# Operating Systems: Lecture 5

# Threads & Concurrency

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# Chapter 4: Threads

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

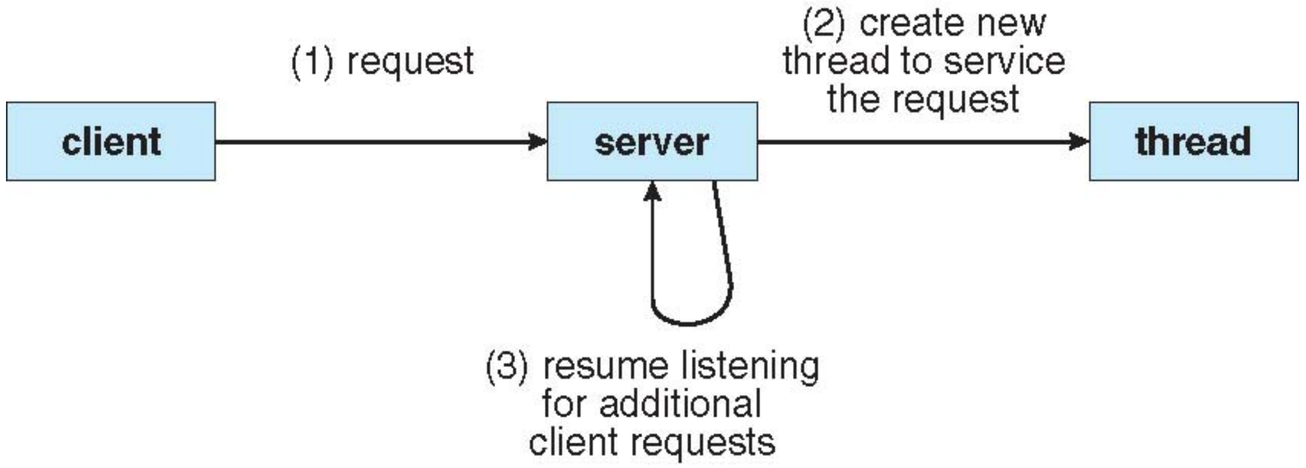
# Objectives

- 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



# 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 incurs lower overhead than context switching
- Scalability
  - process can take advantage of multiprocessor architectures

# What is Parallel Computing?

- In the simplest sense, ***parallel computing*** is the simultaneous use of multiple compute resources to solve a computational problem

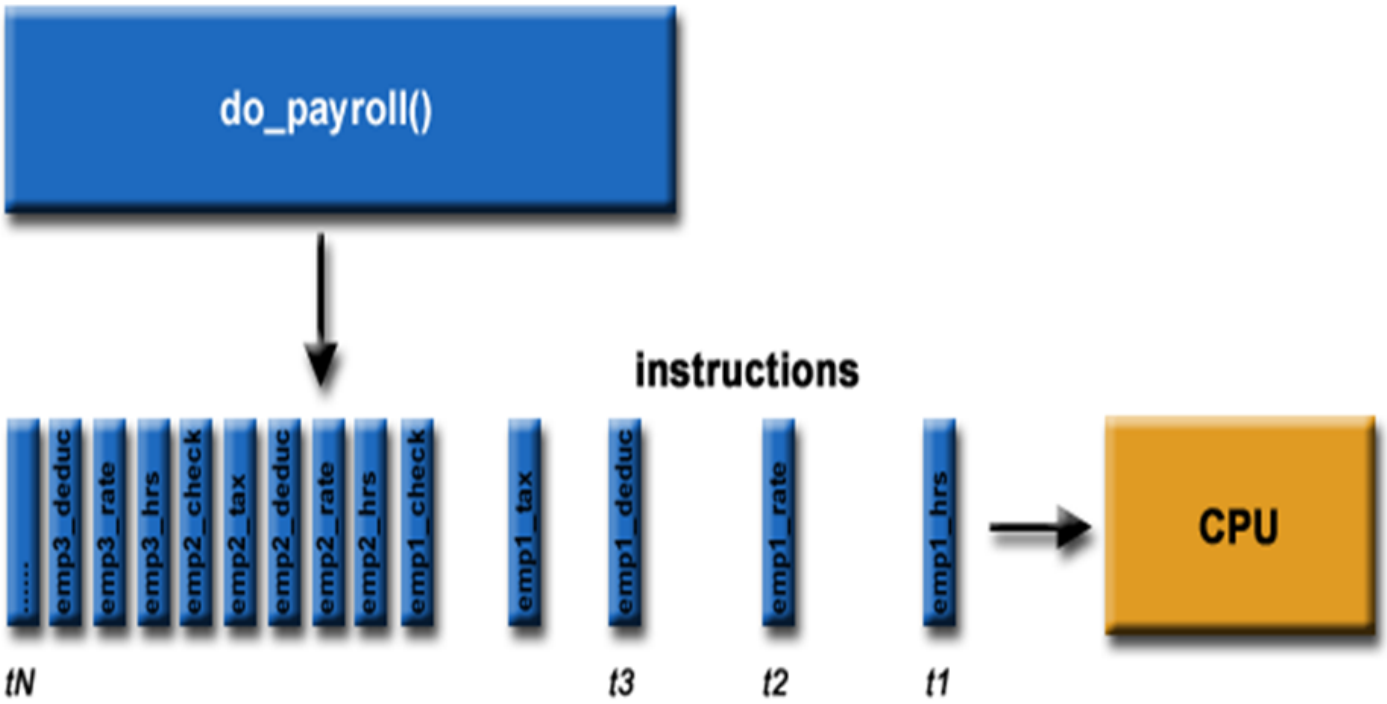
- Steps
  - A problem is broken into discrete parts that can be solved concurrently
  - Each part is further broken down to a series of instructions
  - Instructions from each part execute in sequence on each processor but simultaneously on different processors
  - An overall control/coordination mechanism is employed

# What is Parallel Computing? (Continued)

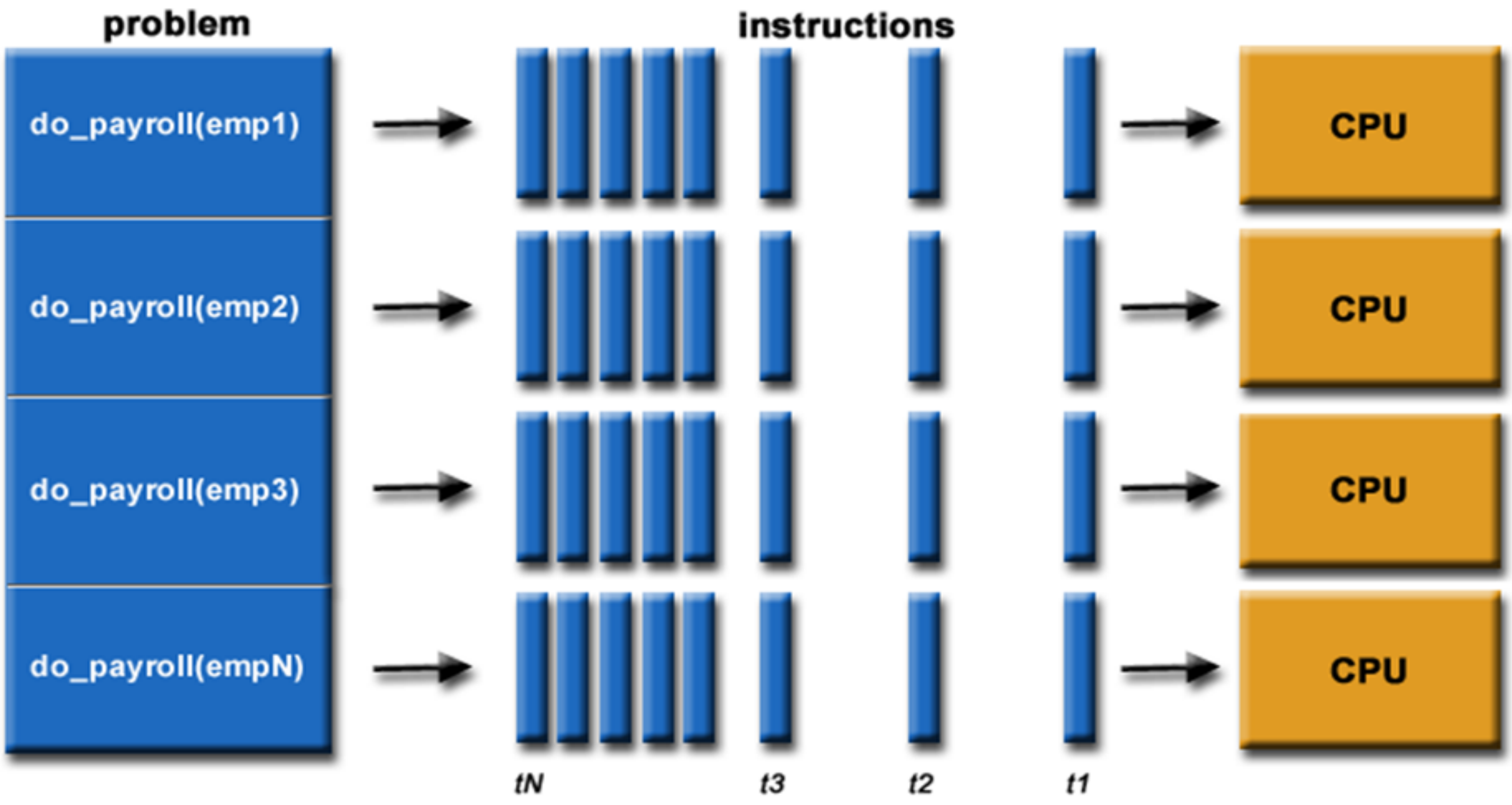
- The computational problem should be able to:
  - Be broken apart into discrete pieces of work that can be solved simultaneously
  - Execute multiple program instructions at any moment in time
  - Be solved in less time with multiple compute resources than with a single compute resource

- The compute resources might be:
  - A single computer with multiple processors
  - An arbitrary number of computers connected by a network
  - A combination of both

# Sequential Computing

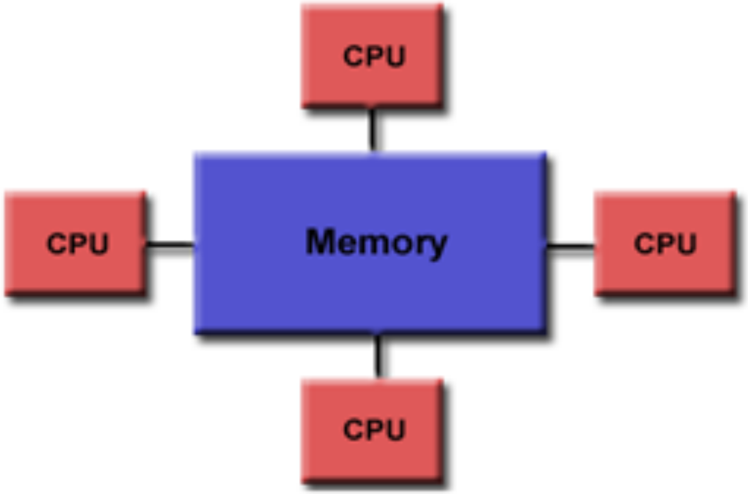


# Parallel Computing



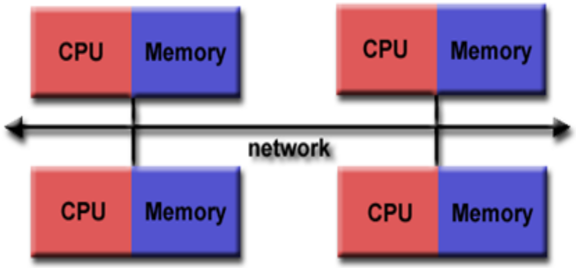
# Shared Memory Architecture

- Shared memory parallel computers vary widely, but generally have in common the ability for all processors to access all memory as ***global*** address space
- Multiple processors can operate independently but share the same memory resources
- Changes in a memory location affected by one processor are visible to all other processors
- The most critical problem to address is that of ***cache coherence***



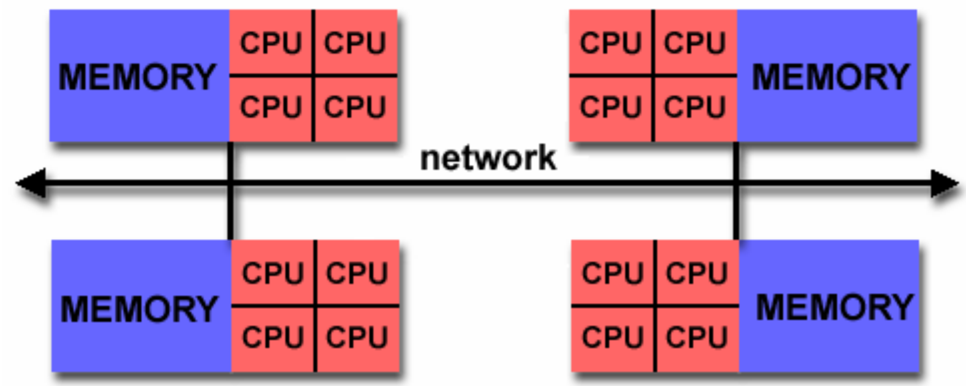
# *Distributed Memory Architecture*

- Processors have their own local memory and runs their own copy of OS
  - Memory addresses in one processor do not map to another processor, so there is no concept of global address space across all processors
- Like shared memory systems, distributed memory systems vary widely but share a common characteristic
  - Distributed memory systems require a communication network to connect inter-processor memory
- When a processor needs access to data in another processor, it is usually the task of the programmer to explicitly define how and when data is communicated
  - Synchronization between tasks is likewise the programmer's responsibility



# *Hybrid Architecture*

- The large computers in the world today employ both shared and distributed memory architectures
- The shared memory component is usually a cache coherent SMP machine
  - Processors on a given SMP can address that machine's memory as global
- The distributed memory component is the networking of multiple SMPs. SMPs know only about their own memory
  - Not the memory on another SMP
  - Therefore, network communications are required to move data from one SMP to another



# *Accelerator-Based Architecture*

- The largest and fastest computers in the world today employ Hybrid Architecture and Accelerators (GPUs)
  - Shared Memory
  - Distributed
  - Hybrid

# History / Timeline

| Decade | Parallel Hardware Platforms | Memory |
| --- | --- | --- |
| 1980s | Vector supercomputers | Shared |
| | Multiprocessors (networked) | Distributed |
| 1990s | Cluster supercomputers | Distributed |
| | Internet | Distributed |
| | Symmetric multiprocessors | Shared |
| 2000s | GPUs | Shared |
| | Multicore processors | Shared |
| 2010s | Hybrid supercomputers/clusters | Both |
| | Coprocessors (w. vector units) | Shared |

# Fundamental Concepts in PDC

- Following are the PDC concepts that are pervasive irrespective of architecture, programming models, and tools
  - Asynchrony
  - Concurrency
  - Locality
  - Performance Measurement and Metric
  - Synchronization
  - Memory Hierarchy

# Asynchrony

- Asynchrony is a characteristics of modern computers
  - Even though it seems like many operations are atomic, they are not
  - This is true for sequential computers too
- To develop parallel algorithms and applications we must understand the cause and effect of asynchrony and think about the mitigation
  - The mitigation often results into additional overhead
    - **Example: Data Race**

# Concurrency

- Concurrency is a property of an algorithm, it exposes potential for parallelization
  - If concurrency is present in an algorithm then the concurrent operations can be executed in parallel (simultaneously) by multiple operation units (CPU's) if available
  - Without concurrency there is no scope for parallelization
- Concurrency can be present in a sequential program
  - parallelization takes advantage of concurrency to increase performance

# Locality

- One of the overarching concepts in computing is that of locality of time, space, and state
- Each computational unit (a CPU in a shared memory machine or a node in a cluster) may have their own clock and their own notion of time
- Memory subsystems proactively predict and cache future memory references based upon recent memory reference patterns
- A challenge with localized control is the detection and management of conflict

# Performance Measurement & Metric

- No matter what computing artifact (program algorithms, hardware) that we are designing, studying, and analyzing, we should be aware of how good the artifact is and strive to make it better

- Space, time, and energy are the basic commodities to measure and the metrics for these commodities may differ based on whether the context is sequential or parallel
  - For example in a sequential program run time may be used as a measure of goodness but in the parallel version of the same program there is an additional variable, the number of cores, so the notion of runtime does not capture the goodness

# *How do We Write Parallel Program: Types of Parallelism*

- Task Parallelism
  - Distributing threads across cores, each thread performing unique operation
    - **Example: two threads, each performing a unique statistical operation on the array of elements**
    - **The threads are operating in parallel on separate computing cores, but each is performing a unique operation**

- Data Parallelism
  - Distributes subsets of the same data across multiple cores, same operation on each
  - Each core carries out similar operations on its part of the data
    - **Example: summing the contents of an array of size N**
    - **For a single-core system, one thread would simply sum the elements [0] . . . [N − 1]**
    - **For a dual-core system, however, thread A, running on core 0, could sum the elements [0] . . . [N/2 − 1] and while thread B, running on core 1, could sum the elements [N/2] . . . [N − 1]**
    - **So the Two threads would be running in parallel on separate computing cores**

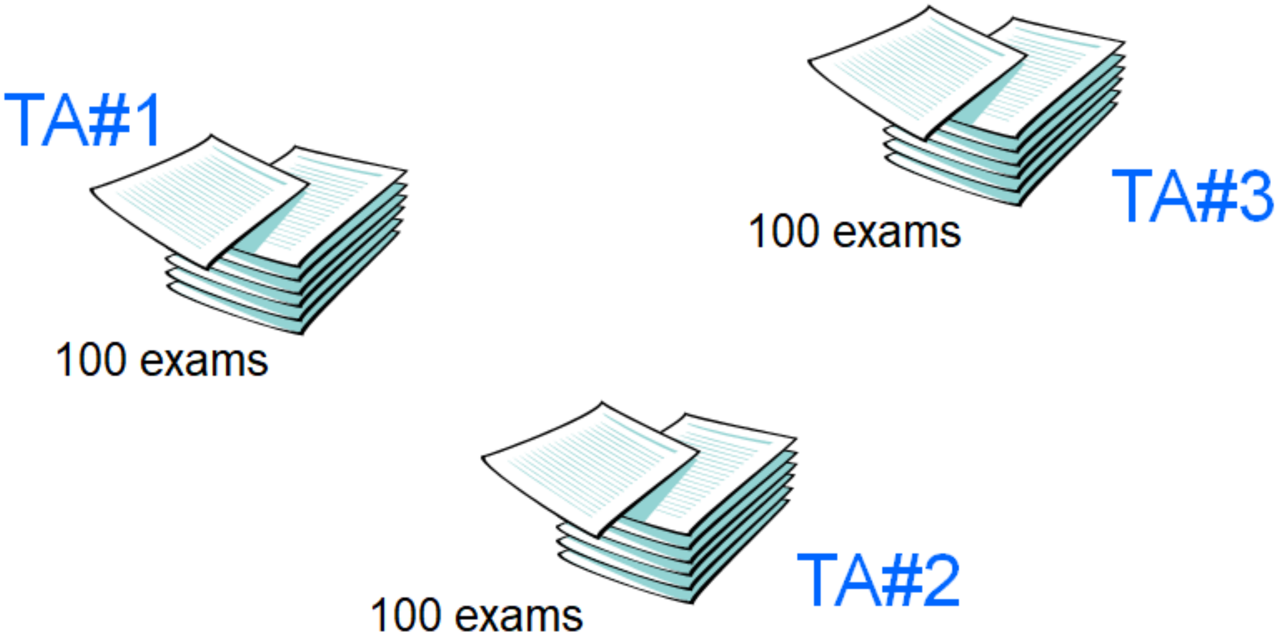
# Professor S(erial)

15 questions

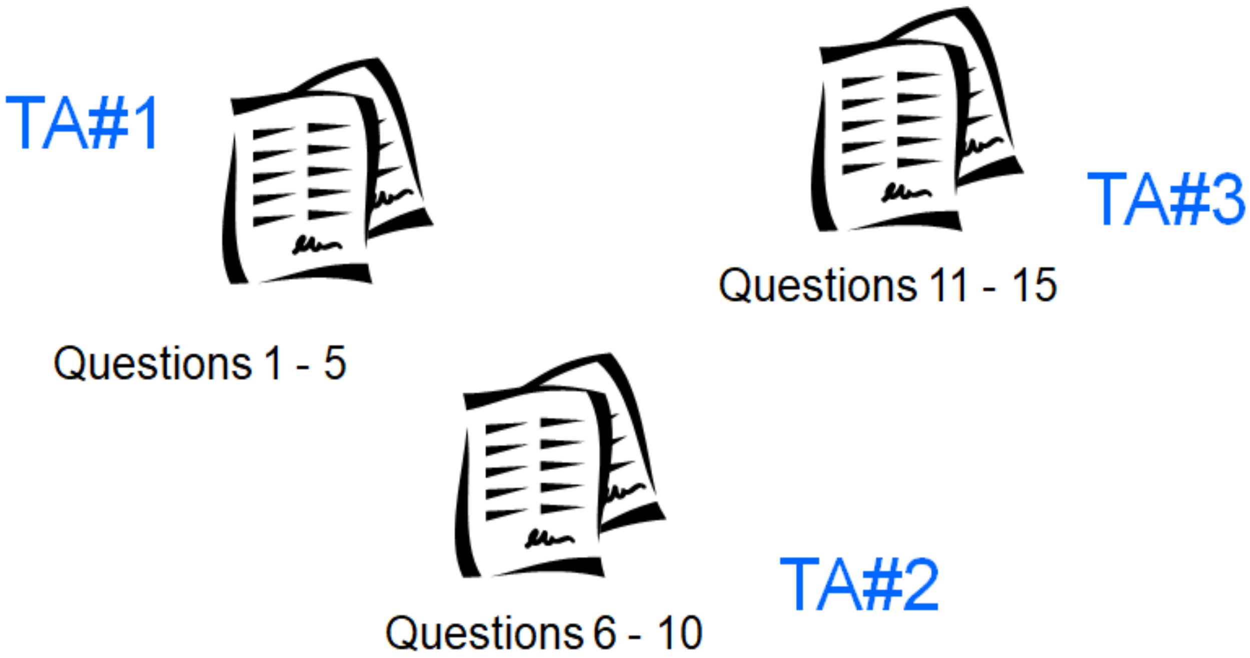
300 exams

# Professor S's Teaching Assistants

# *Division of work – Data or Task parallelism ???*



# *Division of work – Data or Task parallelism ???*



# Multicore Programming

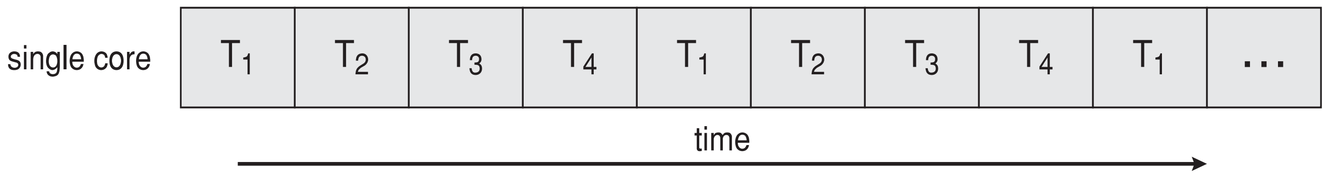
- Multicore or multiprocessor systems putting pressure on programmers, challenges include:
  - Dividing activities
  - Balance
  - Data splitting
  - Data dependency
  - Testing and debugging

- *Concurrency* supports more than one task making progress
  - Single processor / core, scheduler providing concurrency

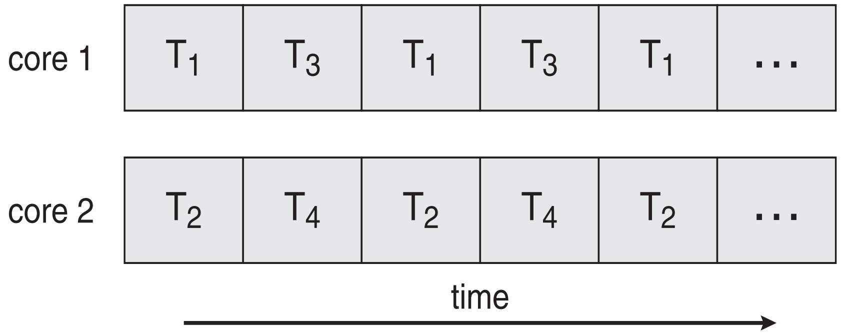
- *Parallelism* implies a system can perform more than one task simultaneously

# Concurrency vs. Parallelism

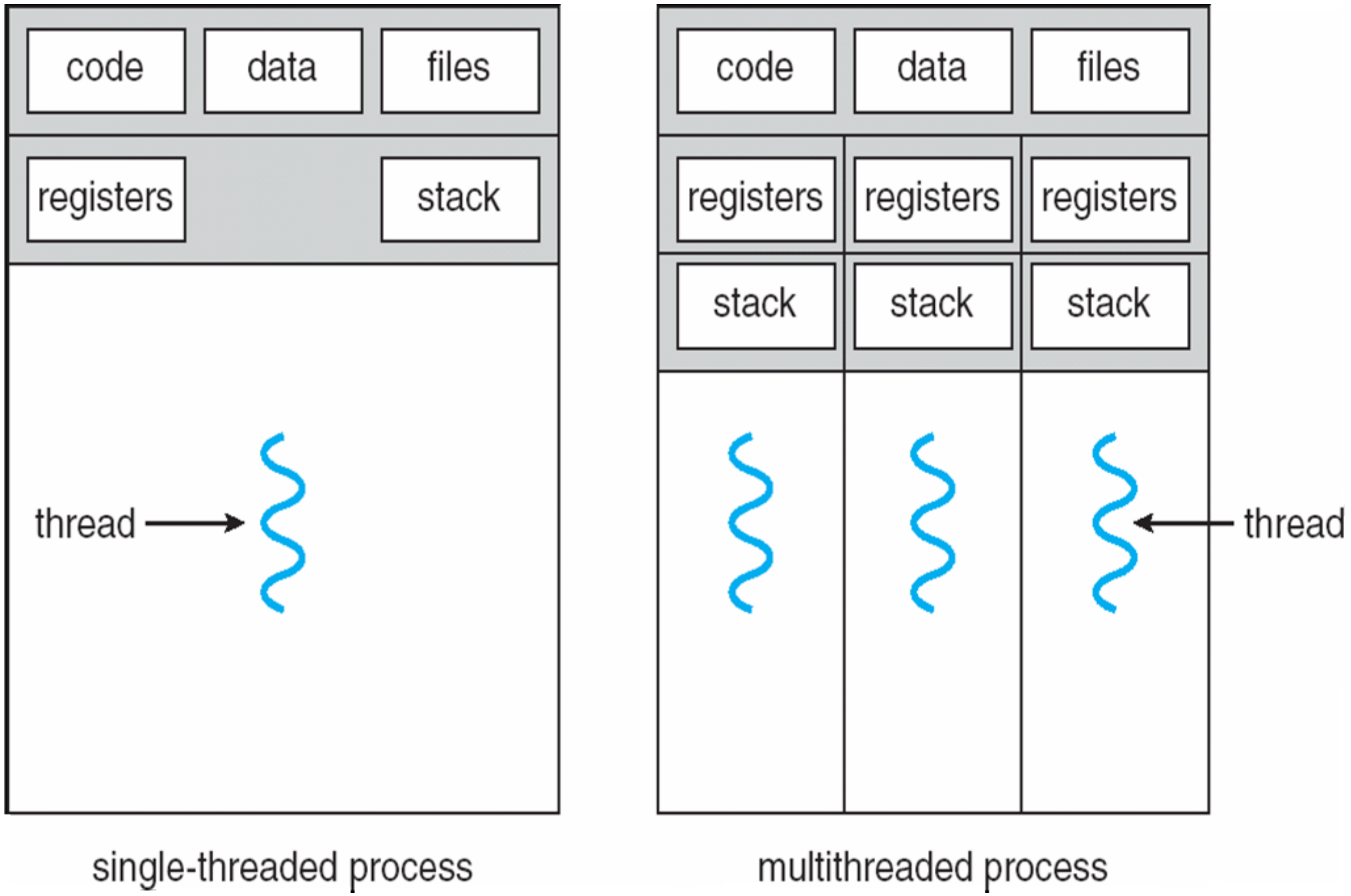
**Concurrent execution on single-core system:**



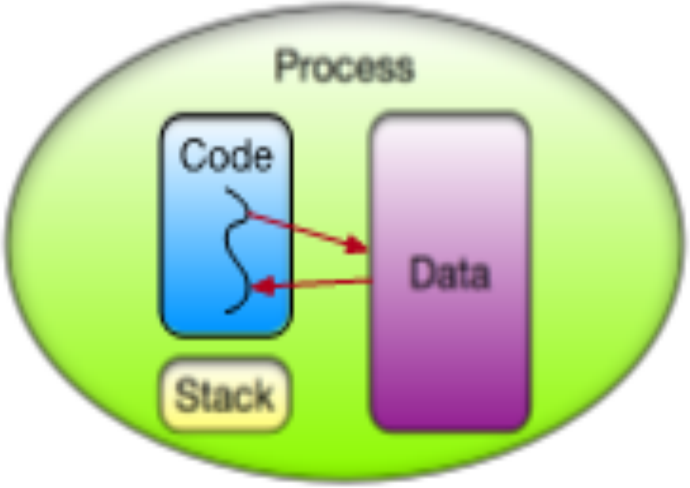

**Parallelism on a multi-core system:**



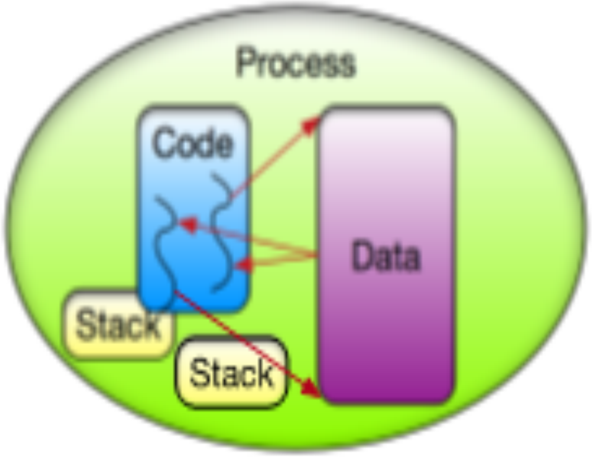
# Single and Multithreaded Processes



# Process vs Thread




**Process with one thread**




**Process with two threads**

# 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 consider 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

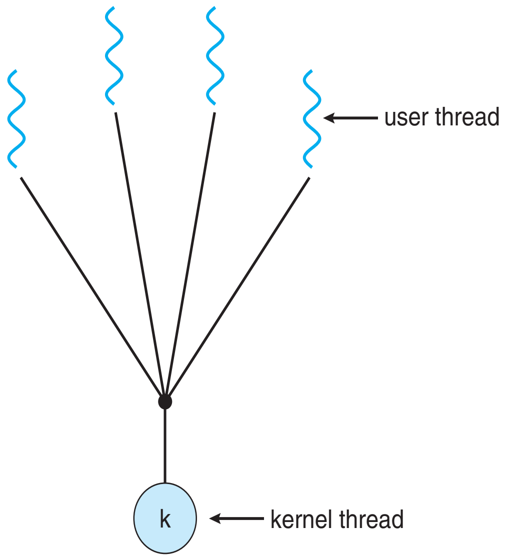
- **Kernel threads** - Supported by the Kernel
- Examples – virtually all general-purpose operating systems, including:
  - Windows
  - Solaris
  - Linux
  - Tru64 UNIX
  - Mac OS X

# *Multithreading Models*

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

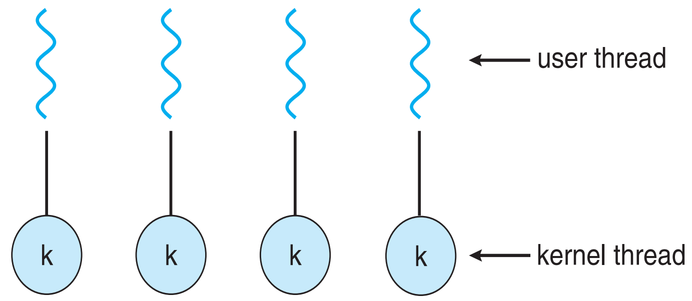
# Many-to-One

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



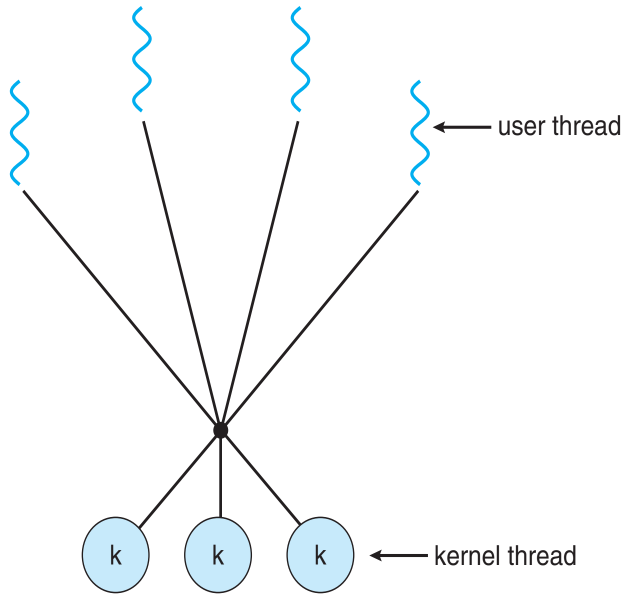
# One-to-One

- 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 NT and later
  - Linux
  - Solaris 9 and later



# Many-to-Many Model

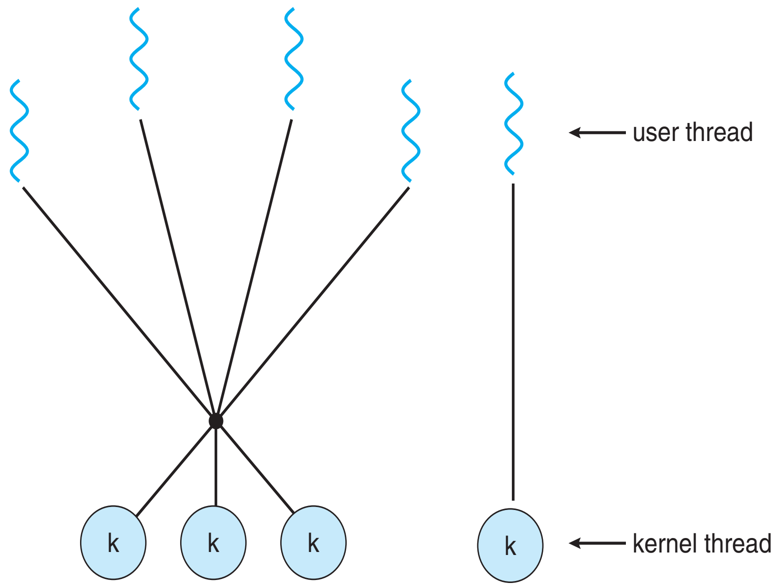
- Allows many user level threads to be mapped to many kernel threads
- Allows the  operating system to create enough kernel threads
- Solaris prior to version 9
- Windows with the *ThreadFiber* package



# *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.
     */
}
```

# *Introduction to OpenMP*

- An Application Program Interface (API) that may be used to explicitly direct ***multi-threaded, shared memory parallelism***

- Comprised of three primary API components
  - Compiler Directives
  - Runtime Library Routines
  - Environment Variables

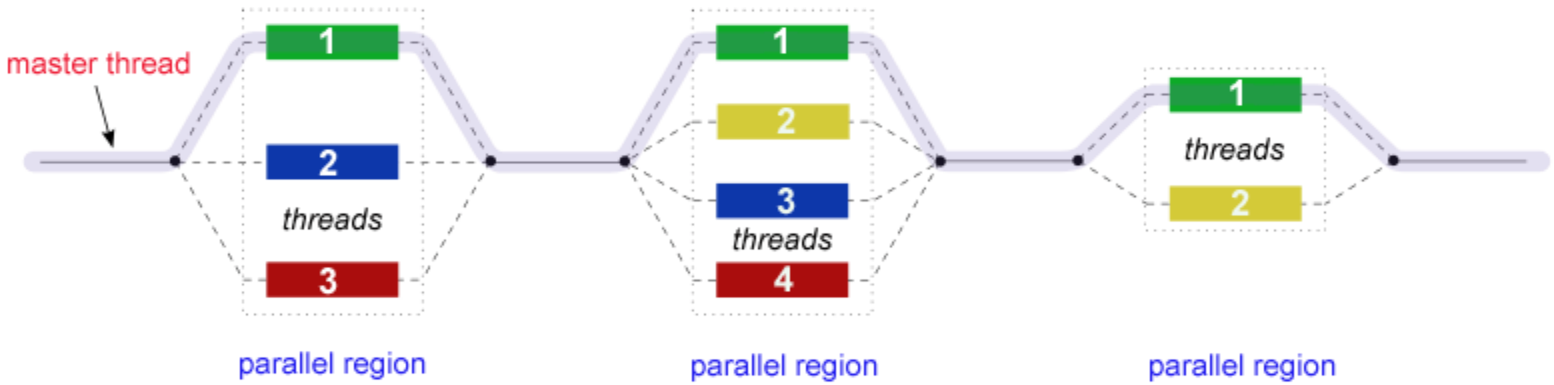
- An abbreviation for
  - Short version: **Open Multi-Processing**
  - Long version: **Open** specifications for **Multi-Processing** via collaborative work between interested parties from the hardware and software industry, government and academia

# OpenMP is Not

- Meant for distributed memory parallel systems (by itself)
- Necessarily implemented identically by all vendors
- Guaranteed to make the most efficient use of shared memory
- Required to check for data dependencies, data conflicts, race conditions, or deadlocks
- Required to check for code sequences that cause a program to be classified as non-conforming
- Meant to cover compiler-generated automatic parallelization and directives to the compiler to assist such parallelization
- Designed to guarantee that input or output to the same file is synchronous when executed in parallel
  - The programmer is responsible for synchronizing input and output

# OpenMP Programming Model

## Fork Join Model



# *Three Components*

- The OpenMP API is comprised of three distinct components. As of version 3.1:
  - Compiler Directives (20)
  - Runtime Library Routines (32)
  - Environment Variables (9)

- The application developer decides how to employ these components

- Implementations differ in their support of all API components
  - For example, an implementation may state that it supports nested parallelism, but the API makes it clear that may be limited to a single thread - the master thread. Not exactly what the developer might expect?

# Compiler Directives

- OpenMP compiler directives are used for various purposes
  - Spawning a parallel region
  - Dividing blocks of code among threads
  - Distributing loop iterations between threads
  - Serializing sections of code
  - Synchronization of work among threads

- Compiler directives have the following syntax:

  ***sentinel directive-name [clause, ...]***

  - \# pragma omp parallel num_threads(thread_count)
  - \# pragma omp parallel default(shared) private(beta,pi)

# Runtime Routines

- The OpenMP API includes an ever-growing number of run-time library routines

- These routines are used for a variety of purposes:
  - Setting and querying the number of threads
  - Querying a thread's unique identifier (thread ID), a thread's ancestor's identifier, the thread team size
  - Setting and querying the dynamic threads feature
  - Querying if in a parallel region, and at what level
  - Setting and querying nested parallelism
  - Setting, initializing and terminating locks and nested locks
  - Querying wall clock time and resolution

# Environment Variable

- OpenMP provides several environment variables for controlling the execution of parallel code at run-time

- These environment variables can be used to control such things as:
  - Setting the number of threads
  - Specifying how loop iterations are divided
  - Binding threads to processors
  - Enabling/disabling nested parallelism; setting the maximum levels of nested parallelism
  - Enabling/disabling dynamic threads
  - Setting thread stack size

# *OpenMP Thread Model*

- Program start with one thread(Master)
- Before parallel region
  - Multiple threads are created
  - Threads have id (0 to p-1)
    - **master thread id is 0**
- At the end of parallel region thread 1 to p-1 join with the thread 0
- There can be multiple parallel region

# OpenMP Code Structure

```
#include <omp.h>
main ()
{
  int var1, var2, var3;
  Serial code . . .
  Beginning of parallel section. Fork a team of threads.   Specify variable scoping
  #pragma omp parallel private(var1, var2) shared(var3)
  {
              Run-time Library calls .
              Other OpenMP directives .

  } All threads join master thread and disband
    Resume serial code . . .
}
```

# Pragmas

- Special preprocessor instructions
- Typically added to a system to allow behaviors that aren't part of the basic C specification
- Compilers that don't support the pragmas ignore #pragma
- OpenMP directives have three parts
  - #pragma omp, Directive, Optional clause (modifies directive)

    Example:

    ```
    # pragma omp  parallel num_thread(6)
    ```

    parallel → Directive; num_thread(6) → Clause

# Parallel Directive

\# pragma omp parallel

- Most basic parallel directive
  - Creates multiple thread
  - Following structured block of code(parallel region) is executed by the threads parallelly (asynchronously)

- There is an implicit barrier at the end of a parallel region

# *How Many Threads*

- Determined by ***num_thread*** clause (more in next slide)
- If ***num_thread*** clause is absent, the number of thread is determined by the value OMP_NUM_THREADS environment variable
- If the variable is not set by the user, then the number of thread is system depended (usually equal to the number of cores-including hyperthreading)

## *num_thread Clause*

- Tells OpenMP runtime systems how many threads to create
- #pragma omp parallel num_thread(8)
  - will create seven new thread (total 8 including master)
- #pragma omp parallel num_thread(x)
  - x must be an integer expression with the runtime value >=1
  - often pass as command line argument

# Restriction on Parallel Region

- A parallel region must be a structured block that does not span multiple routines or code files
- It is illegal to branch (including **goto**) into or out of a parallel region
- Only a single **IF** clause is permitted
- Only a single **NUM_THREADS** clause is permitted

# Runtime Functions

- Following are two most used runtime functions

- int omp_get_num_threads()

  returns *number of threads* in the team

- int omp_get_thread_num()

  returns *thread id* (between 0 to p-1) of thread which called this function

# Hello World Revisited

```
#include <iostream>
#include <omp.h>
int main(int argc, int *argv[])
{
     int p = atoi(argv[1]);
     #pragma omp parallel num_thread(p)
     {
         int thread_count = omp_get__num_threads();
         int my_id = omp_get_thread_num();
         std::cout << “Hello World from ” << my_id << “ of ” <<
        thread_count << std::endl;
     }
     return 0;
}
```

# *Parallel Directive Clauses*

#pragma omp parallel *[clause ...] newline*

num_threads *(integer-expression)*

private *(list)*

shared *(list)*

default (shared | none)

**defines variable scope** (private, shared, default)

reduction *(operator: list)*

firstprivate *(list)*

*lastprivate(list)*

copying*(list)*

If *(scalar_expression)*

*and more ……...*

**will discuss later** (reduction through and more)

# *Scope of Variable*

- In serial programming, the scope of a variable consists of those *parts of a program in which the variable can be used*
- In OpenMP, the scope of a variable refers to the *set of threads* that can access the variable in a *parallel block*

# *Variable Scope in OpenMP*

- A variable that can be accessed by all the threads in the team has **shared** scope

- A variable that can only be accessed by a single thread has **private** scope

- The **default** scope for variables declared *before* a parallel block is **shared** and variable declared *in* the block are **private**

- The default scope can be changed by default, private and shared clause

```
#pragma omp parallel default(shared) private(beta,pi)
```

# *Data Scope Clauses*

- Private
  - A new object of the same type is declared once for each thread in the team
  - All references to the original object are replaced with references to the new object
  - Variables declared **PRIVATE** should be assumed to be uninitialized for each thread

- Shared
  - The SHARED clause declares variables in its list to be shared among all threads in the team
  - It is the programmer's responsibility to ensure that multiple threads properly access **SHARED** variables (such as via **CRITICAL** sections)

# *Default Data Scope Clauses*

- The **DEFAULT** clause allows the user to specify a default scope for all variables in the lexical extent of any parallel region

- Using **NONE** as a default requires that the programmer explicitly scope all variables

- Only one **DEFAULT** clause can be specified on a PARALLEL directive

# Data Scope Example

```
#include <iostream>
#include <omp.h>
int main(int argc, int *argv[1]){
     int p = atoi(argv[1], total = 0);
     #pragma omp parallel num_thread(p)
     {    int x = 0;
          int thread_count = omp_get_num_threads();
          int my_id = omp_get_thread_num();
          x = (my_id + 1) * thread_count;
          total = total + x;
          std::cout << "Id = " << my_id << " x = " << x <<
         std::endl;
      }
     std::cout << "Total= " << total << std::endl;
     return 0;
}
```

# *Synchronization with CRITICAL Directive*

- Private
  - The CRITICAL directive specifies a region of code that must be executed by only one thread at a time
    - **If a thread is currently executing inside a CRITICAL region and another thread reaches that CRITICAL region and attempts to execute it, it will block until the first thread exits that CRITICAL region.**
    - **It is illegal to branch into or out of a CRITICAL block**

```
#pragma omp parallel shared(x)
{
   #pragma omp critical
    x = x + 1;
} /* end of parallel section */
```

# Synchronization Example

```
#include <iostream>
#include <omp.h>
int main(int argc, int *argv[1]){
     int p = atoi(argv[1]);
     int total = 0;
     #pragma omp parallel num_thread(p)
     {  int x = 0;
        int thread_count = omp_get_num_threads();
        int my_id = omp_get_thread_num();
        x = (my_id+1)*thread_count;
        #pragma omp critical
            total = total + x;
        std::cout << "Id = " << my_id << " x = " << x << std::endl;
     }
     std::cout << "Total= " << total << std::endl;
     return 0;
}
```

# Project #2

For this assignment you need to write a parallel program in C++ using OpenMP for vector addition. Assume A, B, C are three vectors of equal length. The program will add the corresponding elements of vectors A and B and will store the sum in the corresponding elements in vector C (in other words C[i] = A[i] + B[i]). Every thread should execute approximately equal number of loop iterations. The only OpenMP directive you are allowed to use is:

```
#pragma omp parallel num_threads(no of threads)
```

The program should take n and the number of threads to use as command line arguments:

```
./parallel_vector_addition <n> <threads>
```

Where ***n*** is the length of the vectors and ***threads*** is the number of threads to be created.

Pseudocode for Assignment

```
mystart = myid*n/p;   // starting index for the individual thread
myend = mystart+n/p;  // ending index for the individual thread
for (i = mystart; i < myend; i++)  // each thread computes local sum
do vector addition                 // and later all local sums combined
```

# Project #2 (Continued)

As an input vector A, initialize its size to 10,000 and elements from 1 to 10,000.

So, A[0] = 1, A[1] = 2, A[2] = 3, … , A[9999] = 10000.

Input vector B will be initialized to the same size with opposite inputs.

So, B[0] = 10000, B[1] = 9999, B[2] = 9998, … , B[9999] = 1

Using above input vectors A and B, create output Vector C which will be computed as

    C[ i ] = A[ i ] + B[ i ];

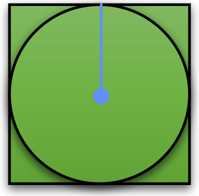
You should check whether your output vector value is 10001 in every C[ i ].

First, start with 2 threads (each thread adding 5,000 vectors), and then do with 4,and and 8 threads. Remember sometimes your vector size can not be divided equally by number of threads. You need to slightly modify pseudo code to handle the situation accordingly. (Hint: If you have p threads, first (p - 1) threads should have equal number of input size and the last thread will take care of whatever the remainder portion.) Check the running time from each experiment and compare the result. Report your findings from this project in a separate paragraph.

Your output should show team of treads do evenly distributed work, but big vector size might cause an issue in output. You can create mini version of original vector in much smaller size of 100 (A[0] = 1, A[1] = 2, A[2] = 3, … , A[99] = 100) and run with 6 threads once and take a snap shop of your output. And run with original size with 2, 4, and 8 threads to compare running times.

# Slightly More Complex Example

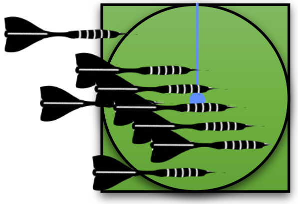
- **Problem: Estimate Pi**



- Consider a circle inside of a square
- Let *p* be the ratio of the area of the circle to the area of the square, then

$$p = \frac{\pi r^2}{4r^2} = \frac{\pi}{4}$$

- So: $\pi = 4p$

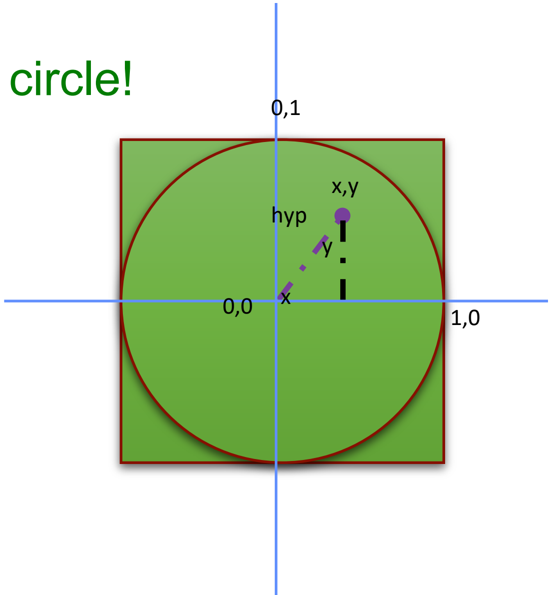


- How do we figure out *p*? The **Monte Carlo** Method
- Throw darts at the square. Lots and lots of darts.
- Count the number of darts that land inside the circle
- Divide the number of darts that land in the circle by total number thrown to estimate *p* !!!
- Multiply by 4, and we have an estimate for $\pi$

# Some Unresolved Questions

- How does a computer throw darts?
  - By generating random x,y coordinates for where the dart would land

- Given an (x,y), how can the computer tell if it landed in the circle
  - Make it simple, use the unit circle, and only throw darts at the upper right quadrant
  - Calculate the distance from 0,0
    - **Just calculate the hypotenuse of the triangle**
  - If *hyp* < 1, then the point falls within the unit circle!



# Java Algorithm

```
class Pi
  function main
    get number of threads from the command line
       argument as numThreads
    create four objects of class Monte
      passing numThreads / 4 to each of their constructors
    for each Runnable object
          create an object of class Thread and pass the Runnable
        to its constructor
          start the thread object
    end for
    wait for 4 threads
    sum answer from each of the four Monte objects into result
    print result
   end function main
end class main
```

```
class Monte implements Runnable
  has integer numIterations
  has double answer

  function run
     create random number generator
     set numInside to 0
     loop numIterations times
       set x to new random number
       set y to new random number
       calculate hyp = square root of x^2+y^2
       if hyp < 1.0
       add 1 to numInside
      end if
    end loop
    set answer to numInside / numIterations
  end function run


  function constructor(iters)
    set numIterations to iters
  end function constructor


end class MyRunnable
```

# Java Code

```java
import java.lang.*;
import java.lang.Math;
import java.util.Random;
import java.util.concurrent.ThreadLocalRandom;

public class Pi {
    public static void main(String[] iters) {
                        int numIter = 0;
                        if (iters.length < 1) {
                            System.err.println("usage: Pi <iterations>");
                            System.exit(0);
                        }
                        try {
                            numIter = Integer.parseInt(iters[0]);
                        } catch (Exception ex) {
                            System.err.println("Bad argument");
                            System.exit(1);
                        }
                        Runnable[] runnables = new Runnable[4];
                        Thread[] threads = new Thread[4];
                        for (int i = 0; i < 4; i++) {
                            runnables[i] = new Monte(numIter/4);
                            threads[i] = new Thread(runnables[i]);
                            threads[i].start();
                        }

                        double answer = 0;
                        try {
                            for (int i = 0; i < 4; i++) {
                                        threads[i].join();
                                        answer += ((Monte)
runnables[i]).getRatio();
                            }
                        } catch (Exception ex) {
                            System.err.println("Thread interrupted");
                            System.exit(2);
                        }

                        System.out.println("Ratio is: " + answer);

    }
}

class Monte implements Runnable {

    private double ratio;
    private int iters;

    public void run() {
                        ratio = findRatio(iters);
    }

    public Monte(int iterations) {
                        iters = iterations;
    }

    public double getRatio() {
                        return ratio;
    }

    private double findRatio(int iterations) {
                        ThreadLocalRandom rand = ThreadLocalRandom.current();
                        int numIn = 0;
                        int numOut = 0;
                        for (int i = 0; i < iterations; i++) {
                            // get random number from 0 to 1
                            double x = rand.nextDouble();
                            double y = rand.nextDouble();
                            double hyp = Math.sqrt(x*x + y*y);
                            if (hyp < 1.0) {
                                        numIn++;
                            } else {
                                        numOut++;
                            }
                        }
                        return ((numIn + 0.0) / (numIn+numOut));
     }

}
```

# *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

# *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**

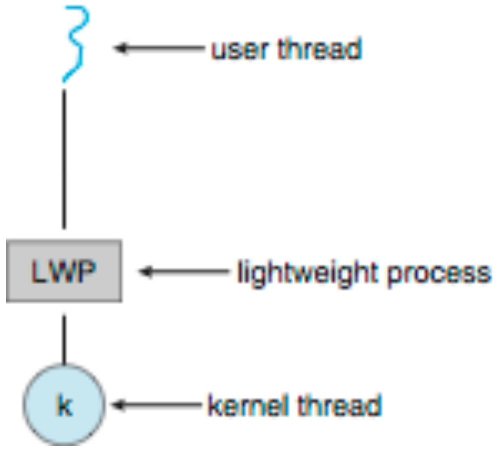
- On Linux systems, thread cancellation is handled through signals

# *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?
- 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, 8 and 10

- Implements the one-to-one mapping, kernel-level

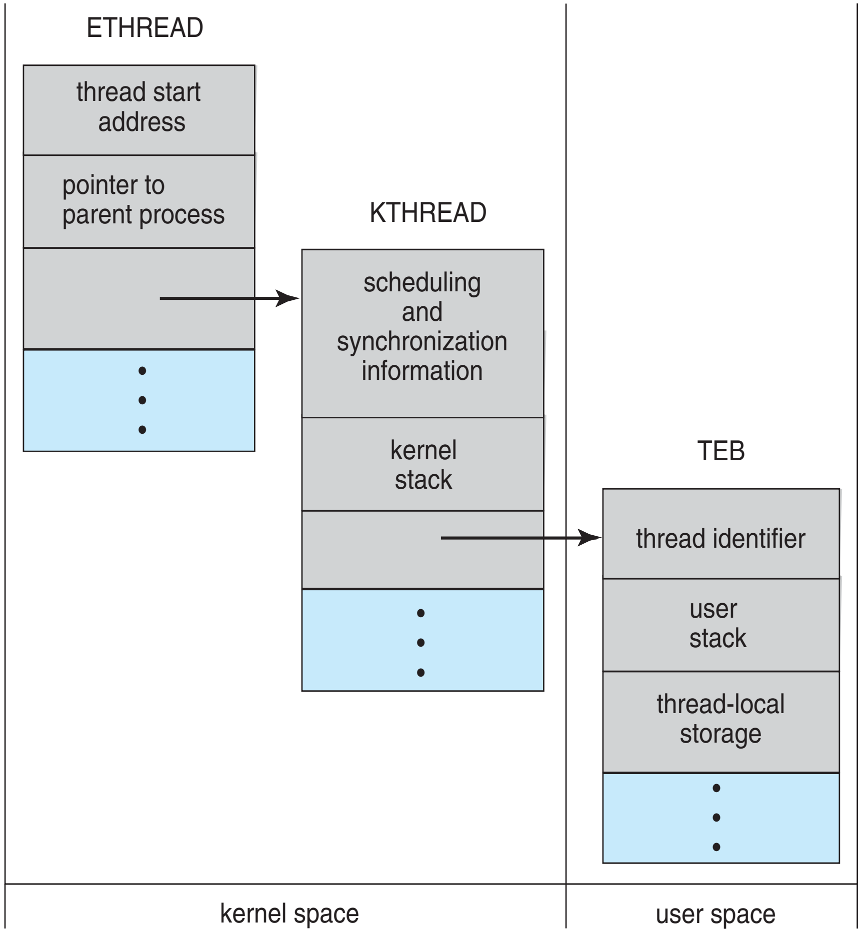
- Each thread contains
  - A thread id
  - Register set representing state of processor
  - Separate user and kernel stacks for when thread runs in user mode or kernel mode
  - Private data storage area used by run-time libraries and dynamic link libraries (DLLs)

- 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)