE];

SumTask task = new SumTask(0, SIZE - 1, array);
int sum = pool.invoke(task);
```

Fork Join in Java

```
import java.util.concurrent.*;

public class SumTask extends RecursiveTask<Integer>
{
   static final int THRESHOLD = 1000;

   private int begin;
   private int end;
   private int[] array;

   public SumTask(int begin, int end, int[] array) {
      this.begin = begin;
      this.end = end;
      this.array = array;
   }

   protected Integer compute() {
      if (end - begin < THRESHOLD) {
         int sum = 0;
         for (int i = begin; i <= end; i++)
            sum += array[i];

         return sum;
      }
      else {
         int mid = (begin + end) / 2;

         SumTask leftTask = new SumTask(begin, mid, array);
         SumTask rightTask = new SumTask(mid + 1, end, array);

         leftTask.fork();
         rightTask.fork();

         return rightTask.join() + leftTask.join();
      }
   }
}
```

Figure 4.18 Fork-join calculation using the Java API.

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(GCD)

- 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 "^{ }" - `ˆ{ printf("I am a block"); }`
- Blocks placed in dispatch queue
  - Assigned to available thread in thread pool when removed from queue

Grand Central Dispatch(GCD)

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."); });
```

4.6 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

Signal Handling

- 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

- Where should a signal be delivered for multi-threaded?
  - Deliver the signal to the thread to which the signal applies (synchronous)
  - Deliver the signal to every thread in the process (<control ><C> signal)
  - Deliver the signal to certain threads in the process
  - Assign a specific thread to receive all signals for the process

Thread Cancellation

- Terminating a thread before it has finished
- Thread to be canceled is **target thread**
- Two general approaches:
  - **Asynchronous cancellation** terminates the target thread immediately
  - **Deferred cancellation** allows the target thread to periodically check if it should be cancelled
- Pthread code to create and cancel a thread:

```
pthread_t tid;

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

. . .

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

Thread Cancellation (Cont.)

Invoking thread cancellation requests cancellation, but actual cancellation depends on thread state (Pthread support three cancellation modes)

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

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

Default type is deferred

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

On Linux systems, thread cancellation is handled through signals

Thread-Local Storage

Thread-local storage (TLS) allows each thread to have its own copy of data

Useful when you do not have control over the thread creation process (i.e., when using a thread pool)

Different from local variables

- Local variables visible only during single function invocation
- TLS visible across function invocations

Similar to **`static`** data

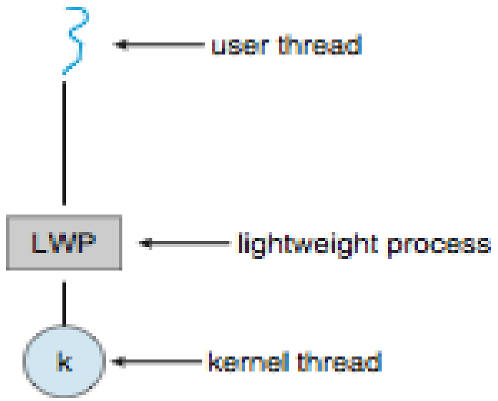
- TLS is unique to each thread

Scheduler Activations

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

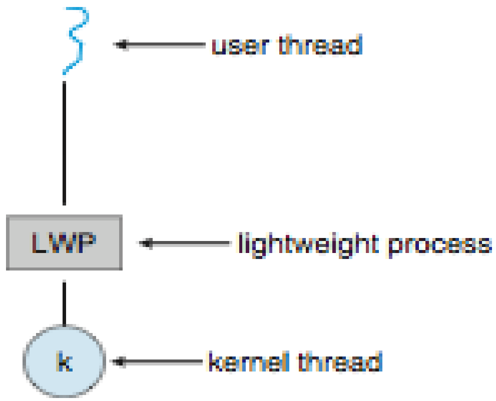
Typically use an intermediate data structure between user and kernel threads – **lightweight process (LWP)**

- Appears to be a virtual processor on which process can schedule user thread to run
- Each LWP attached to kernel thread
- How many LWPs to create? (CPU bound : 1 I/O bound : many)



Scheduler Activations

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

5 steps

- Kernel thread is about to block
- Upcall with thread ID
- Kernel allocates a new virtual processor
- Application runs an upcall handler on it (save the state of the blocking thread and relinguishes the virthual processor)
- Upcall handler schedules another thread to run on the new virtual processor

4.7 Operating System Examples

Windows Threads

Linux Thread

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)

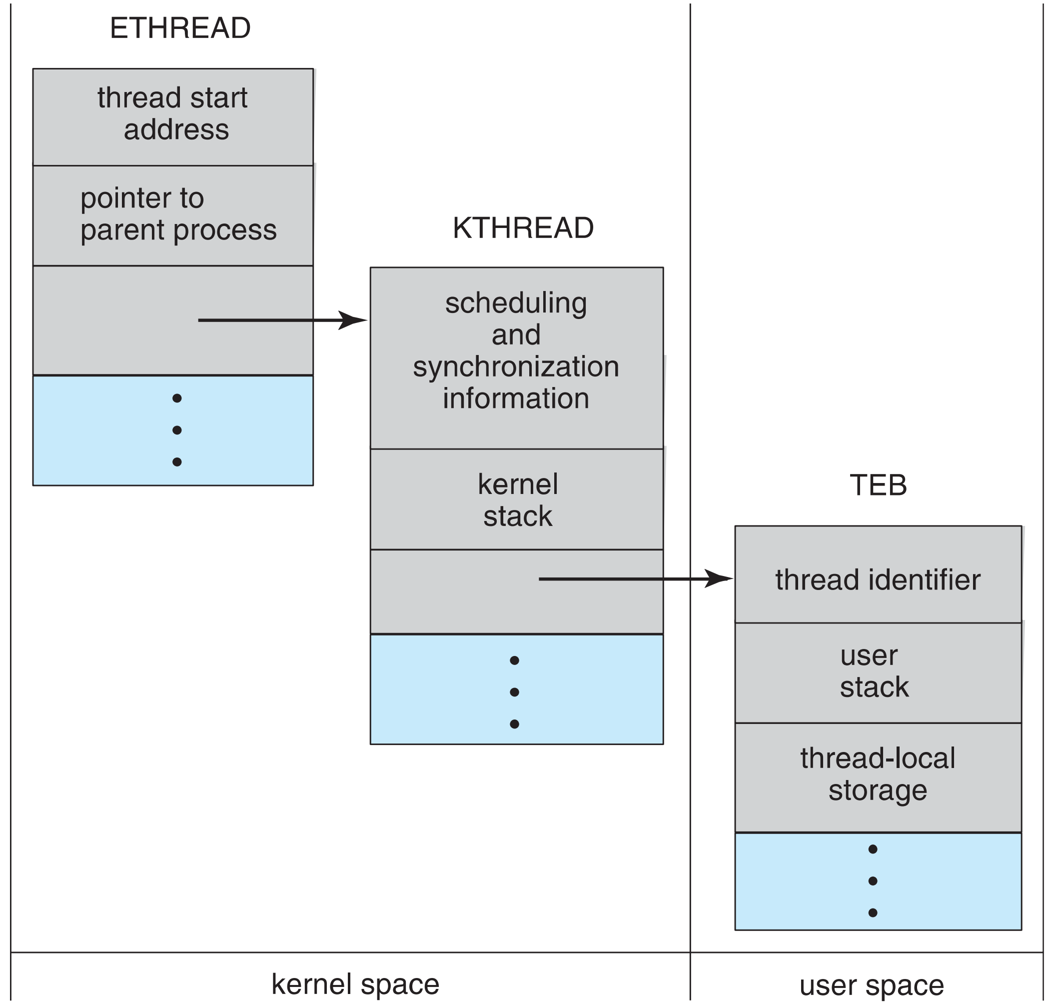
Windows Threads

The register set, stacks, and private storage area are known as the **context** of the thread

The primary data structures of a thread include:

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

Windows Threads Data Structures



Linux Threads

Linux provides the ***fork ()*** system call with the traditional functionality of duplicating a process

Linux refers to a flow of control within a program 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)

Different between fork( ) (copy all) and clone( ) (may be pointer)

End of Chapter 4