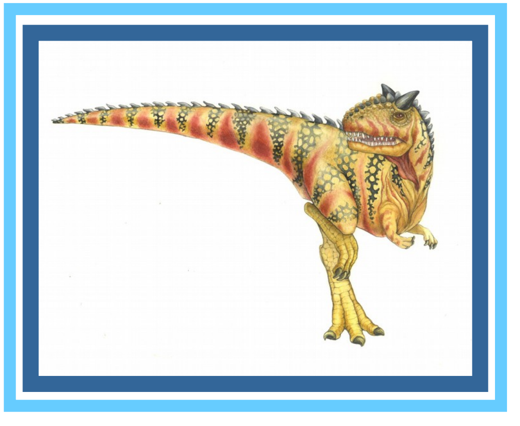
Chapter 4: Threads & Concurrency



Chapter 4: Threads

- Overview
- Multi-core Programming
- Multi-threading Models
- Thread Libraries
- Implicit Threading
- Threading Issues
- Operating System Examples

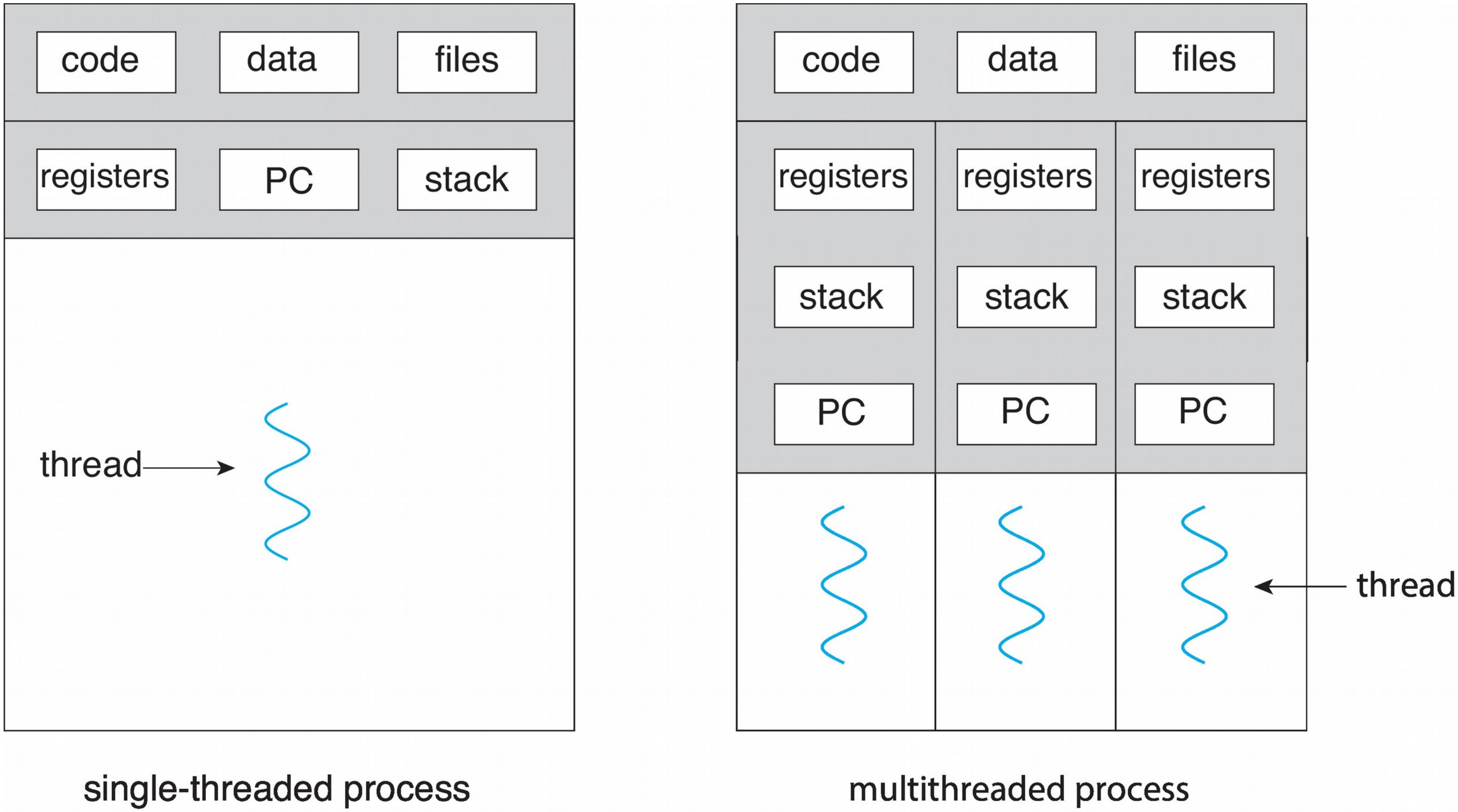
Objectives

- Identify the basic components of a thread, and contrast threads and processes
- Describe the benefits and challenges of designing multi-threaded applications
- Illustrate different approaches to implicit threading, including thread pools and fork-join
- Describe how the Linux operating system represents threads
- Explore multi-threaded applications using the Pthreads, Java, and Windows threading APIs

Motivation

- Kernels are generally multi-threaded
- Most modern applications are multi-threaded
- Whereas cooperating processes are independent, cooperating threads run within the same process (think application)
- Multiple functions or tasks within an application can be implemented by separate threads. Example decomposition:
  - A thread to update display
  - A thread to fetch data from a database
  - A thread to run a tool such as a spell-checker
  - A thread to respond to a network request
- Process creation is costly and slow, whereas thread creation is light-weight
- Proper threading can simplify code, increase efficiency

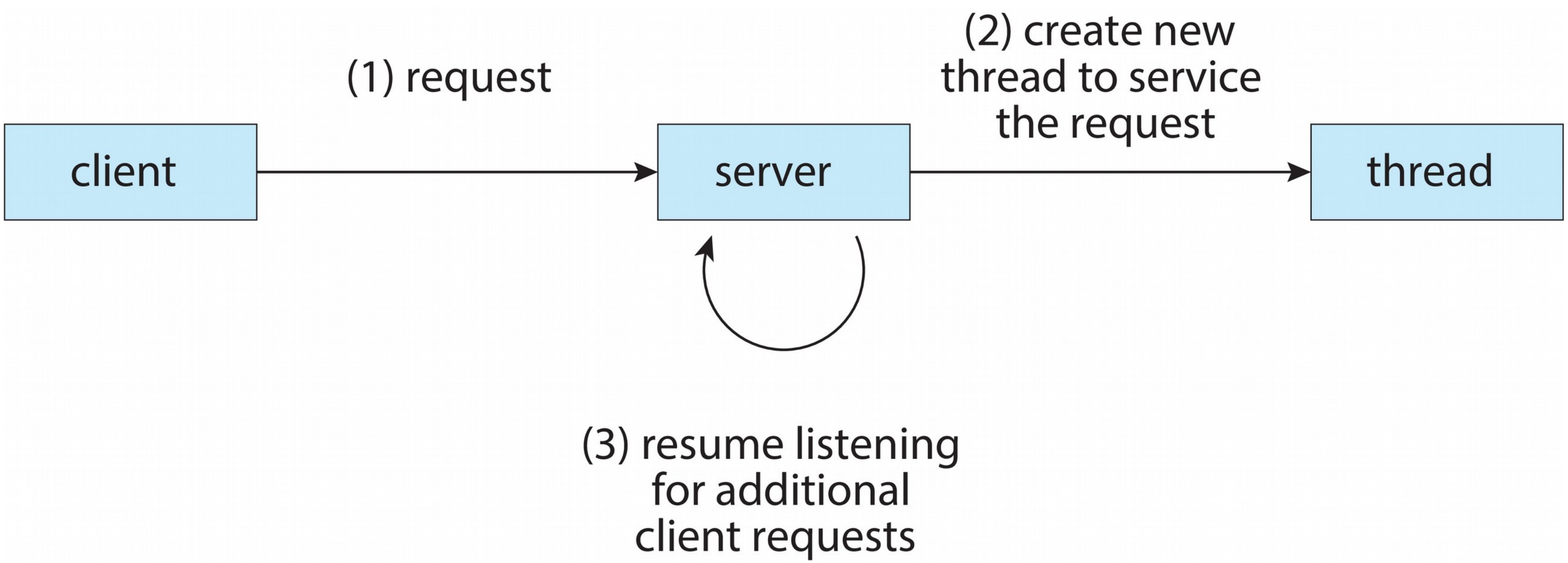
Single versus Multi-threaded Processes



Each thread has its own register set, stack, and PC.

Multi-threaded Server Architecture

1) client sends request to server;
2) server creates a thread to process the request, and
3) immediately returns to listening for the next request
   from a client in the same main thread.



Benefits of Threads

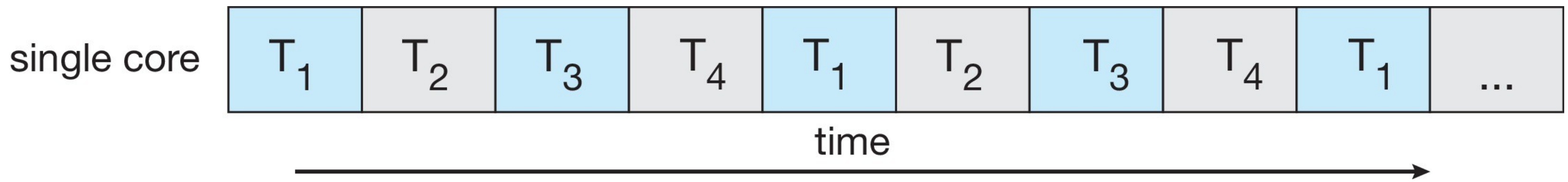
- **Responsiveness –** may allow continued execution if part of process is blocked, or some slow operation in a different thread - especially important for user interfaces
- **Resource Sharing –** threads share same address space in single process, easier than processes using shared memory or message passing
- **Cost –** cheaper than process creation, thread switching lower overhead than context switching
- **Scalability –** process can take advantage of multi-core architectures

Concurrency vs. Parallelism

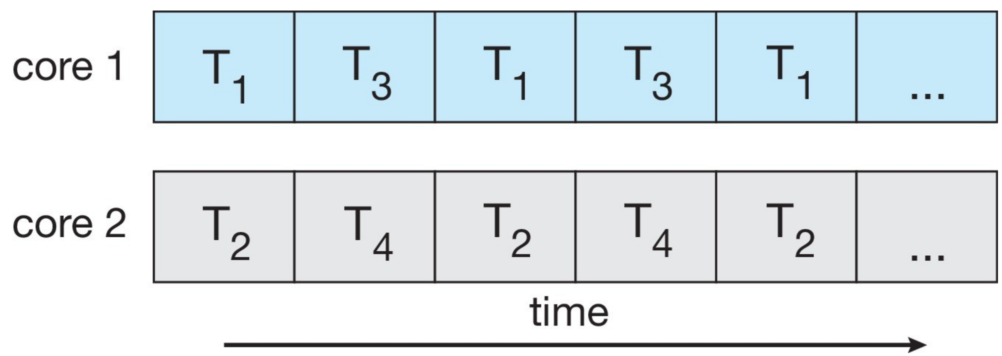
- Two or more sequences of instructions are said to be **concurrent** if no matter what order they are executed in relation to each other, the final result of their combined computation is the same.
- This means that they can be executed simultaneously on different processors, or interleaved on a single processor in any order, and whatever outputs they produce will be the same.
- A system with two ore more concurrent processes is called a **concurrent program** or a **concurrent system**.
- Two processes or threads execute **in parallel** if they execute at the same time on different processors.
- **Parallel programs** are those containing instruction sequences that can be executed in parallel. A parallel program is always a concurrent program, but a system can have concurrency even though it is not a parallel program.

Concurrency vs. Parallelism

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



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



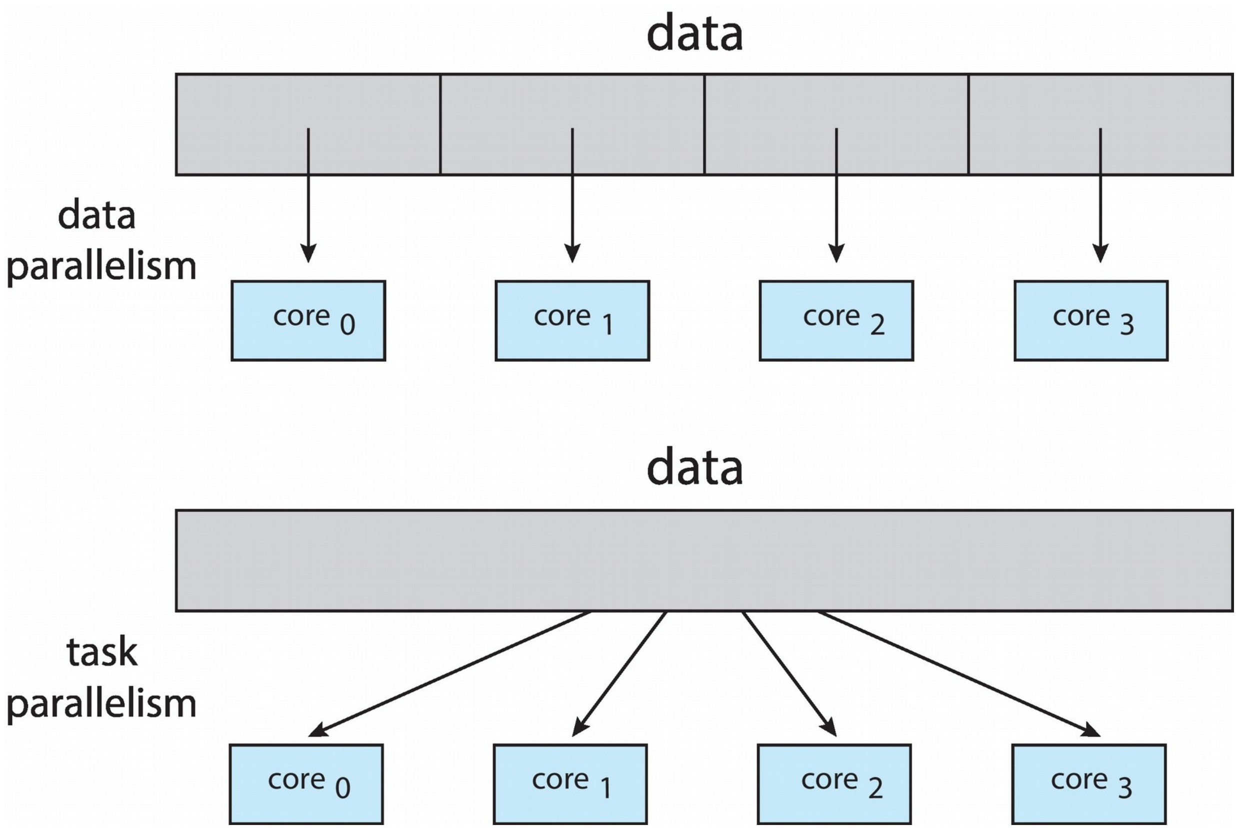
Multi-core Programming

- **Multi-core** or **multi-processor** systems challenge programmers to take advantage of hardware, but it is not easy:
  - **How to decompose a single task into many independent parallel tasks**
  - **How to load-balance the tasks**
  - **How to split data onto separate cores/processors**
  - **How to identify data dependency and handle synchronization**
  - **How to test and debug parallel programs**

Multi-core Programming (cont.)

- Types of inherent parallelism:
  - **Data parallelism** – distributes subsets of the same data across multiple cores, same operation on each
    - an image on which the same operation is applied to all pixels
    - a payroll with taxes to be calculated for all individuals
    - a set of points to be rotated through same angle in space
  - **Task parallelism** – distributing threads across cores, each thread performing unique operation
    - same data set evaluated by multiple algorithms for some property (census data analyzed for demographics, financials, geographic, etc)

Data and Task Parallelism



Amdahl's Law

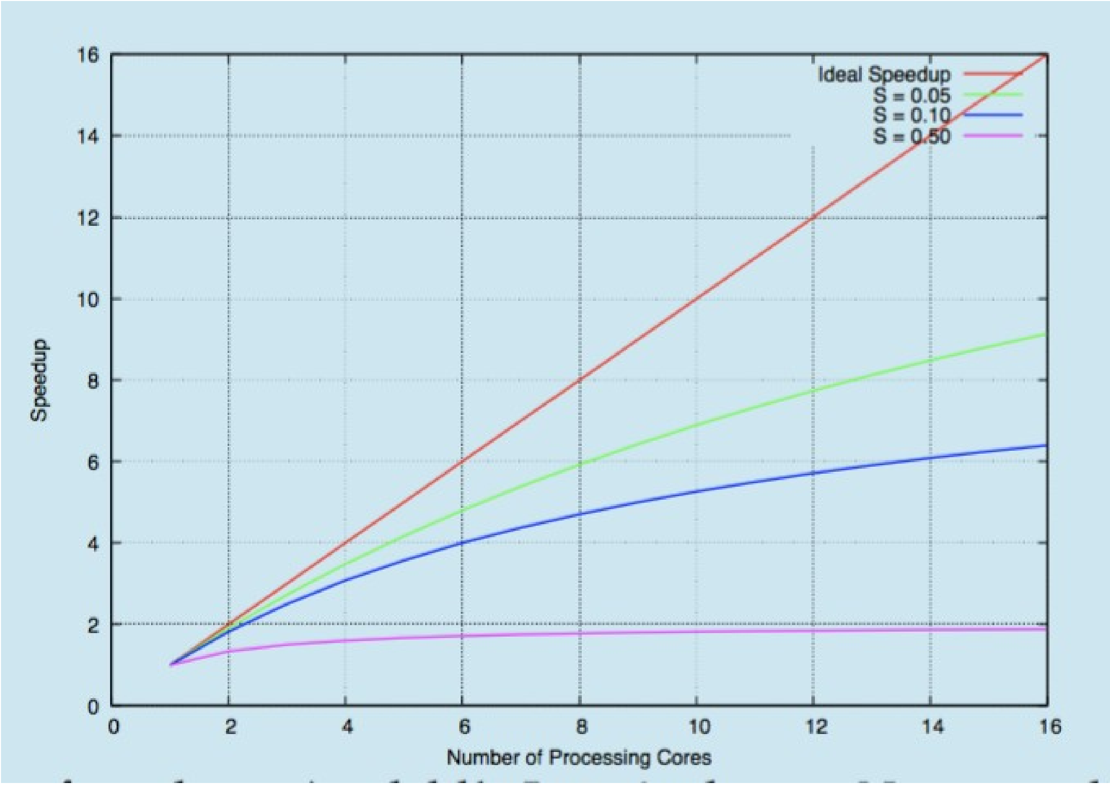
- In 1967, Gene Amdahl argued that there was an inherent limitation to the amount of speedup that could be obtained by performing a computation using more processors. His argument is known as "Amdahl's Law". If
  - *S, 0 <= S <= 1,* is the fraction of operations that must be executed serially (in sequence), and
  - *N* is the number of processing cores, then the speed-up is bounded above:

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

- Example: if program is 75% parallel / 25% serial, (S=0.25) moving from 1 to 2 cores (N=2) results in speedup of 1/((1/4) + (3/4)/2)) = 1.6
- As *N* approaches infinity, speedup approaches 1 / *S*

Serial portion of an application limits maximum performance gained by adding additional cores

Amdahl's Law Graphically

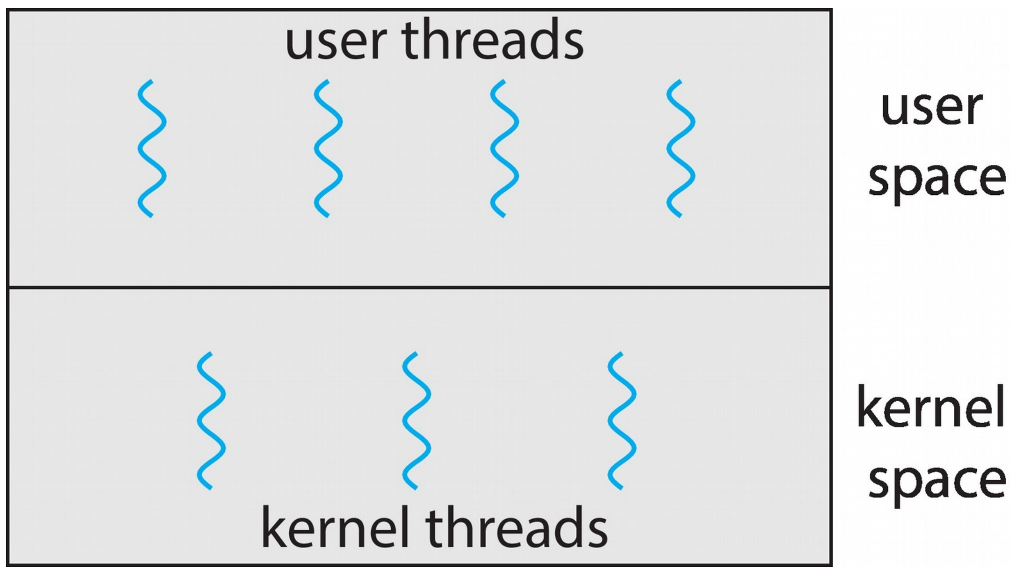


User Threads and Kernel Threads

- **User threads** are supported by user-level libraries
- Three primary user thread libraries:
  - POSIX **Pthreads**
  - Windows threads
  - Java threads
- **Kernel threads** are supported directly by the kernel
  - Examples – virtually all modern operating systems, including:
    - Windows
    - Linux
    - Mac OS X
    - iOS
    - Android

User and Kernel Threads

- When threads are provided as user threads, they still must be mapped onto kernel threads.
- There is not necessarily an equal number of user and kernel threads.

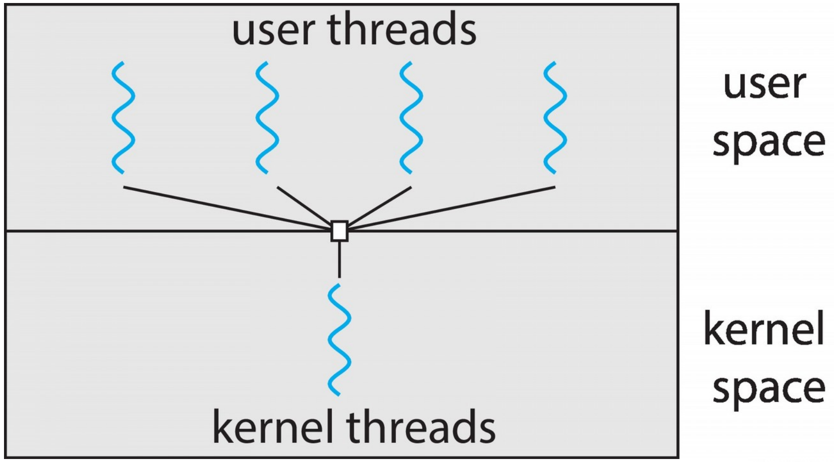


Multi-threading Models

- How to map user threads to kernel threads?
- Three different models:
  - Many-to-One: many user-level threads map to single kernel thread
  - One-to-One: one user-level thread maps to one kernel thread
  - Many-to-Many: many user-level threads map to many kernel threads

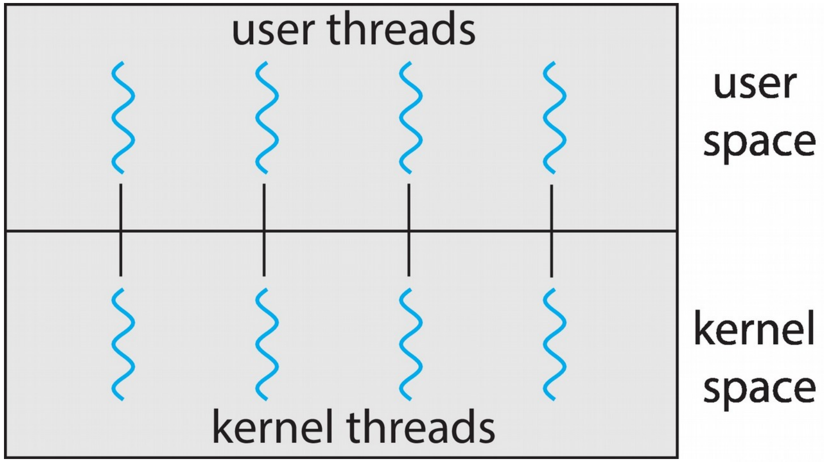
Many-to-One

- Many user-level threads mapped to single kernel thread.
- Weaknesses:
  - One thread blocking causes all to block
  - Multiple threads may not run in parallel on multi-core system because only one may be in kernel at a time
- Few systems currently use this model because modern systems have many cores which are not utilized well.
- Examples:
  - **Solaris Green Threads**
  - **GNU Portable Threads**



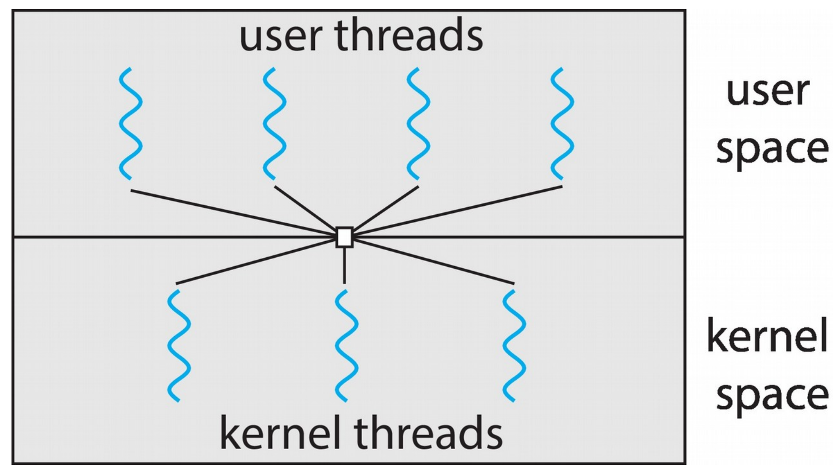
One-to-One

- Each user-level thread maps to one 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:
  - Creating a user thread requires creating a kernel thread, and too many kernel threads can degrade performance of system.
- Examples
  - Windows
  - Linux



Many-to-Many Model

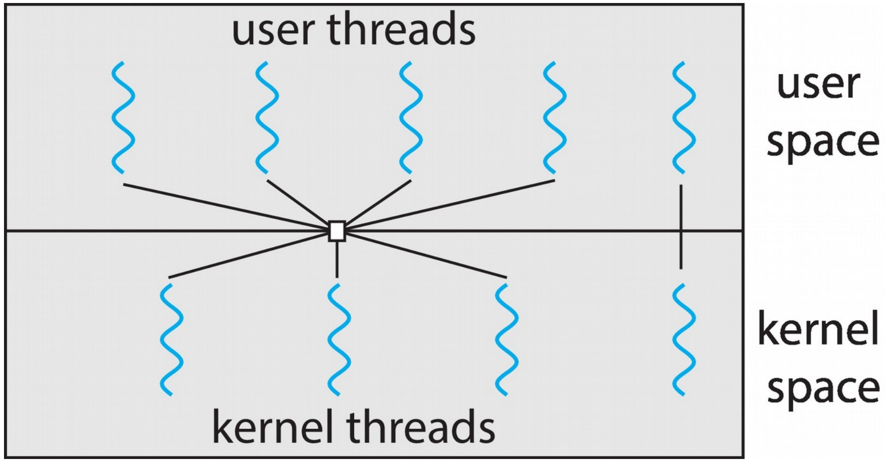
- Allows many user level threads to be multiplexed onto an equal or smaller number of kernel threads
- Allows the operating system to create a sufficient number of kernel threads
- Program can have as many user threads as necessary, and the corresponding kernel threads can run in parallel on a multiprocessor. If thread blocks, kernel can schedule a different thread.



- Windows with the ThreadFiber package
- Otherwise not very common

Two-level Model

- Similar to the many-to-many, except that it allows a user thread to be **bound** to a kernel thread.



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
- Three prevalent libraries: POSIX threads (Pthreads), Windows, and Java threads.

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 (Linux & Mac OS X)

Pthreads Example 1

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

void* hello_world( void* unused)
{
    printf("The child says, \"Hello world!\"\n");
    pthread_exit(NULL) ;
}

int main( int argc, char *argv[])
{
    pthread_t  child_thread;

    /* Create the thread and launch it. */
    if ( 0 != pthread_create(&child_thread, NULL,
       hello_world, NULL ) ){
        printf("pthread_create failed.\n");
        exit(1);
    }
    printf("This is the parent thread.\n");
    /* Wait for the child thread to terminate. */
    pthread_join(child_thread, NULL);
    return 0;
}
```

Pthreads Example 2

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

#include <stdlib.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 */

   /* set the default attributes of the thread */
   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);
}
```

Pthreads Example 2 (cont)

```
/* The thread will execute 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 Multi-threaded C Program

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

/* The thread will execute in this function */
DWORD WINAPI Summation(LPVOID Param)
{
   DWORD Upper = *(DWORD*)Param;
   for (DWORD i = 1; i <= Upper; i++)
      Sum += i;
   return 0;
}
```

Windows Multi-threaded C Program (Cont.)

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

   Param = atoi(argv[1]);
   /* 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 */

    /* now wait for the thread to finish */
   WaitForSingleObject(ThreadHandle,INFINITE);

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

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

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
- Five methods explored
  - Thread Pools
  - Fork-Join
  - OpenMP
  - Grand Central Dispatch
  - Intel Threading Building Blocks

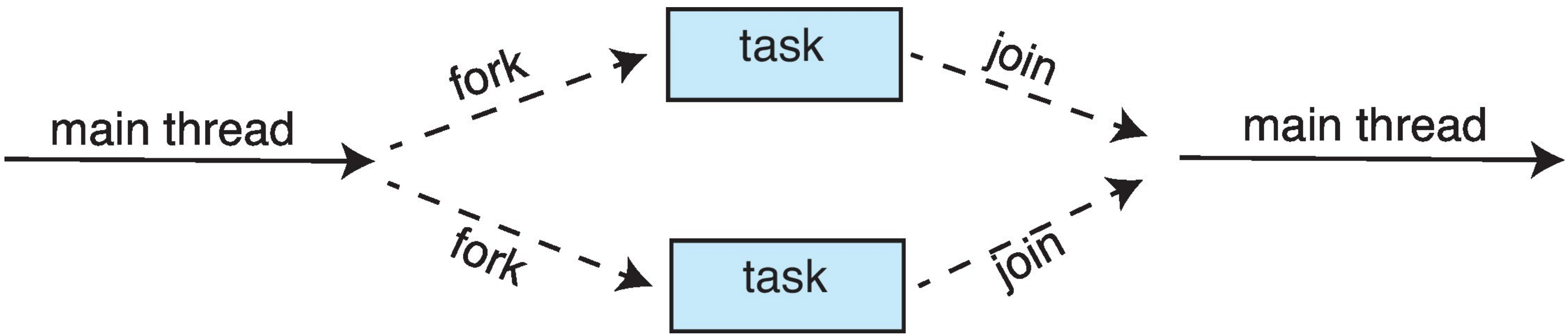
Thread Pools

- 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.
    */
}
```

Fork-Join Parallelism

- Multiple threads (tasks) are **forked**, and then **joined**.



Fork-Join Parallelism

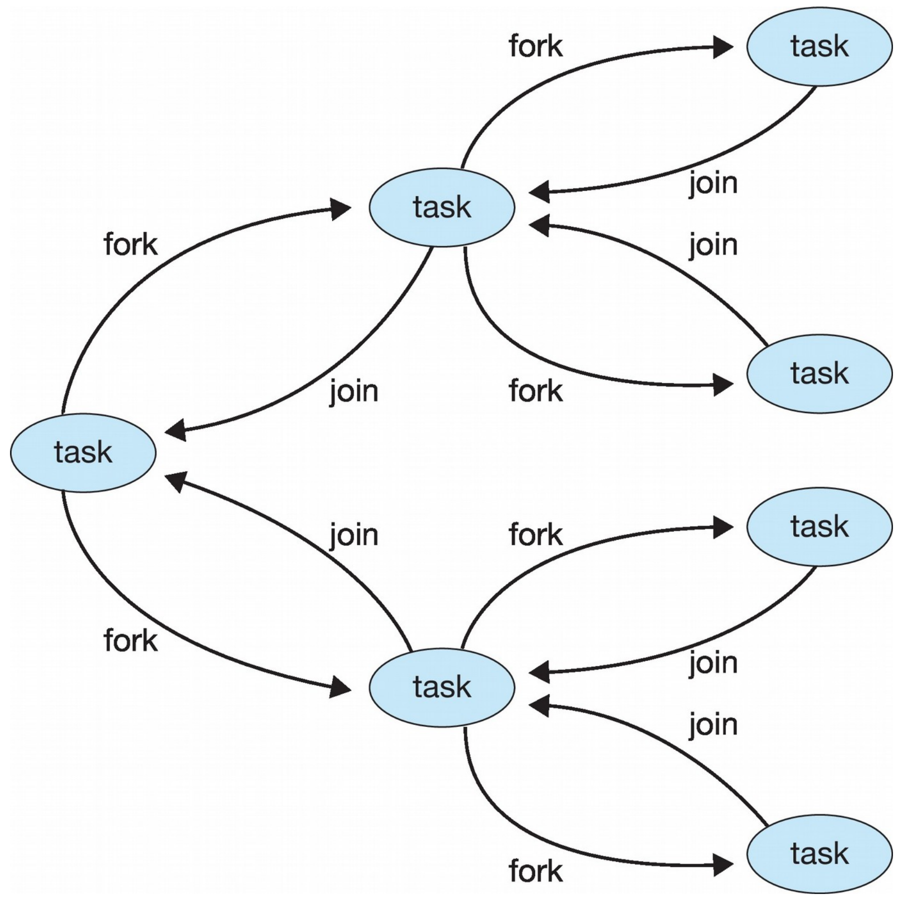
- General algorithm for fork-join strategy:

```
Task(problem)
   if problem is small enough
      solve the problem directly
   else
      subtask1 = fork(new Task(subset of problem)
      subtask2 = fork(new Task(subset of problem)

      result1 = join(subtask1)
      result2 = join(subtask2)

      return combined results
```

Fork-Join Parallelism



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

```
#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;
}
```

OpenMP Example

- Run the for loop in parallel

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

Grand Central Dispatch

- Apple technology for macOS and iOS operating systems
- Extensions to C, C++ and Objective-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 (cont)

- 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
    - Four system wide queues divided by quality of service:
      - `QOS_CLASS_USER_INTERACTIVE`
      - `QOS_CLASS_USER_INITIATED`
      - `QOS_CLASS_USER_UTILITY`
      - `QOS_CLASS_USER_BACKGROUND`

Grand Central Dispatch (3)

- For the Swift language a task is defined as a closure – similar to a block, minus the caret
- Closures are submitted to the queue using the `dispatch_async()` function:

```
let queue = dispatch_get_global_queue
   (QOS_CLASS_USER_INITIATED, 0)

dispatch_async(queue,{ print("I am a closure.") })
```

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);

/* wait for the thread to terminate */
pthread_join(tid,NULL);
```

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

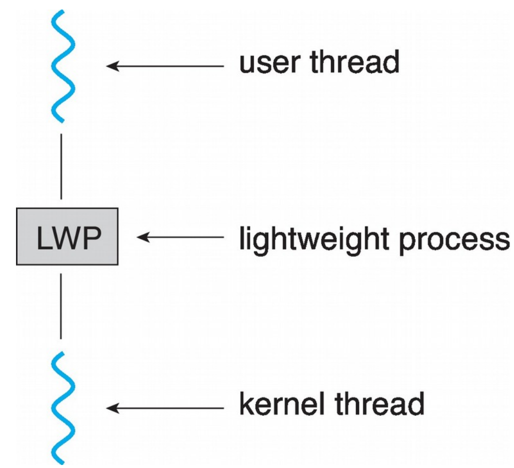
- If thread has cancellation disabled, cancellation remains pending until thread enables it
- Default type is deferred
  - Cancellation only occurs when thread reaches **cancellation point**
    - I.e. **`pthread_testcancel()`**
    - Then **cleanup handler** is invoked
- On Linux systems, thread cancellation 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

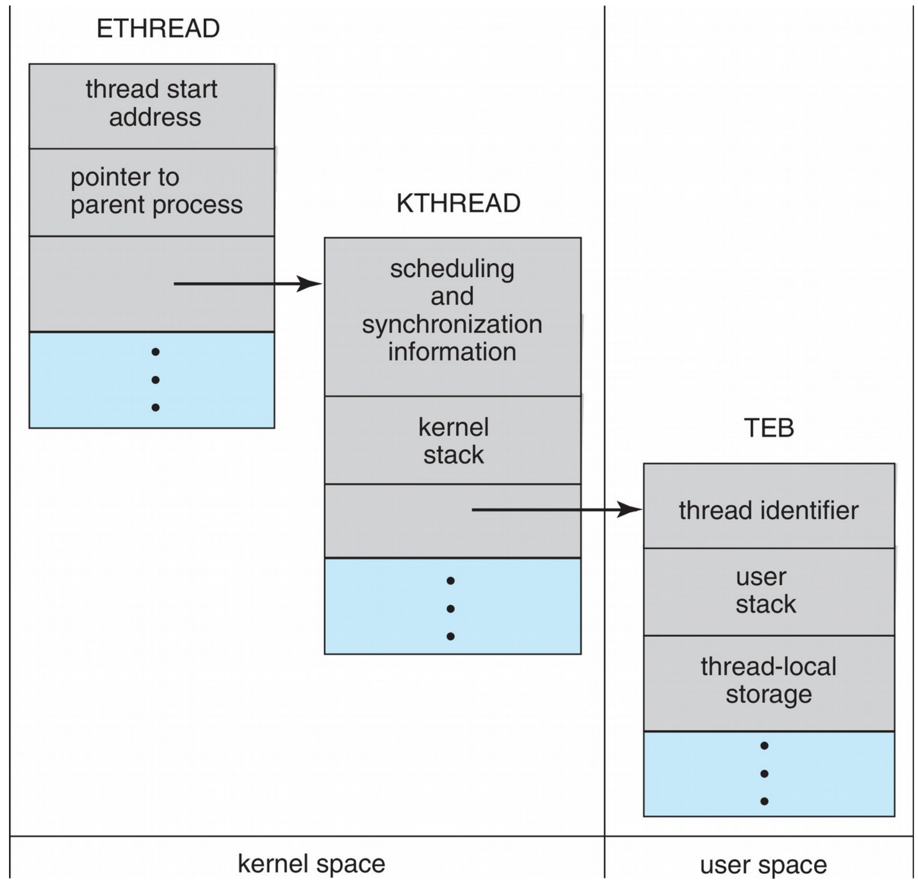
Windows Threads

- Windows API – primary API for Windows applications
- 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