Abstractions 1: Threads and Processes

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CS 162: Operating Systems and System Programming

Lecture 3

https://inst.eecs.berkeley.edu/~cs162/su20

Read: A&D 3.1, 5.1-5.3

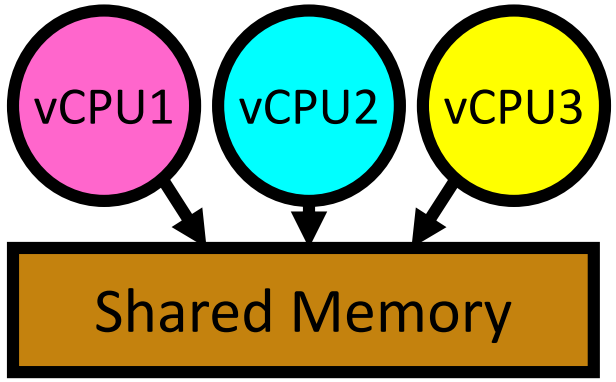
Recall: Four Fundamental OS Concepts

- **Thread: Execution Context**
  - Program Counter, Registers, Execution Flags, Stack
- **Address Space** (with **Translation**)
  - Program's view of memory is distinct from physical machine
- **Process: Instance of a Running Program**
  - Address space + one or more threads + …
- **Dual-Mode Operation and Protection**
  - Only the "system" can access certain resources
  - Combined with translation, isolates programs from each other

Recall: Thread

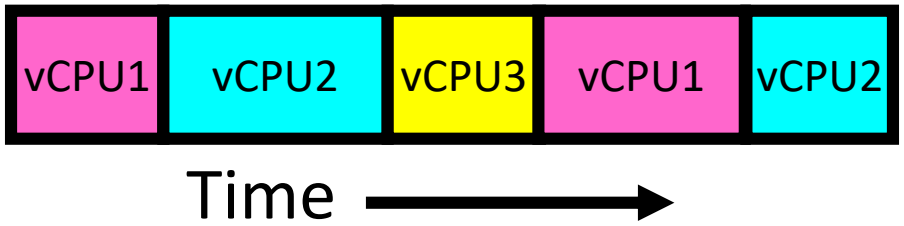
- Definition: **A single, unique execution context**
  - Program counter, registers, stack
- **A thread is the OS abstraction for a CPU core**
  - A "virtual CPU" of sorts
- Registers hold the root state of the thread:
  - Including program counter – pointer to the currently executing instruction
  - The rest is "in memory"
- Registers point to thread state in memory:
  - Stack pointer to the top of the thread's (own) stack

Recall: Illusion of Multiple Processors



- Threads are **virtual cores**
- Multiple threads: **Multiplex** hardware in time
- **A thread is *executing* on a processor when it is resident in that processor's registers**

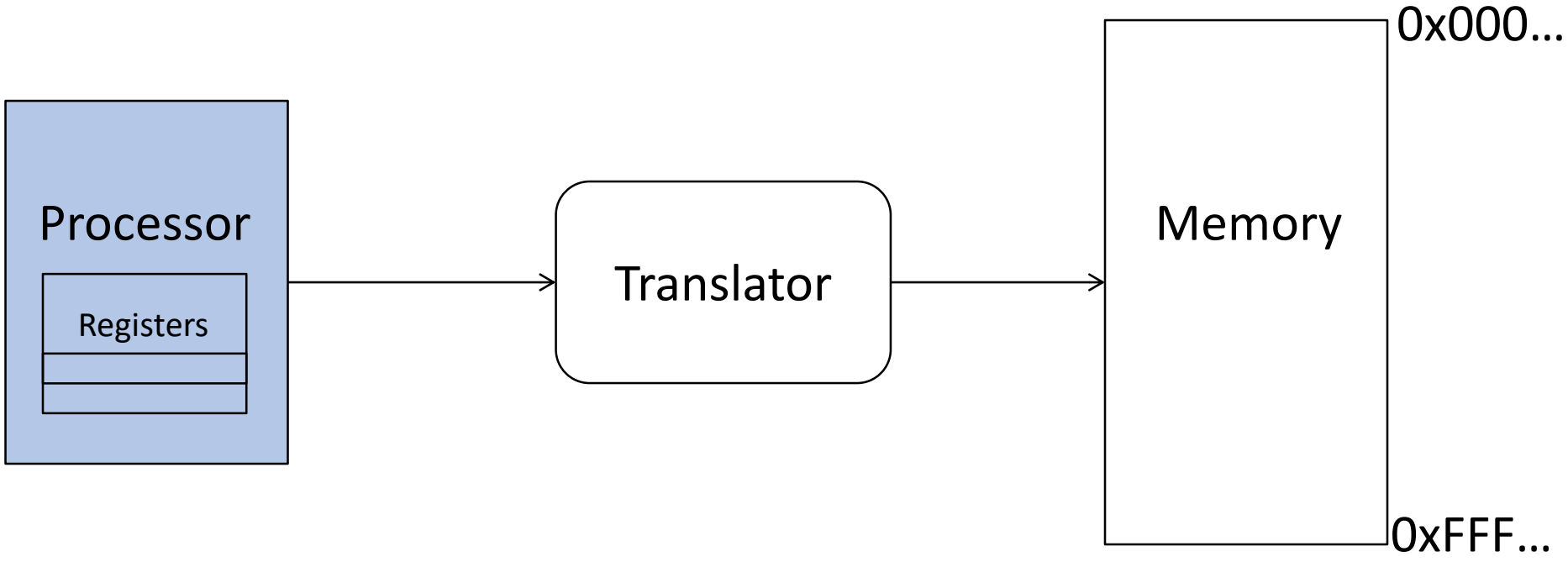
On a single physical CPU:



- Each virtual core (thread) has PC, SP, Registers
- Where is it?
  - On the real (physical) core, or
  - Saved in memory – called the Thread Control Block (TCB)

Recall: Address Space

- Program operates in an address space that is distinct from the physical memory space of the machine



Recall: Process

- 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**

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)

- Together, address translation and dual-mode operation allow the kernel to ***protect*** processes from each other and itself from processes

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

What Threads Are

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

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 communicatoin

Threads Allow Handling MTAO

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

Concurrency is not Parallelism

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

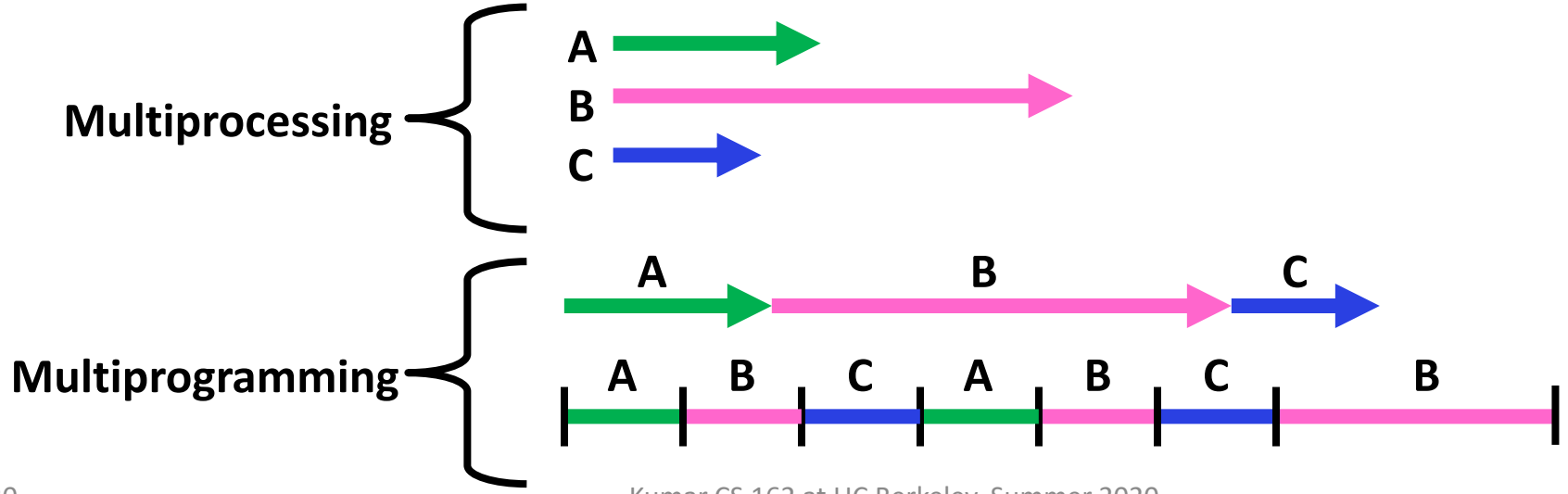
- Example: Two threads on a single-core system...
  - … execute concurrently …
  - … but *not* in parallel

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

Multiprocessing vs. Multiprogramming

- Multiprocessing: Multiple 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



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

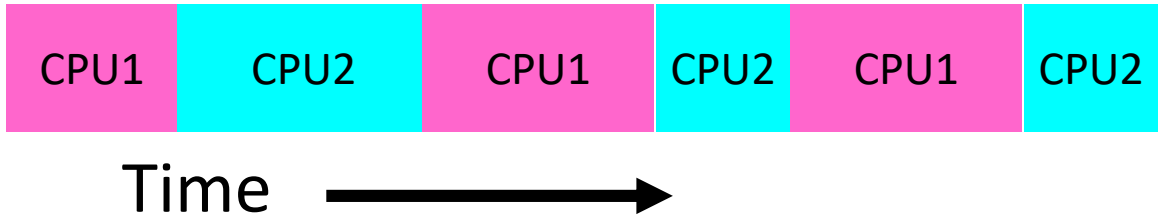
Adding Threads

- 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



More Practical Motivation

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

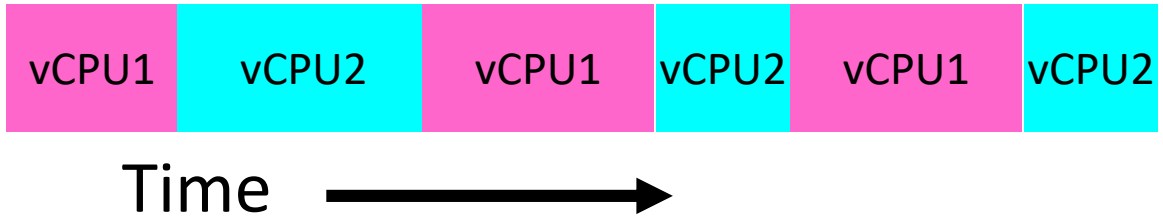
L1 cache reference	0.5 ns
Branch mispredict	5 ns
L2 cache reference	7 ns
Mutex lock/unlock	25 ns
Main memory reference	100 ns
Compress 1K bytes with Zippy	3,000 ns
Send 2K bytes over 1 Gbps network	20,000 ns
Read 1 MB sequentially from memory	250,000 ns
Round trip within same datacenter	500,000 ns
Disk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

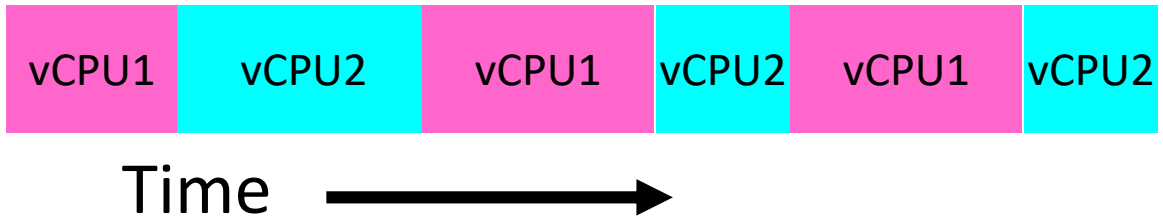
- A thread is in one of the following three states:
  - RUNNING – running
  - READY – eligible to run, but not currently running
  - BLOCKED – ineligible to run

- 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

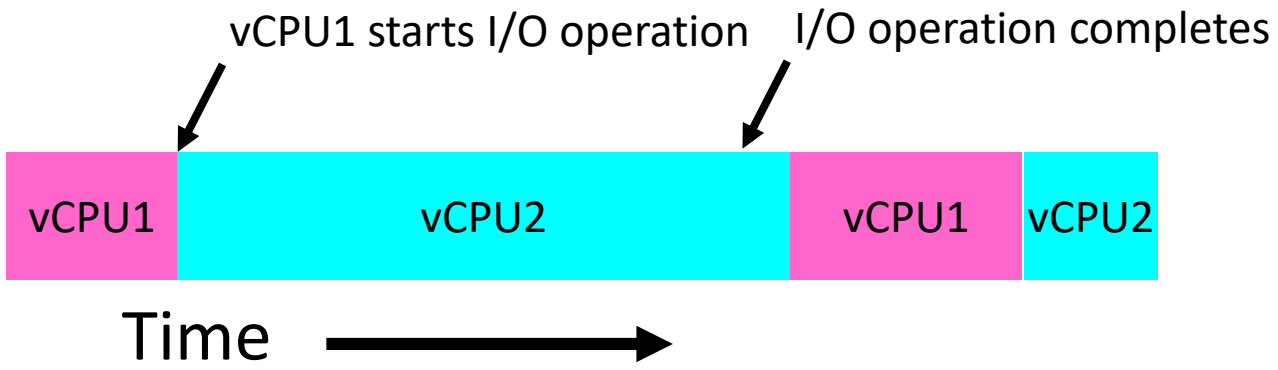


Threads Mask I/O Latency

- If no thread performs I/O:



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



Little 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

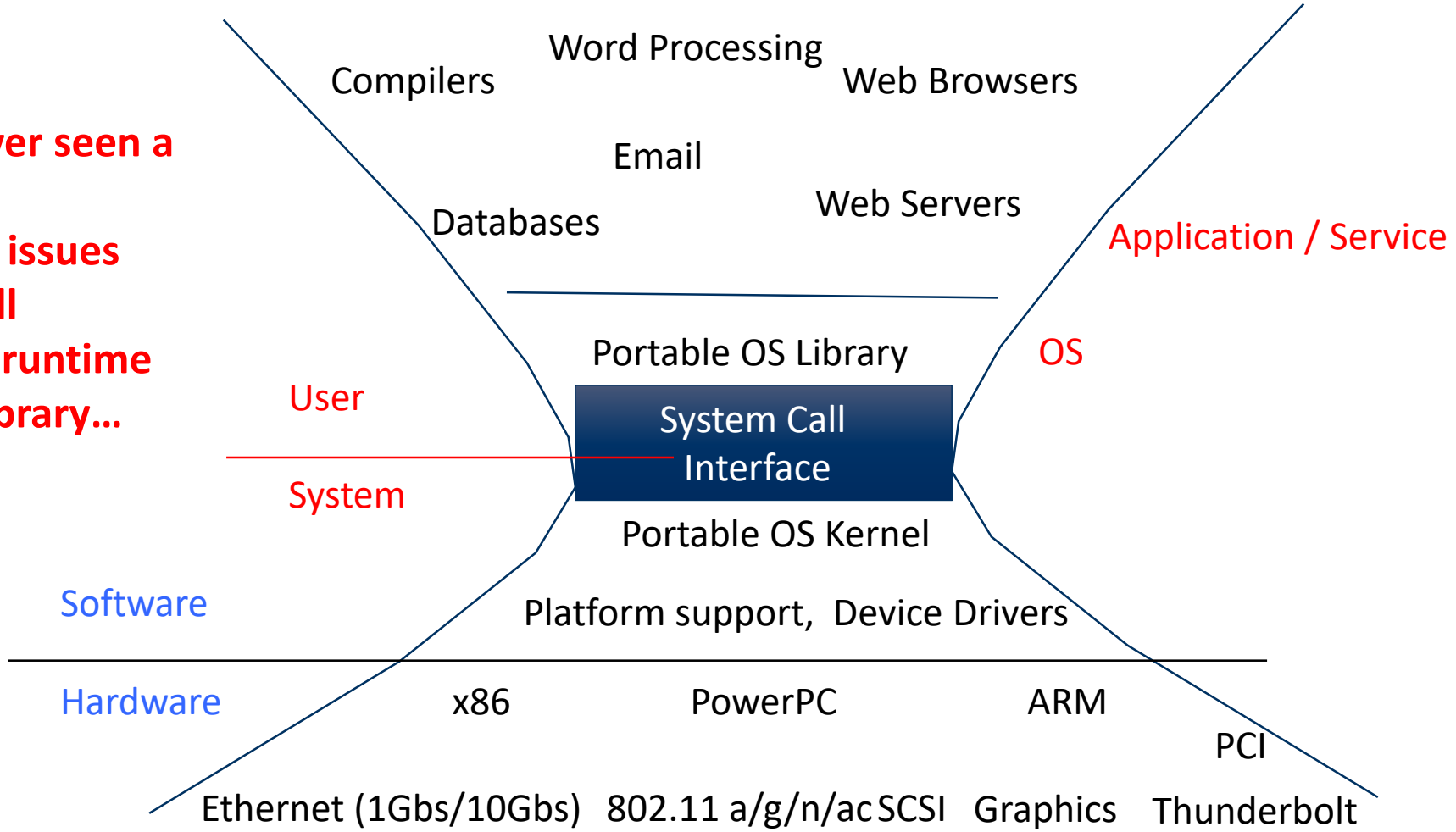
Multithreaded Programs

- 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, globals, 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

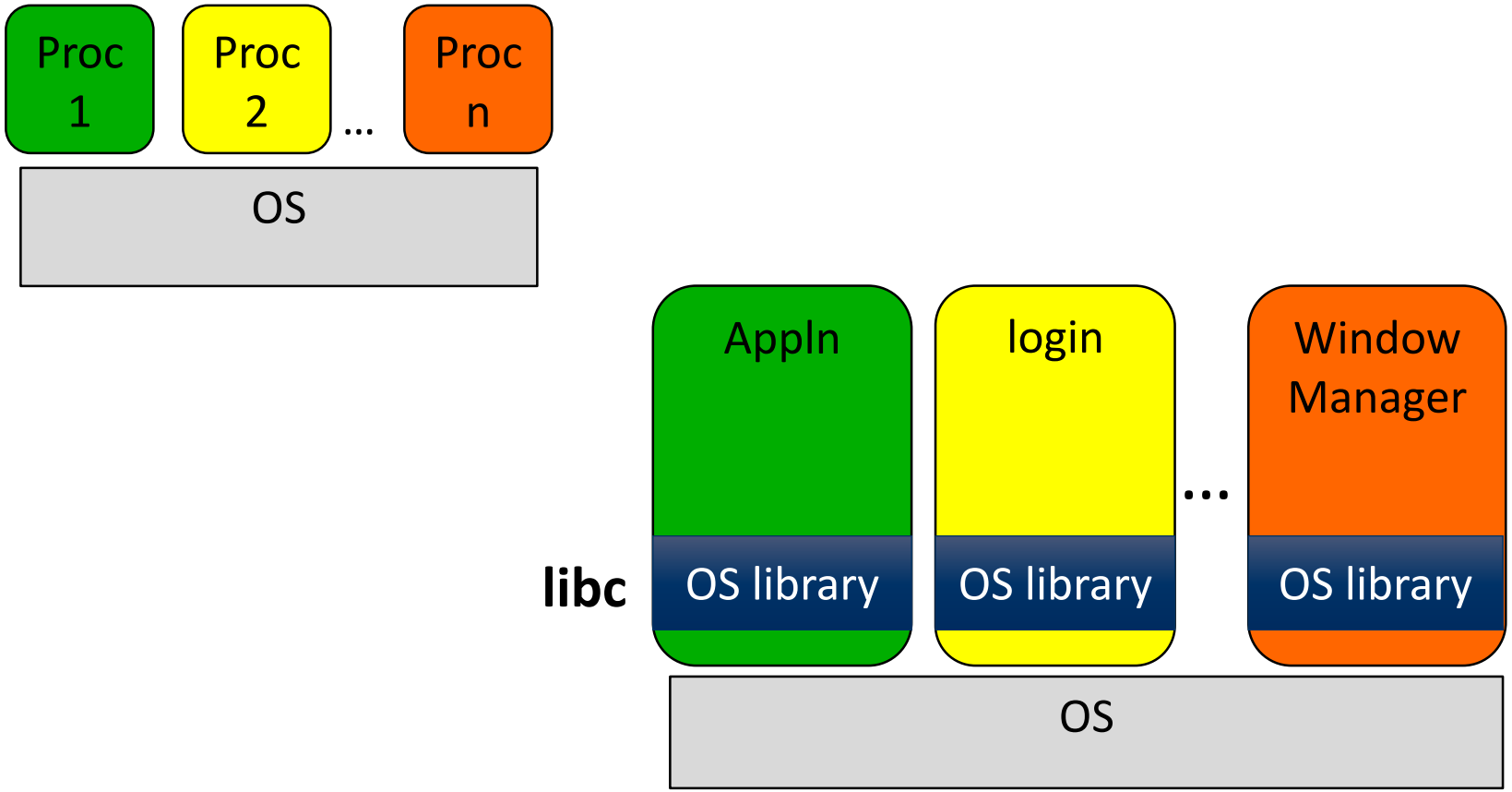
System Calls ("Syscalls")

"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*.

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…
   };
```

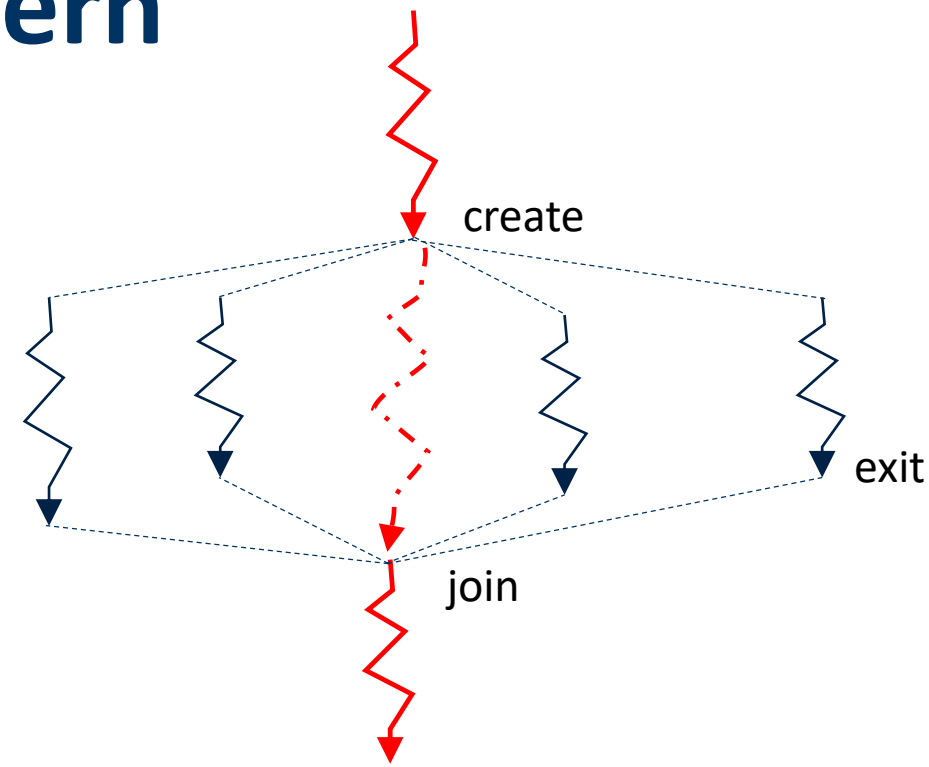
Threads Example

```
(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)
```

- 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?

```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  */
}
```

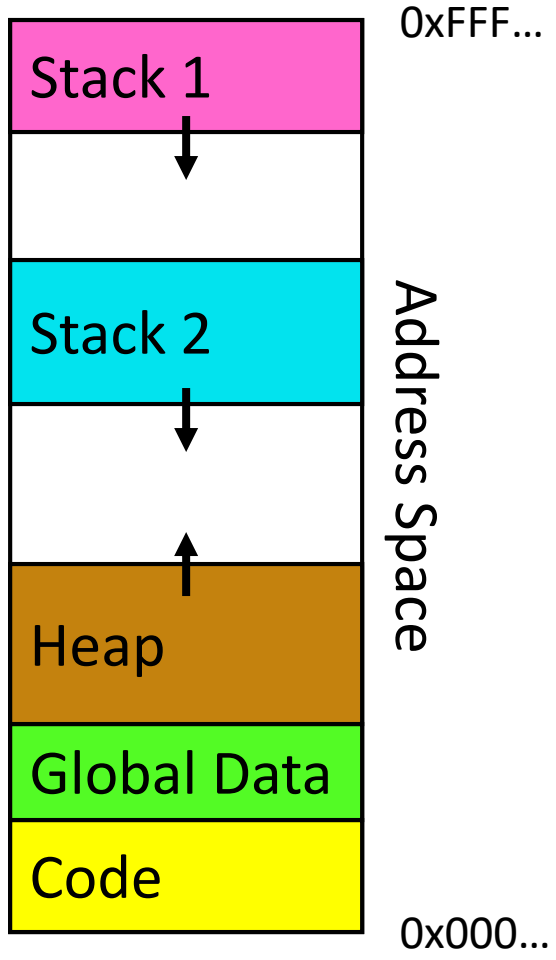
Fork-Join Pattern



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

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?

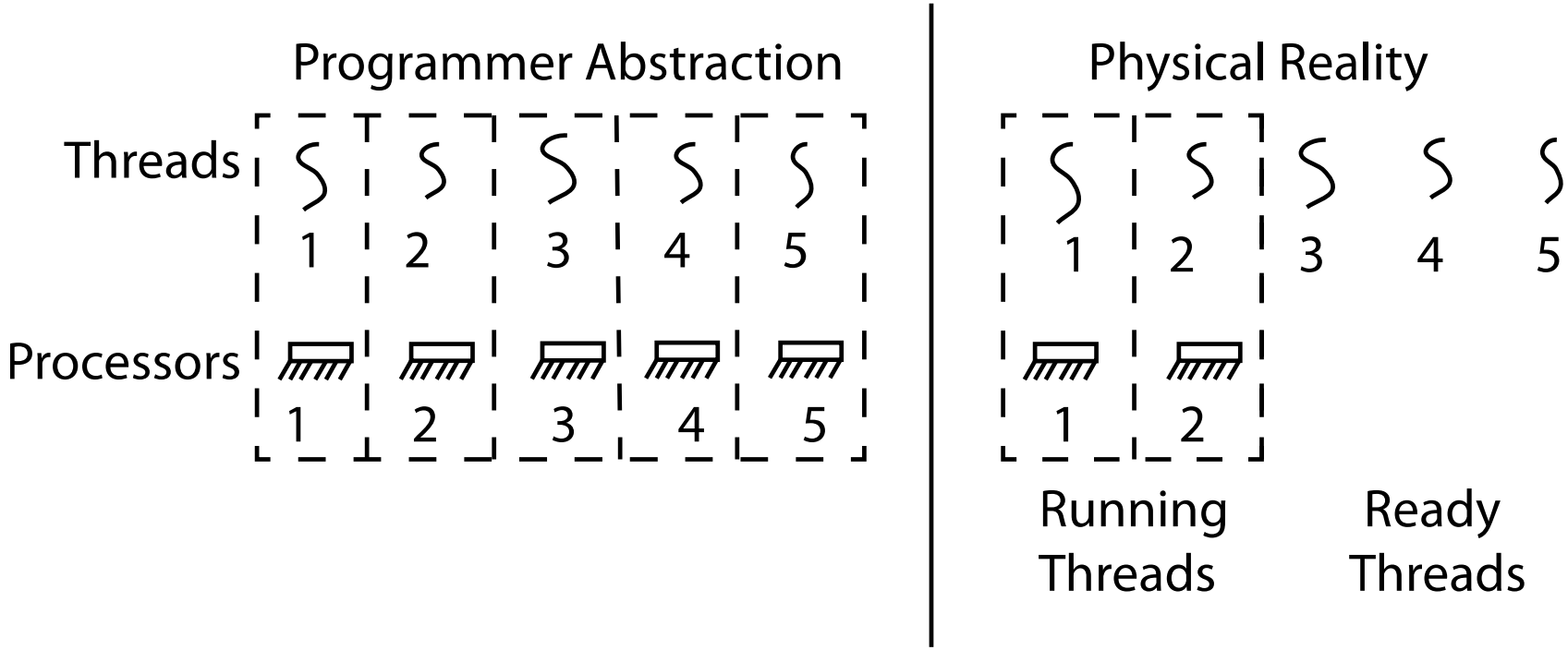


Announcements

- Homework 0 due tomorrow night
  - Start on it soon if you have not done so already
- Quiz 0 available on online exam platform today right after lecture
- C Review Session tomorrow 6-7 PM
- Reminder to look for groups
  - “Search for Teammates” thread on Piazza
  - Work with prospective teammates on Project 0

Interleaving and Nondeterminism

Thread Abstraction

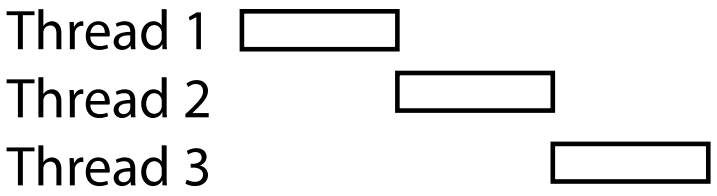


- Illusion: Infinite number of processors
- Reality: Threads execute with variable "speed"
  - Programs must be designed to work with any schedule

Programmer vs. Processor View

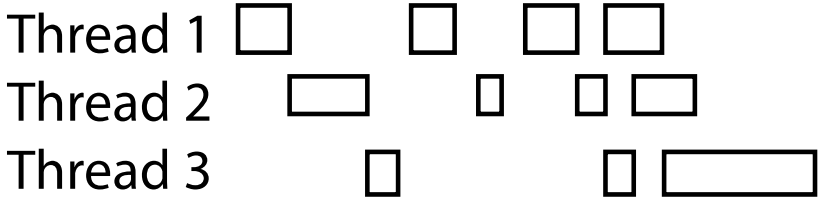
Programmer's View	Possible Execution #1	Possible Execution #2	Possible Execution #3
.	.	.	.
.	.	.	.
.	.	.	.
x = x + 1;	x = x + 1;	x = x + 1	x = x + 1
y = y + x;	y = y + x;	.....	y = y + x
z = x +5y;	z = x + 5y;	thread is suspended	.....
.	.	other thread(s) run	thread is suspended
.	.	thread is resumed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

- What are the possible values of x below after all threads finish?
- Initially `x == 0` and `y == 0`

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

- Must be **1**. Thread B does not interfere.

Race Conditions

- What are the possible values of x below?
- Initially `x == 0` and `y == 0`

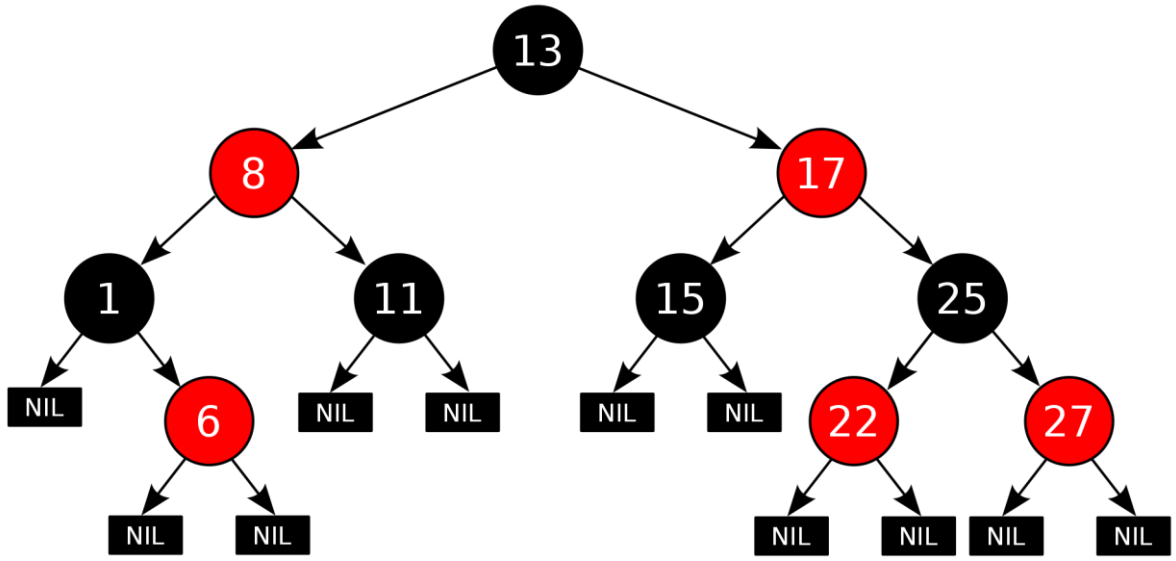
Thread A	Thread B
`x = y + 1;`	`y = 2;`
	`y = y * 2;`

- 1 or 3 or 5 (non-deterministic)
- 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

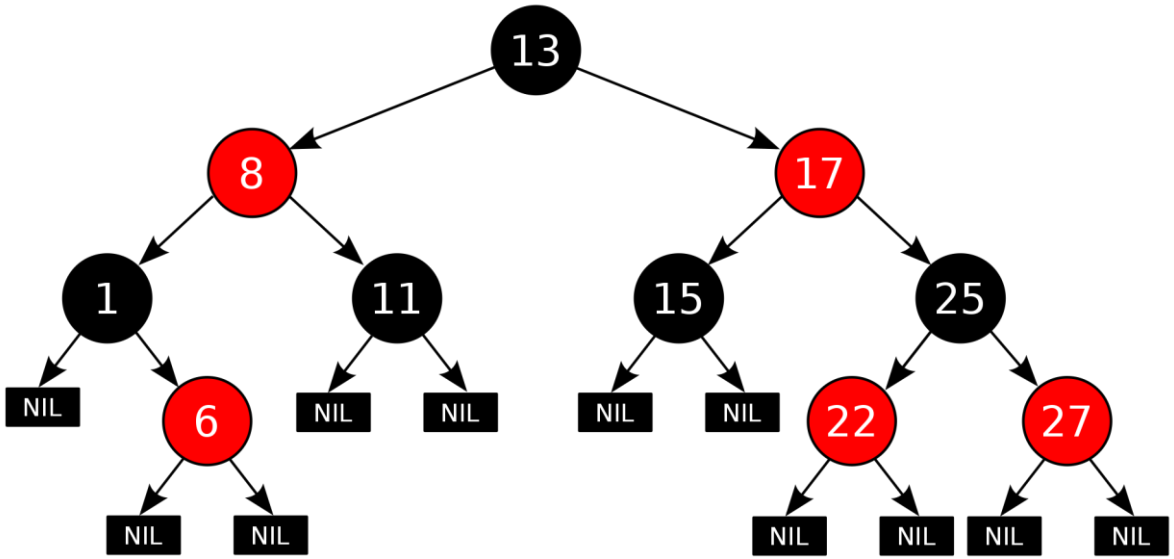
- For now, don't worry about how to implement locks!
  - We'll cover that in substantial depth later on in the class

Example: Shared Data Structure

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

```
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);
}
```

Semaphore

- 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 Important Semaphore Patterns

- **Mutual Exclusion:** (Like lock)
  - Called a "binary semaphore"

```
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();
}
```

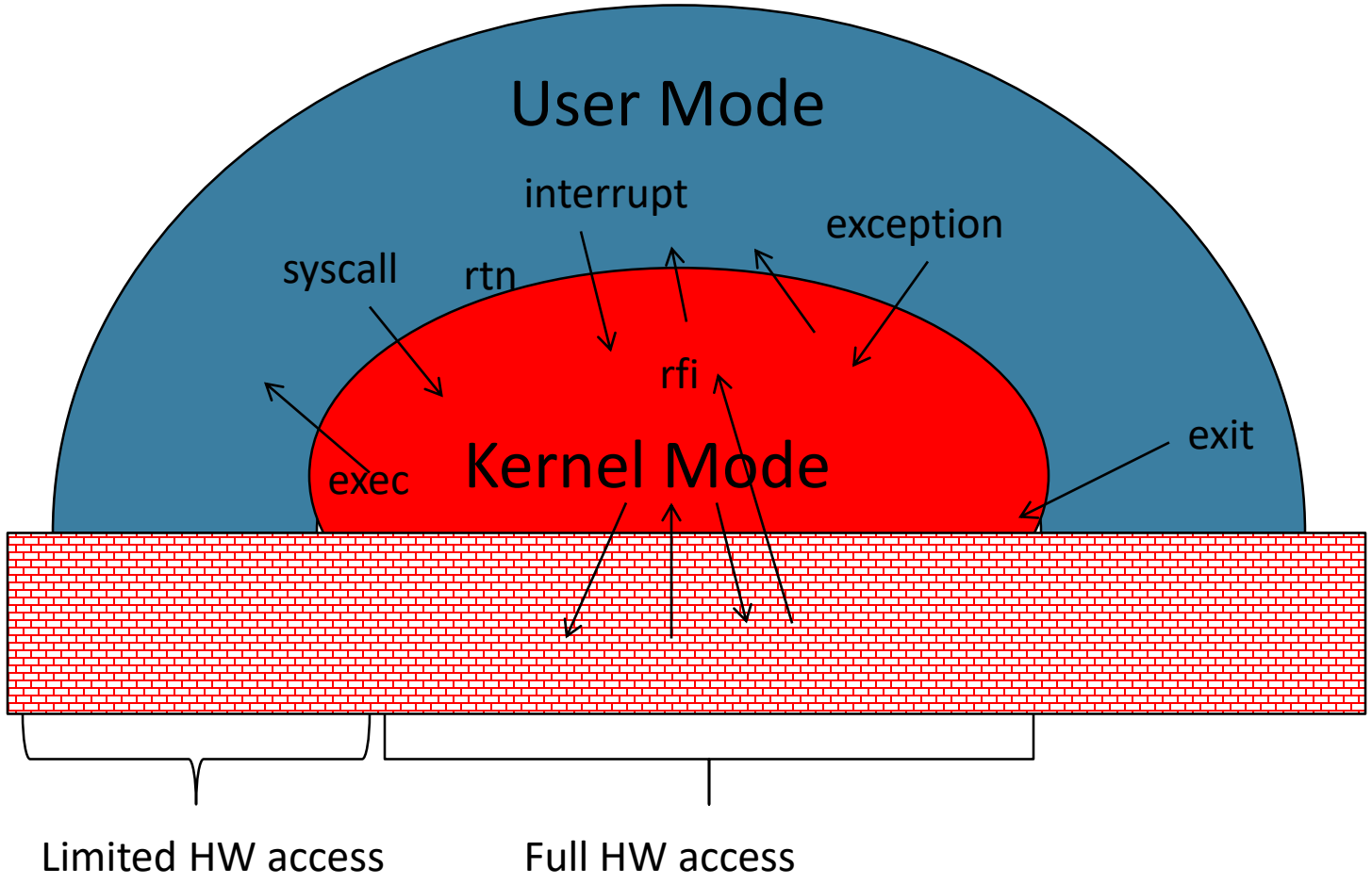
```
ThreadFinish {
    semaphore.up();
}
```

Break (If Time)

Recall: Process

- 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**

Recall: Life of a Process



Processes

- How to manage process state?
  - How to create a process?
  - How to exit from a process?

- Remember: Everything outside of the kernel is running in a process!
  - Including the shell! (Homework 2)

- Processes are created and managed… by processes!

Bootstrapping

- If processes are created by other processes, how does the first process start?

- First process is started by the kernel
  - Often configured as an argument to the kernel *before* the kernel boots

- After this, all processes on the system are created by other processes

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

Process Management API

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pid.c

```
#include <stdlib.h>
#include <stdio.h>
#include <string.h>
#include <unistd.h>
#include <sys/types.h>
int main(int argc, char *argv[])
{
  /* get current processes PID */
  pid_t pid = getpid();
  printf("My pid: %d\n", pid);

  exit(0);
}
```

Q: What if we let `main` return without ever calling `exit`?

- The OS Library calls `exit()` for us!
- The entrypoint of the executable is in the OS library
- OS library calls `main`
- If `main` returns, OS library calls `exit`
- You'll see this in Project 0: `init.c`

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

Creating Processes

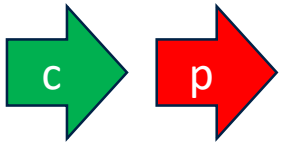
- `pid_t fork()` – copy the current process
  - New process has different pid
  - New process contains a single thread
- Return value from **`fork()`**: pid (like an integer)
  - When > 0:
    - Running in (original) Parent process
    - return value is pid of new child
  - When = 0:
    - Running in 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…

fork1.c

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

int main(int argc, char *argv[]) {
  pid_t cpid, mypid;
  pid_t pid = getpid();            /* get current processes PID */
  printf("Parent pid: %d\n", pid);
  cpid = fork();
  if (cpid > 0) {                  /* Parent Process */
    mypid = getpid();
    printf("[%d] parent of [%d]\n", mypid, cpid);
  } else if (cpid == 0) {          /* Child Process */
    mypid = getpid();
    printf("[%d] child\n", mypid);
  } else {
    perror("Fork failed");
  }
}
```

fork1.c




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

int main(int argc, char *argv[]) {
  pid_t cpid, mypid;
  pid_t pid = getpid();            /* get current processes PID */
  printf("Parent pid: %d\n", pid);
  cpid = fork();
  if (cpid > 0) {                  /* Parent Process */
    mypid = getpid();
    printf("[%d] parent of [%d]\n", mypid, cpid);
  } else if (cpid == 0) {          /* Child Process */
    mypid = getpid();
    printf("[%d] child\n", mypid);
  } else {
    perror("Fork failed");
  }
}
```

fork1.c

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

int main(int argc, char *argv[]) {
  pid_t cpid, mypid;
  pid_t pid = getpid();            /* get current processes PID */
  printf("Parent pid: %d\n", pid);
  cpid = fork();
  if (cpid > 0) {                  /* Parent Process */
    mypid = getpid();
    printf("[%d] parent of [%d]\n", mypid, cpid);
  } else if (cpid == 0) {          /* Child Process */
    mypid = getpid();
    printf("[%d] child\n", mypid);
  } else {
    perror("Fork failed");
  }
}
```

p

c

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);
  }
}
```

- What does this print?
- Would adding the calls to `sleep` matter?

Recall: a process consists of one or more threads executing in an address space

- In this case, each process has a single thread
- These threads execute concurrently

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);
}
…
```

Running Another Program

- With threads, we could call `pthread_create` to create a new thread executing a separate function

- With processes, the equivalent would be spawning a new process executing a different program

- How can we do this?

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

fork3.c

```
…
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);
}
…
```

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) {}
}
```

Q: What would happen if the process receives a SIGINT signal, but does not register a signal handler?
A: The process dies!

For each signal, there is a default handler defined by the system

Common POSIX Signals

- `SIGINT` – control-C
- `SIGTERM` – default for `kill` shell command
- `SIGSTP` – control-Z (default action: stop process)

- `SIGKILL`, `SIGSTOP` – terminate/stop process
  - Can't be changed with `sigaction`
  - Why?

Shell

- A shell is a job control system
  - Allows programmer to create and manage a set of programs to do some task

- You will build your own shell in Homework 2…
  - … using `fork` and `exec` system calls to create new processes…
  - … and the File I/O system calls we'll see next time to link them together

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 next time

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

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?

- Depends on how much isolation we want
  - Threads are lighter weight [why?]
  - Processes are more strongly isolated

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