CS370 Operating Systems

Colorado State University

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Fall 2024 Lecture 8 Threads

Slides based on

- Text by Silberschatz, Galvin, Gagne
- Various sources

Today

- Threads
- Amdahl's law
- Kernel support for threads
- Pthreads
- Java Threads
- Implicit threading

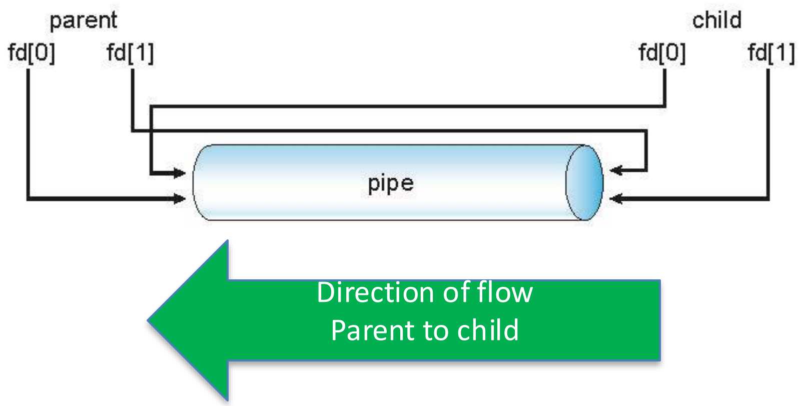
UNIX pipe example

Parent Process:

```
        #define READ_END        0
        #define WRITE_END       1
      int fd[2];
 create the pipe:
        if (pipe(fd) == -1) {
                fprintf(stderr,"Pipe failed");
                return 1;
 fork a child process:
        pid = fork();
 parent process:
        close(fd[READ_END]);    /* close the unused end of the pipe */
        write(fd[WRITE_END], write_msg, strlen(write_msg)+1);    /* write to the pipe */
        close(fd[WRITE_END]);   /* close the write end of the pipe */
```

child process:

```
        close(fd[WRITE_END]);    /* close the unused end of the pipe */
        read(fd[READ_END], read_msg, BUFFER_SIZE);     /* read from the pipe */
        printf("child read %s\n",read_msg);
        close(fd[READ_END]);    /* close the write end of the pipe */
```



Synchronization not considered here to keep illustration simple.

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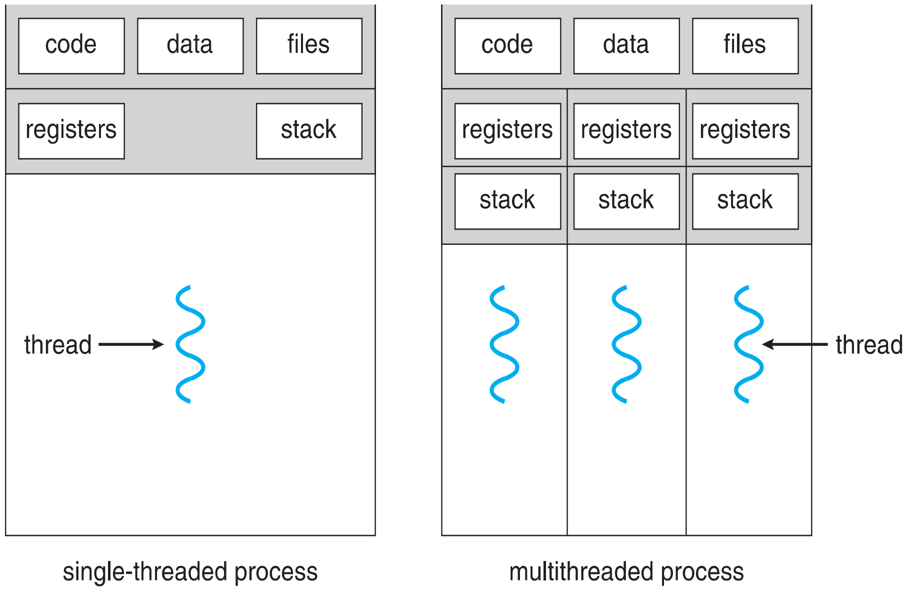
Chapter 4: Threads

Objectives:

- Thread—basis of multithreaded systems
- APIs for the Pthreads and Java thread libraries
- implicit threading, multithreaded programming
- OS support for threads



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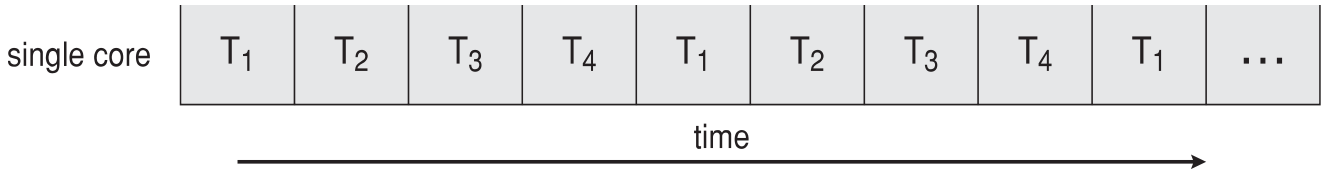
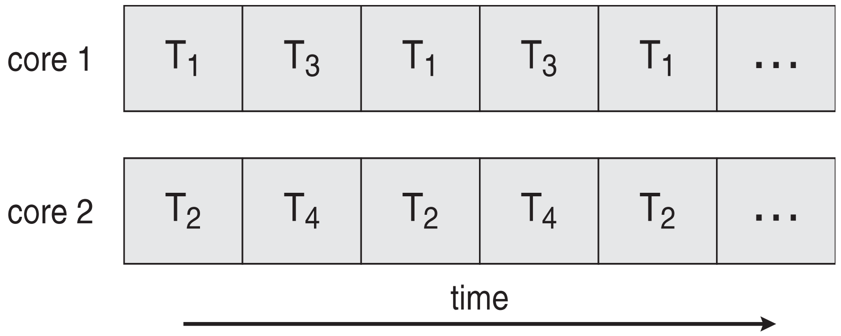
Concurrency vs. Parallelism

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



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



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Amdahl's Law: Multicore systems

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

- *S* is serial portion (as a fraction) that cannot be broken into parallel operations.
- Some things can possibly be done in parallel.
- *N* processing cores

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

- **Example**: if application is 75% parallel / 25% serial, moving from 1 to 2 cores results in speedup of

  1/(0.25+ 0.75/2) = 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

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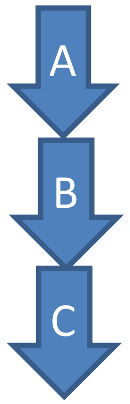
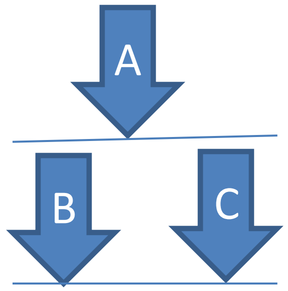
Amdahls law: ordinary life example

- Amdahls law: ordinary life example.

  Which of the two option is faster?

  - Person A cooks, person B eats and then Person C eats.
  - Person A cooks, then both person B and person C eat at the same time.





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User Threads and Kernel Threads

- **User threads** - management done by user-level threads library
- Three main thread libraries:
  - POSIX **Pthreads**
  - Windows threads
  - Java threads
- **Kernel threads** - Supported by the Kernel
  - Examples – virtually all general-purpose operating systems, including:
    - Windows
    - Linux
    - Mac OS X

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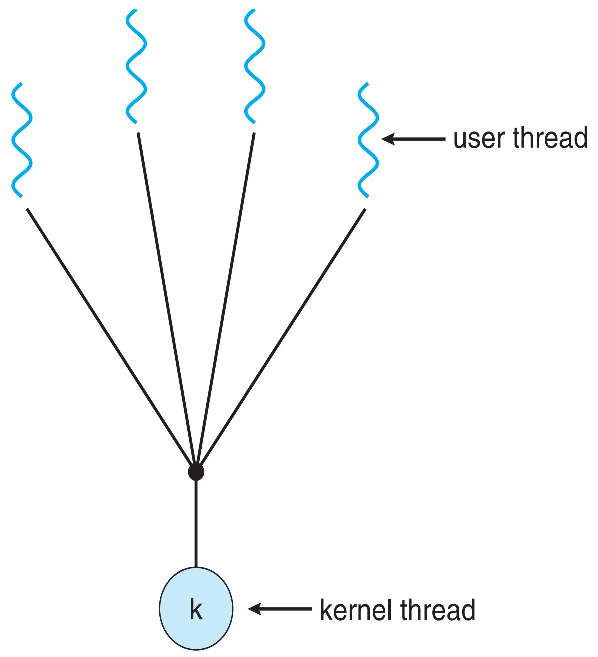
Multithreading Models

How do kernel threads support user process threads?

- Many-to-One: Many user-level threads mapped to single kernel thread (thread library in user space older model)
- One-to-One: (now common)
- Many-to-Many: Allows many user level threads to be mapped to smaller or equal number of kernel threads (older systems)

Many-to-One

- Many user-level threads mapped to single kernel thread (thread library in user space older model)
- 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 for Java 1996
  - GNU Portable Threads 2006



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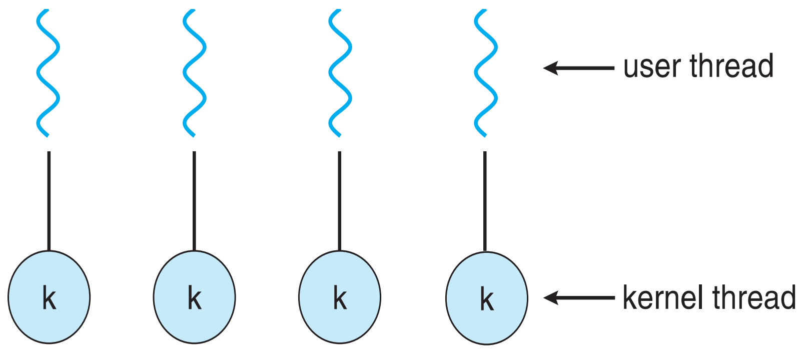
One-to-One

- 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



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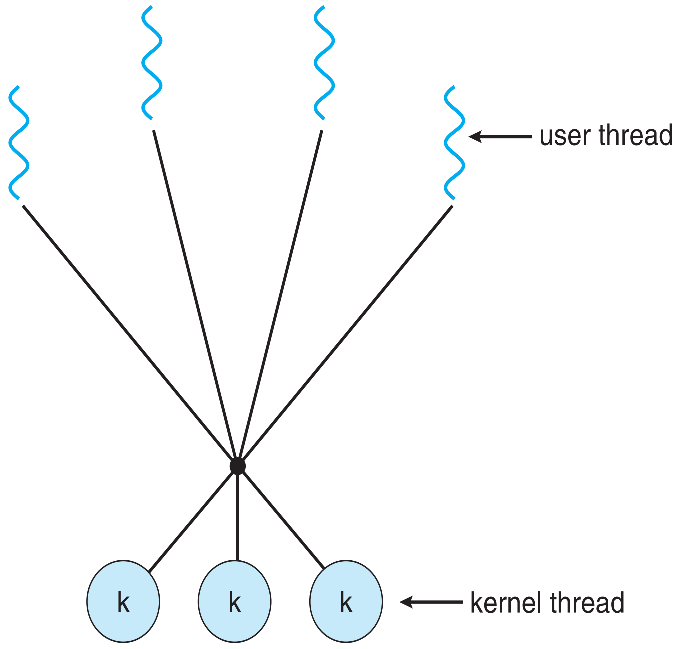
Many-to-Many Model

- Allows many user level threads to be mapped to smaller or equal number of kernel threads
- Allows the operating system to create a sufficient number of kernel threads
- Solaris prior to version 9 2002-3
- Windows with the *ThreadFiber* package NT/2000



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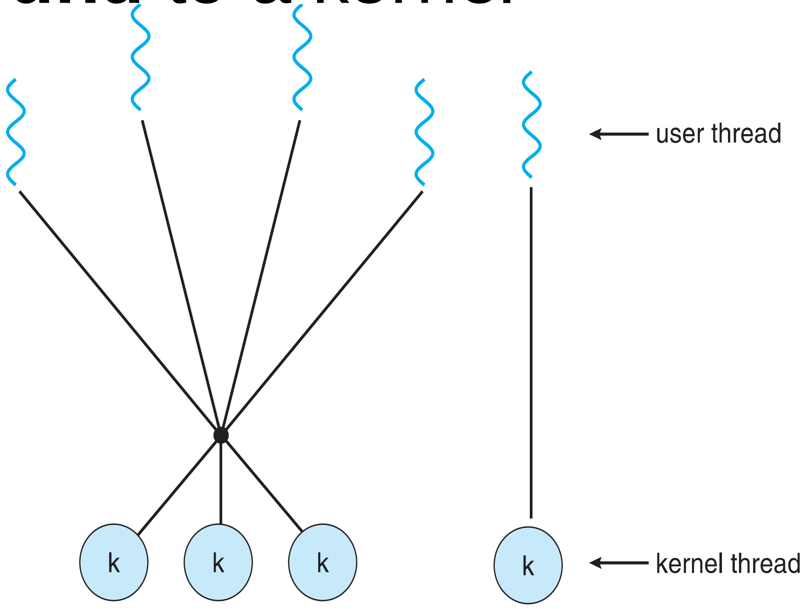
Two-level Model

- Similar to M:M, except that it allows a user thread to be **bound** to a kernel thread
- Examples
  - IRIX -2006
  - HP-UX
  - Tru64 UNIX
  - Solaris 8 and earlier



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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

POSIX Pthreads

- May be provided either as user-level or kernel-level
- A POSIX standard (IEEE 1003.1c) API for thread creation and synchronization 1991
- ***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)

Some Pthread management functions

POSIX function	Description
pthread_cancel	Terminate a thread
pthread_create	Create a thread
pthread_detach	Set thread to release resources
pthread_exit	Exit a thread without exiting process
pthread_kill	Send a signal to a thread
pthread_join	Wait for a thread
pthread_self	Find out own thread ID

- Return 0 if successful

POSIX: Thread creation pthread_create()

- Automatically makes the thread runnable without a start operation
- Takes 3 parameters:
  - Points to ID of newly created thread
  - Attributes for the thread
    - Stack size, scheduling information, etc.
  - Name of function that the thread calls when it begins execution with argument

```
/* create the thread */
pthread_create(&tid, &attr, runner, argv[1]);
```

POSIX: Detaching and Joining

- pthread_detach()
  - Sets internal options to specify that storage for thread can be reclaimed when it exits
  - 1 parameter: Thread ID of the thread to detach
  - Undetached threads don't release resources until
    - Another thread calls pthread_join for them
    - Or the whole process exits
- pthread_join
  - Takes ID of the thread to wait for
  - Suspends calling thread till target terminates
  - Similar to waitpid at the process level

```
pthread_join(tid, NULL);
```

POSIX: Exiting and cancellation

- If a process calls exit, **all** threads terminate
- Call to pthread_exit causes only the calling thread to terminate

pthread_exit(0)

- Threads can force other threads to return through a *cancellation* mechanism
  - pthread_cancel ( ): takes thread ID of target
  - Actual cancellation depends on *type* and *state* of thread

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Pthreads Example (next 2 slides)

- This process will have two threads
  - Initial/main thread to execute the main ( ) function. It crates a new thread and waits for it to finish.
  - A new thread that runs function runner ( )
    - It will get a parameter, an integer, and will compute the sum of all integers from 1 to that number.
    - New thread leaves the result in a global variable **sum**.
  - The main thread prints the result.

Pthreads Example Pt 1

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

int sum; /* this global data is shared by the thread(s) */

void *runner(void *param); /* the thread */

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

if (argc != 2) {
                fprintf(stderr,"usage: a.out <integer value>\n");
                /*exit(1);*/
                return -1;
}

if (atoi(argv[1]) < 0) {
                fprintf(stderr,"Argument %d must be non-negative\n",atoi(argv[1]));
                /*exit(1);*/
                return -1;
}
```

thread runner will perform summation of integers 1,2, ..n

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Pthreads Example Pt 2

```
/* get the default attributes */
pthread_attr_init(&attr);
/* create the thread */
pthread_create(&tid, &attr, runner, argv[1]);   <- Second thread begins in runner () function
/* now 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;
          if (upper > 0) {
                    for (i = 1; i <= upper; i++)
                              sum += i;
          }
          pthread_exit(0);
}
```

Compile using
gcc thrd.c –lpthread

Execution:
```
%./thrd 4
sum = 10
```

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Pthreads Code for Multiple Threads

```
/* create the threads */
for (i = 0; i < NUM_THREADS; i++)
            pthread_create(&tid[i], &attr, runner, NULL);

/* now join on each thread */
for (i = 0; i < NUM_THREADS; i++)
            pthread_join(tid[i], NULL);
}
/* Each thread will begin control in this function */

void *runner(void *param)
{
            /* do some work ... */
pthread_exit(0);
}
```

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
    - Override its run() method
  - More commonly, implementing the Runnable interface

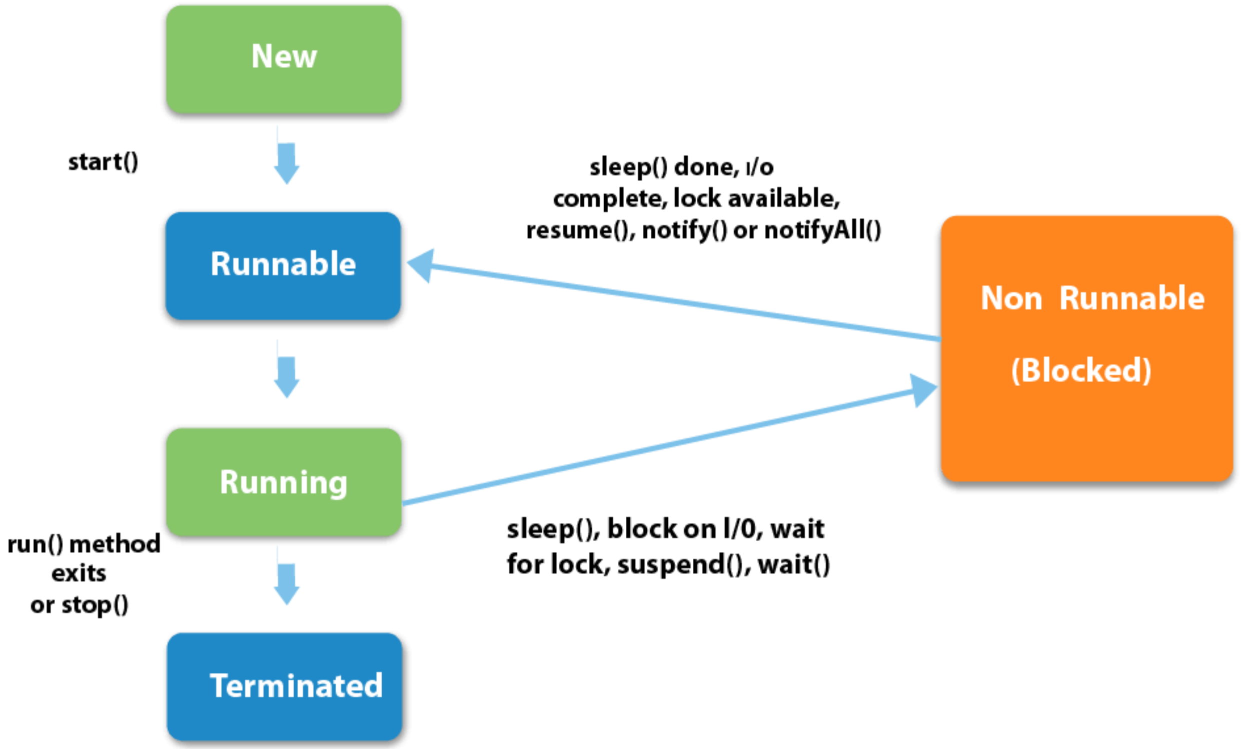
Runnable interface is defined by

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

1. Has 1 method run()
2. Create new Thread class by passing a I object to its constructor
3. start( ) method creates a new thread by calling the run( ) method.

- new features available in java.util.concurrent package

Java Thread States


New
start()
Runnable
sleep() done, I/o complete, lock available, resume(), notify() or notifyAll()
Non Runnable (Blocked)
Running
sleep(), block on I/0, wait for lock, suspend(), wait()
run() method exits or stop()
Terminated

https://www.javatpoint.com/life-cycle-of-a-thread

Ex: Using Java Threads (1/3)

Java version of a multithreaded program that computes summation of a non-negative integer.
This program creates a separate thread by implementing the Runnable interface.

```
class Sum
{
            private int sum;

            public int get() {
                        return sum;
            }

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

Program Overall Structure

```
class sum
{    }
class summation implements runnable
{ …
    public void run( ) { ..   }
}
Public class Driver
 {  …..
    public static void main(String[ ] args) {

      Thread worker = new Thread(new summation( …
      worker.start();
      try {
             worker.join();   ….
                                  }
```

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Ex: Using Java Threads (2/3)

```
class Summation implements Runnable
{
        private int upper;
        private Sum sumValue;
//constructor
        public Summation(int upper, Sum sumValue) {
                if (upper < 0)
                        throw new IllegalArgumentException();

                this.upper = upper;
                this.sumValue = sumValue;
        }

//this method runs as a separate thread
        public void run() {
                int sum = 0;

                for (int i = 0; i <= upper; i++)
                        sum += i;

                sumValue.set(sum);
        }
}
```

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Ex: Using Java Threads (3/3)

```
public class Driver
{
        public static void main(String[ ] args) {
                if (args.length != 1) {
                        System.err.println("Usage Driver <integer>");
                        System.exit(0);
                }

                Sum sumObject = new Sum();
                int upper = Integer.parseInt(args[0]);

                Thread worker = new Thread(new Summation(upper, sumObject));
                worker.start( );
                try {
                        worker.join();
                } catch (InterruptedException ie) { }
                System.out.println("The sum of " + upper + " is " + sumObject.get());
        }
}
```

A call to run( )

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

Implicit Threading1: 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
- Posix thread pools
- Windows API supports thread pools.

Implicit Threading2: 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

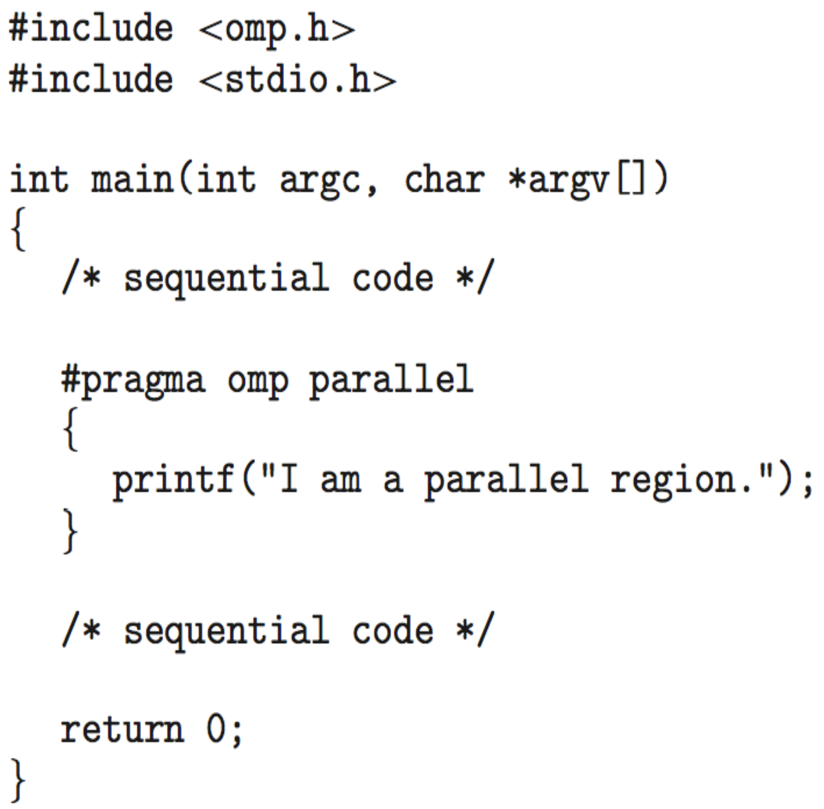
```
#pragma omp parallel
```

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

Compile using
gcc -fopenmp openmp.c



```
#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;
}
```

Self exercise 3, 4 available now.

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Implicit Threading3: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

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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

Semantics of fork() and exec()

- Does **`fork()`** duplicate only the calling thread or all threads?
  - Some UNIXes have two versions of fork
  - 1. when exec( ) will replace the entire process, dup just that thread
  - 2. duplicate all threads
- **`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 process?
  - 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? common

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

    `pthread_setcanceltype (PTHREAD_CANCEL_ASYNCHRONOUS, NULL);`
  - **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);
```

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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

- A thread’s cancelation type (mode) and state can be set.
- 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)
  - Ex: Each transaction has a thread and a transaction identifier is needed.
- 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

Is complexity always good?

- Is something that is
  - More advanced
  - More complex

  Generally better?

Hyper-threading

“Hyper-threading”: “simultaneous multithreading”:

- Hardware support for multiple threads in the same core (CPU)

- Performance:
  - performance improvements are very application-dependent
  - Higher energy consumption ARM 2006
  - Not better than out-of-order execution Intel 2013
  - Intel has dropped it in some chips Core i7-9700K 2018 8 cores, 8 threads, Core i-9 10900K 2020 10 cores, 20 threads
  - Can cause security issues. Sometimes disabled by default.
  - May be enabled/disabled using firmware

Forms of Parallelism

- Pipelining: instruction flows though multiple levels
- Multiple issue: Instruction level Parallelism (ILP)
  - Multiple instructions fetched at the same time
  - Static: compiler scheduling of instructions
  - Dynamic: hardware assisted scheduling of operations
    - "Superscalar" processors
    - CPU decides whether to issue 0, 1, 2, … instructions each cycle
- Thread or task level parallelism (TLP)
  - Multiple processes or threads running at the same time

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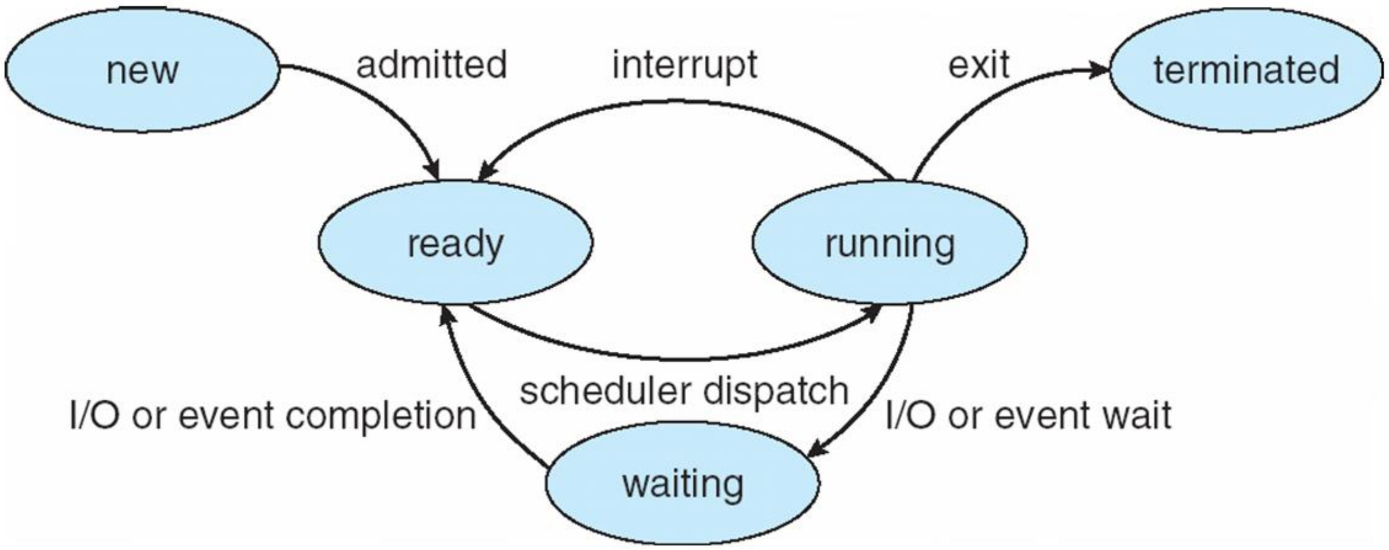
Chapter 5: CPU Scheduling

- Basic Concepts
- Scheduling Criteria
- Scheduling Algorithms
- Thread Scheduling
- Multiple-Processor Scheduling
- Real-Time CPU Scheduling
- Operating Systems Examples
- Algorithm Evaluation

Diagram of Process State



Ready to Running: scheduled by scheduler
Running to Ready: scheduler picks another process, back in ready queue
Running to Waiting (Blocked) : process blocks for input/output
Waiting to Ready: Input available