CS162
Operating Systems and Systems Programming
Lecture 3

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

September 5th, 2024

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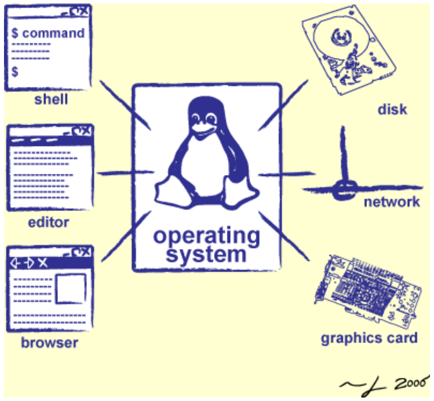
http://cs162.eecs.Berkeley.edu

Slides courtesy of David Culler, Natacha Crooks, Anthony D. Joseph, John Kubiatowicz, AJ Shankar, Alex Aiken, Eric Brewer, Ras Bodik, Doug Tygar, and David Wagner.

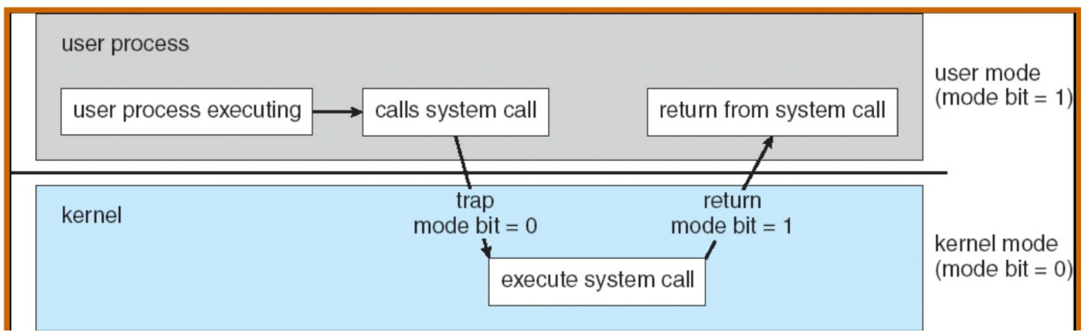
Goals for Today: The Thread Abstraction

- **What** threads are
  - And what they are not
- **Why** threads are useful (motivation)
- **How** to write a program using threads
- **Alternatives** to using threads

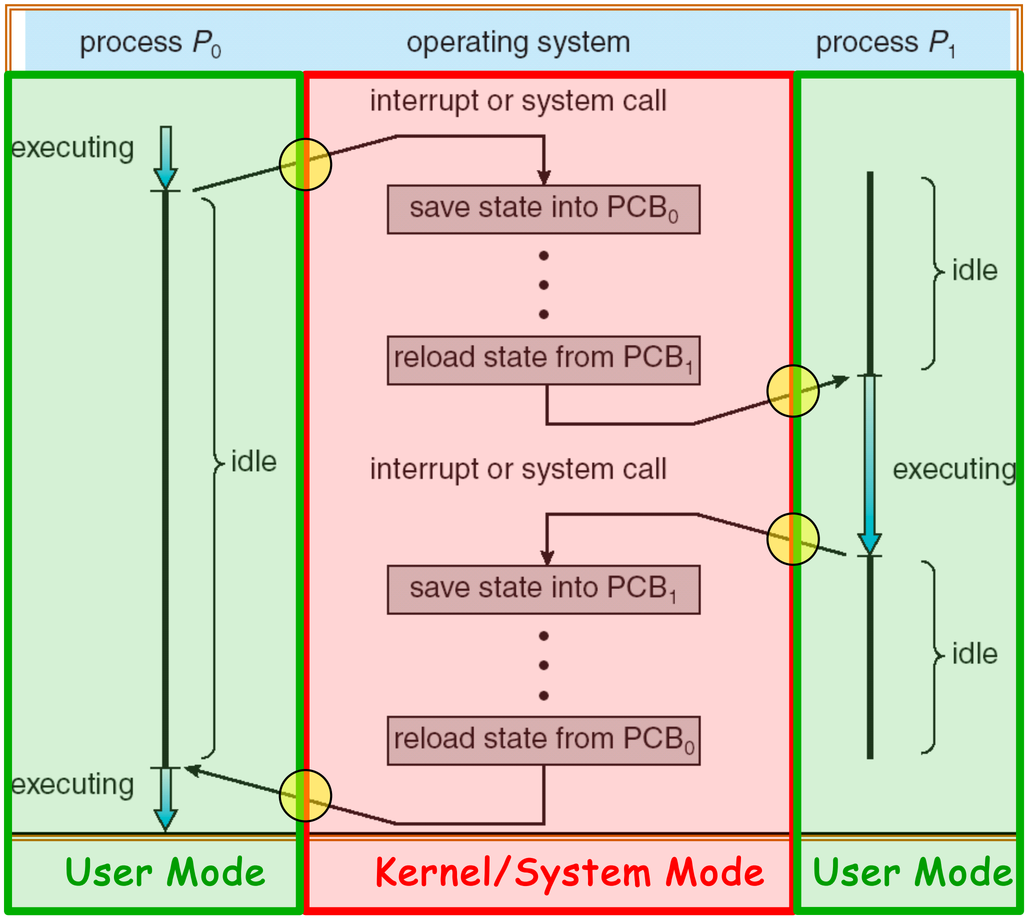


Recall: Dual Mode Operation

- Processes (i.e., programs you run) execute in user mode
  - To perform privileged actions, processes request services from the OS kernel
  - Carefully controlled transition from user to kernel mode
- Kernel executes in kernel mode
  - Performs privileged actions to support running processes
  - … and configures hardware to properly protect them (e.g., address translation)
- Carefully controlled transitions between user mode and kernel mode
  - System calls, interrupts, exceptions



Adding Protection: CPU Switch From Process A to Process B



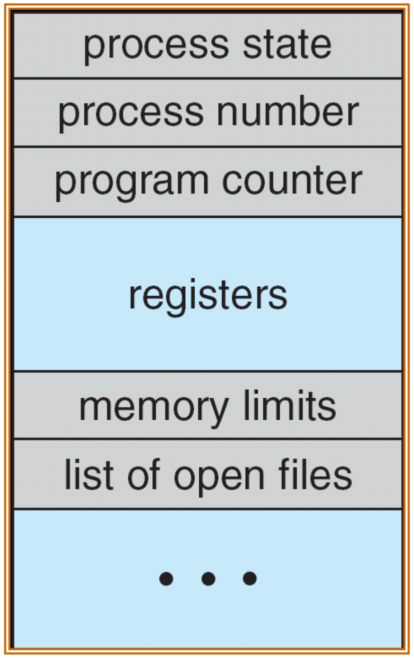
Running Many Programs

- We have the basic *mechanism* to:
  – switch between user processes and the kernel,
  – the kernel can switch among user processes,
  – protect OS from user processes and processes from each other

- Questions:
  – How do we represent user processes in the OS?
  – How do we decide which user process to run?
  – How do we pack up the process and set it aside?
  – How do we get a stack and heap for the kernel?
  – Aren't we wasting a lot of memory?

Multiplexing Processes: The Process Control Block

- Kernel represents each process with a process control block (PCB)
  - Status (running, ready, blocked, …)
  - Register state (when not ready)
  - Process ID (PID), User, Executable, Priority, …
  - Execution time, …
  - Memory space, translation, …
- Kernel *Scheduler* maintains a data structure containing the PCBs
  - Give out CPU to different processes
  - This is a Policy Decision
- Give out non-CPU resources
  - Memory/IO
  - Another policy decision



Process Control Block

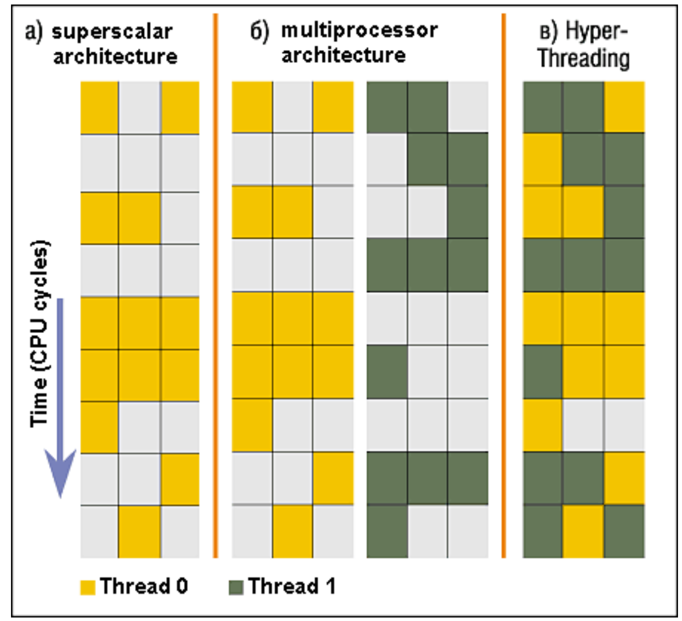
Scheduler

```
if ( readyProcesses(PCBs) ) {
        nextPCB = selectProcess(PCBs);
        run( nextPCB );
} else {
        run_idle_process();
}
```

- Scheduling: Mechanism for deciding which processes/threads receive hardware CPU time, when, and for how long
- Lots of different scheduling policies provide …
  - – Fairness or
  - – Realtime guarantees or
  - – Latency optimization or ..

Simultaneous MultiThreading/Hyperthreading

- Hardware scheduling technique
  - Avoids software overhead of multiplexing
  - Superscalar processors can execute multiple instructions that are independent.
  - Hyperthreading duplicates register state to make a second "thread," allowing more instructions to run.
- Can schedule each thread as if were separate CPU
  - But, sub-linear speedup!



Colored blocks show instructions executed

- Original technique called "Simultaneous Multithreading"
  - http://www.cs.washington.edu/research/smt/index.html
  - SPARC, Pentium 4/Xeon ("Hyperthreading"), Power 5

More About Threads: What are they?

- Definition from before: *A single unique execution context*
  – Describes its representation

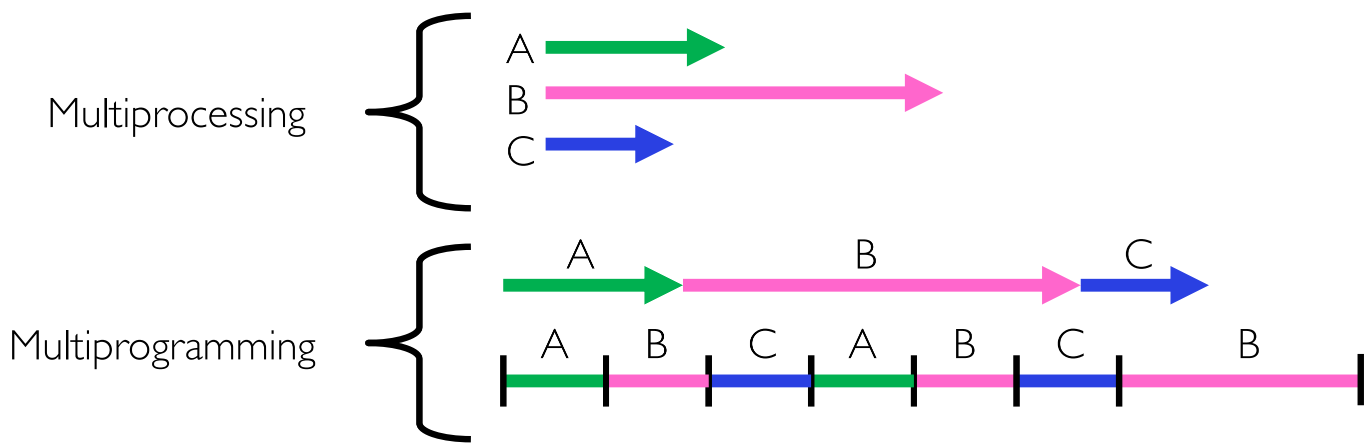
- It provides the abstraction of: *A single execution sequence that represents a separately schedulable task*
  – Also a valid definition!

- Threads are a mechanism for *concurrency* (overlapping execution)
  – However, they can also run in *parallel* (simultaneous execution)

- Protection is an orthogonal concept
  – A protection domain can contain one thread or many

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
- 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

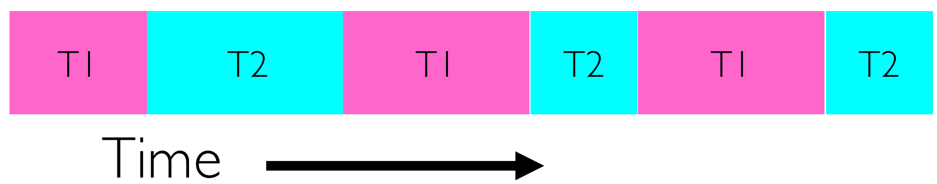
Adding Threads

- Version of program with threads (loose syntax):

```
main() {
    create_thread(ComputePI, “pi.txt”);                 → T1*
    create_thread(PrintClassList, “classlist.txt”);     → T2
}
```

- `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



*we use thread (T) and vCPU interchangeable. vCPU suggests that the OS provides a virtual CPU abstraction to the thread.

More Practical Motivation: Compute/IO overlap

Back to Jeff Dean's "Numbers Everyone Should Know"

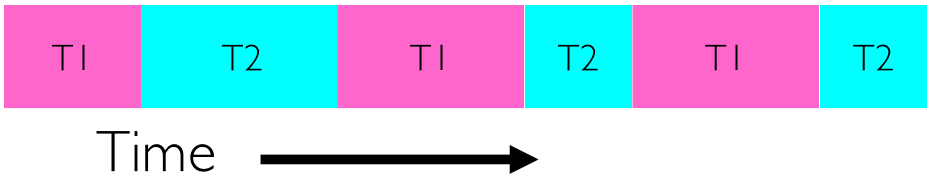
L1 cache reference	0.5 ns
Branch mispredict	5 ns
L2 cache reference	7 ns
Mutex lock/unlock	25 ns
Main memory reference	100 ns
Compress 1K bytes with Zippy	3,000 ns
Send 2K bytes over 1 Gbps network	20,000 ns
Read 1 MB sequentially from memory	250,000 ns
Round trip within same datacenter	500,000 ns
Disk seek	10,000,000 ns
Read 1 MB sequentially from disk	20,000,000 ns
Send packet CA->Netherlands->CA	150,000,000 ns

Handle I/O in separate thread, avoid blocking other progress

Threads Mask I/O Latency

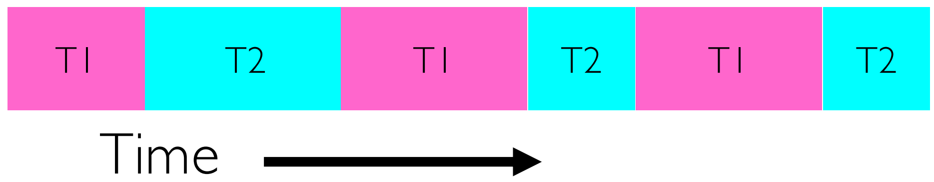
- A thread is in one of the following three states:
  - RUNNING – running
  - READY – eligible to run, but not currently running
  - BLOCKED – ineligible to run

- 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

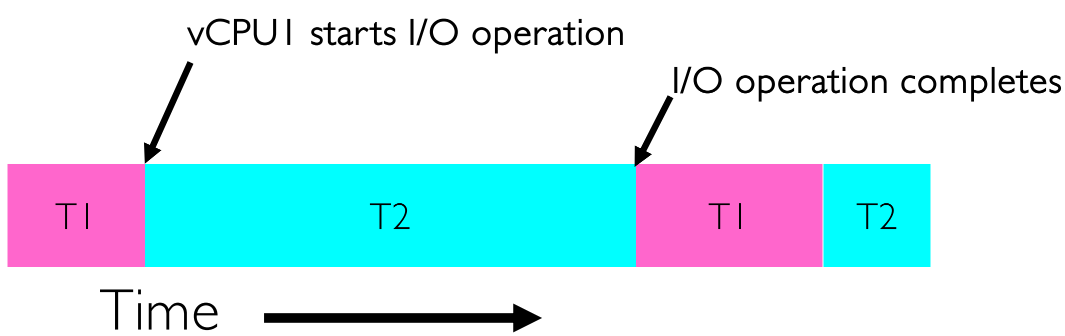


Threads Mask I/O Latency

- If no thread performs I/O:



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



A Better Example for Threads

```
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

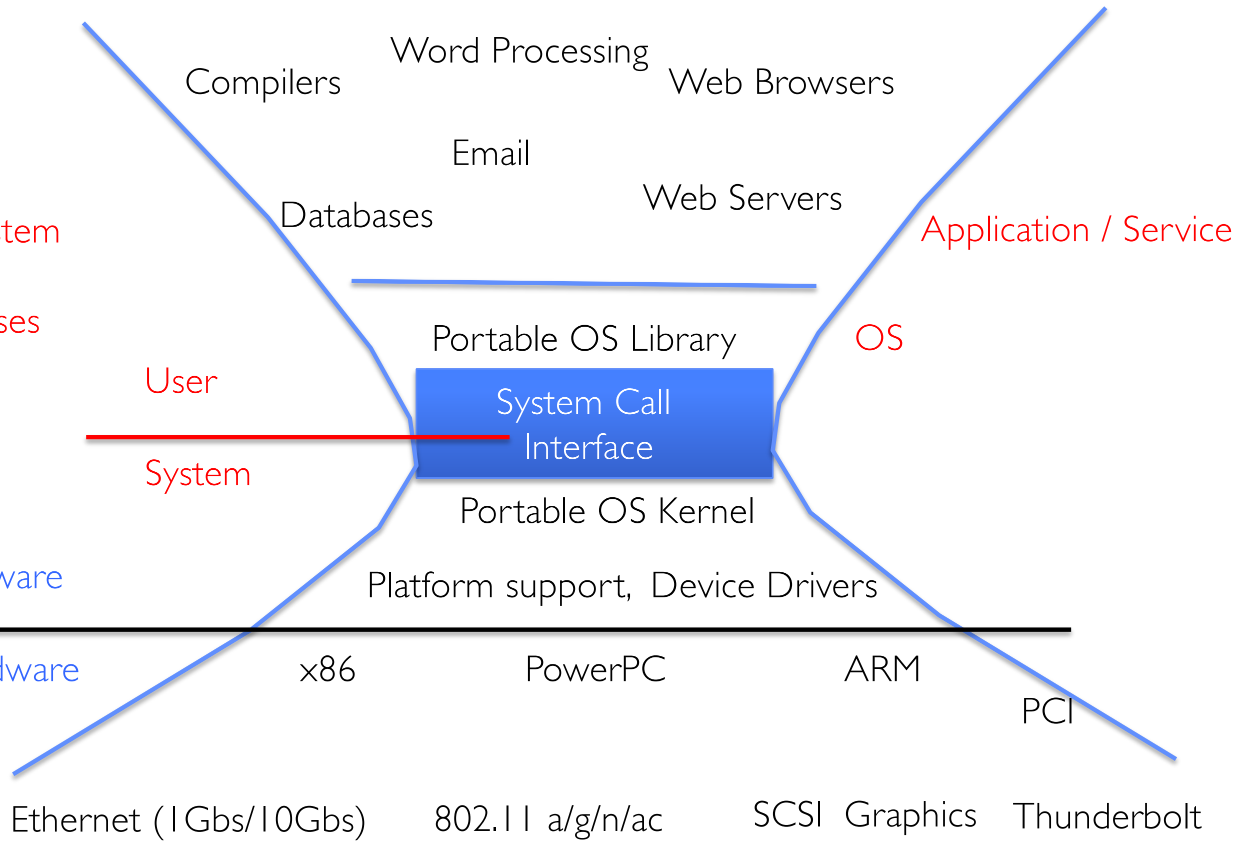
Multithreaded Programs

- 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

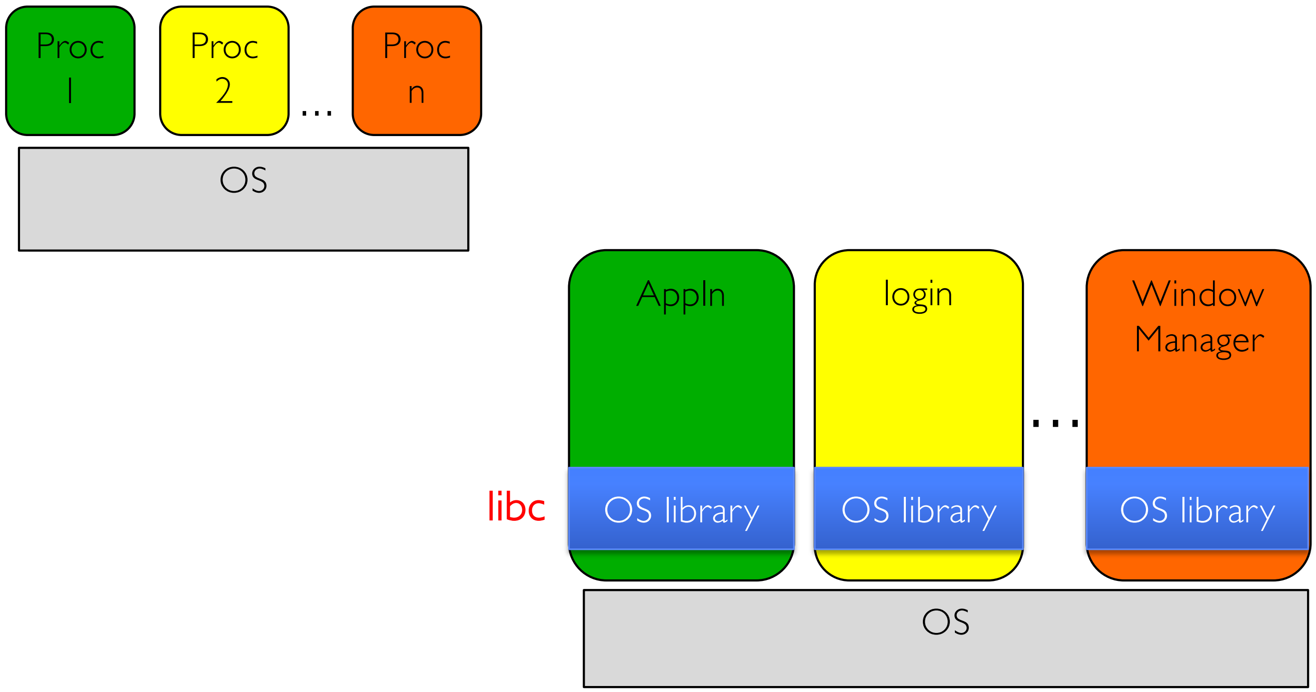
System Calls ("Syscalls")

"But, I've never seen a syscall!"

- OS library issues system call
- Language runtime uses OS library…



OS Library Issues Syscalls



Administrivia: Getting started!

- Ion's office hour:
  - Tuesday 11-12pm, in 465 Soda Hall
- Homework 0: Due Tomorrow!
  - Get familiar with the cs162 tools
  - configure your VM, submit via git
  - Practice finding out information:
    - » How to use GDB? How to understand output of unix tools?
    - » We don't assume that you already know everything!
    - » Learn to use "man" (command line), "help" (in gdb, etc), google
- Project 0: Started two days ago!
  - Learn about Pintos and how to modify and debug kernel
  - Important for getting started on projects!
- Should be going to sections now – Important information there
  - Any section will do until groups assigned

Administrivia (Con't)

- THIS Friday is Drop Deadline! HARD TO DROP LATER!
  - If you know you are going to drop, do so now to leave room for others on waitlist!
  - Why do we do this? So that groups aren't left without members!
- Group sign up via autograder form next week
  - Get finding groups of 4 people ASAP
  - Priority for same section; if cannot make this work, keep same TA
  - Remember: Your TA needs to see you in section!
- Midterm 1: 10/3
  - 7-9PM in person
  - We will say more about material when we get closer…

OS Library API for Threads: *pthreads*

Here: the "p" is for "POSIX" which is a part of a standardized API

```
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
– (attr contains info like stack size, scheduling policy, etc)

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

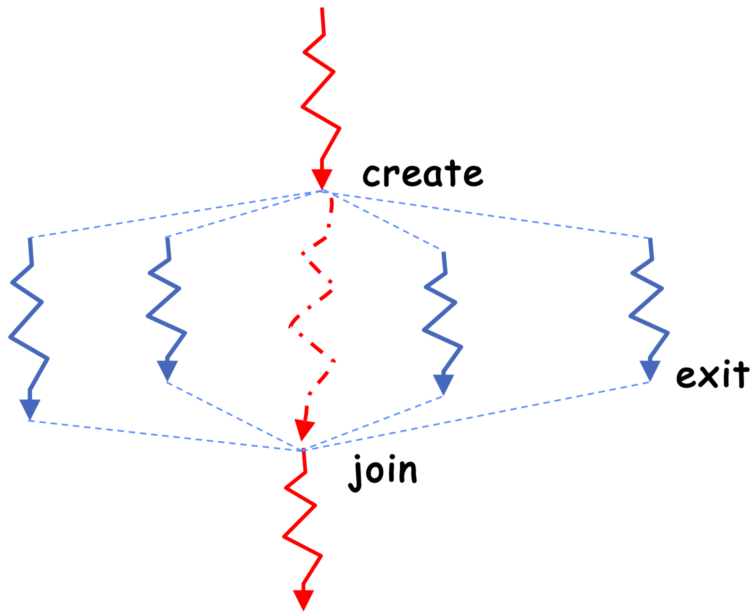
– terminates the thread and makes *value_ptr* available to any successful join

```
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

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.

pThreads Example

- How many threads are in this program?
- What function does each thread run?
- One possible result:

```
(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)
```

- Does the main thread join with the threads in the same order that they were created?
  - Yes: Loop calls Join in thread order
- Do the threads exit in the same order they were created?
  - No: Depends on scheduling order!
- Would the result change if run again?
  - Yes: Depends on scheduling order!
- Is this code safe/correct???
  - No – threads share a variable that is used without locking and there is a race condition!

```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 */
}
```

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
```

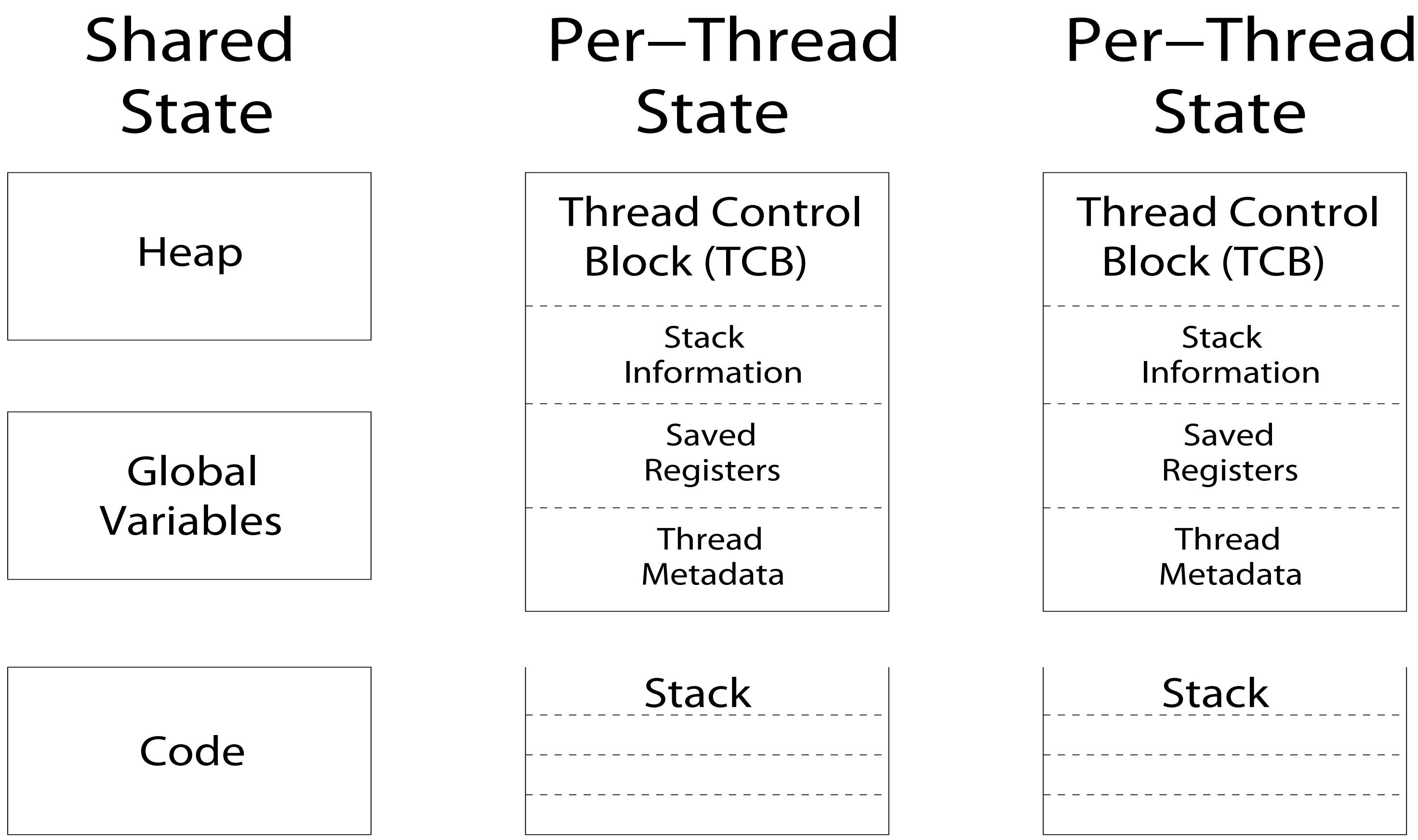
```
      get return values from regs
      Do some more work like a normal fn…
   };
```

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

Shared vs. Per-Thread State



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);
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exit:
```

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

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Stack Pointer →

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A: tmp=1
   ret=exit
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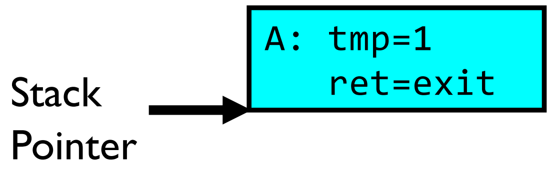

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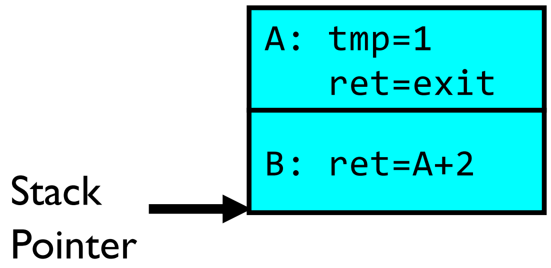

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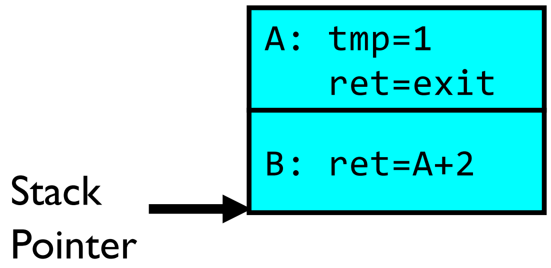

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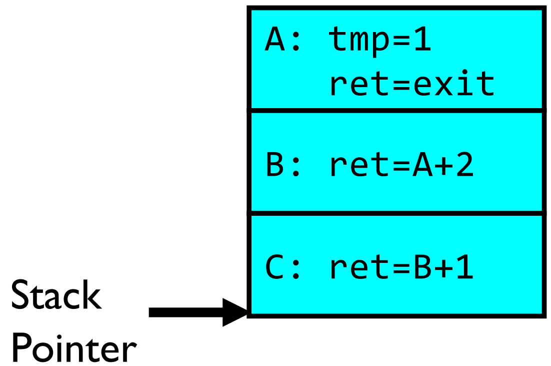

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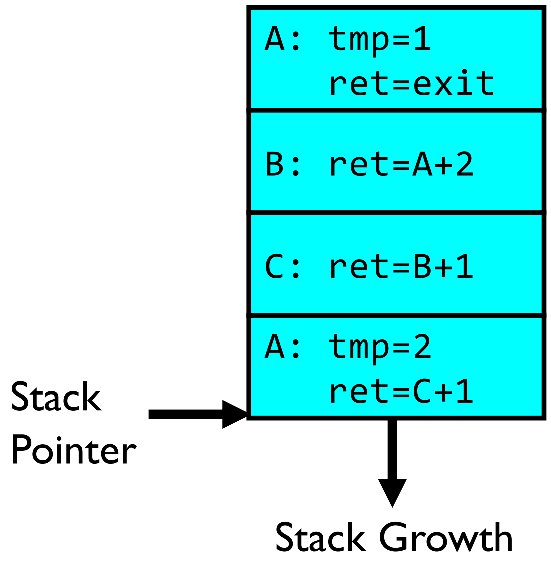

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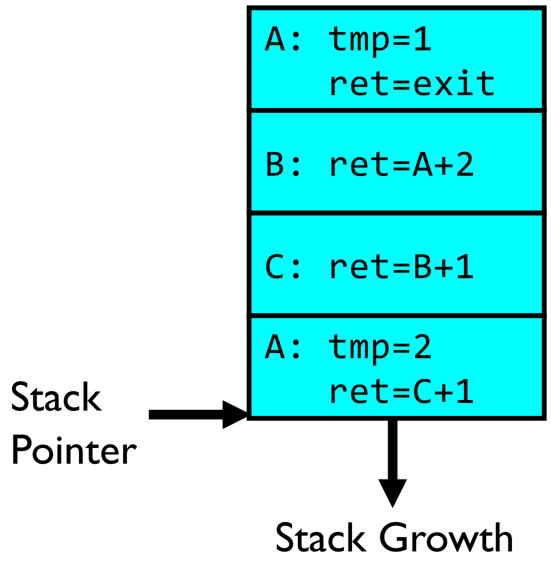

Output: >2

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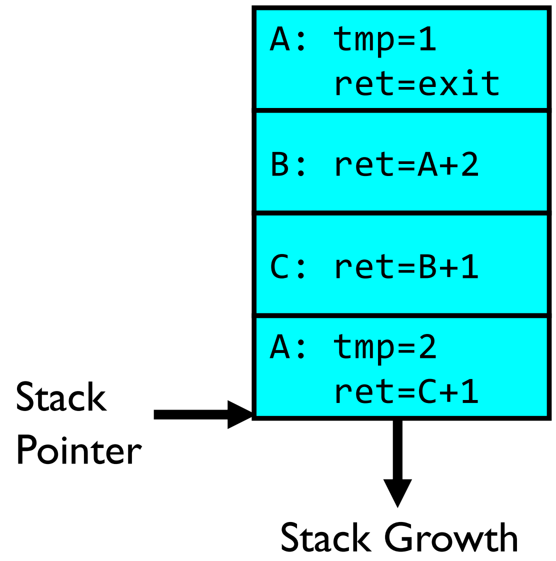

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```

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

Stack Pointer

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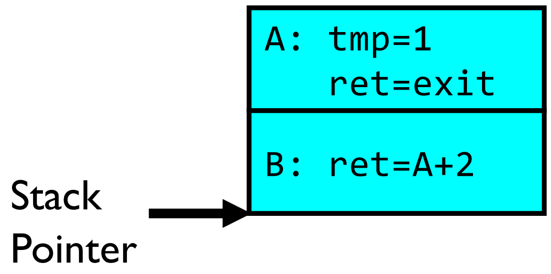

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}
B() {
  C();
}
C() {
  A(2);
}
A(1);
```
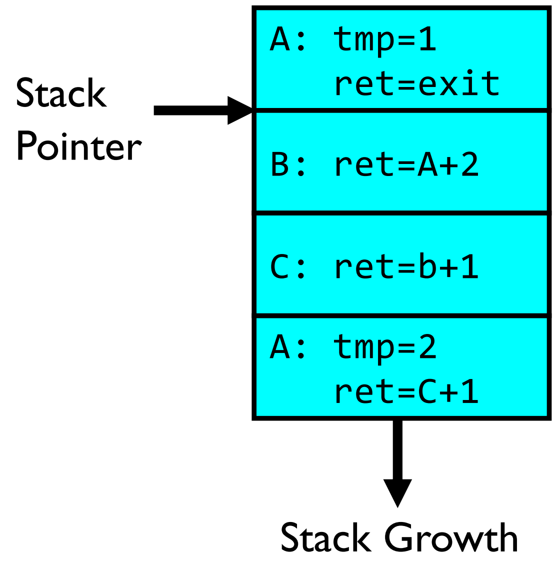
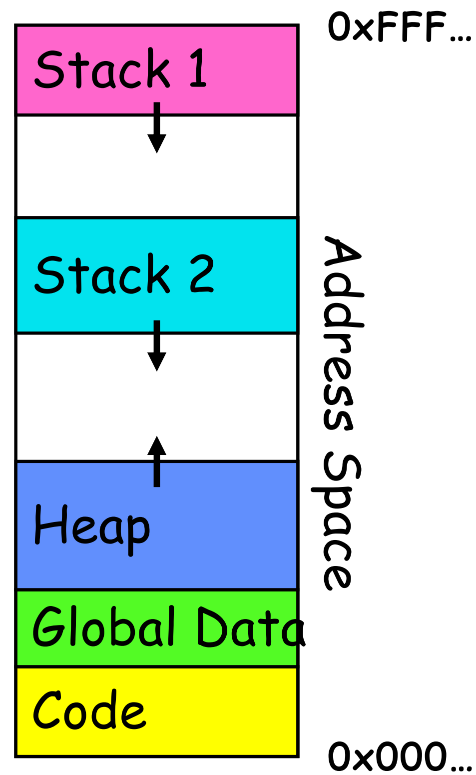



- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

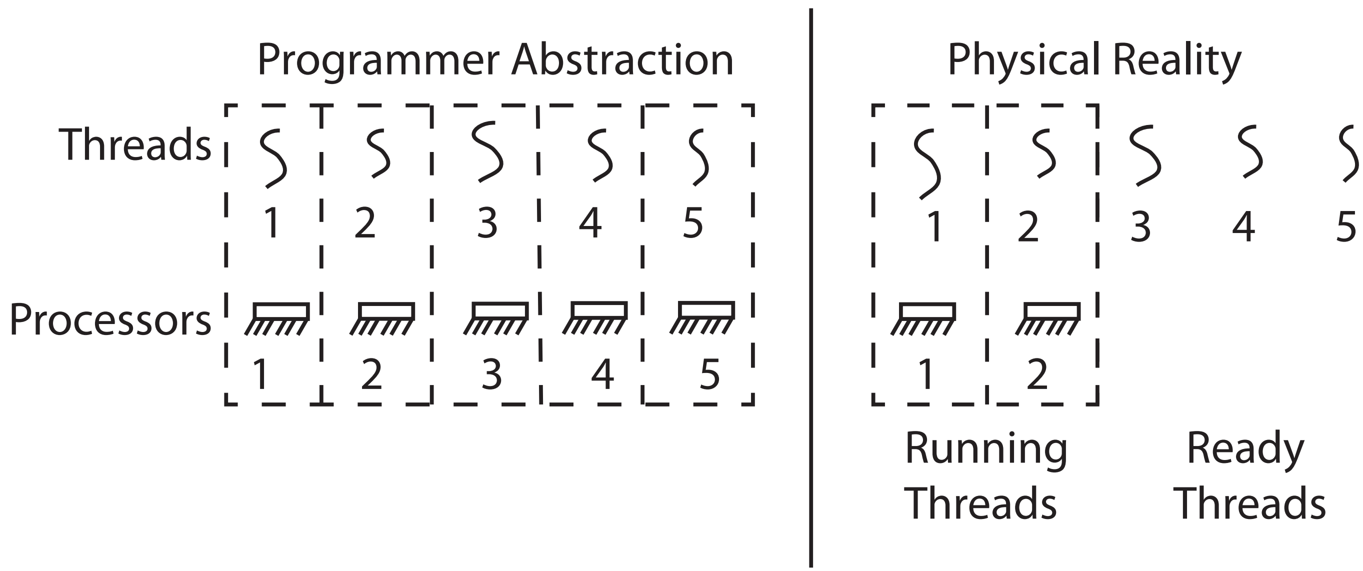
Memory Layout with Two Threads

- Two sets of CPU registers
- Two sets of Stacks
- Issues:
  - How do we position stacks relative to each other?
  - What maximum size should we choose for the stacks?
  - What happens if threads violate this?
  - How might you catch violations?



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;
.
.
.

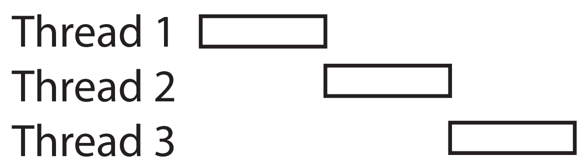
Possible Execution #2

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

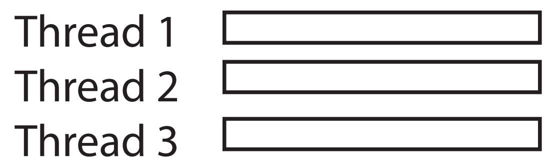
Possible Execution #3

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

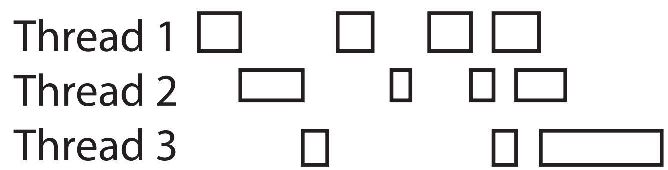
Possible Executions



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: Example 1

- 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: Example 2

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

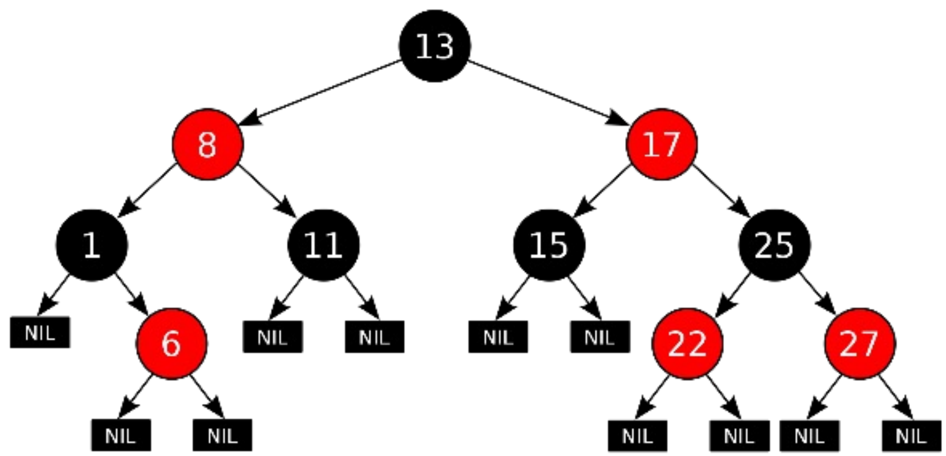
```
Thread A        Thread B
x = y + 1;      y = 2;
                y = y * 2;
```

- 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)`

How do we make sure this executes correctly?

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

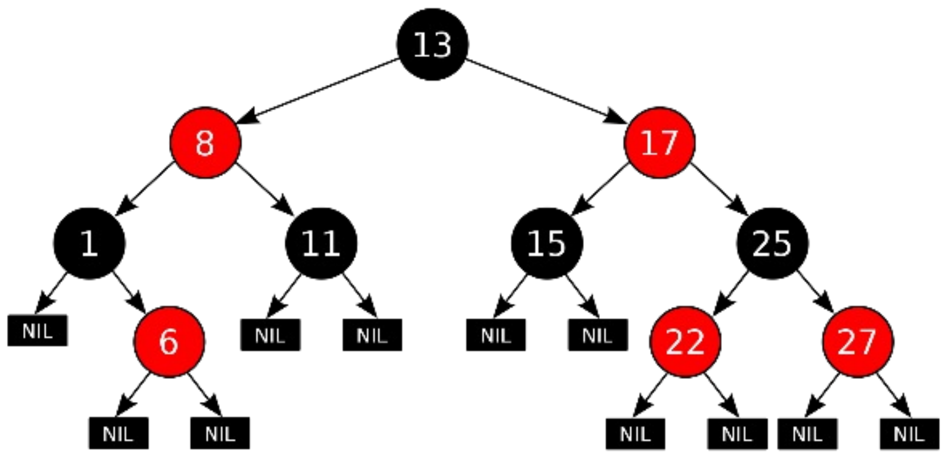
- Locks provide two **atomic** operations:
  – Lock.acquire() – wait until lock is free; then mark it as busy
    » After this returns, we say the calling thread *holds* the lock
  – Lock.release() – mark lock as free
    » Should only be called by a thread that currently holds the lock
    » After this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

You'll get a chance to use these in Homework 1

Our Example

Critical section

```c
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
- 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

Recall: Four Fundamental OS Concepts

- **Thread: Execution Context**
  - Fully describes program state
  - Program Counter, Registers, Execution Flags, Stack
- **Address space** (with or w/o **translation**)
  - Set of memory addresses accessible to program (for read or write)
  - May be distinct from memory space of the physical machine (in which case programs operate in a virtual address space)
- **Process: an instance of a running program**
  - Protected Address Space + One or more Threads
- **Dual mode operation / Protection**
  - Only the "system" has the ability to access certain resources
  - Combined with translation, isolates programs from each other and the OS from programs