Operating Systems
(Honor Track)

Abstractions 1: Threads
A quick, programmer's viewpoint

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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

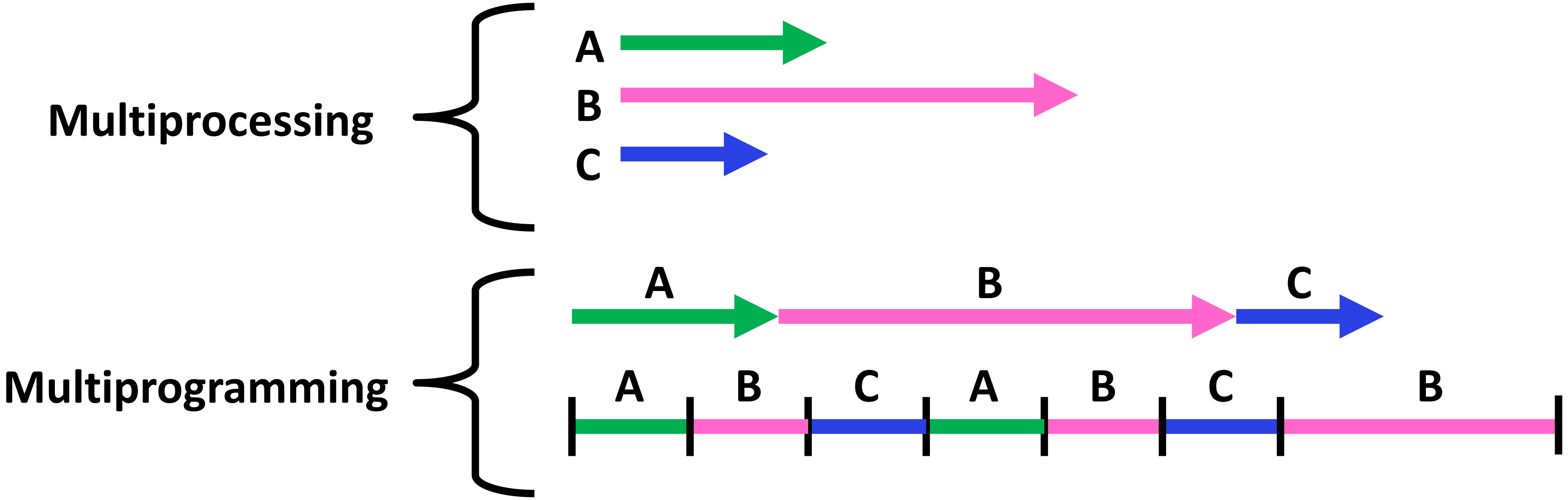
- Operating systems must handle multiple things at once (MTAO)
  - Processes, interrupts, background system maintenance
- Networked servers must handle MTAO
  - Multiple connections handled simultaneously
- Parallel programs must handle MTAO
  - To achieve better performance
- Programs with user interface 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

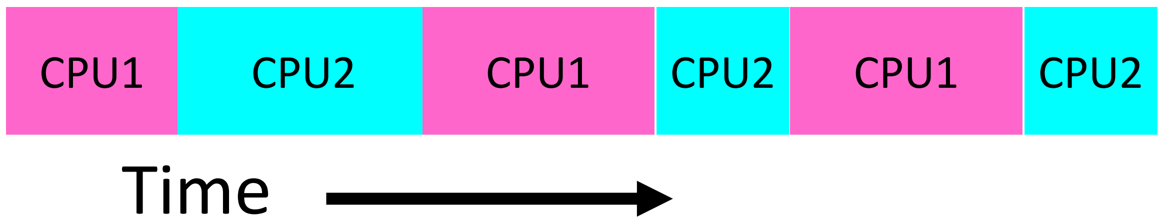
Adding Threads

- 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

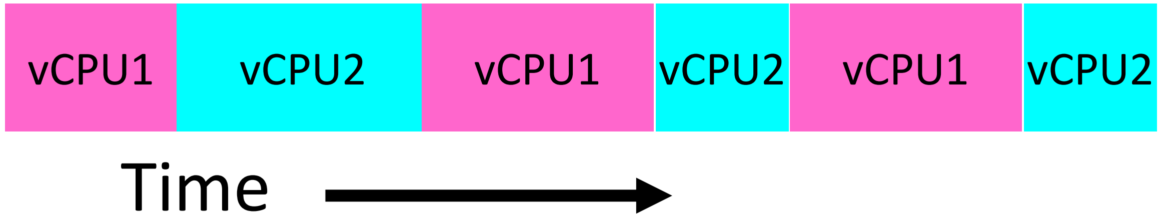
- Now, you would actually see the class list



Threads Mask I/O Latency

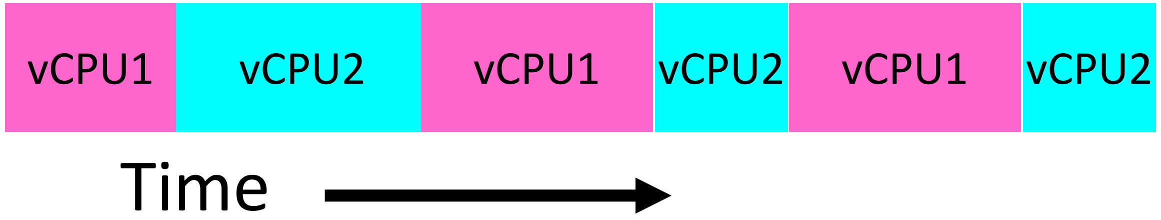
- A thread is in one of the following three states:
  - RUNNING – running
  - READY – eligible to run, but not currently running
  - BLOCKED – ineligible to run

- 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

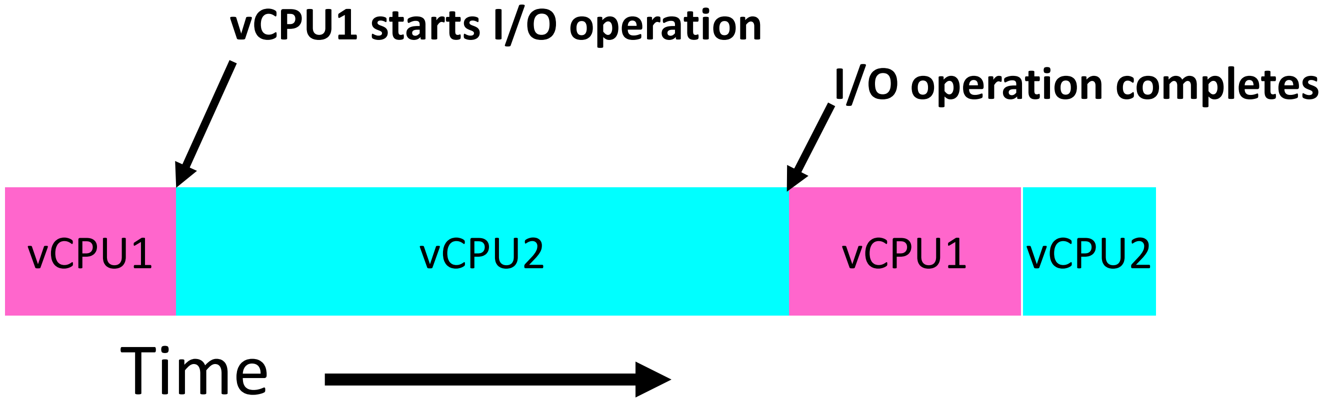


Threads Mask I/O Latency

- 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

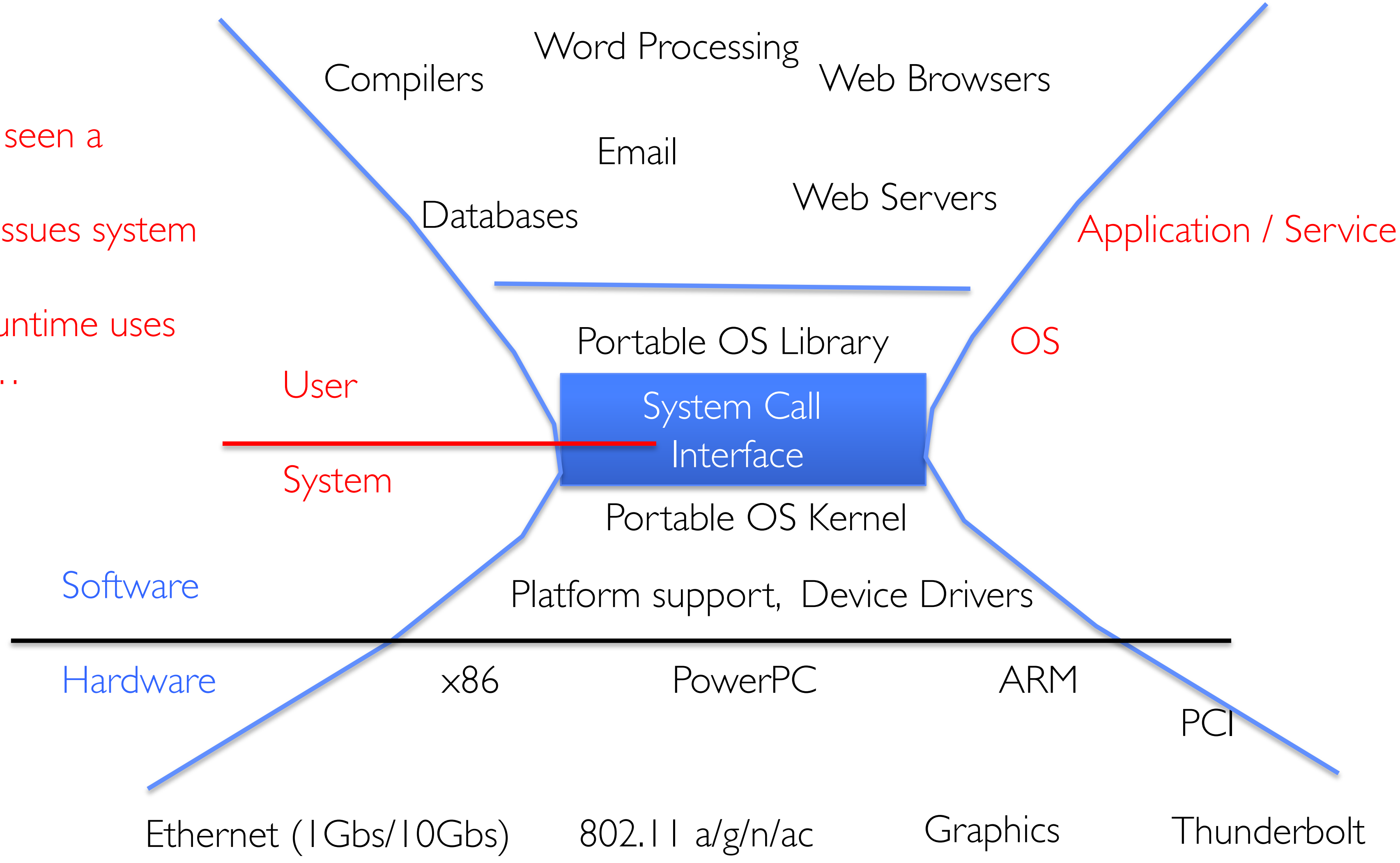
- Initially, this new process has *one thread* in its own address space
  - With code, global variables, etc. as specified in the executable

- 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

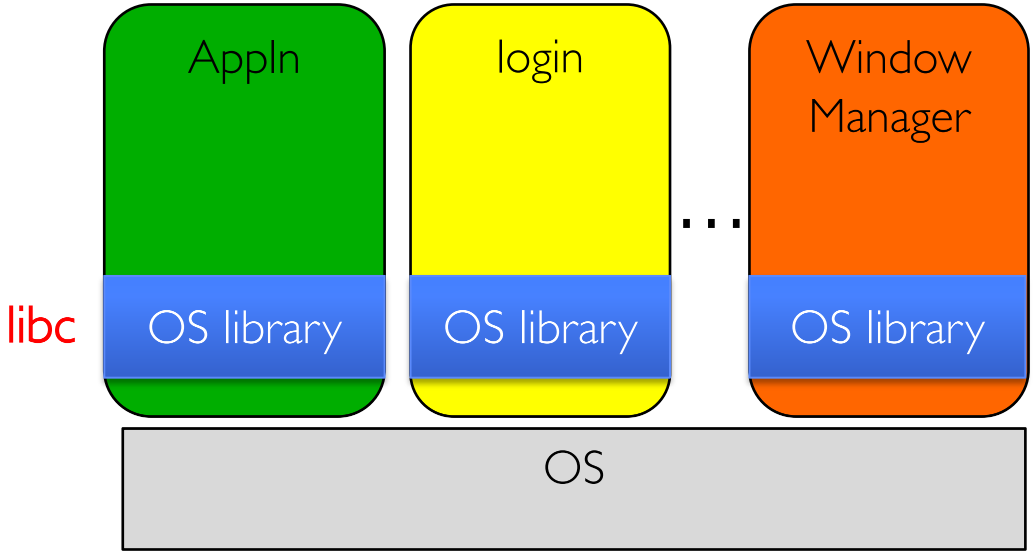
System Calls ("Syscalls")

"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?

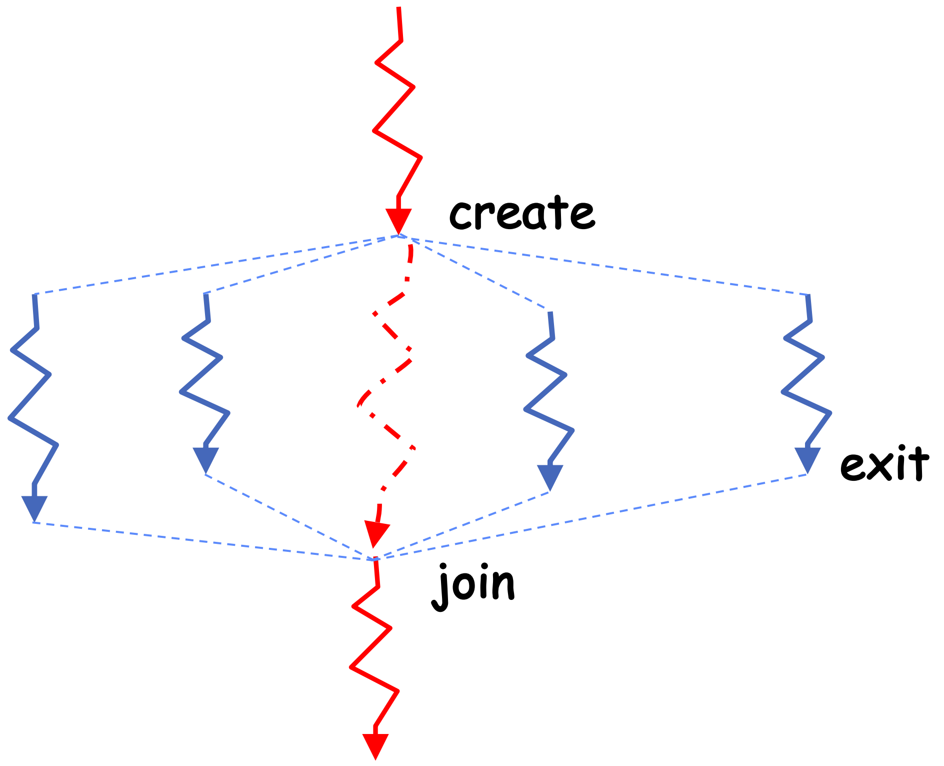
```
Library:
  int pthread_create(…) {
    Do some work like a normal fn…

    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;

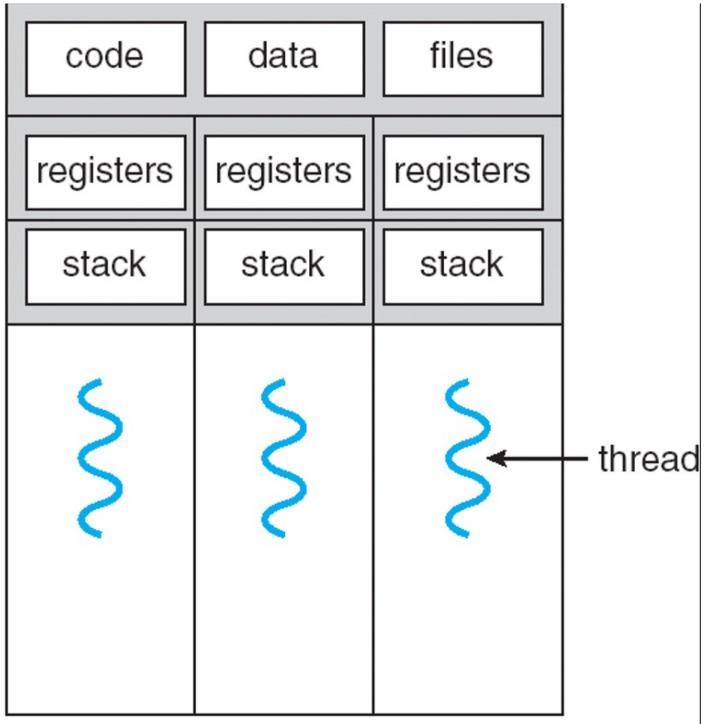
void *threadfun(void *threadid)
{
  long tid = (long)threadid;
  printf("Thread #%lx stack: %lx common: %lx (%d)\n", tid,
         (unsigned long) &tid, (unsigned long) &common, common++);
  pthread_exit(NULL);
}

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



multithreaded process

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

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         A(int tmp) {
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Stack Pointer →

```
A: tmp=1
   ret=exit
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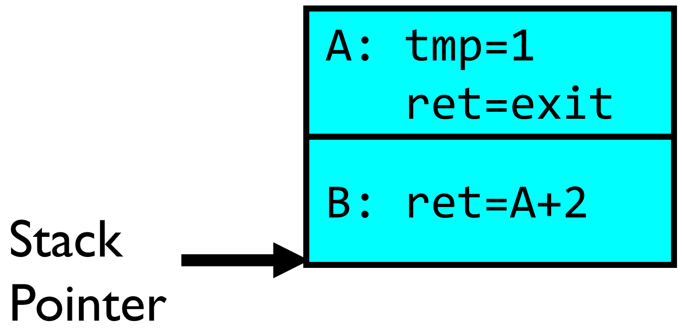

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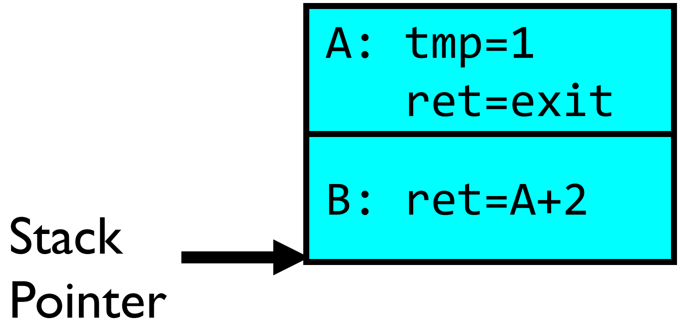

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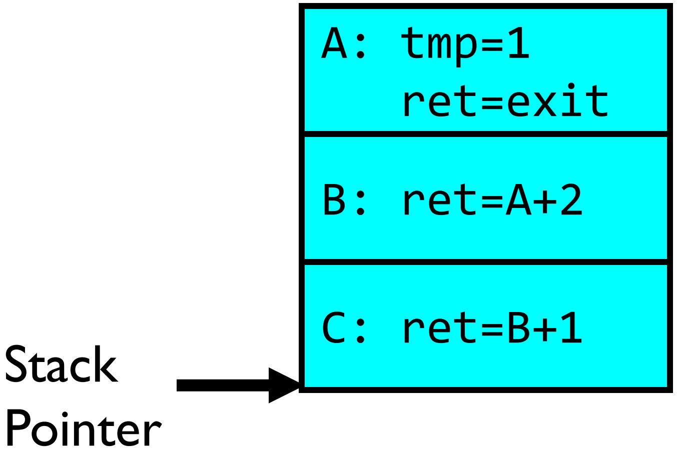

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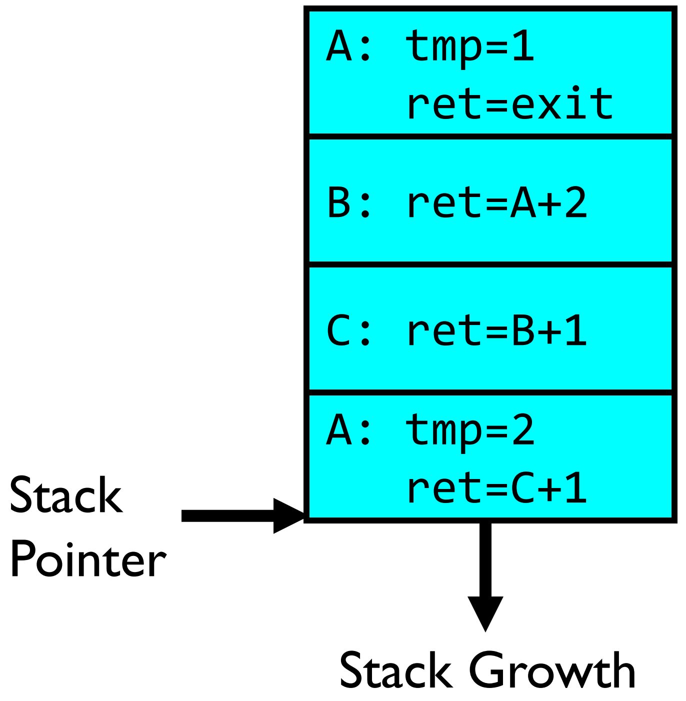

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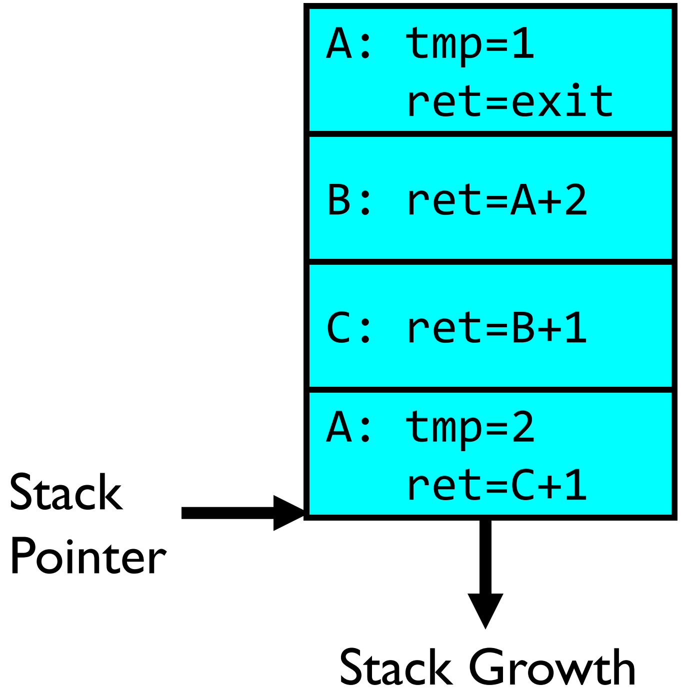

Output: >2

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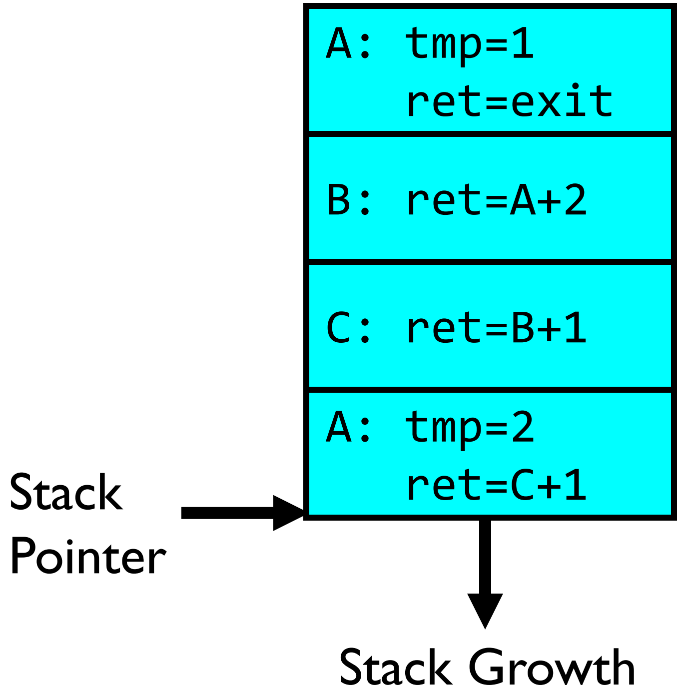

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        }
        B() {
B:        C();
B+1:    }
        C() {
C:        A(2);
C+1:    }
        A(1);
exit:
```

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

Stack Pointer

Output: >2

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Execution Stack Example

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exit:
```

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

Stack Pointer

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      A(1);
exit:
```

Stack Pointer →

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A: tmp=1
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Output: `>2 1`

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

Output: >2 1

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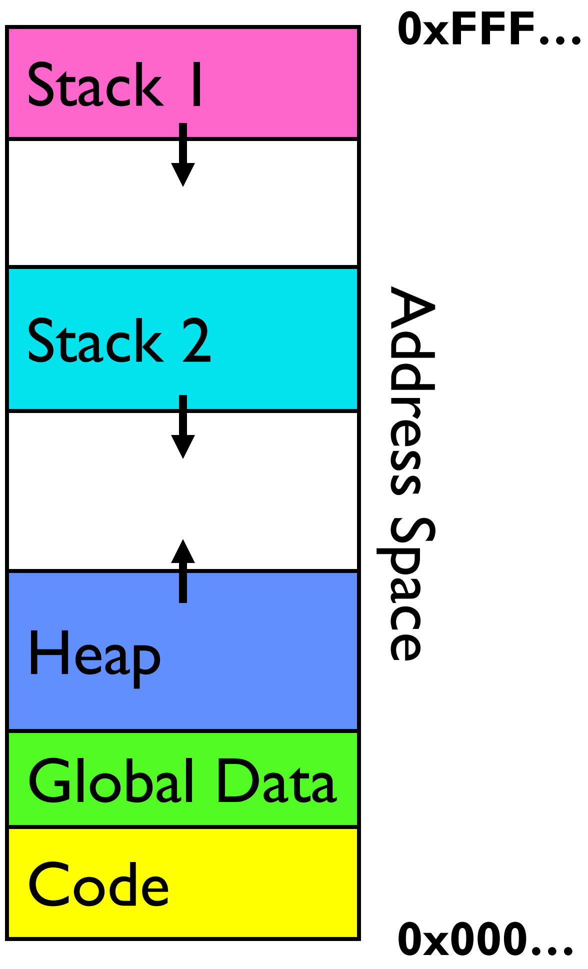
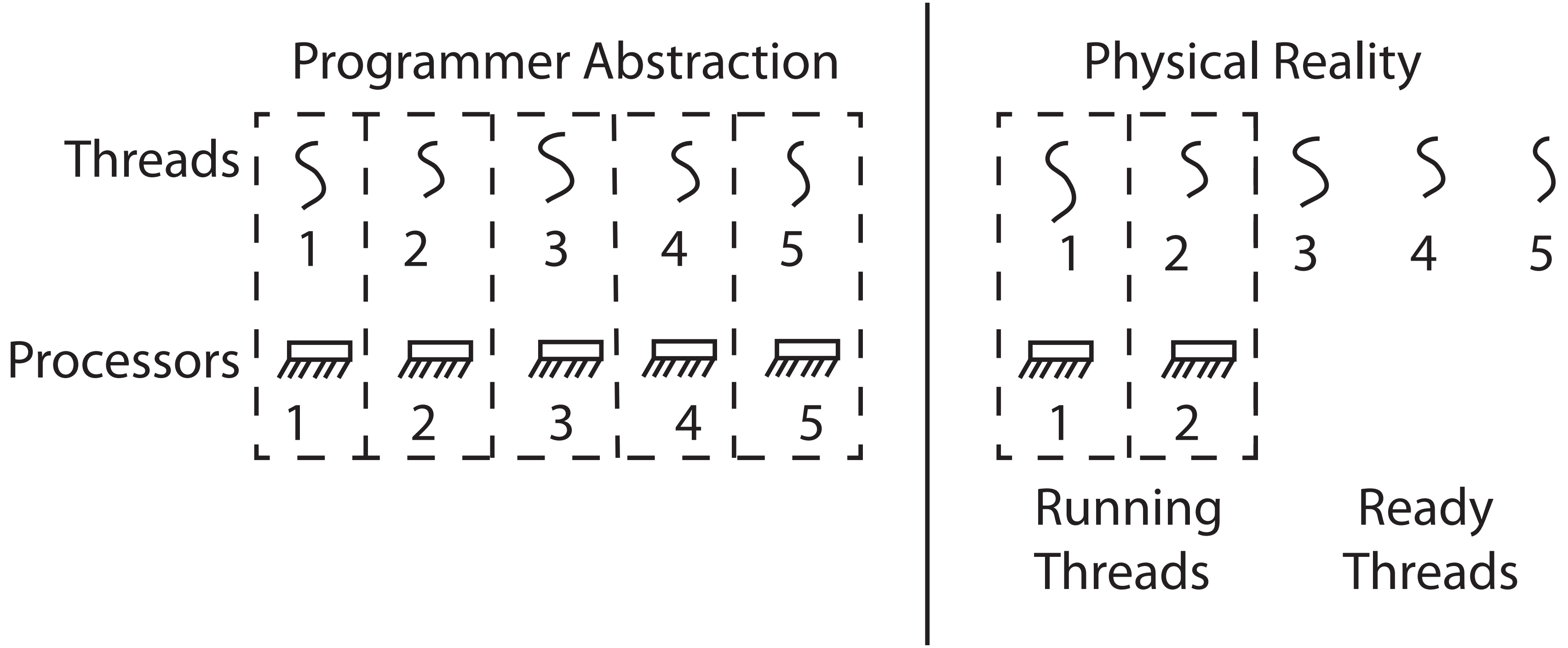
Memory Layout with Two Threads



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

Thread Abstraction

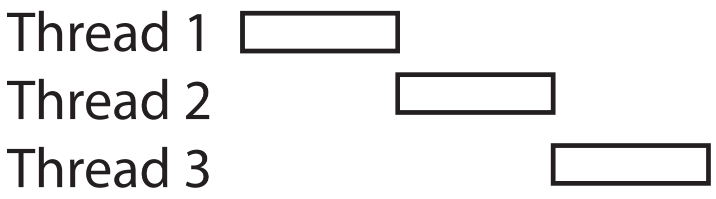


- Illusion: Infinite number of processors
- Reality: Threads execute with variable "speed"
  - Programs must be designed to work with any schedule

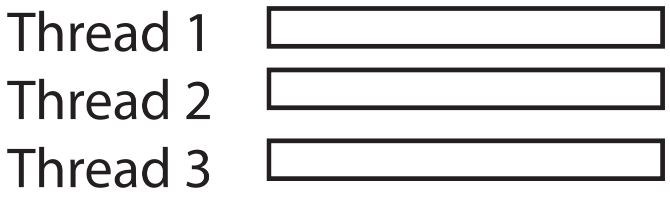
Programmer vs. Processor View

Programmer's View	Possible Execution #1	Possible Execution #2	Possible Execution #3
.	.	.	.
.	.	.	.
.	.	.	.
x = x + 1;	x = x + 1;	x = x + 1	x = x + 1
y = y + x;	y = y + x;	....	y = y + x
z = x +5y;	z = x + 5y;	thread is suspended	....
.	.	other thread(s) run	thread is suspended
.	.	thread is resumed	other thread(s) run
.	.	....	thread is resumed
		y = y + x	....
		z = x + 5y	z = x + 5y

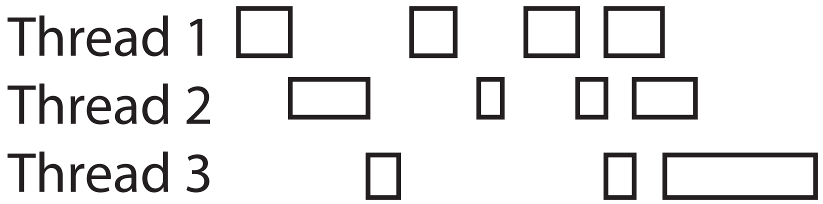
Possible Executions



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!

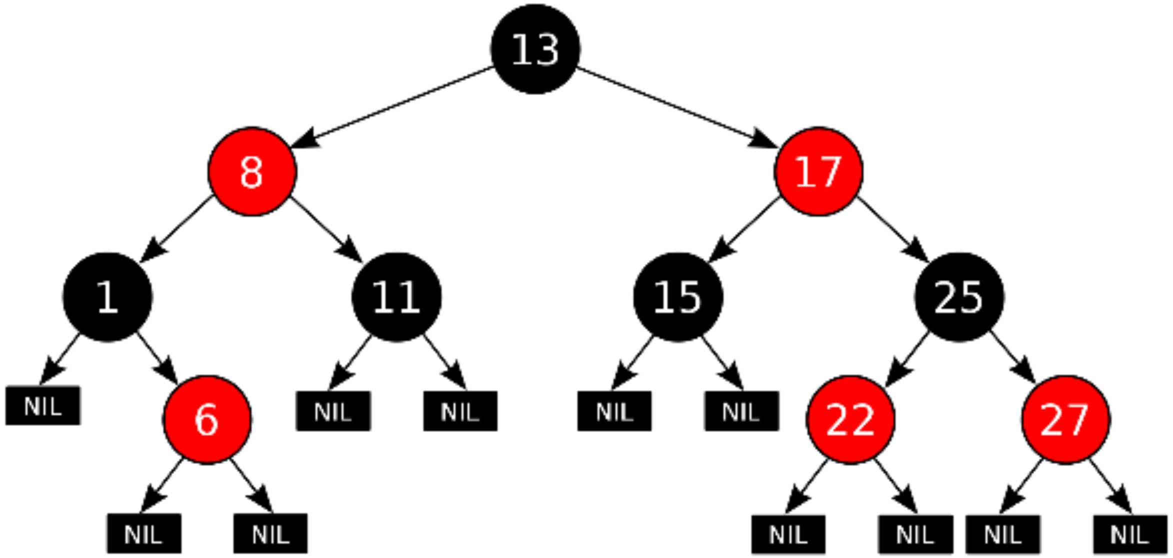
Example: Shared Data Structure

<u>Thread A</u>

```
Insert(3)
```

<u>Thread B</u>

```
Insert(4)
Get(6)
```



Tree-Based Set Data Structure

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

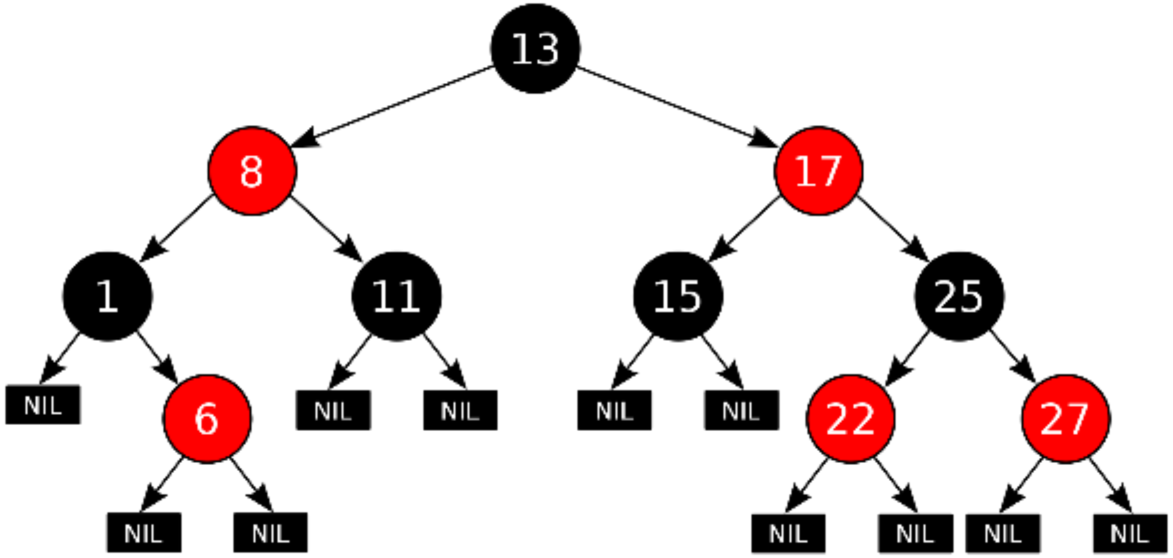
- Locks provide two **atomic** operations:
  - Lock.acquire() – wait until lock is free; then mark it as busy
    - After this returns, we say the calling thread *holds* the lock
  - Lock.release() – mark lock as free
    - Should only be called by a thread that currently holds the lock
    - After this 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);
}
```

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

- We saw the role of the OS library
  - Provide API to programs
  - Interface with the OS to request services