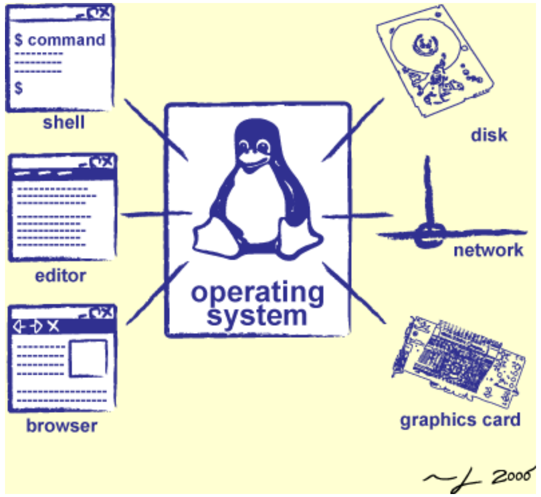
CS162
Operating Systems and Systems Programming
Lecture 3

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

Goals for Today: The Thread Abstraction

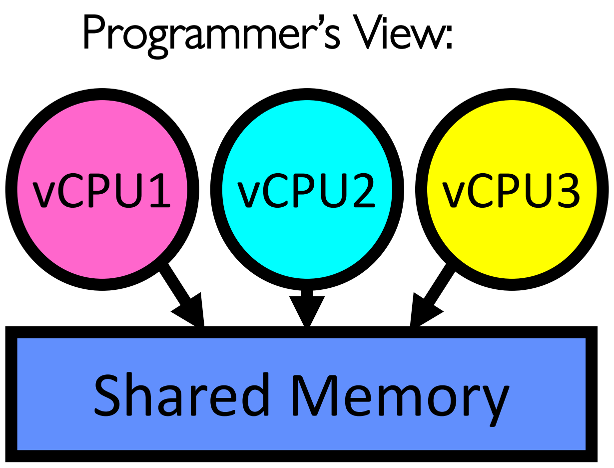
- **What** threads are (and what they are not)
- **Why** threads are useful (motivation)
- **How** to write a program using threads
- **Alternatives** to using threads

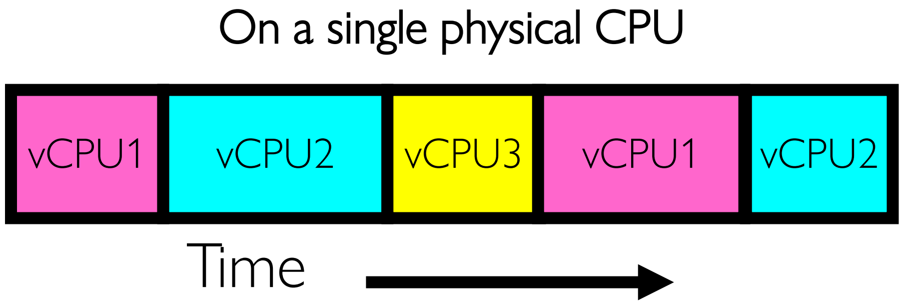


Recall: Four Fundamental OS Concepts

- Thread: Execution Context
- Address space (with or w/o **translation**)
  - Set of memory addresses accessible to program
- 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

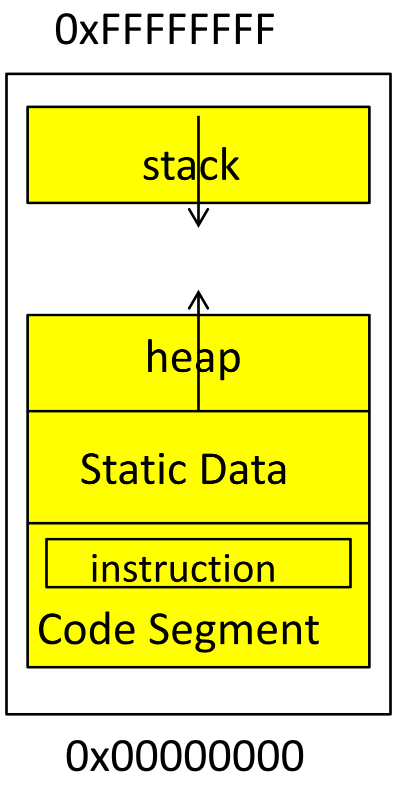
Recall: Illusion of Multiple Processors





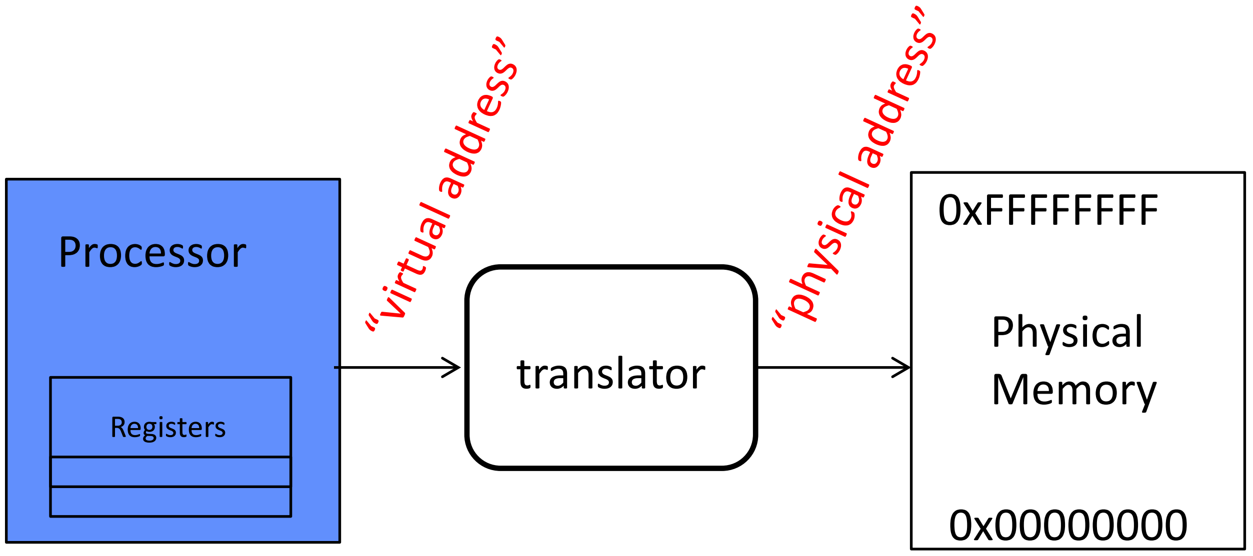
- Threads are *virtual cores*
- Multiple threads: *Multiplex* hardware in time
- Each virtual core (thread) has:
  - Program counter (PC), stack pointer (SP)
  - Registers
- Where is "it" (the thread)?
  - On the real (physical) core, or
  - Saved in chunk of memory – called the *Thread Control Block (TCB)*

Recall: (Virtual) Address Space



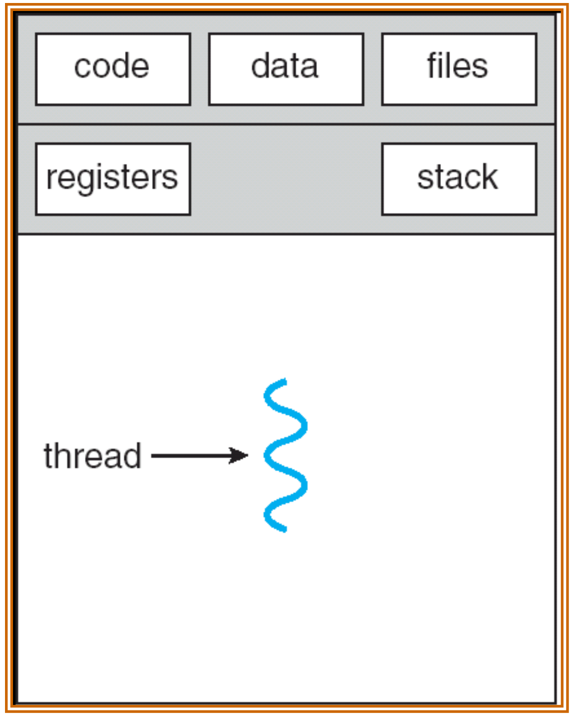
- Address space ⇒ the set of accessible addresses + state associated with them:
  - For 32-bit processor: 2^{32} = 4 billion (10^9) addresses
  - For 64-bit processor: 2^{64} = 18 quintillion (10^{18}) addresses

- Virtual Address Space ⇒ Processor's view of memory:
  - Address Space is independent of physical storage



Recall: Process

- **Definition:** execution environment with Restricted Rights
  - **One or more threads executing in a (protected) Address Space**
  - Owns memory (address space), 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
- Why **processes**?
  - Protected from each other!
  - OS Protected from them



Single-Threaded 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
- 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

What Threads Are

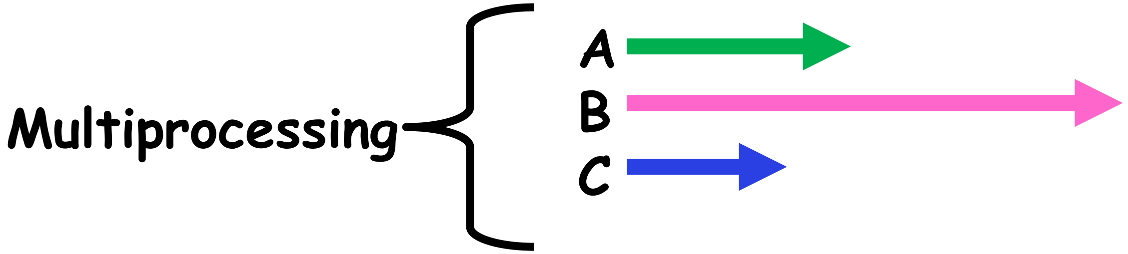
- Definition from before a *single unique execution context*
  – Describes its representation
- It provides the abstraction of a *single execution sequence that represents a separately schedulable task*
- Threads are a mechanism for *concurrency* and *parallelism*
- Protection is an orthogonal concept
  – A protection domain can contain one thread or many

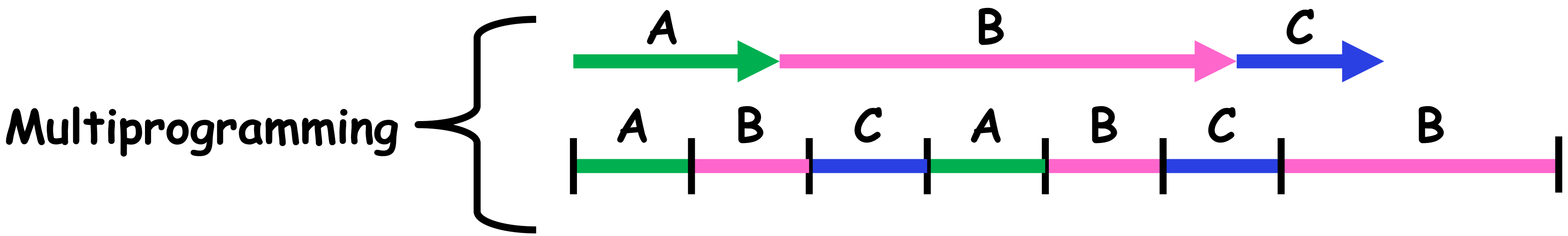
Motivation for Threads

- Operating systems must handle multiple things at once
  - Processes, interrupts, background system maintenance
- Networked servers must handle concurrent requests
- Parallel programs must parallelise for performance
- Programs with user interface need threading to ensure responsiveness
- Network and disk bound programs use threading to hide network/disk latency

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
- Parallel => concurrent, but not the other way round!

Silly Example for Threads

- Imagine the following program:

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

- What is the behaviour 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: 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

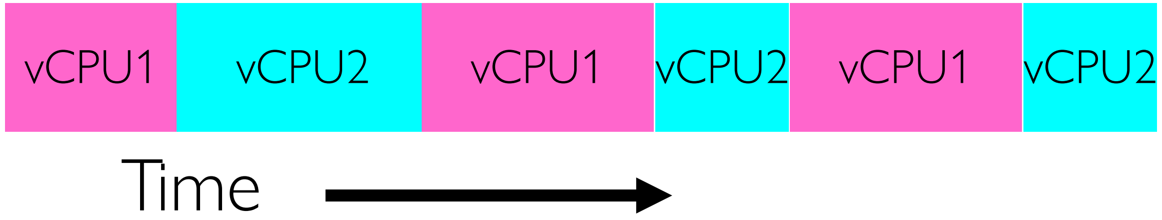
Handle I/O in separate thread, avoid blocking other progress

Threads Mask I/O Latency

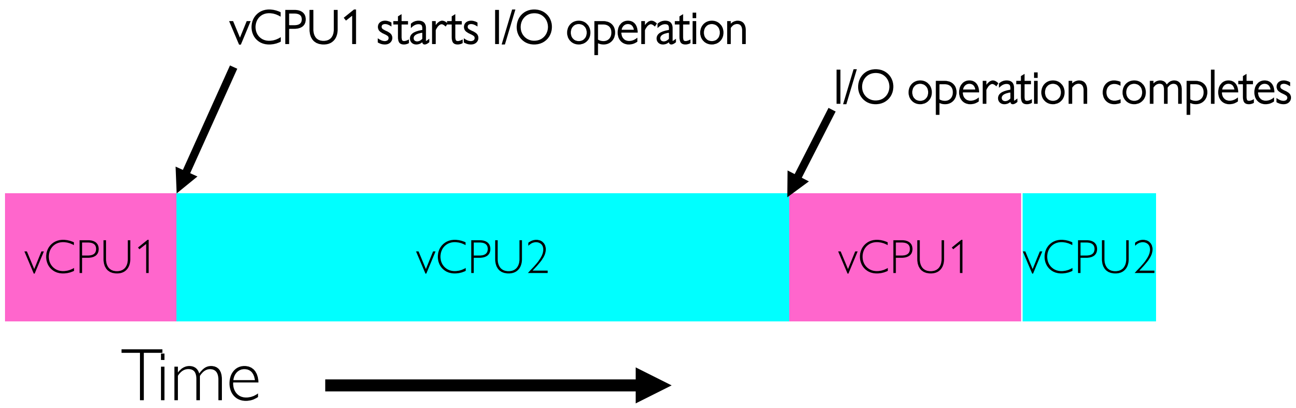
- A thread is in one of the following three states:
  - RUNNING – running
  - READY – eligible to run, but not currently running
  - BLOCKED – ineligible to run
- If a thread is waiting for an I/O to finish, the OS marks it as BLOCKED
- Once the I/O finally finishes, the OS marks it as READY

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

- 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

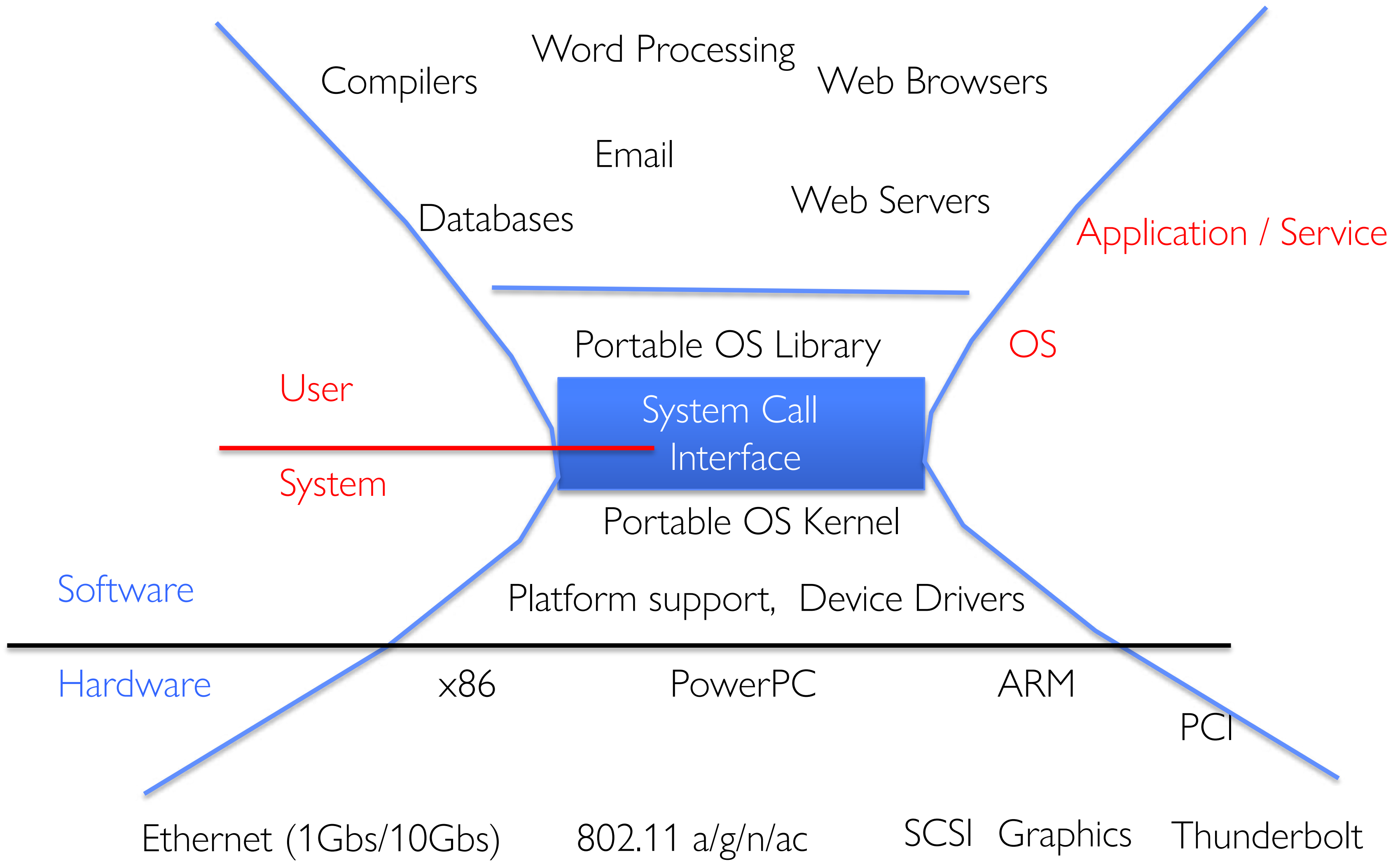
Multithreaded Programs

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

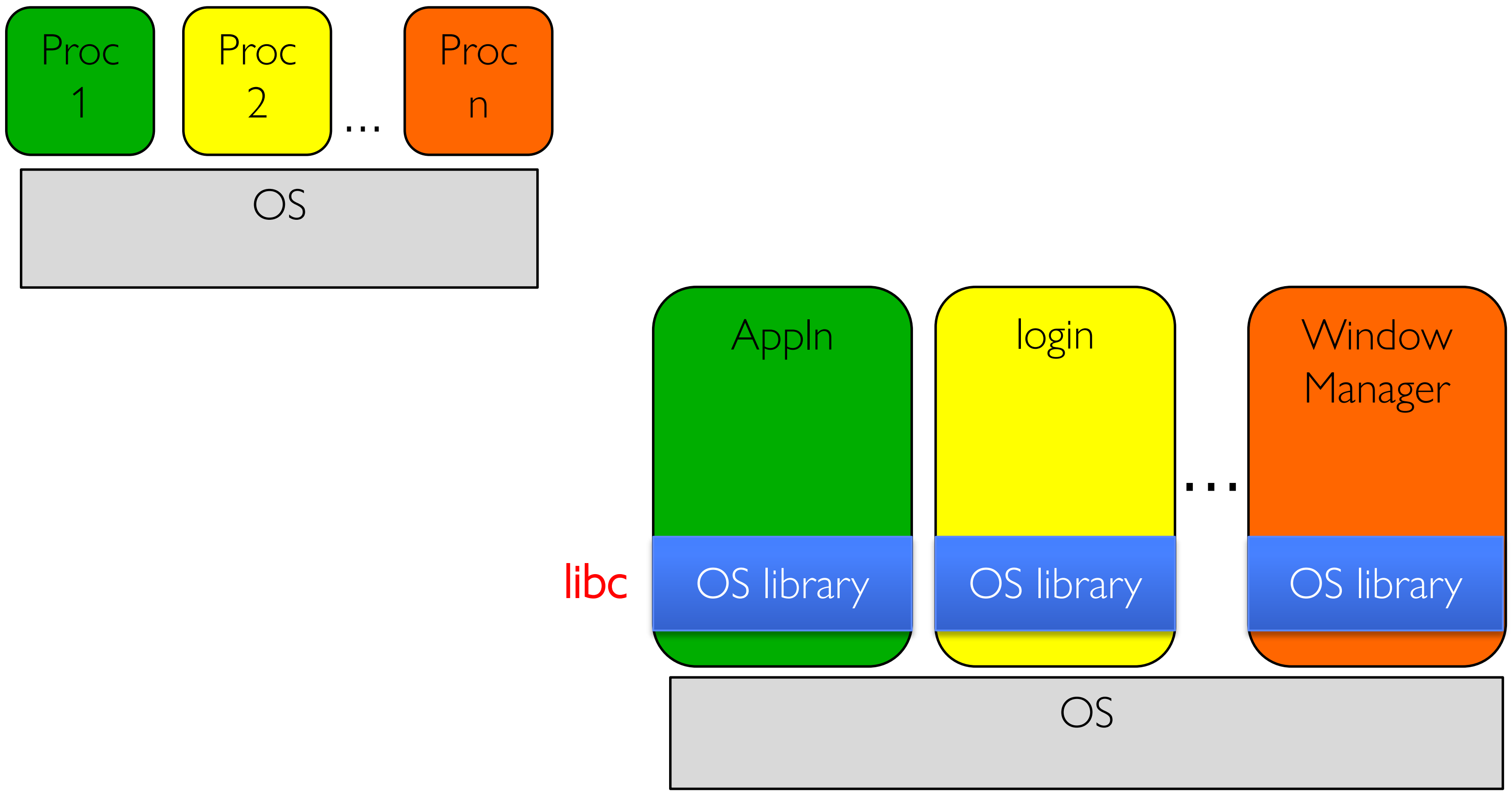
- Initially, this new process has *one thread* in its own address space
  – With code, globals, etc. as specified in the executable

- 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")



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);
```

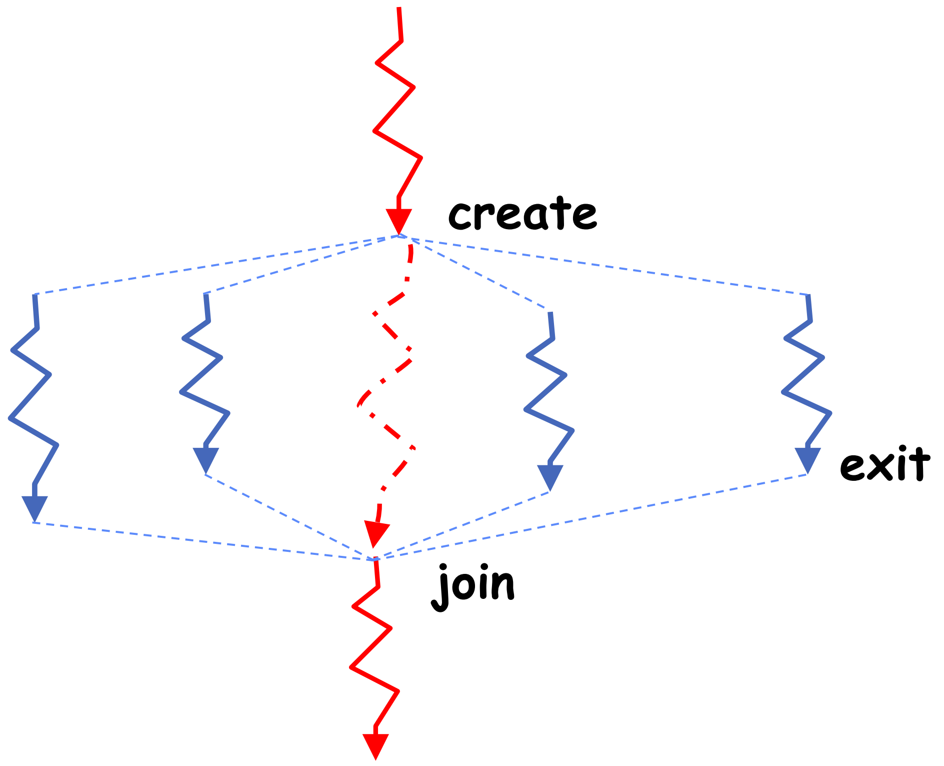
- suspends execution of the calling thread until the target *thread* terminates.
- On return with a non-NULL *value_ptr* the value passed to *pthread_exit()* by the terminating thread is made available in the location referenced by *value_ptr*.

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.

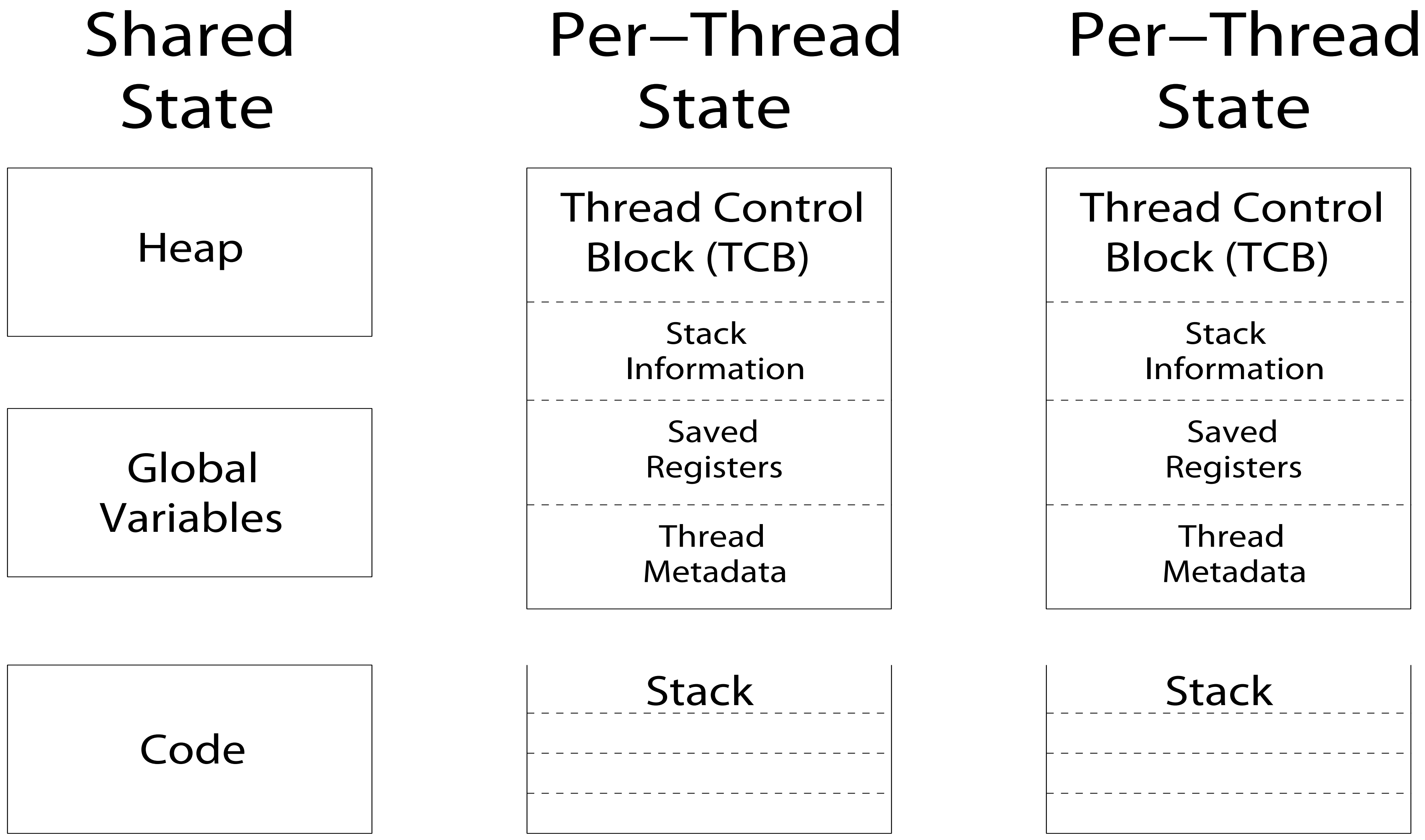
pThreads Example

- 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 */
}
```

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);
C+1:   }
       A(1);
exit:
```

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

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Stack Pointer →

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

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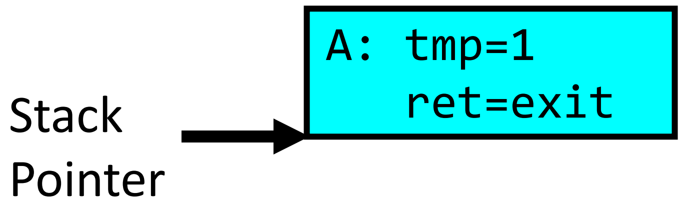

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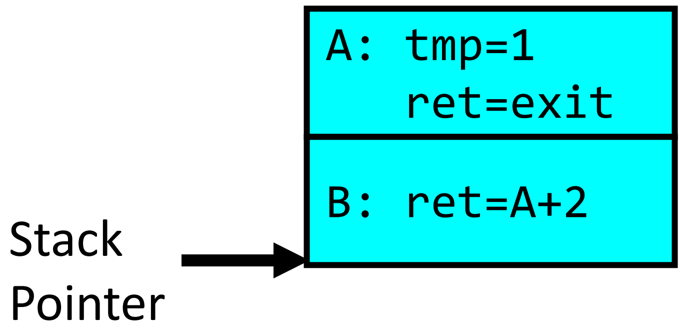

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Stack
A: tmp=1 ret=exit
B: ret=A+2

Stack Pointer

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```

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

Stack Pointer

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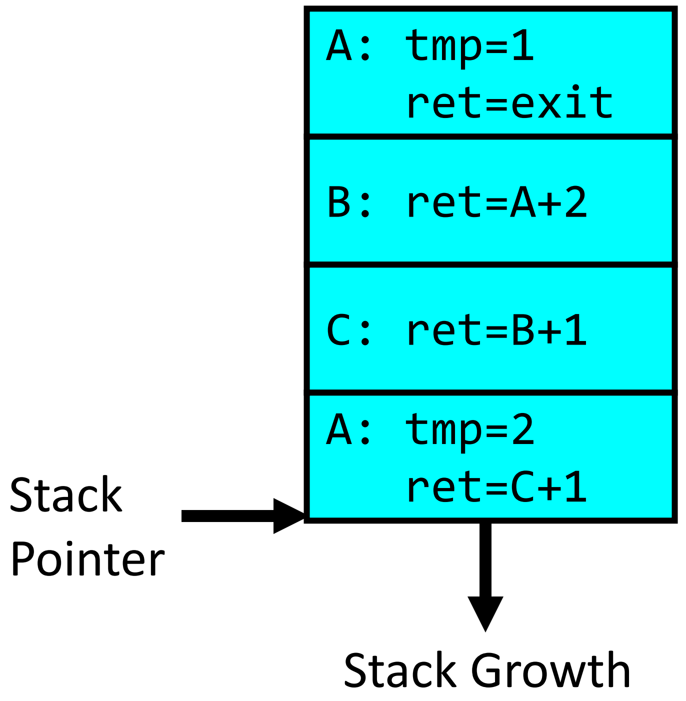

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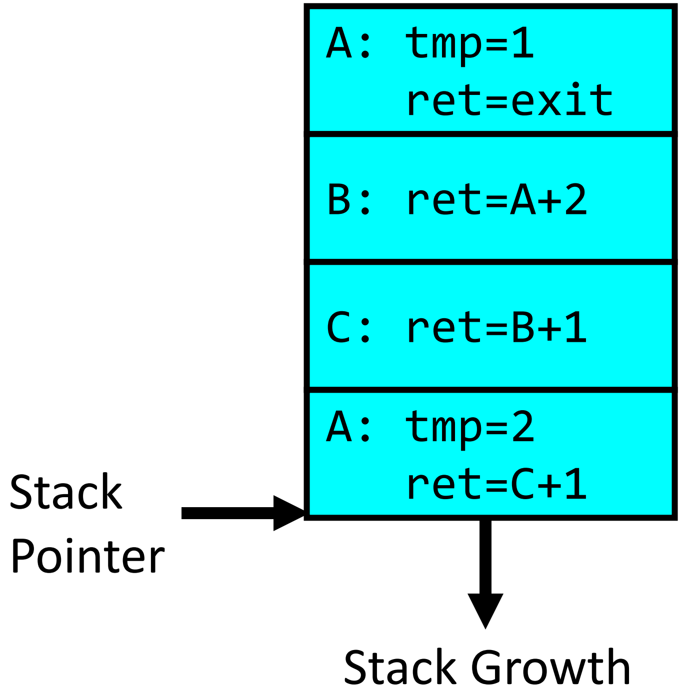

Output: >2

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```

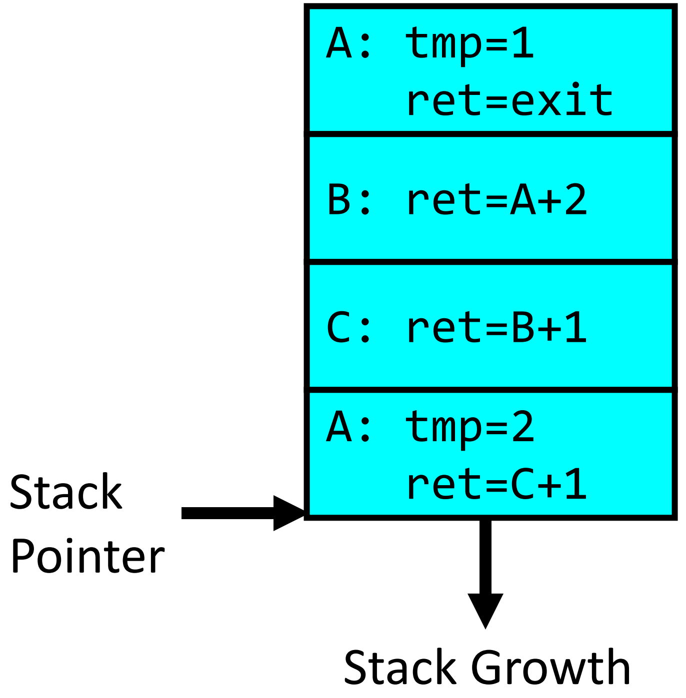

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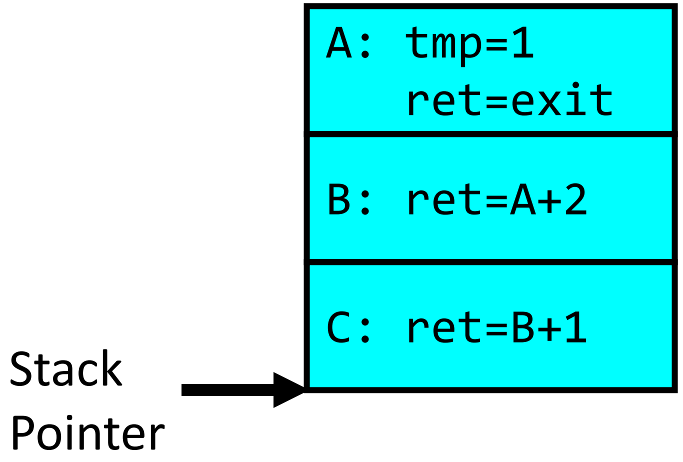

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exit:
```

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

Stack Pointer

Output: >2

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exit:
```

Stack Pointer →

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

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exit:
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Stack Pointer →

A: tmp=1 ret=exit

Output: `>2 1`

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

Output: >2 1

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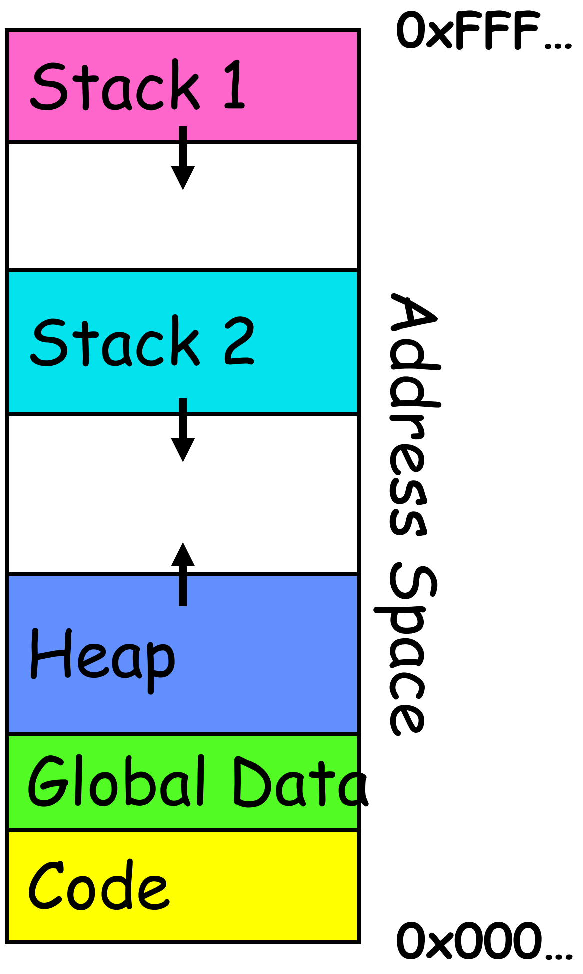
Memory Layout with Two Threads

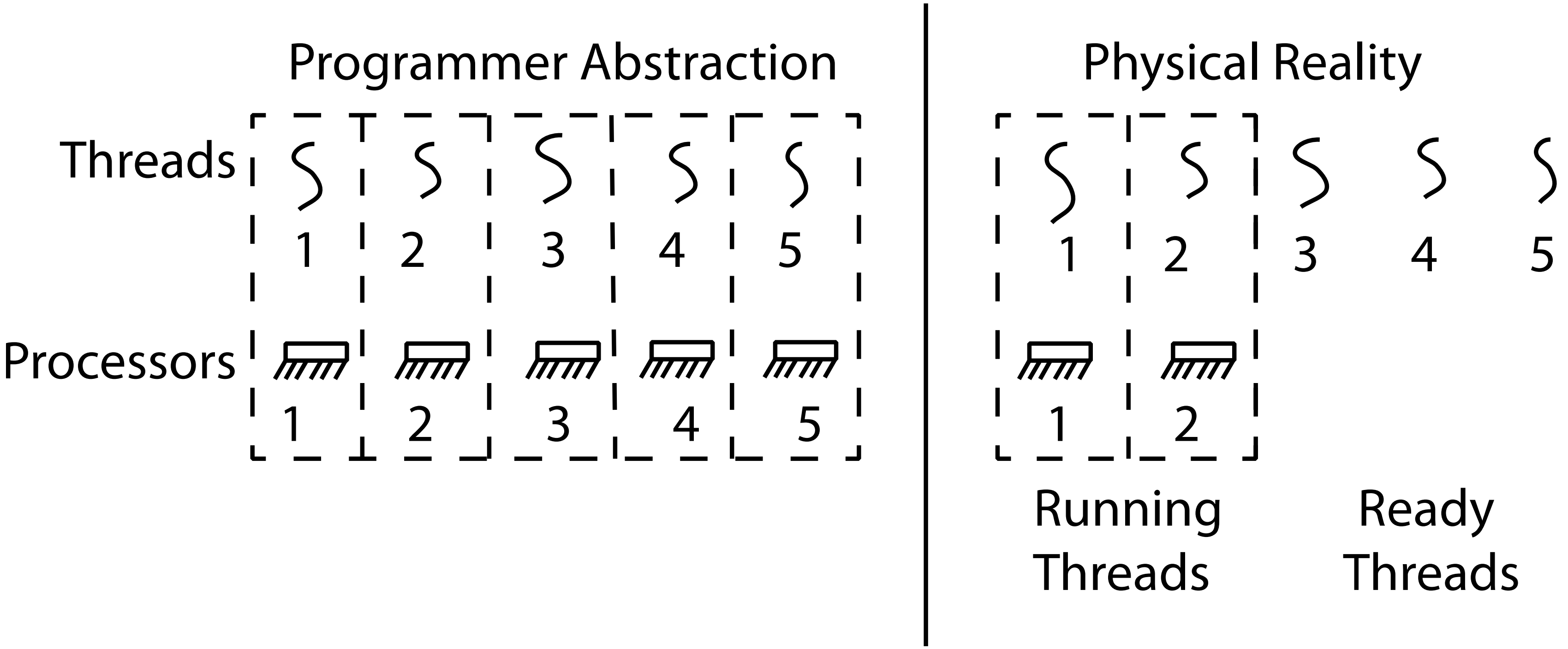
- Two sets of CPU registers
- Two sets of Stacks

- 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?



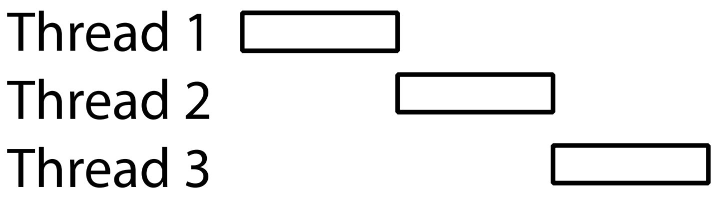
INTERLEAVING AND NONDETERMINISM
(The beginning of a long discussion!)

Thread Abstraction

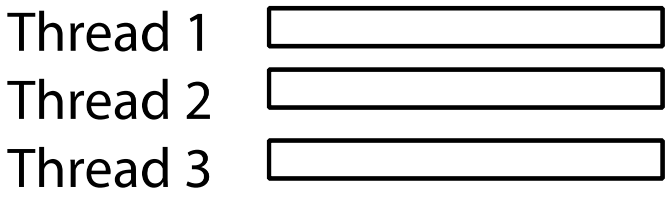


- Illusion: Infinite number of processors
- Reality: Threads execute with variable "speed"
  – Programs must be designed to work with any schedule

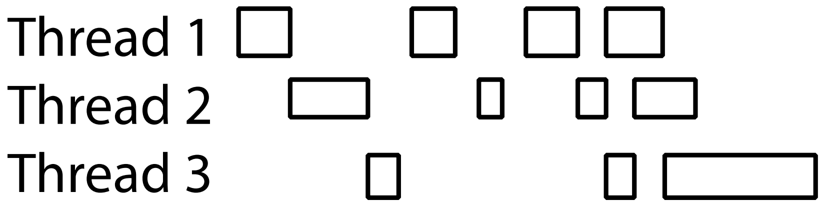
Possible Executions



a) One execution



b) Another execution



c) Another execution

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

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!

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

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

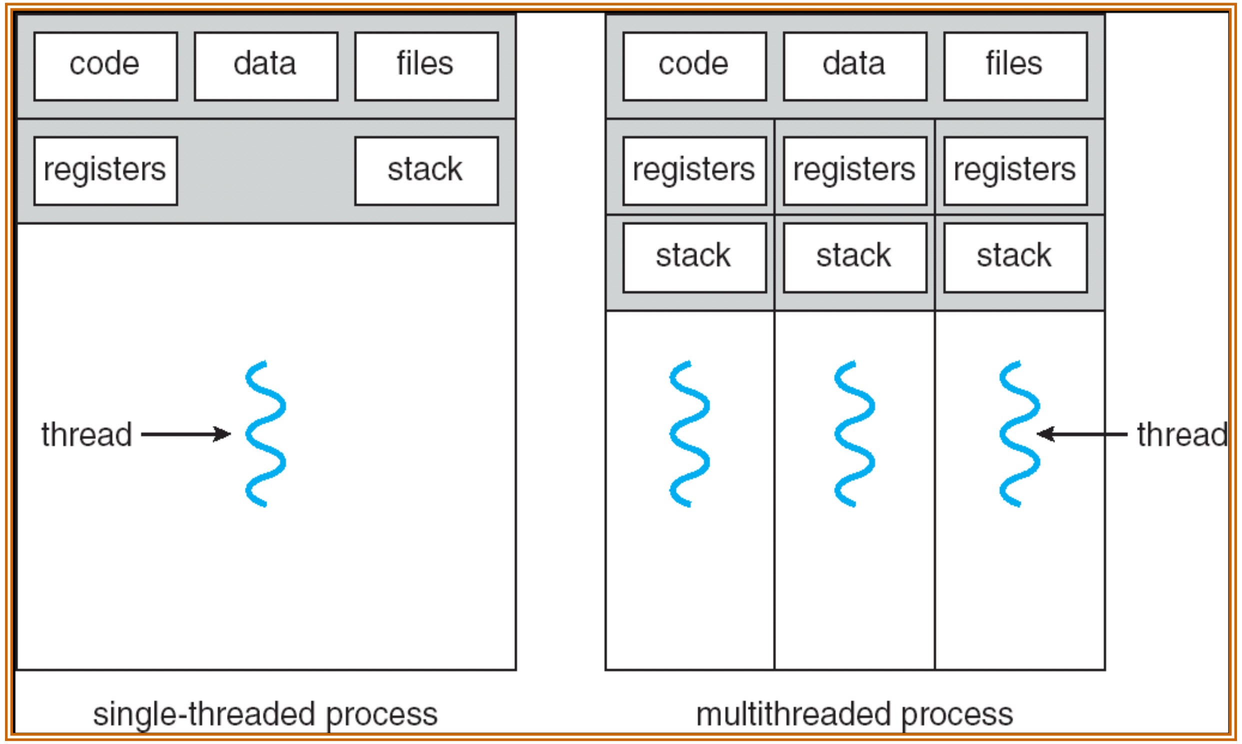
Our Example

Critical section

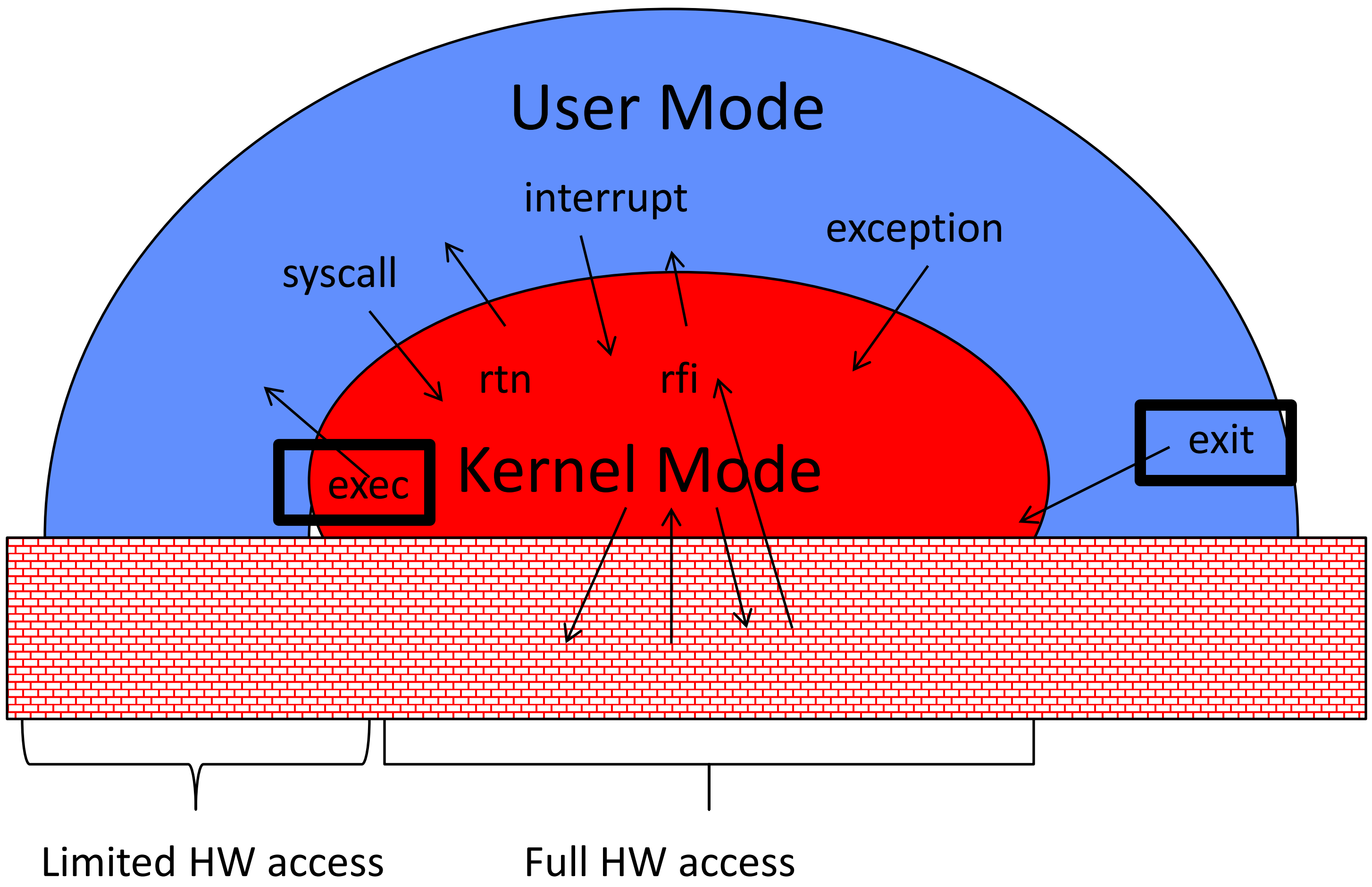
```
int common = 162;
pthread_mutex_t common_lock = PTHREAD_MUTEX_INITIALIZER;

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);
}
```

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!



Recall: Life of a Process?



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
  - Often called the "init" process

- 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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- `sigaction` – set handlers for signals

pid.c

```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

State of original process duplicated in *both* Parent and Child!
Address Space (Memory), File Descriptors (covered later), etc…

fork1.c

```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 */
p   mypid = getpid();
    printf("[%d] parent of [%d]\n", mypid, cpid);
  } else if (cpid == 0) {           /* Child Process */
c   mypid = getpid();
    printf("[%d] child\n", mypid);
  } else {
    perror("Fork failed");
  }
}
```

fork_race.c

```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);
  }
}
```

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

- Here, each process has a single thread
- These threads execute concurrently

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

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
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- `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

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);
}
…
```

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

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

Administrivia: Getting started

- Should be working on Homework 0 already! ⇒ Due Wednesday (27/1)
  - cs162-xx account, Github account, registration survey
  - Vagrant and VirtualBox – VM environment for the course
    - » Consistent, managed environment on your machine
  - Get familiar with all the cs162 tools, submit to autograder via git

- Start working on Project 0 now! ⇒ Due Monday 01/02
  - To be done on your own – like a homework!

- Friday (29/1) is drop day!
  - Very hard to drop afterwards…
  - Please drop sooner if you are going to anyway ⇒ Let someone else in!