Operating Systems (Honor Track)

Abstractions 1: Threads and Processes A quick, programmer's viewpoint

Xin Jin

Spring 2024

Acknowledgments: Ion Stoica, Berkeley CS 162

Recall: Four fundamental OS concepts

- **Thread**
  - Single unique execution context
  - Program Counter, Registers, Execution Flags, Stack
- **Address Space** w/ translation
  - Programs execute in an *address space* that is distinct from the memory space of the physical machine
- **Process**
  - An instance of an executing program is *a process consisting of an address space and one or more threads of control*
- **Dual Mode** operation/protection
  - Only the "system" has the ability to access certain resources
  - The OS and the hardware are protected from user programs and user programs are isolated from one another by *controlling the translation* from program virtual addresses to machine physical addresses

Motivation for Threads

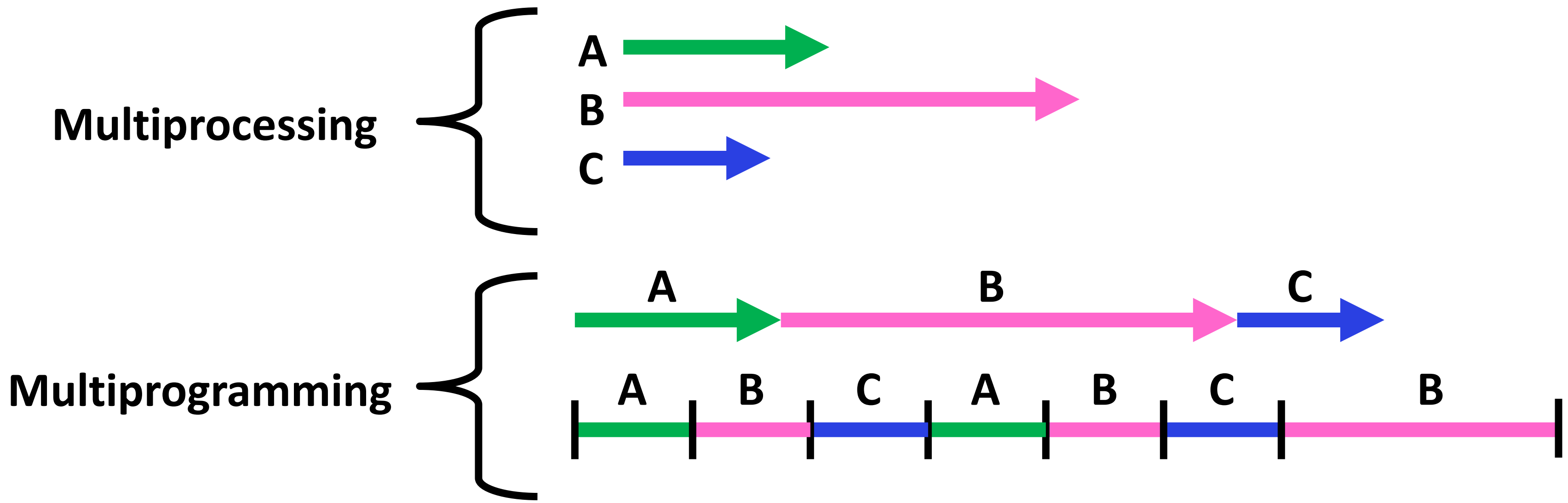
- Operating systems must handle multiple things at once (MTAO)
  - Processes, interrupts, background system maintenance
- Networked servers must handle MTAO
  - Multiple connections handled simultaneously
- Parallel programs must handle MTAO
  - To achieve better performance
- Programs with user interface often must handle MTAO
  - To achieve user responsiveness while doing computation
- Network and disk bound programs must handle MTAO
  - To hide network/disk latency
  - Sequence steps in access or communication

Threads Allow Handling MTAO

- Threads are a unit of *concurrency* provided by the OS
- Each thread can represent one thing or one task

Multiprocessing vs. Multiprogramming

- Some Definitions:
  - Multiprocessing: Multiple CPUs (cores)
  - Multiprogramming: Multiple jobs/processes
  - Multithreading: Multiple threads/processes
- What does it mean to run two threads concurrently?
  - Scheduler is free to run threads in any order and interleaving
  - Thread may run to completion or time-slice in big chunks or small chunks



Concurrency is not Parallelism

- Concurrency is about handling multiple things at once (MTAO)
- Parallelism is about doing multiple things *simultaneously*

- Example: Two threads on a single-core system...
  - … execute concurrently …
  - … but *not* in parallel

- Each thread handles or manages a separate thing or task…
- But those tasks are not necessarily executing simultaneously!

Silly Example for Threads

- Imagine the following program:

```
main() {
     ComputePI("pi.txt");
     PrintClassList("classlist.txt");
}
```

- What is the behavior here?
  - Program would never print out class list
- Why?
  - `ComputePI` would never finish

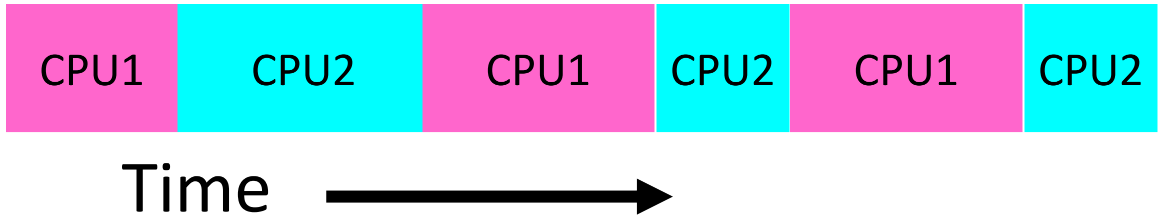
Adding Threads

- Version of program with threads (loose syntax):

```
main() {
    create_thread(ComputePI, "pi.txt");
    create_thread(PrintClassList, "classlist.txt");
}
```

- `create_thread`: Spawns a new thread running the given procedure
  - *Should* behave as if another CPU is running the given procedure

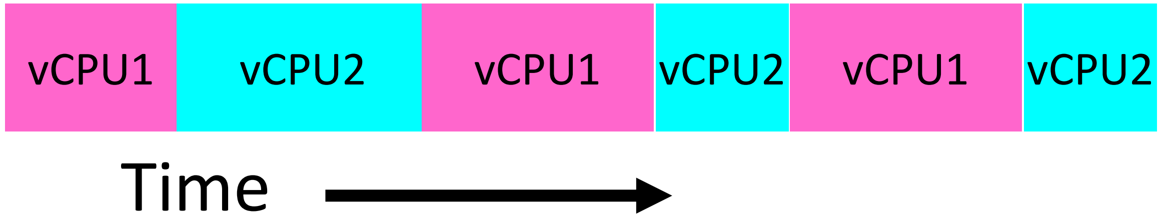
- Now, you would actually see the class list



Threads Mask I/O Latency

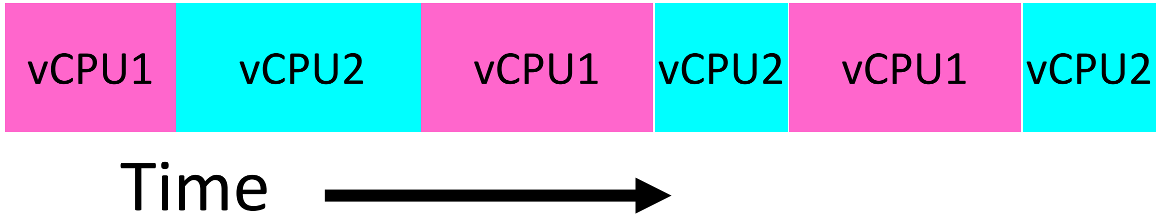
- A thread is in one of the following three states:
  - RUNNING – running
  - READY – eligible to run, but not currently running
  - BLOCKED – ineligible to run

- If a thread is waiting for an I/O to finish, the OS marks it as BLOCKED
- Once the I/O finally finishes, the OS marks it as READY

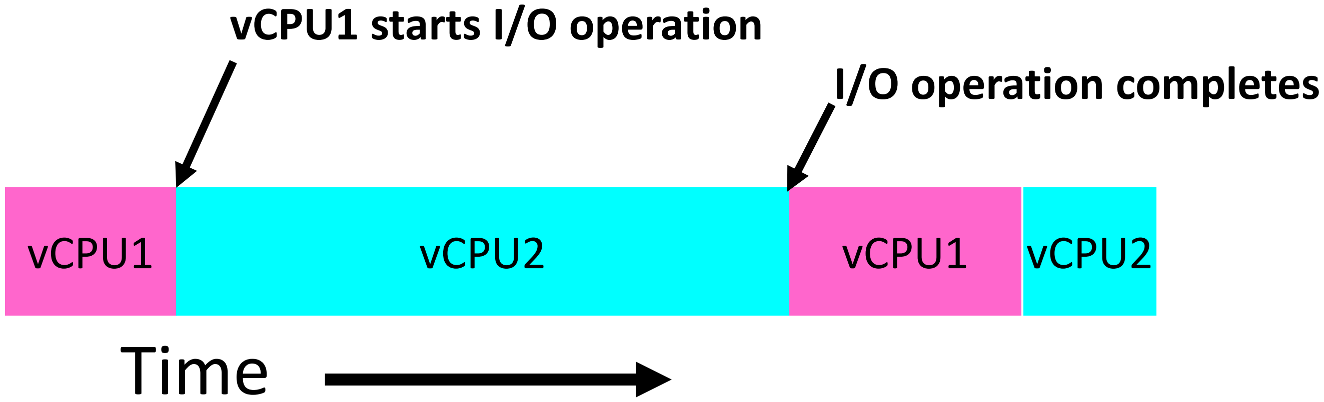


Threads Mask I/O Latency

- If no thread performs I/O:



- If thread 1 performs a blocking I/O operation:



A Better Example for Threads

- Version of program with threads (loose syntax):

```
main() {
    create_thread(ReadLargeFile, “pi.txt”);
    create_thread(RenderUserInterface);
}
```

- What is the behavior here?
  - Still respond to user input
  - While reading file in the background

Multithreaded Programs

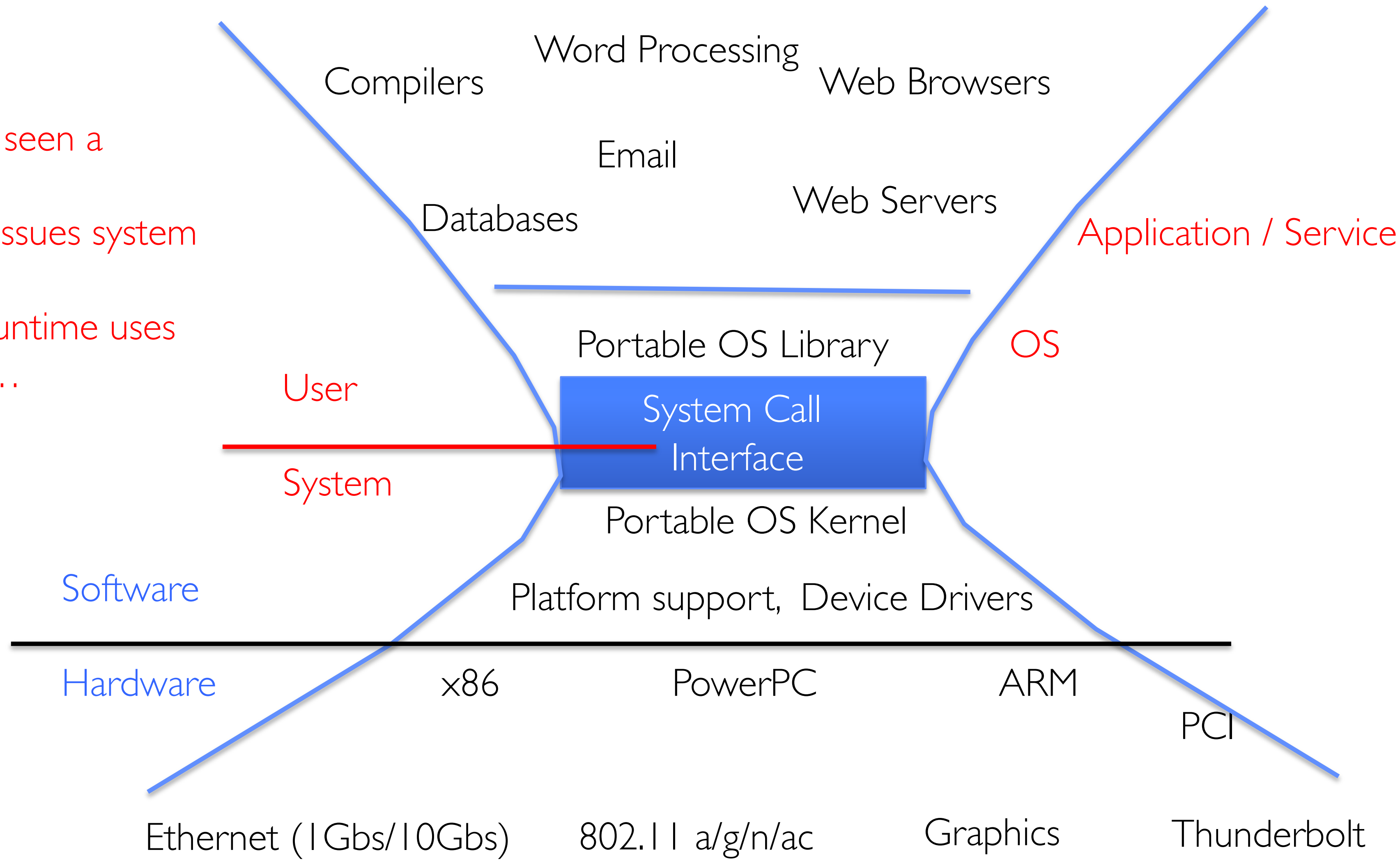
- You know how to compile a C program and run the executable
  - This creates a process that is executing that program

- Initially, this new process has *one thread* in its own address space
  - With code, global variables, etc. as specified in the executable

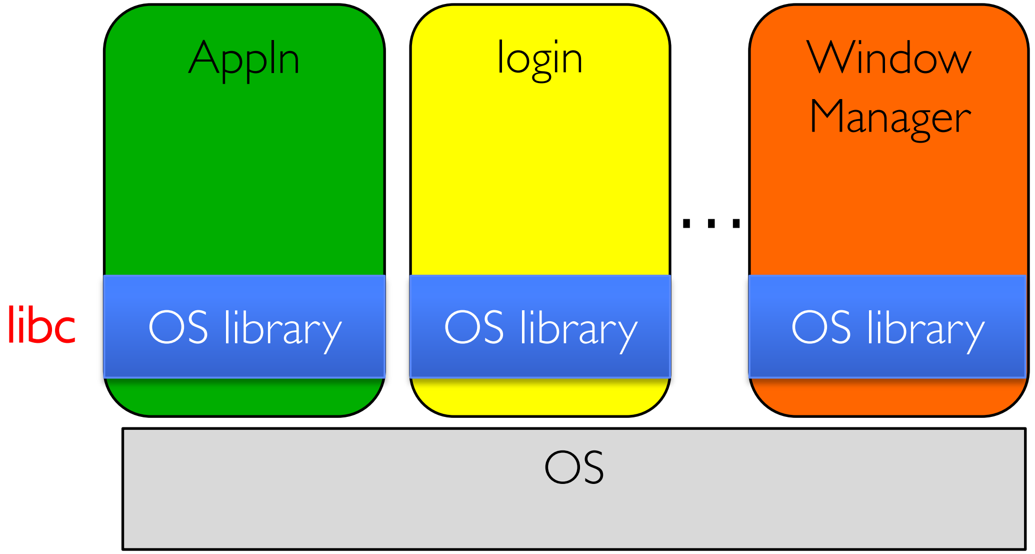
- Q: How can we make a multithreaded process?
- A: Once the process starts, it issues *system calls* to create new threads
  - These new threads are part of the process: they share its address space

System Calls ("Syscalls")

"But, I've never seen a syscall!"
- OS library issues system call
- Language runtime uses OS library…



OS Library Issues Syscalls



OS Library API for Threads: *pthreads*

```
int pthread_create(pthread_t *thread, const pthread_attr_t *attr,
                   void *(*start_routine)(void*), void *arg);
```

- thread is created executing *start_routine* with *arg* as its sole argument.
- return is implicit call to pthread_exit

```
void pthread_exit(void *value_ptr);
```

- terminates the thread and makes *value_ptr* available to any successful join

```
int pthread_join(pthread_t thread, void **value_ptr);
```

- suspends execution of the calling thread until the target *thread* terminates.
- On return with a non-NULL *value_ptr* the value passed to *pthread_exit()* by the terminating thread is made available in the location referenced by *value_ptr*.

prompt% man pthread
https://pubs.opengroup.org/onlinepubs/7908799/xsh/pthread.h.html

Peeking Ahead: System Call Example

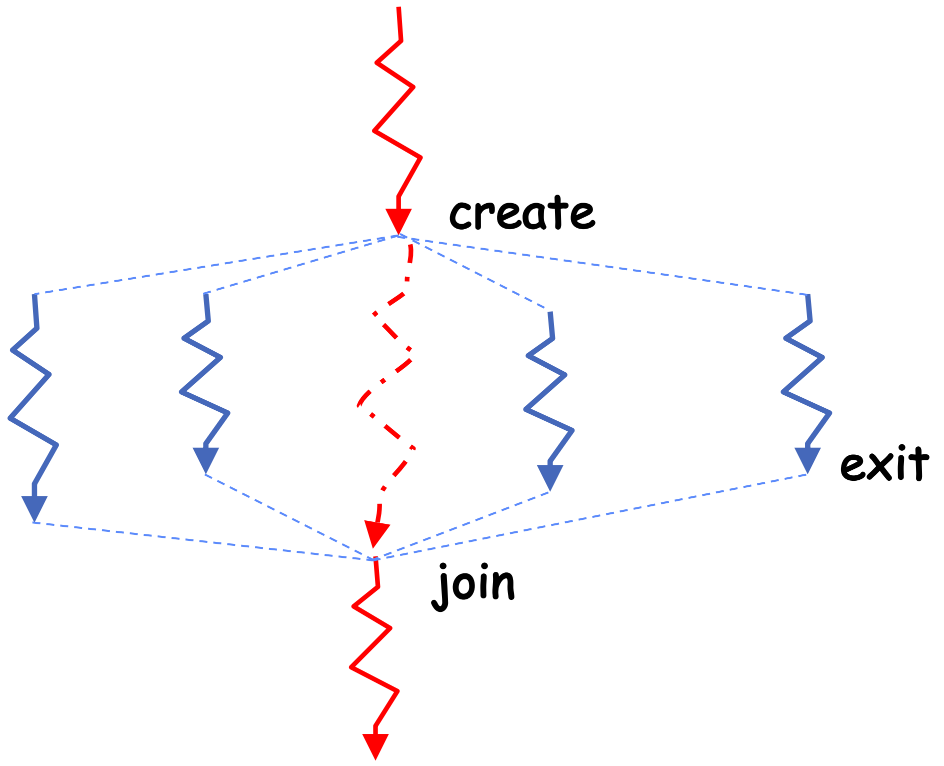
- What happens when `pthread_create(…)` is called in a process?

```
Library:
    int pthread_create(…) {
        Do some work like a normal fn…

        asm code … syscall # into %eax
        put args into registers %ebx, …
        special trap instruction
```

```
Kernel:
    get args from regs
    dispatch to system func
    Do the work to spawn the new thread
    Store return value in %eax
```

```
        get return values from regs
        Do some more work like a normal fn…
    };
```

New Idea: Fork-Join Pattern



- Main thread *creates* (forks) collection of sub-threads passing them args to work on…
- … and then *joins* with them, collecting results.

Group Discussion: pThreads Example

Discuss in groups of two to three students

- How many threads are in this program?
- Does the main thread join with the threads in the same order that they were created?
- Do the threads exit in the same order they were created?
- If we run the program again, would the result change?

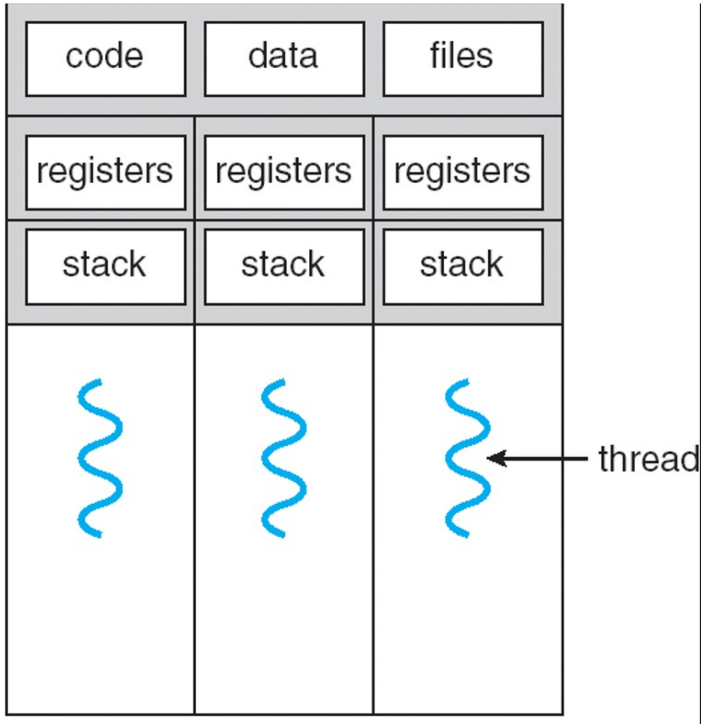
```
(base) CullerMac19:code04 culler$ ./pthread 4
Main stack: 7ffee2c6b6b8, common: 10cf95048 (162)
Thread #1 stack: 70000d83bef8 common: 10cf95048 (162)
Thread #3 stack: 70000d941ef8 common: 10cf95048 (164)
Thread #2 stack: 70000d8beef8 common: 10cf95048 (165)
Thread #0 stack: 70000d7b8ef8 common: 10cf95048 (163)
```

```c
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>
#include <string.h>

int common = 162;

void *threadfun(void *threadid)
{
  long tid = (long)threadid;
  printf("Thread #%lx stack: %lx common: %lx (%d)\n", tid,
         (unsigned long) &tid, (unsigned long) &common, common++);
  pthread_exit(NULL);
}

int main (int argc, char *argv[])
{
  long t;
  int nthreads = 2;
  if (argc > 1) {
    nthreads = atoi(argv[1]);
  }
  pthread_t *threads = malloc(nthreads*sizeof(pthread_t));
  printf("Main stack: %lx, common: %lx (%d)\n",
         (unsigned long) &t,(unsigned long) &common, common);
  for(t=0; t<nthreads; t++){
    int rc = pthread_create(&threads[t], NULL, threadfun, (void *)t);
    if (rc){
      printf("ERROR; return code from pthread_create() is %d\n", rc);
      exit(-1);
    }
  }

  for(t=0; t<nthreads; t++){
    pthread_join(threads[t], NULL);
  }
  pthread_exit(NULL);           /* last thing in the main thread */
}
```

Thread State

- State shared by all threads in process/address space
  - Content of memory (global variables, heap)
  - I/O state (file descriptors, network connections, etc.)

- State "private" to each thread
  - Kept in TCB ≡ Thread Control Block
  - CPU registers (including, program counter)
  - Execution stack – what is this?



multithreaded process

- Execution Stack
  - Parameters, temporary variables
  - Return PCs are kept while called procedures are executing

Execution Stack Example

```
          A(int tmp) {
    A:      if (tmp<2)
  A+1:        B();
  A+2:      printf(tmp);
          }
          B() {
    B:      C();
  B+1:    }
          C() {
    C:      A(2);
  C+1:    }
          A(1);
exit:
```

- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Execution Stack Example

```
      A(int tmp) {
A:      if (tmp<2)
A+1:      B();
A+2:    printf(tmp);
      }
      B() {
B:      C();
B+1:  }
      C() {
C:      A(2);
C+1:  }
      A(1);
exit:
```

Stack Pointer →

```
A: tmp=1
   ret=exit
```

- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Execution Stack Example

```
       A(int tmp) {
A:       if (tmp<2)
A+1:       B();
A+2:     printf(tmp);
       }
       B() {
B:       C();
B+1:   }
       C() {
C:       A(2);
C+1:   }
       A(1);
exit:
```

Stack Pointer →

```
A: tmp=1
   ret=exit
```

- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Execution Stack Example

```
       A(int tmp) {
A:       if (tmp<2)
A+1:       B();
A+2:     printf(tmp);
       }
       B() {
B:       C();
B+1:   }
       C() {
C:       A(2);
C+1:   }
       A(1);
exit:
```

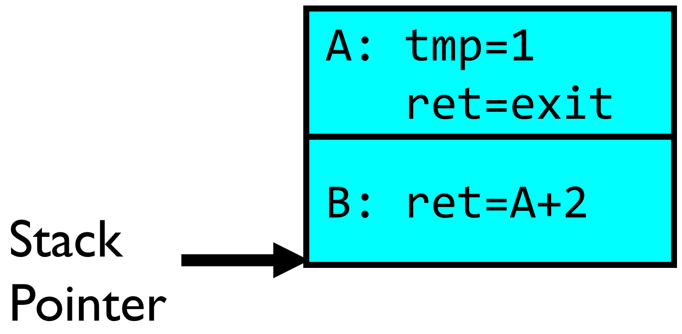
Stack Pointer →

```
A: tmp=1
   ret=exit
```

- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Execution Stack Example

```
        A(int tmp) {
A:        if (tmp<2)
A+1:        B();
A+2:      printf(tmp);
        }
        B() {
B:        C();
B+1:    }
        C() {
C:        A(2);
C+1:    }
        A(1);
exit:
```



- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Execution Stack Example

```
          A(int tmp) {
A:          if (tmp<2)
A+1:          B();
A+2:        printf(tmp);
          }
          B() {
B:          C();
B+1:      }
          C() {
C:          A(2);
C+1:      }
          A(1);
exit:
```

A: tmp=1 ret=exit
B: ret=A+2

Stack Pointer

- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Execution Stack Example

```
        A(int tmp) {
A:        if (tmp<2)
A+1:        B();
A+2:      printf(tmp);
        }
        B() {
B:        C();
B+1:    }
        C() {
C:        A(2);
C+1:    }
        A(1);
exit:
```

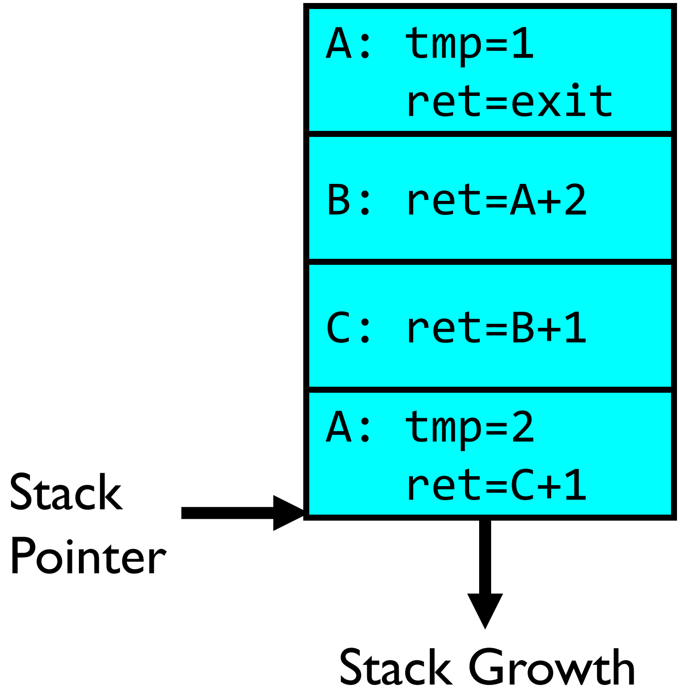
A: tmp=1 ret=exit
B: ret=A+2
C: ret=B+1

Stack Pointer →

- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Execution Stack Example

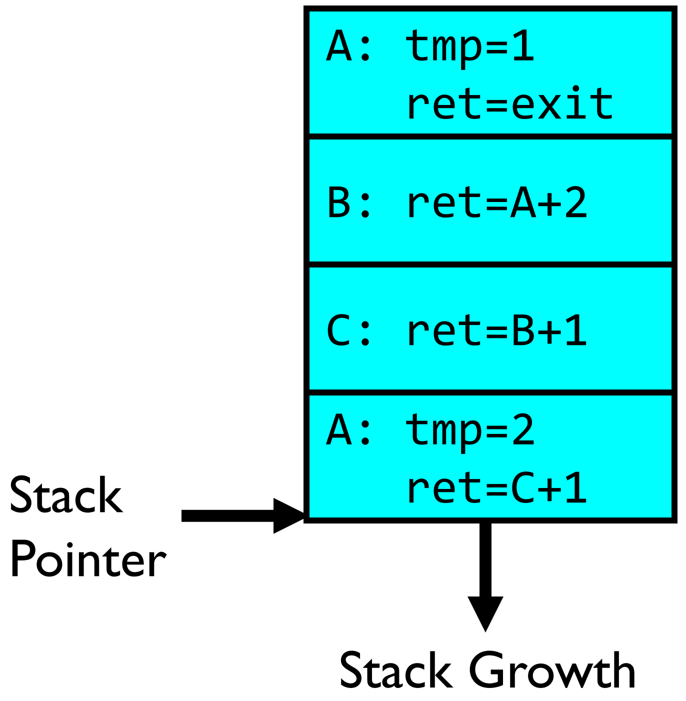
```
      A(int tmp) {
A:      if (tmp<2)
A+1:      B();
A+2:    printf(tmp);
      }
      B() {
B:      C();
B+1:  }
      C() {
C:      A(2);
C+1:  }
      A(1);
exit:
```



- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Execution Stack Example

```
        A(int tmp) {
A:        if (tmp<2)
A+1:        B();
A+2:      printf(tmp);
        }
        B() {
B:        C();
B+1:    }
        C() {
C:        A(2);
C+1:    }
        A(1);
exit:
```

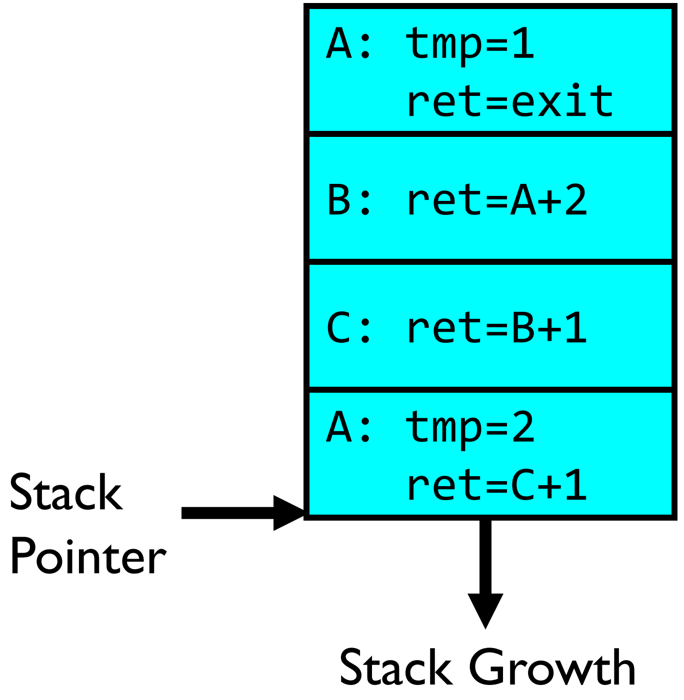


Output: >2

- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Execution Stack Example

```
      A(int tmp) {
A:      if (tmp<2)
A+1:      B();
A+2:    printf(tmp);
      }
      B() {
B:      C();
B+1:  }
      C() {
C:      A(2);
C+1:  }
      A(1);
exit:
```

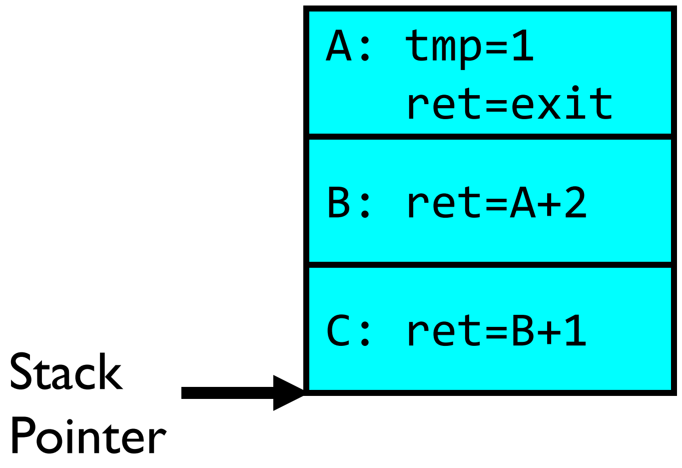


Output: >2

- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Execution Stack Example

```
      A(int tmp) {
A:      if (tmp<2)
A+1:      B();
A+2:    printf(tmp);
      }
      B() {
B:      C();
B+1:  }
      C() {
C:      A(2);
C+1:  }
      A(1);
exit:
```



Output: >2

- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Execution Stack Example

```
      A(int tmp) {
A:      if (tmp<2)
A+1:      B();
A+2:    printf(tmp);
      }
      B() {
B:      C();
B+1:  }
      C() {
C:      A(2);
C+1:  }
      A(1);
exit:
```

A: tmp=1 ret=exit
B: ret=A+2

Stack Pointer

Output: >2

- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Execution Stack Example

```
          A(int tmp) {
A:          if (tmp<2)
A+1:          B();
A+2:        printf(tmp);
          }
          B() {
B:          C();
B+1:      }
          C() {
C:          A(2);
C+1:      }
          A(1);
exit:
```

Stack Pointer →

```
A: tmp=1
   ret=exit
```

Output: >2 1

- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Execution Stack Example

```
      A(int tmp) {
A:      if (tmp<2)
A+1:      B();
A+2:    printf(tmp);
      }
      B() {
B:      C();
B+1:  }
      C() {
C:      A(2);
C+1:  }
      A(1);
exit:
```

Stack Pointer →

```
A: tmp=1
   ret=exit
```

Output: `>2 1`

- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

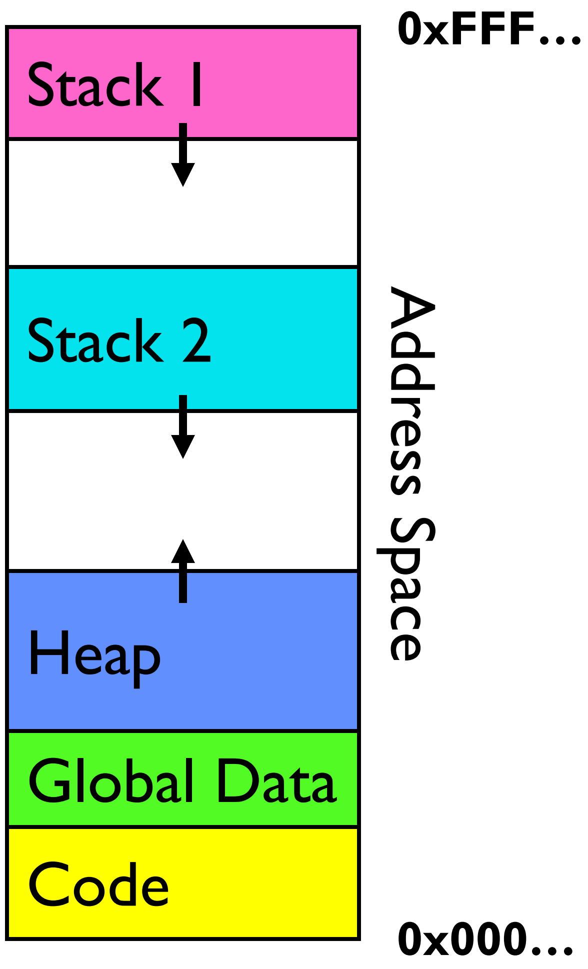
Execution Stack Example

```
A(int tmp) {
  if (tmp<2)
    B();
  printf(tmp);
}
B() {
  C();
}
C() {
  A(2);
}
A(1);
```

Output: `>2 1`

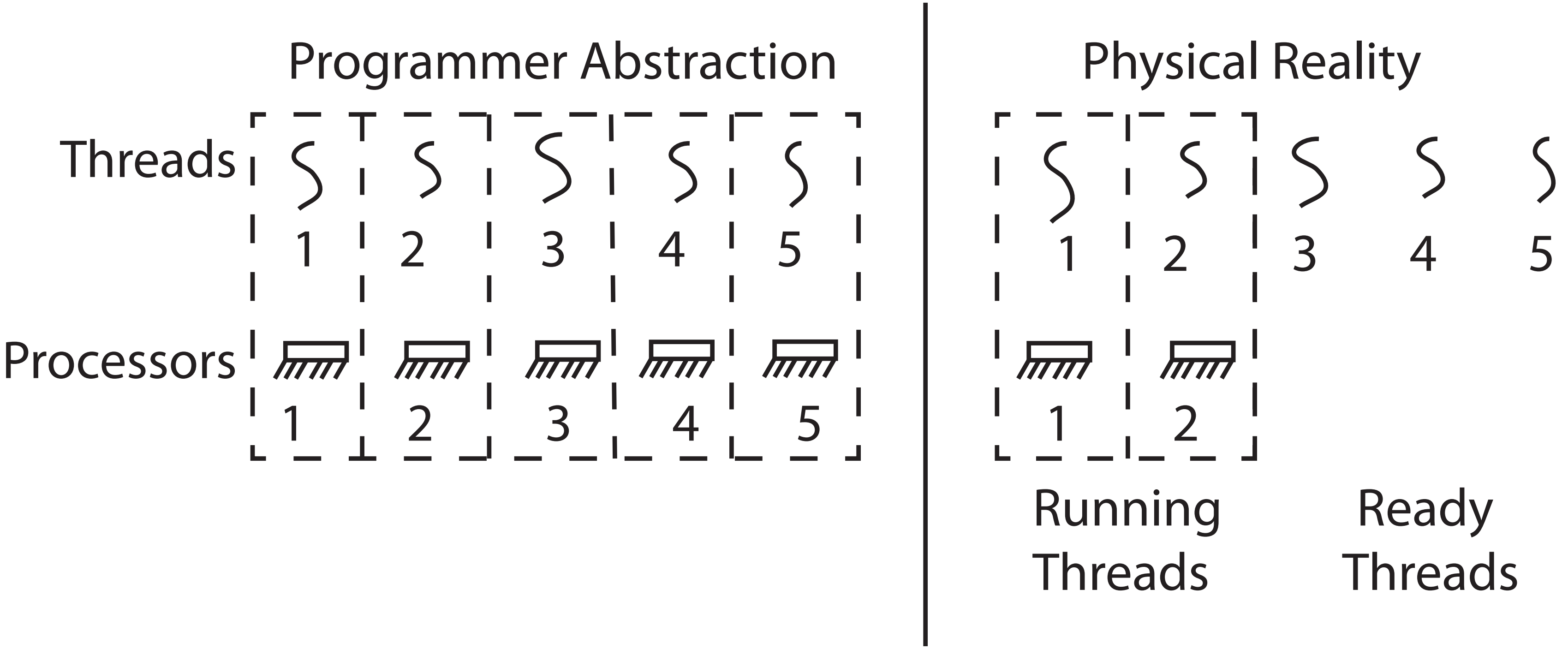
- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Memory Layout with Two Threads



INTERLEAVING AND NONDETERMINISM
(The beginning of a long discussion!)

Thread Abstraction



- Illusion: Infinite number of processors
- Reality: Threads execute with variable "speed"
  - Programs must be designed to work with any schedule

Programmer vs. Processor View

Programmer's View

.
.
.
x = x + 1;
y = y + x;
z = x +5y;
.
.
.

Possible Execution #1

.
.
.
x = x + 1;
y = y + x;
z = x + 5y;
.
.
.

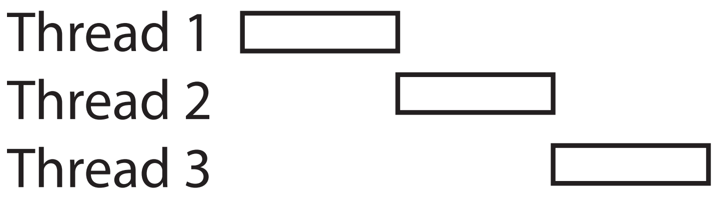
Possible Execution #2

.
.
.
x = x + 1
....
thread is suspended
other thread(s) run
thread is resumed
....
y = y + x
z = x + 5y

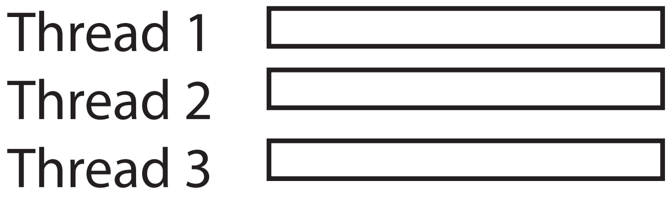
Possible Execution #3

.
.
.
x = x + 1
y = y + x
....
thread is suspended
other thread(s) run
thread is resumed
....
z = x + 5y

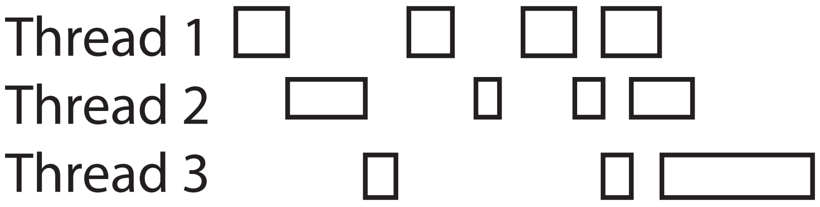
Possible Executions



a) One execution



b) Another execution



c) Another execution

Correctness with Concurrent Threads

- Non-determinism:
  - Scheduler can run threads in **any order**
  - Scheduler can switch threads **at any time**
  - This can make testing very difficult
- *Independent Threads*
  - No state shared with other threads
  - Deterministic, reproducible conditions
- *Cooperating Threads*
  - Shared state between multiple threads
- **Goal: Correctness by Design**

Race Conditions

- Initially `x == 0 and y == 0`

```
Thread A        Thread B
x = 1;          y = 2;
```

- What are the possible values of x below after all threads finish?
- Must be **1**. Thread B does not interfere

Race Conditions

- Initially `x == 0 and y == 0`

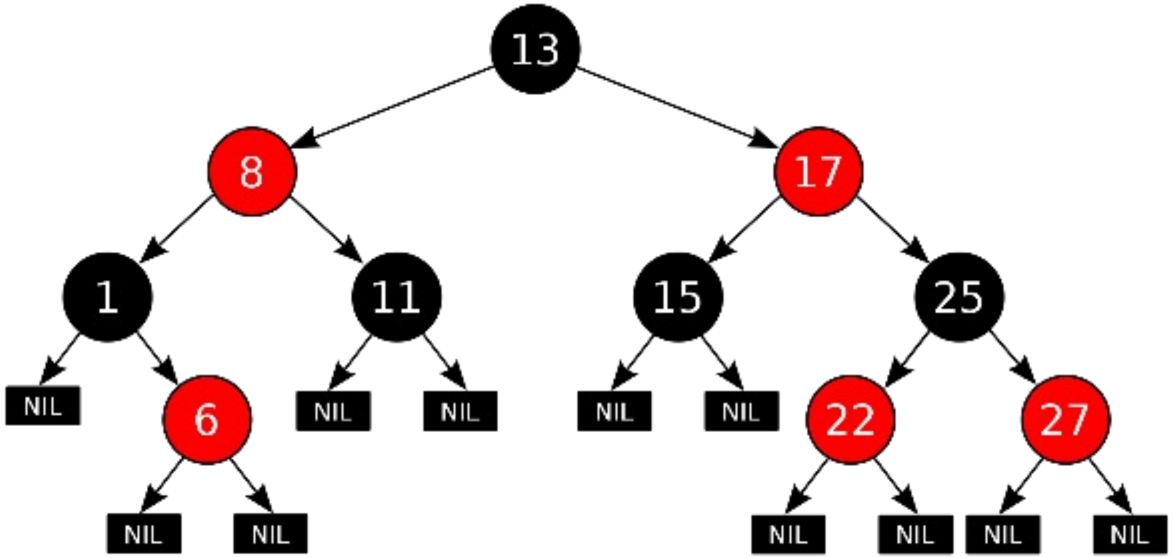
```
    Thread A          Thread B
    x = y + 1;        y = 2;
                      y = y * 2;
```

- What are the possible values of x below?
- 1 or 3 or 5 (non-deterministically)
- Race Condition: Thread A races against Thread B!

Example: Shared Data Structure

Thread A

`Insert(3)`



Tree-Based Set Data Structure

Thread B

`Insert(4)`

`Get(6)`

Relevant Definitions

- Synchronization: Coordination among threads, usually regarding shared data
- Mutual Exclusion: Ensuring only one thread does a particular thing at a time (one thread *excludes* the others)
  - Type of synchronization
- Critical Section: Code exactly one thread can execute at once
  - Result of mutual exclusion
- Lock: An object only one thread can hold at a time
  - Provides mutual exclusion

Locks

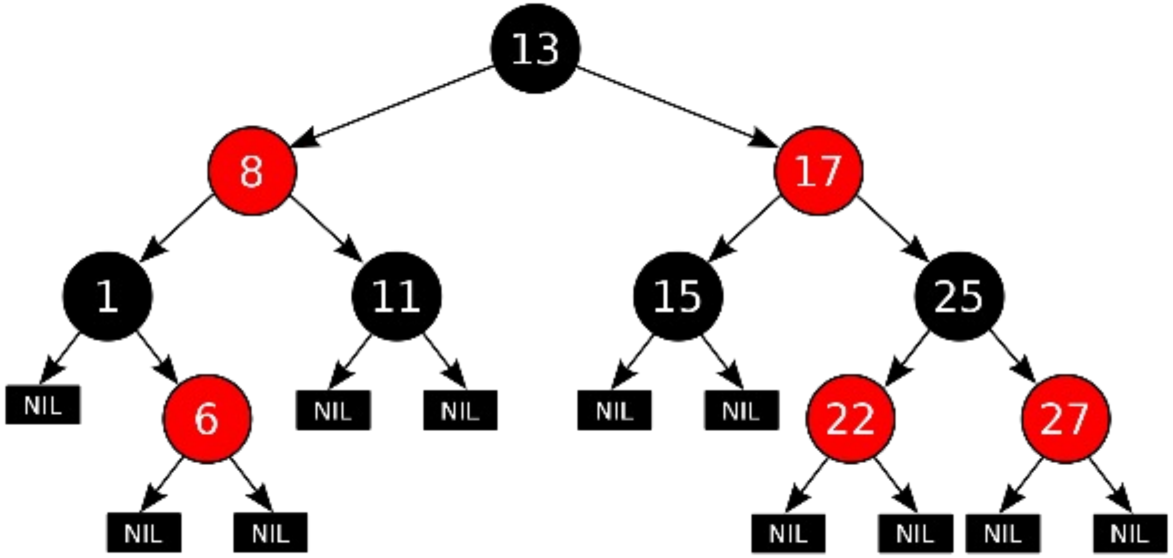
- Locks provide two **atomic** operations:
  - Lock.acquire() – wait until lock is free; then mark it as busy
    - After this returns, we say the calling thread *holds* the lock
  - Lock.release() – mark lock as free
    - Should only be called by a thread that currently holds the lock
    - After this returns, the calling thread no longer holds the lock

- For now, don't worry about how to implement locks!
  - We'll cover that in substantial depth later on in the class

Thread A

Insert(3)

- Lock.acquire()
- Insert 3 into the data structure
- Lock.release()



Tree-Based Set Data Structure

Thread B

Insert(4)

- Lock.acquire()
- Insert 4 into the data structure
- Lock.release()

Get(6)

- Lock.acquire()
- Check for membership
- Lock.release()

OS Library Locks: *pthreads*

```
int pthread_mutex_init(pthread_mutex_t *mutex,
                       const pthread_mutexattr_t *attr)

int pthread_mutex_lock(pthread_mutex_t *mutex);
int pthread_mutex_unlock(pthread_mutex_t *mutex);
```

Our Example

Critical section

```
int common = 162;
pthread_mutex_t common_lock = PTHREAD_MUTEX_INITIALIZER;

void *threadfun(void *threadid)
{
  long tid = (long)threadid;
  pthread_mutex_lock(&common_lock);
  int my_common = common++;
  pthread_mutex_unlock(&common_lock);

  printf("Thread #%lx stack: %lx common: %lx (%d)\n", tid,
         (unsigned long) &tid,
         (unsigned long) &common, my_common);
  pthread_exit(NULL);
}
```

Semaphores: A quick look

- Semaphores are a kind of *generalized lock*
  - First defined by Dijkstra in late 60s
  - Main synchronization primitive used in original UNIX (& Pintos)
- Definition: a Semaphore has a non-negative integer value and supports the following two operations:
  - `P()` or `down()`: atomic operation that waits for semaphore to become positive, then decrements it by 1
  - `V()` or `up()`: an atomic operation that increments the semaphore by 1, waking up a waiting P, if any

`P()` stands for "*proberen*" (to test) and `V()` stands for "*verhogen*" (to increment) in Dutch

Two Semaphore Patterns

- **Mutual Exclusion:** (like lock)
  – Called a "binary semaphore“ or “mutex”

```
initial value of semaphore = 1;
semaphore.down();
      // Critical section goes here
semaphore.up();
```

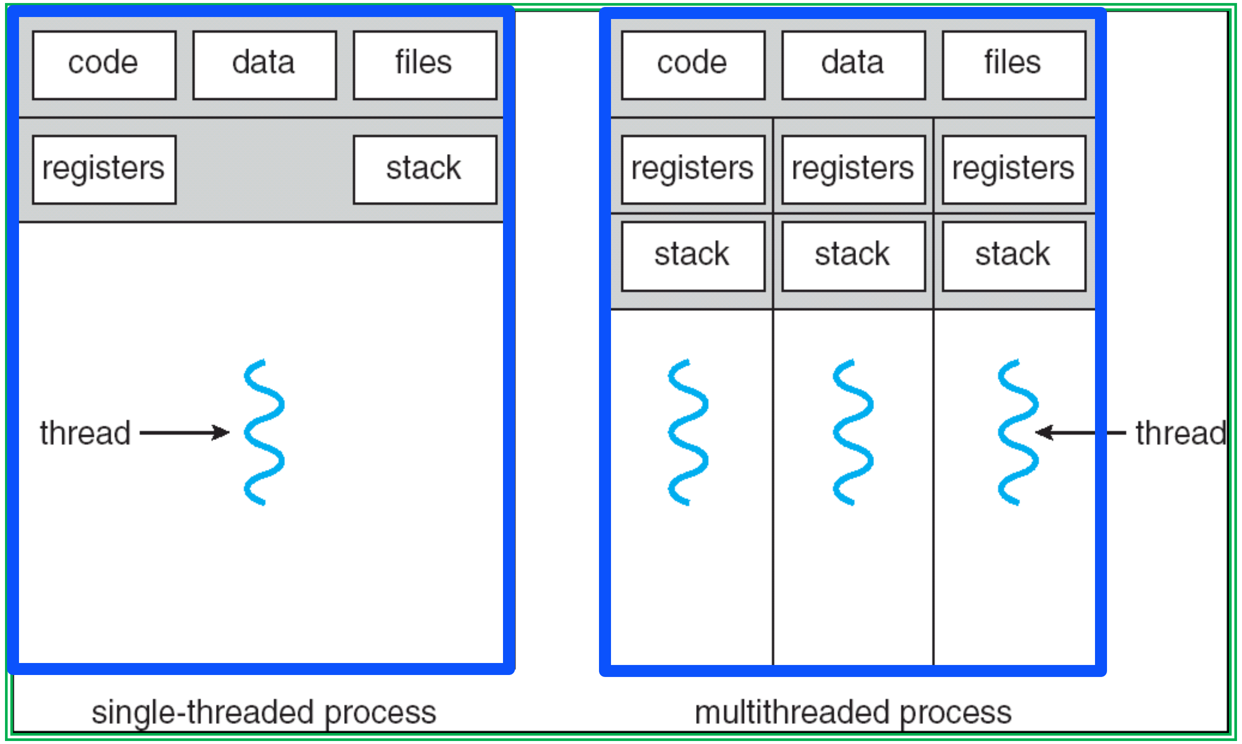
- **Signaling** other threads, e.g. **`ThreadJoin`**

```
Initial value of semaphore = 0

ThreadJoin {
   semaphore.down();
}
```

```
ThreadFinish {
   semaphore.up();
}
```

Processes

- Definition: execution environment with restricted rights
  - One or more threads executing in a single address space
  - Owns file descriptors, network connections
- Instance of a running program
  - When you run an executable, it runs in its own process
  - Application: one or more processes working together



- Protected from each other; OS protected from them
- **In modern OSes, anything that runs outside of the kernel runs in a process**

Creating Processes

- `pid_t fork()` – copy the current process
  - New process has different pid
  - New process contains a single thread
- Return value from **`fork()`**: pid (like an integer)
  - When > 0:
    - » Running in (original) Parent process
    - » return value is pid of new child
  - When = 0:
    - » Running in new Child process
  - When < 0:
    - » Error! Must handle somehow
    - » Running in original process
- State of original process duplicated in *both* Parent and Child!
  - Address Space (Memory), File Descriptors (covered later), etc…

fork_race.c

```
int i;
pid_t cpid = fork();
if (cpid > 0) {
  for (i = 0; i < 10; i++) {
    printf("Parent: %d\n", i);
    // sleep(1);
  }
} else if (cpid == 0) {
  for (i = 0; i > -10; i--) {
    printf("Child: %d\n", i);
    // sleep(1);
  }
} else { /* ERROR! */ }
```

Parent Process
Runs HERE!

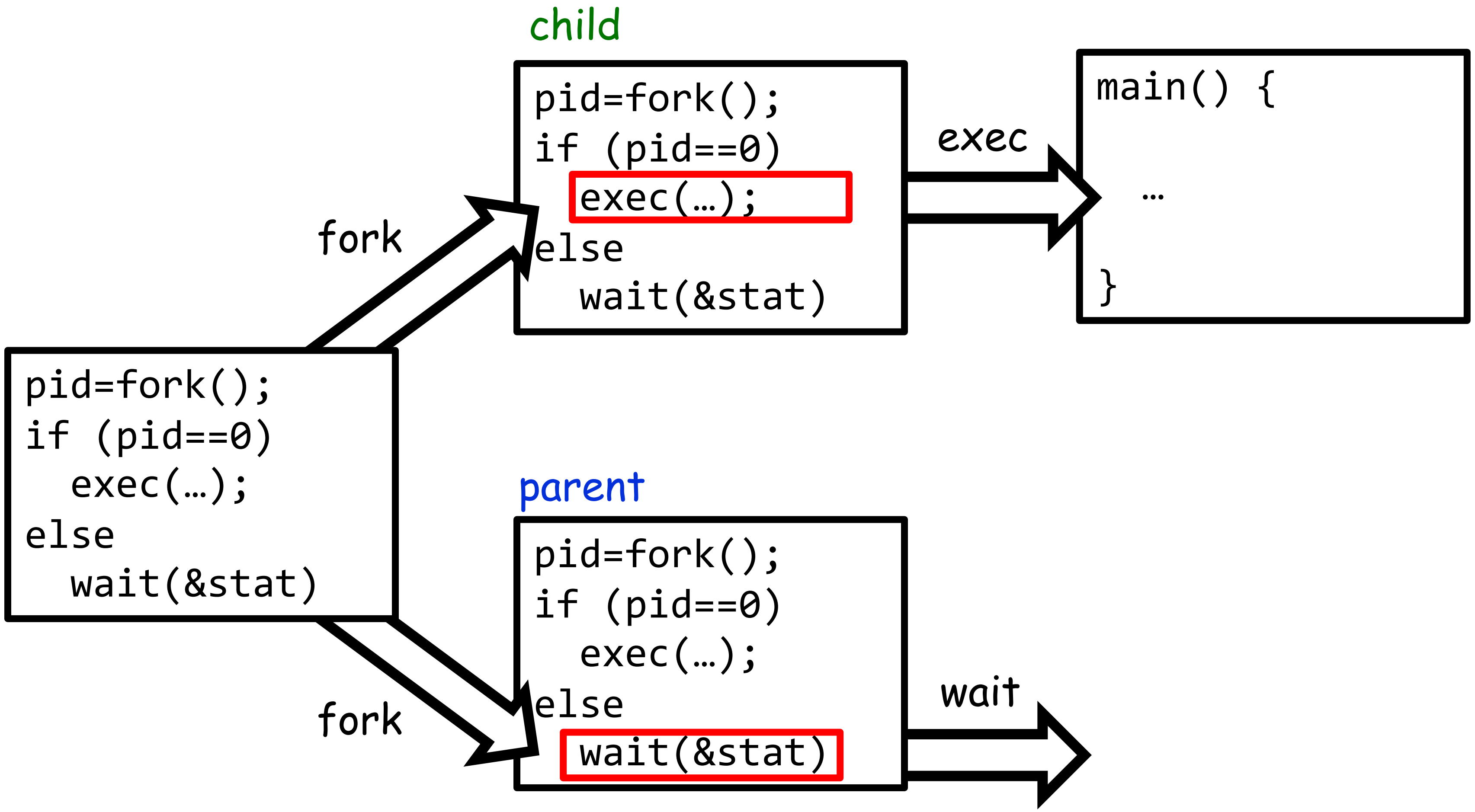
Child Process
Runs HERE!

- Group discussion
  - What does this print?
  - Would adding the calls to `sleep()` matter?

Start new Program with exec

```
…
cpid = fork();
if (cpid > 0) {                  /* Parent Process */
  tcpid = wait(&status);
} else if (cpid == 0) {        /* Child Process */
  char *args[] = {“ls”, “-l”, NULL};
  execv(“/bin/ls”, args);

  /* execv doesn’t return when it works.
     So, if we got here, it failed! */

  perror(“execv”);
  exit(1);
}
…
```

Starting New Program (for instance in Shell)



Finishing up: Process Management API

- `exit` – terminate a process
- `fork` – copy the current process
- `exec` – change the *program* being run by the current process
- `wait` – wait for a process to finish
- `kill` – send a *signal* (interrupt-like notification) to another process
- `sigaction` – set handlers for signals

`fork2.c` – parent waits for child to finish

```
int status;
pid_t tcpid;
…
cpid = fork();
if (cpid > 0) {                  /* Parent Process */
  mypid = getpid();
  printf("[%d] parent of [%d]\n", mypid, cpid);
  tcpid = wait(&status);
  printf("[%d] bye %d(%d)\n", mypid, tcpid, status);
} else if (cpid == 0) {      /* Child Process */
  mypid = getpid();
  printf("[%d] child\n", mypid);
  exit(42);
}
…
```

Finishing up: Process Management API

- `exit` – terminate a process
- `fork` – copy the current process
- `exec` – change the *program* being run by the current process
- `wait` – wait for a process to finish
- `kill` – send a *signal* (interrupt-like notification) to another process
- `sigaction` – set handlers for signals

inf_loop.c

```
#include <stdlib.h>
#include <stdio.h>
#include <sys/types.h>
#include <unistd.h>
#include <signal.h>

void signal_callback_handler(int signum) {
  printf("Caught signal!\n");
  exit(1);
}
int main() {
  struct sigaction sa;
  sa.sa_flags = 0;
  sigemptyset(&sa.sa_mask);
  sa.sa_handler = signal_callback_handler;
  sigaction(SIGINT, &sa, NULL);
  while (1) {}
}
```

Process vs. Thread APIs

- Why have `fork()` and `exec()` system calls for processes, but just a `pthread_create()` function for threads?
  - Convenient to `fork` without `exec`: put code for parent and child in one executable instead of multiple
  - It will allow us to programmatically control child process' state
    - » By executing code before calling `exec()` in the child
  - We'll see this in the case of File I/O later

- Windows uses `CreateProcess()` instead of `fork()`
  - Also works, but a more complicated interface

Group Discussion

- Topic: Threads vs. Processes
  - If we have two tasks to run concurrently, do we run them in separate threads, or do we run them in separate processes?
  - What are the pros and cons?

- Discuss in groups of two to three students
  - Each group chooses a leader to summarize the discussion
  - In your group discussion, please do not dominate the discussion, and give everyone a chance to speak

Conclusion

- Threads are the OS unit of concurrency
  - Abstraction of a virtual CPU core
  - Can use `pthread_create`, etc., to manage threads within a process
  - They share data → need synchronization to avoid data races
- Processes consist of one or more threads in an address space
  - Abstraction of the machine: execution environment for a program
  - Can use fork, exec, etc. to manage threads within a process
- We saw the role of the OS library
  - Provide API to programs
  - Interface with the OS to request services