- Project 2 questions
  - To receive the bonus, you must submit to the **Project 2 Bonus** gradescope dropbox
- Exam questions
- Threads

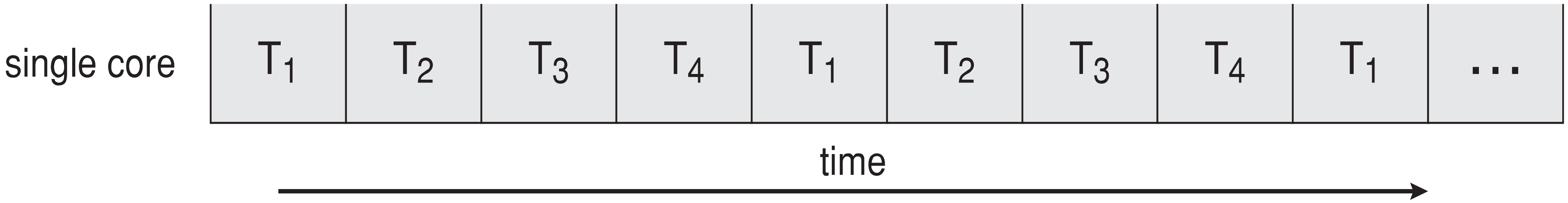
Threads

CS 3113

Concurrency vs Parallelism

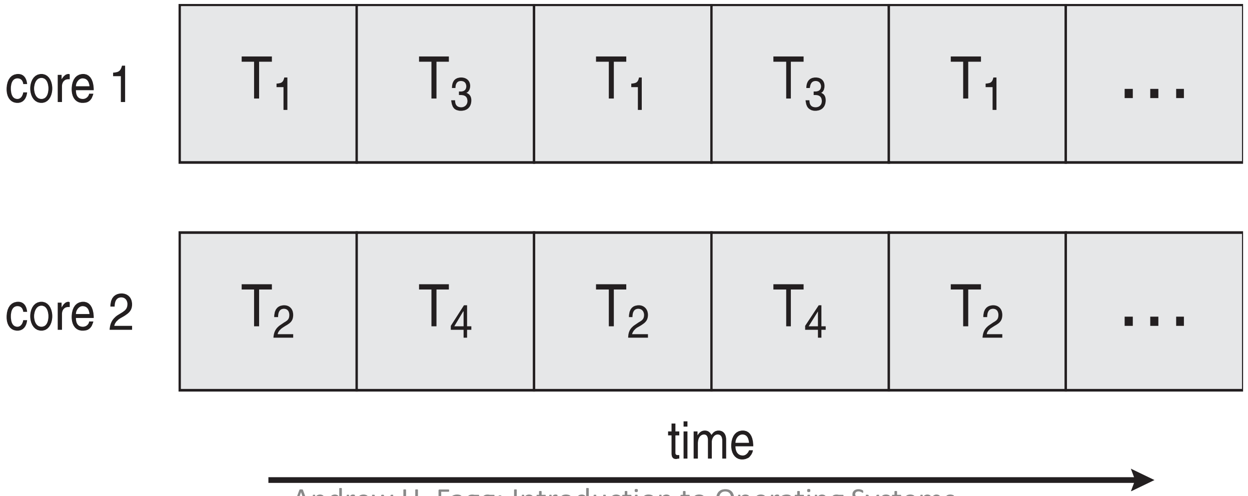
Concurrency vs Parallelism

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



single core	T_1	T_2	T_3	T_4	T_1	T_2	T_3	T_4	T_1	…

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



core 1	T_1	T_3	T_1	T_3	T_1	…
core 2	T_2	T_4	T_2	T_4	T_2	…

Concurrency vs Parallelism

- Concurrency: rapid switching of processes onto the CPU, which gives the illusion that multiple processes are executing at once
- Parallelism: have hardware support to execute multiple things at once

Concurrency vs Parallelism

Parallelism: have hardware support to execute multiple things at once

- Core: physical unit of code execution (instruction decoding, registers, etc.)
- CPU: Nominally (today), the computing hardware on a single chip. Can contain multiple cores
- Today, we often have multiple CPU machines, with each CPU containing multiple cores

Multi-Core Programming

We can explicitly write a program that has multiple execution contexts

- Distribute across the available cores
- Do different parts of the work in parallel

Processes

Often exist in isolation:

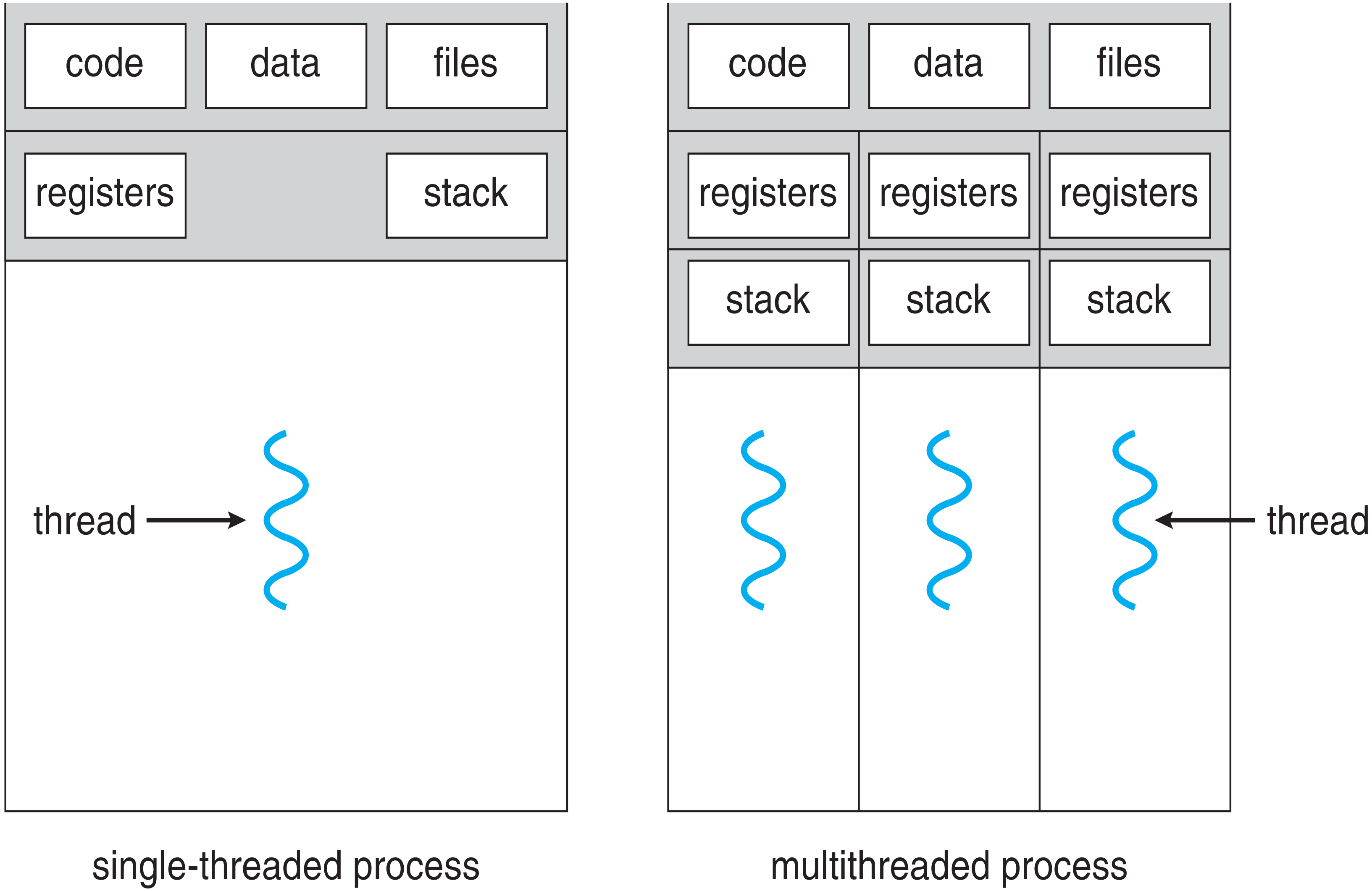
- Separate memory
  - Program
  - Data (globals, heap, etc)
- Separate execution context
  - Program counter
  - Registers

Threads

- Memory is shared!
  - Program
  - Data (globals, heap, etc)
- Separate execution context
  - Program counter
  - Registers

We refer to an execution context as a ***thread***

Process vs Threads within a Process



Advantages of Multi-Thread Programming

- **Implementation:** Can divide a big task into many, easy to implement tasks
- **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, and thread switching has lower overhead than context switching
- **Scalability:** process can take advantage of multiprocessor architectures

Multi-Thread Programming

Types of parallelism

- **Data parallelism** – distributes subsets of the same data across multiple cores, same operation on each
- **Task parallelism** – distributing threads across cores, each thread performing unique operation

Multi-Thread Programming

Architectural support for threading has increased in the last couple of decades

- Core: hardware pipeline for execution of instructions
  - Single instruction in CISC processors requires many steps (including operand fetch, multiple execution step, store of result)
- Hardware thread:
  - One physical thread appears to the OS as multiple independent cores
  - Implementation: have instructions in the pipeline from more than one hardware thread
- Oracle SPARC T4 with 8 cores, and 8 hardware threads per core

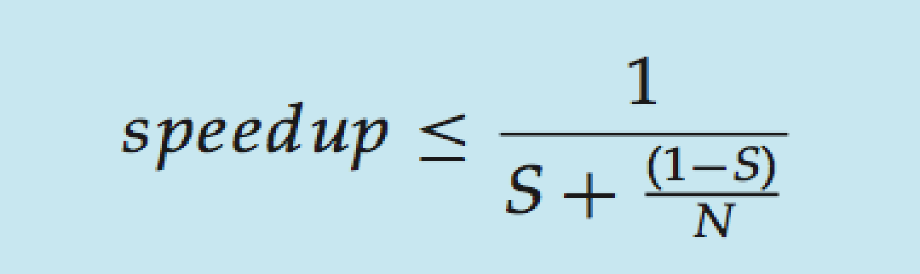
Multi-Thread Programming

How much faster can work be done with parallelism?

Amdahl’s Law

Performance speedup with parallelization

- *S*: fraction of task that is necessarily serial (rest is parallel)
- N: number of processors/cores



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

Amdahl’s Law

Performance speedup with parallelization

- *What happens as S approaches 0?*
- *What happens as S approaches 1?*
- *What happens as N approaches infinity?*

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

Support for Threads

Management of threads: must address the scheduling of threads for execution

- User space
  - Managed by libraries that live entirely in the user space
  - More general / portable
- Kernel space
  - Managed through systems calls to the kernel
  - Allows us to take more advantage of the available hardware
  - But: can be more hardware specific

Support for Threads

User space examples

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

Support for Threads

Kernel space provided by all modern OSes, including:

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

Multithreading Models

What is the relationship between programming of threads in the user space and the implementation in the kernel space?

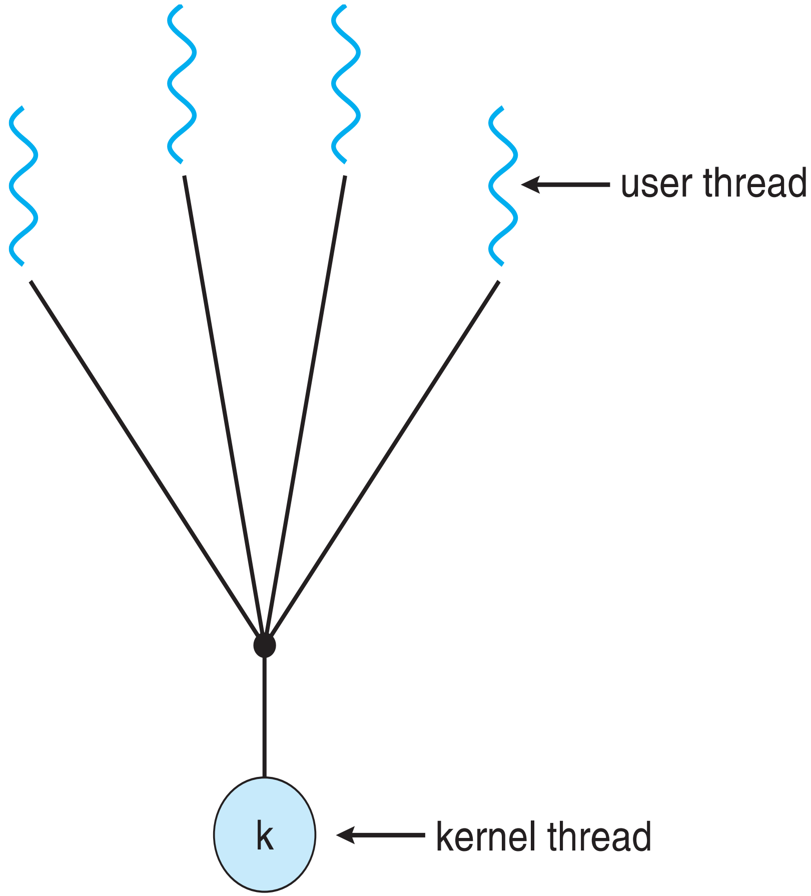
Multithreading Models

Relationship between user space threads and kernel threads. Options include:

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

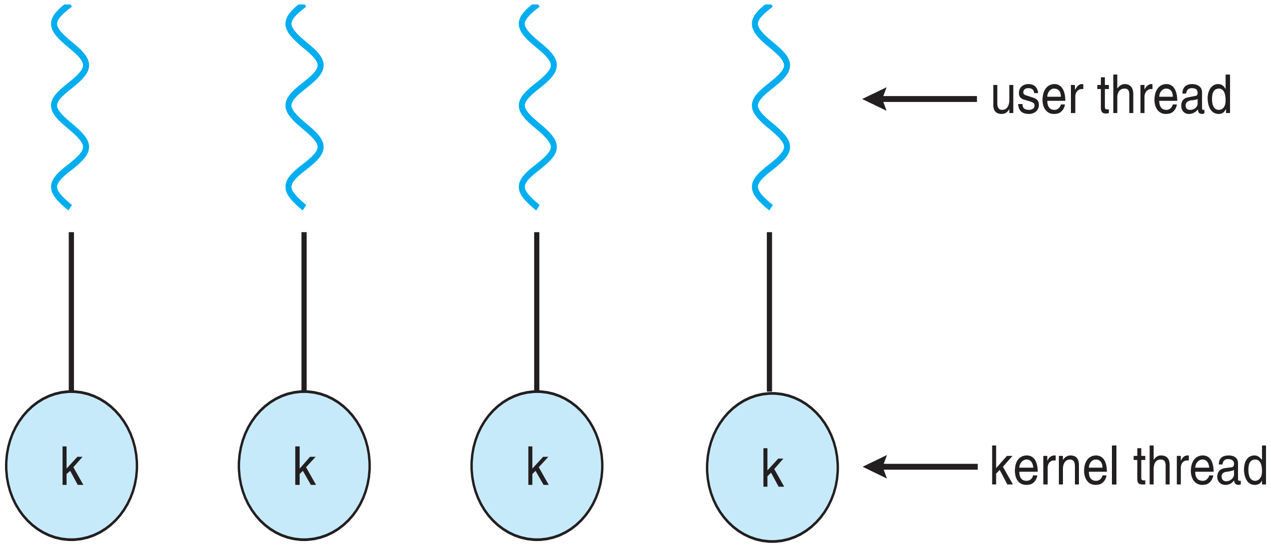
Many-to-One

- 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**



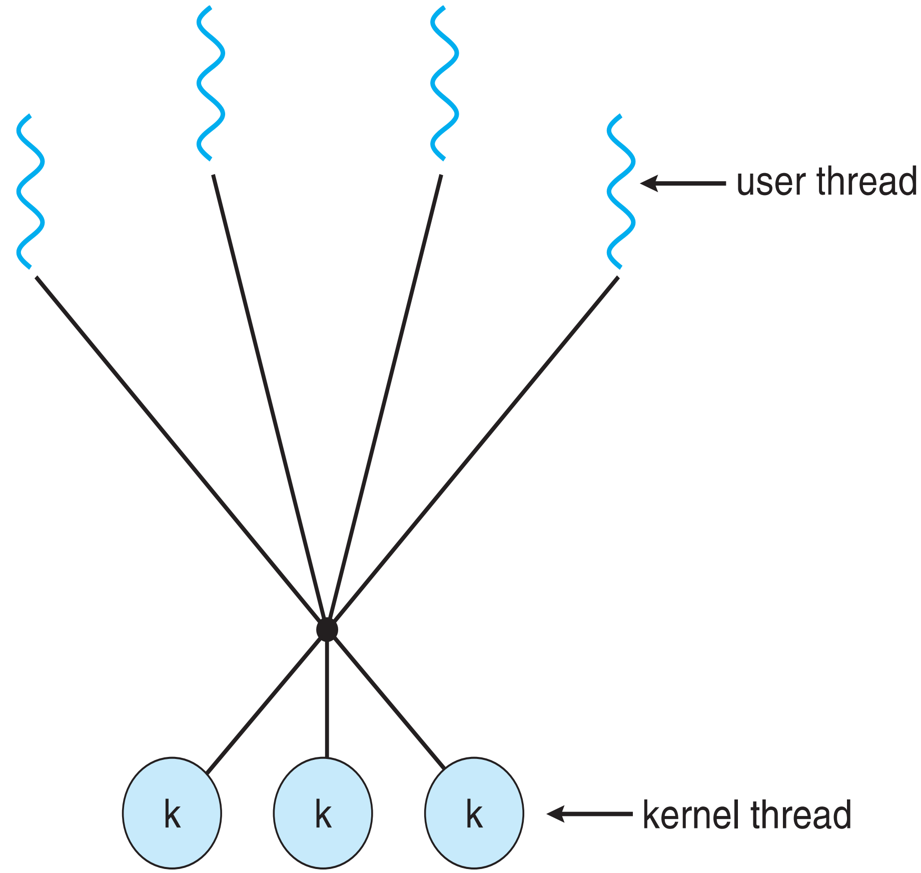
One-to-One

- 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
    - Linux
    - Solaris 9 and later



Many-to-Many Model

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



Thread Libraries

Programmer API for doing multithreading

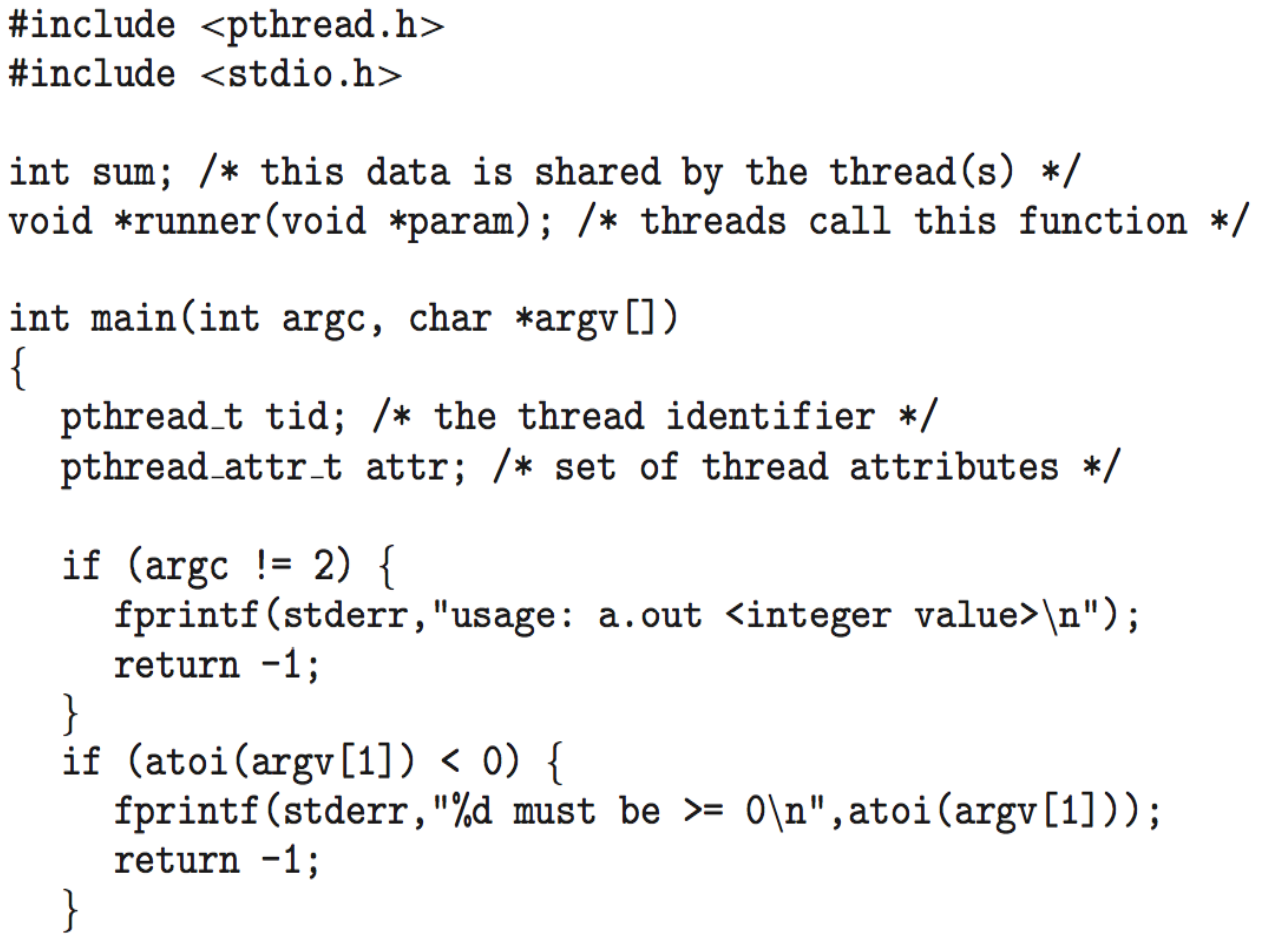
Pthreads

- 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

Set up:

- Global variable(!): sum
- Function prototype: runner



```
#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;
  }
```

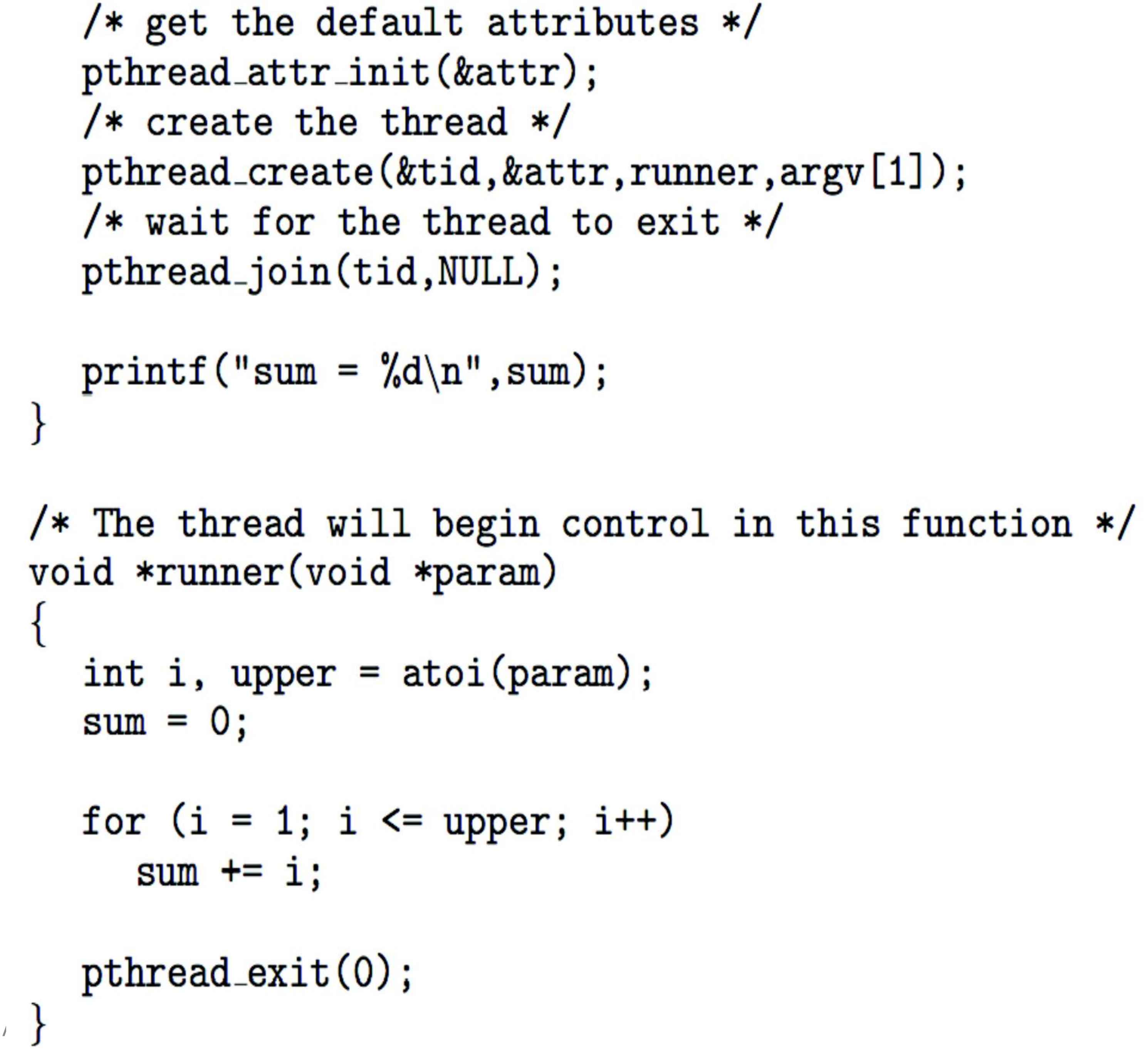
Pthreads

Parent:

- Create a single thread
  - Starts execution
- Join: parent waits for the child to exit

Child:

- Writes result to global variable

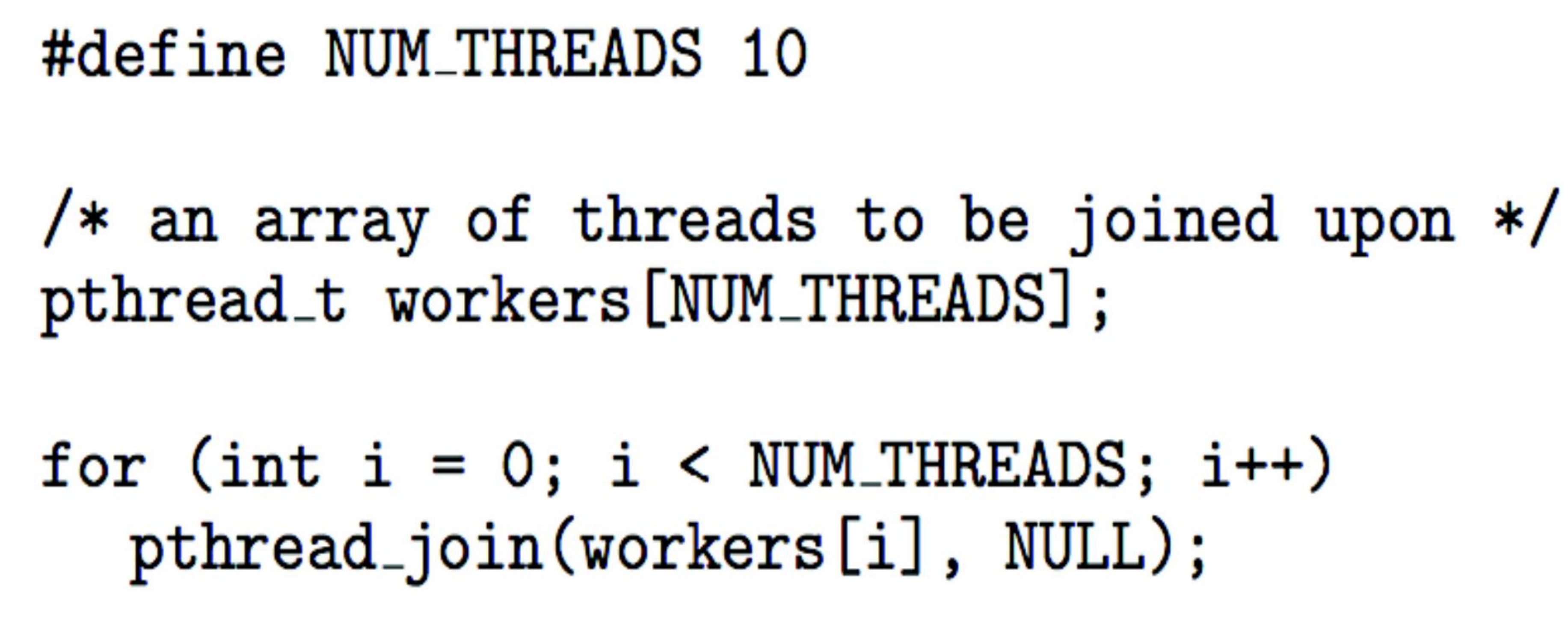


```
  /* get the default attributes */
  pthread_attr_init(&attr);
  /* create the thread */
  pthread_create(&tid,&attr,runner,argv[1]);
  /* wait for the thread to exit */
  pthread_join(tid,NULL);

  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 demo

Pthreads

- Join requires specific thread ID
- If the thread has already quit by the time join() is called, then it returns immediately



```
#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);
```

Implicit Threading

Creation and management of threads done by compilers and run-time libraries rather than programmers

- Growing in popularity as numbers of threads increase, program correctness more difficult with explicit threads
- Methods include:
  - Thread Pools
  - OpenMP
- Other methods include Microsoft Threading Building Blocks (TBB), **`java.util.concurrent`** package

Thread Pools

- Create a number of persistent threads in a pool where they await work
- When a process decides that a new task is to be executed (this is a function to be executed by a thread), it is placed into a queue
- Existing threads in the pool, as they are available, take tasks from the queue to execute

Thread Pools

- 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

- Thread pools support: Windows, Android, …

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

OpenMP

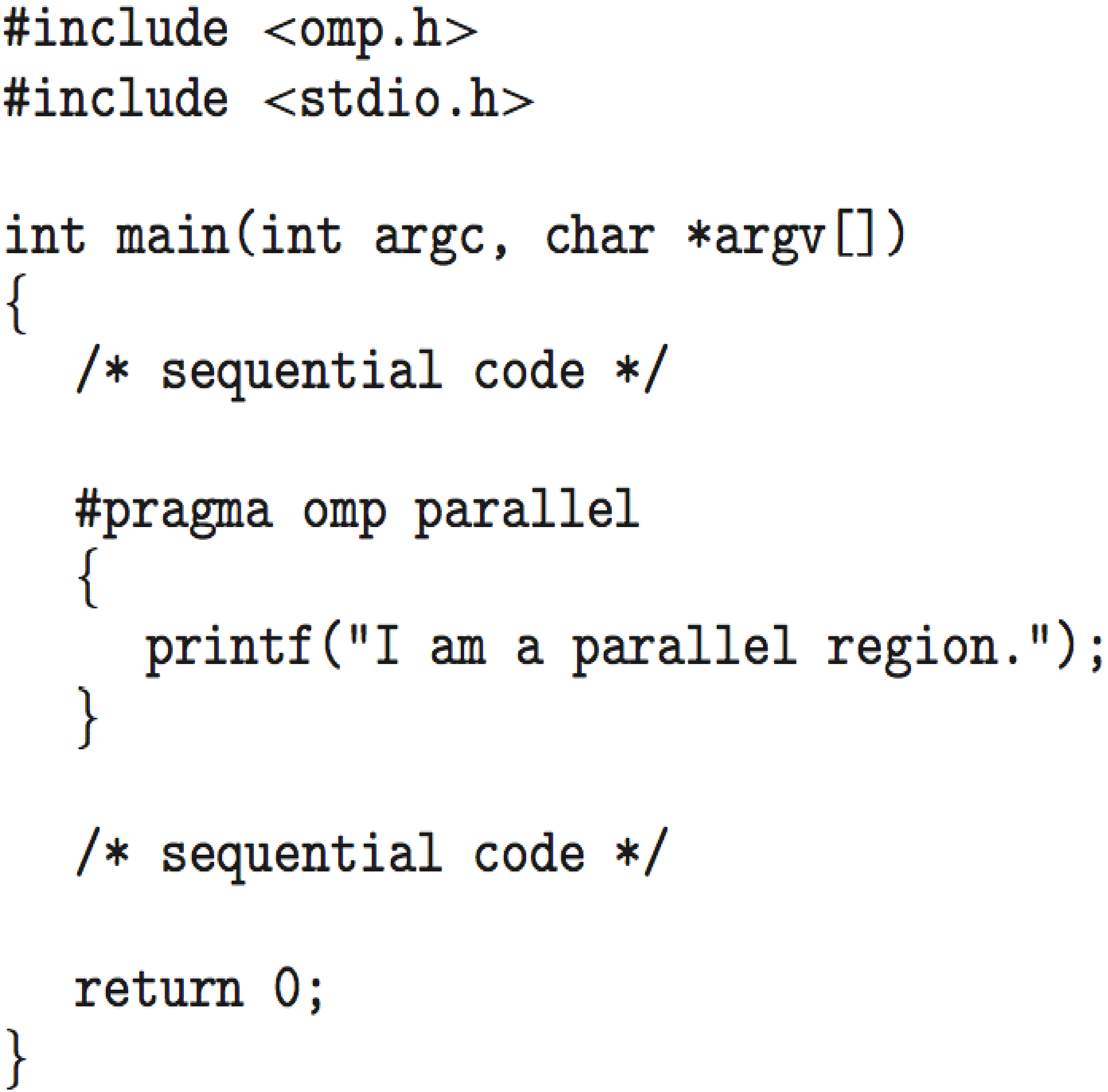
Create as many threads as there are cores:

```
#pragma omp parallel
```

Run for loop in parallel:

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

OpenMP



```
#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;
}
```

Interaction Between Processes and Threads

- Process-level operations: fork() and exec()
- Should fork() copy all currently running threads? Or just the one that called fork()?
  - Some OSes provide both types of fork()
  - Which one we choose depends on what the parent/child do next
  - If the child calls exec() immediately after being created, then we probably don’t need to copy all of the other threads