Abstractions 1: Threads and Processes

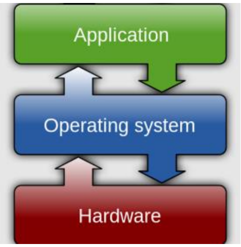
Lecture 3

Hartmut Kaiser

https://teaching.hkaiser.org/spring2025/csc4103/

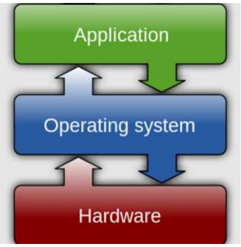
Recall: Four Fundamental OS Concepts

- 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

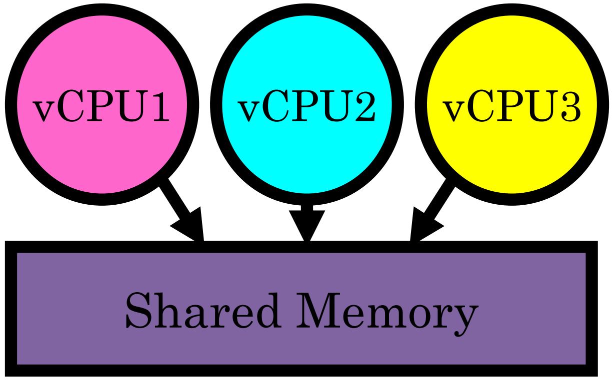


Recall: Thread

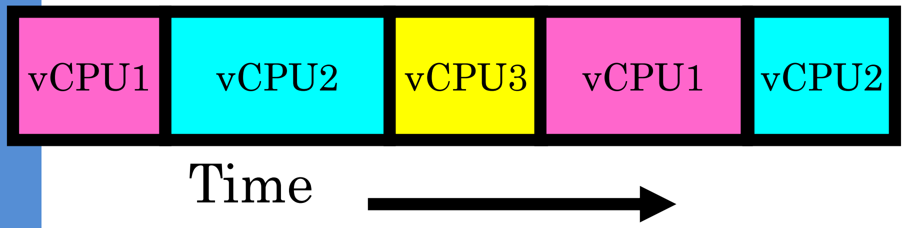
- Definition: A single, unique execution context
  - Program counter, registers, stack
- A thread is the OS abstraction for a CPU core
  - A "virtual CPU" of sorts
- Registers hold the root state of the thread:
  - Including program counter – pointer to the currently executing instruction
  - The rest 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

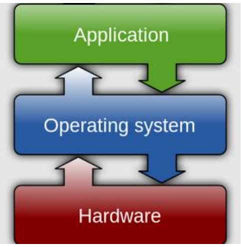


On a single physical CPU:



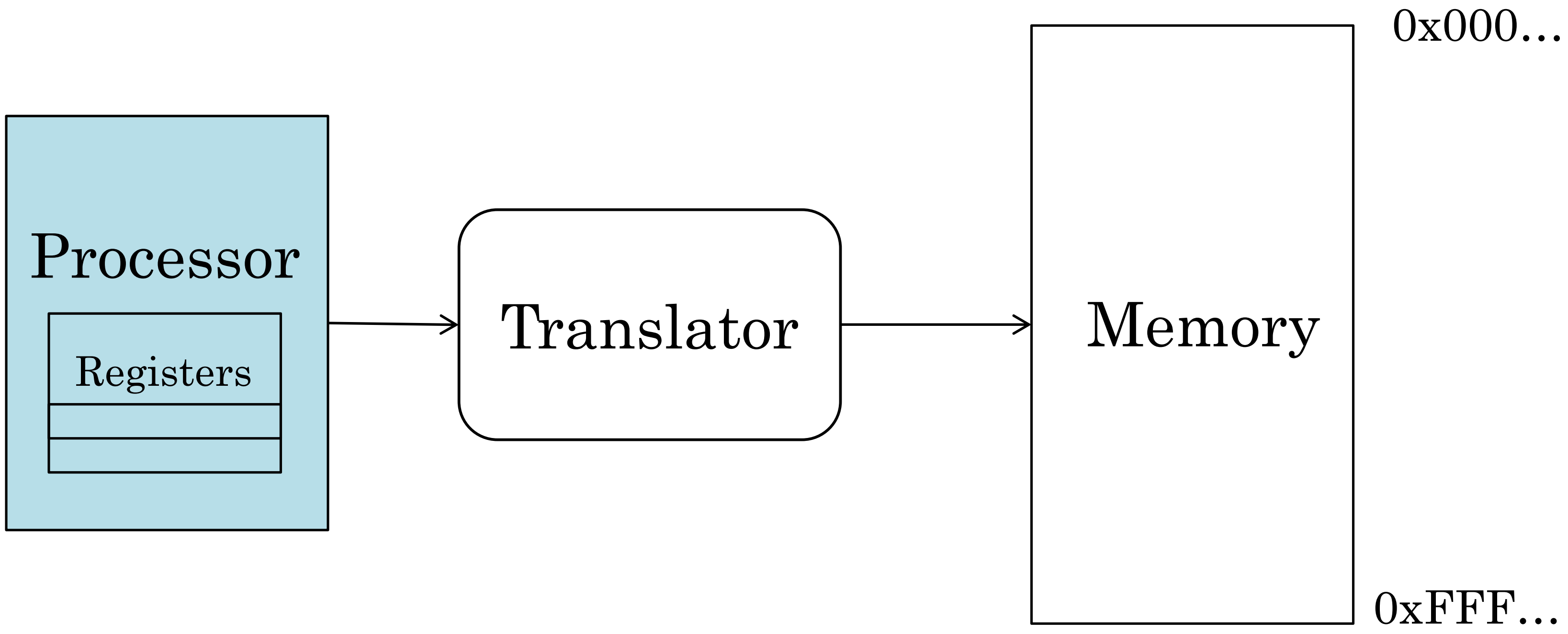
- Threads are **virtual cores**
- Multiple threads: **Multiplex** hardware in time
- **A thread is *executing* on a processor when it is resident in that processor's registers**

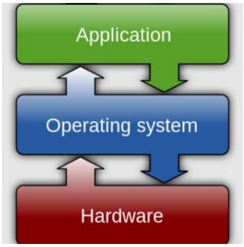
- Each virtual core (thread) has PC, SP, Registers
- Where is it?
  - On the real (physical) core, or
  - Saved in memory – called the Thread Control Block (TCB)



Recall: Address Space

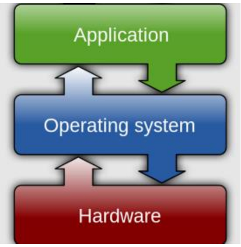
- Program operates in an address space that is distinct from the physical memory space of the machine





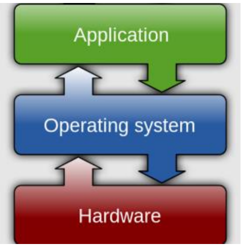
Recall: Process

- 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



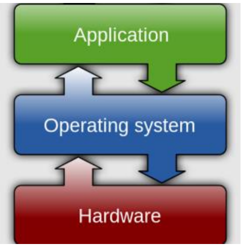
Recall: Dual-Mode Operation

- 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

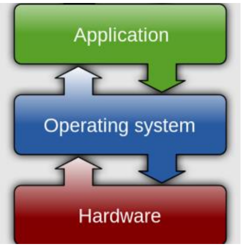
- What threads are
  - And what they are not
- Why threads are useful (motivation)
- How to write a program using threads
- Alternatives to using threads



Threads

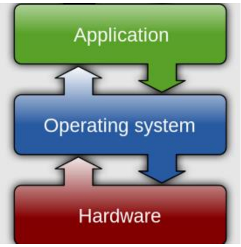
What Threads Are

- 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



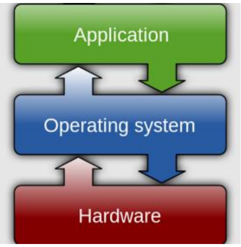
Motivation for Threads

- 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



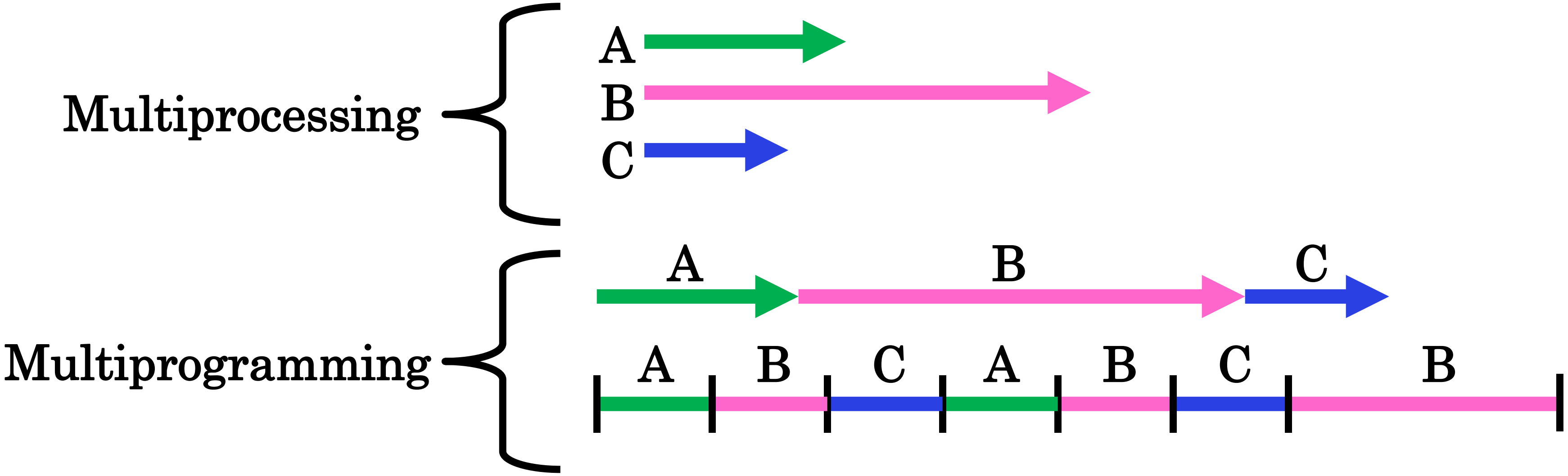
Threads Allow Handling MTAO

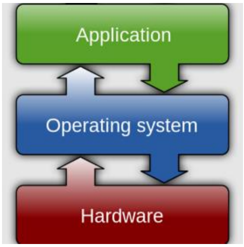
- Threads are a unit of concurrency provided by the OS
- Each thread can represent one thing or one task



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



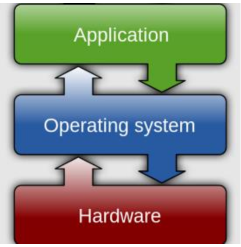


Silly Example for Threads

- Imagine the following program:

```
int main() {
    compute_pi("pi.txt");
    print_class_list("classlist.txt");
}
```

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

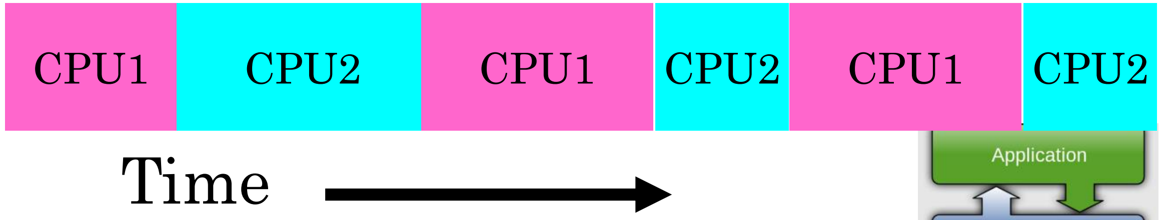


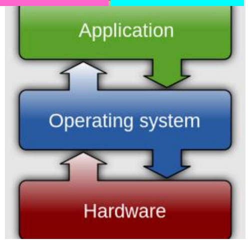
Adding Threads

- Version of program with threads (loose syntax):

```
int main() {
    create_thread(compute_pi, "pi.txt");
    create_thread(print_class_list, "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

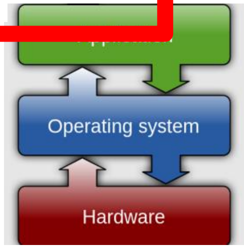




More Practical Motivation

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

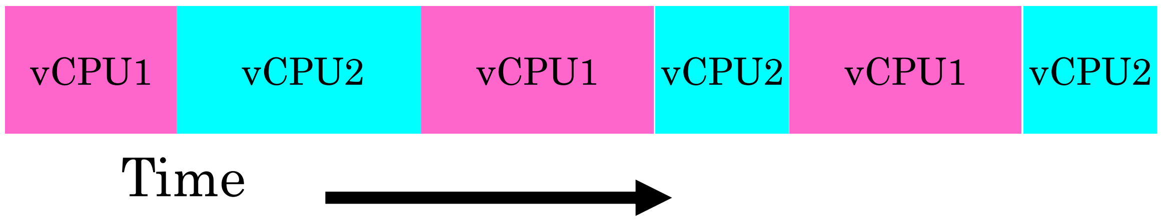
Handle I/O in separate thread, avoid blocking other progress

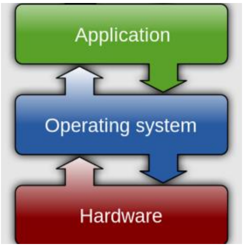


Threads Mask I/O Latency

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

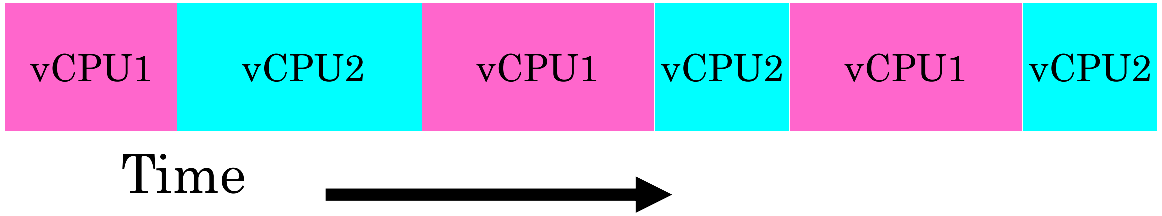
- If a thread is waiting for an I/O to finish, the OS marks it as `BLOCKED`
- Once the I/O finally finishes, the OS marks it as `READY`



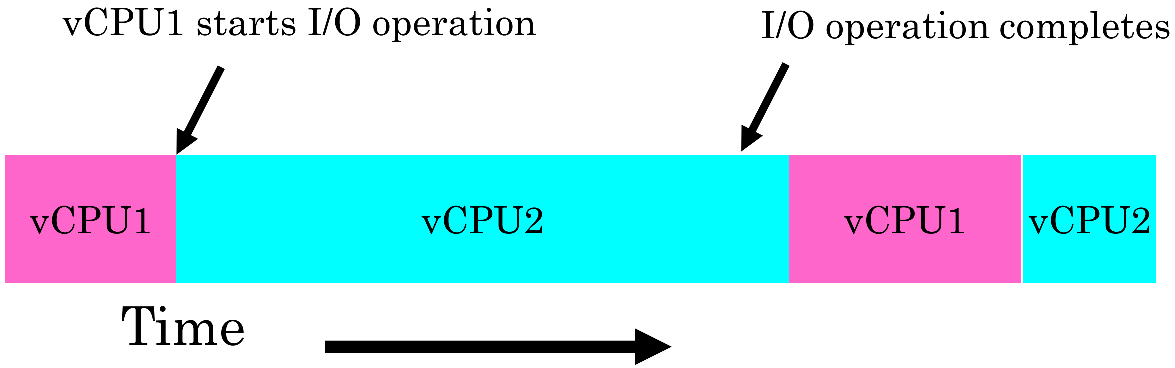


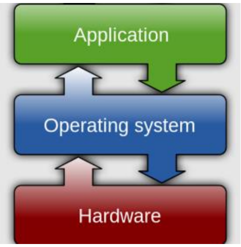
Threads Mask I/O Latency

- If no thread performs I/O:



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



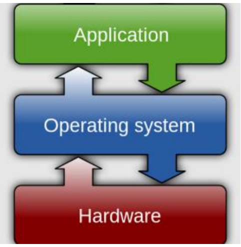


Little Better Example for Threads

- Version of program with threads (loose syntax):

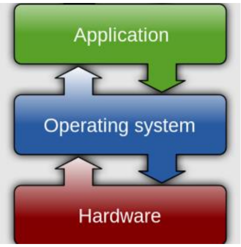
```
main() {
    create_thread(read_large_file, "pi.txt");
    create_thread(render_user_interface);
}
```

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



Multithreaded Programs

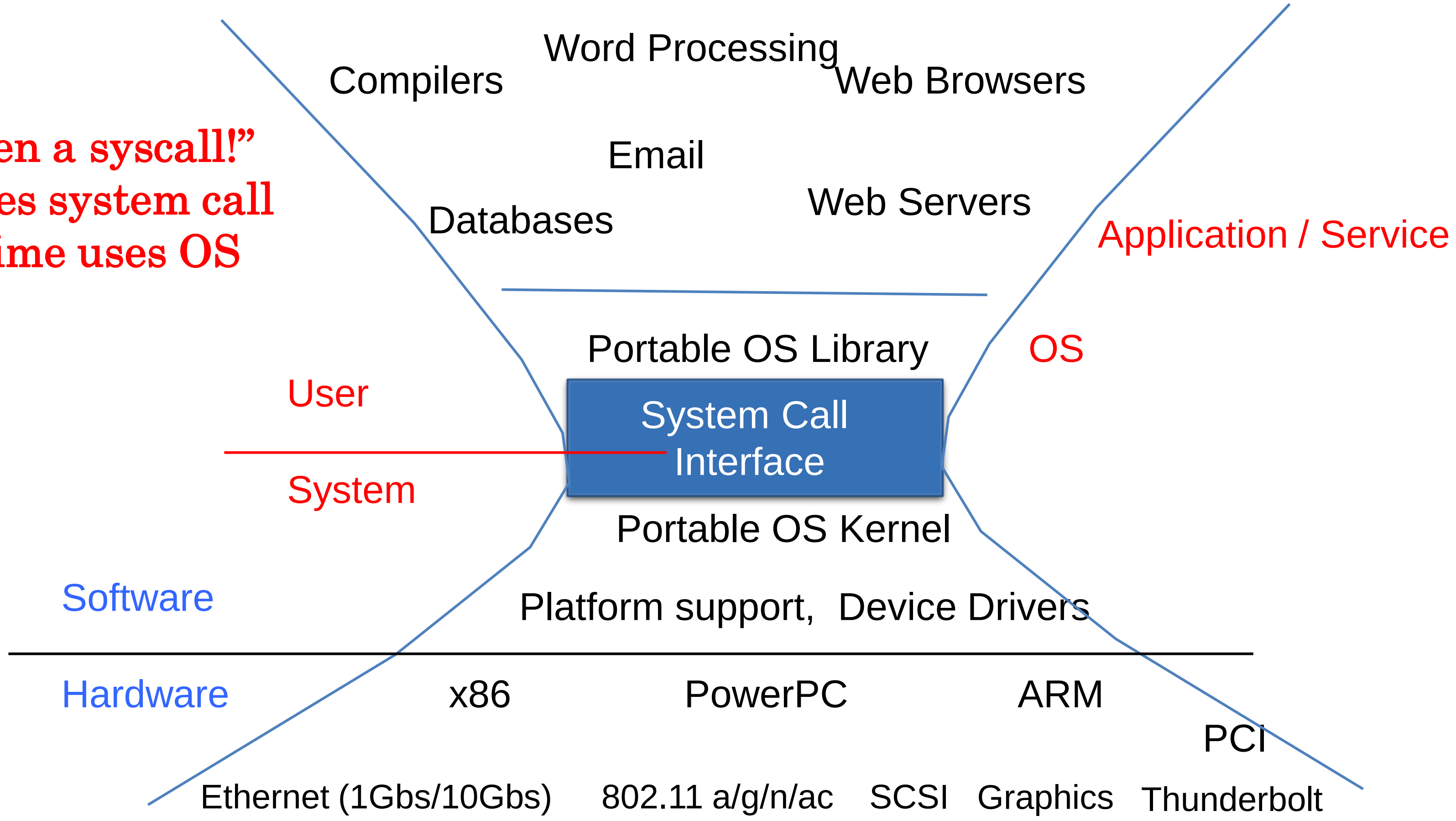
- You know how to compile a C program and run the executable
  - This creates a process that is executing that program
- Initially, this new process has one thread in its own address space
  - With code, globals, etc. as specified in the executable
  - This thread runs `main()`
- Q: How can we make a 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

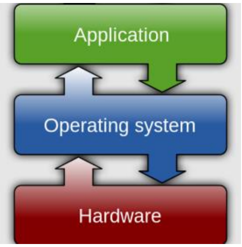


System Calls ("Syscalls")

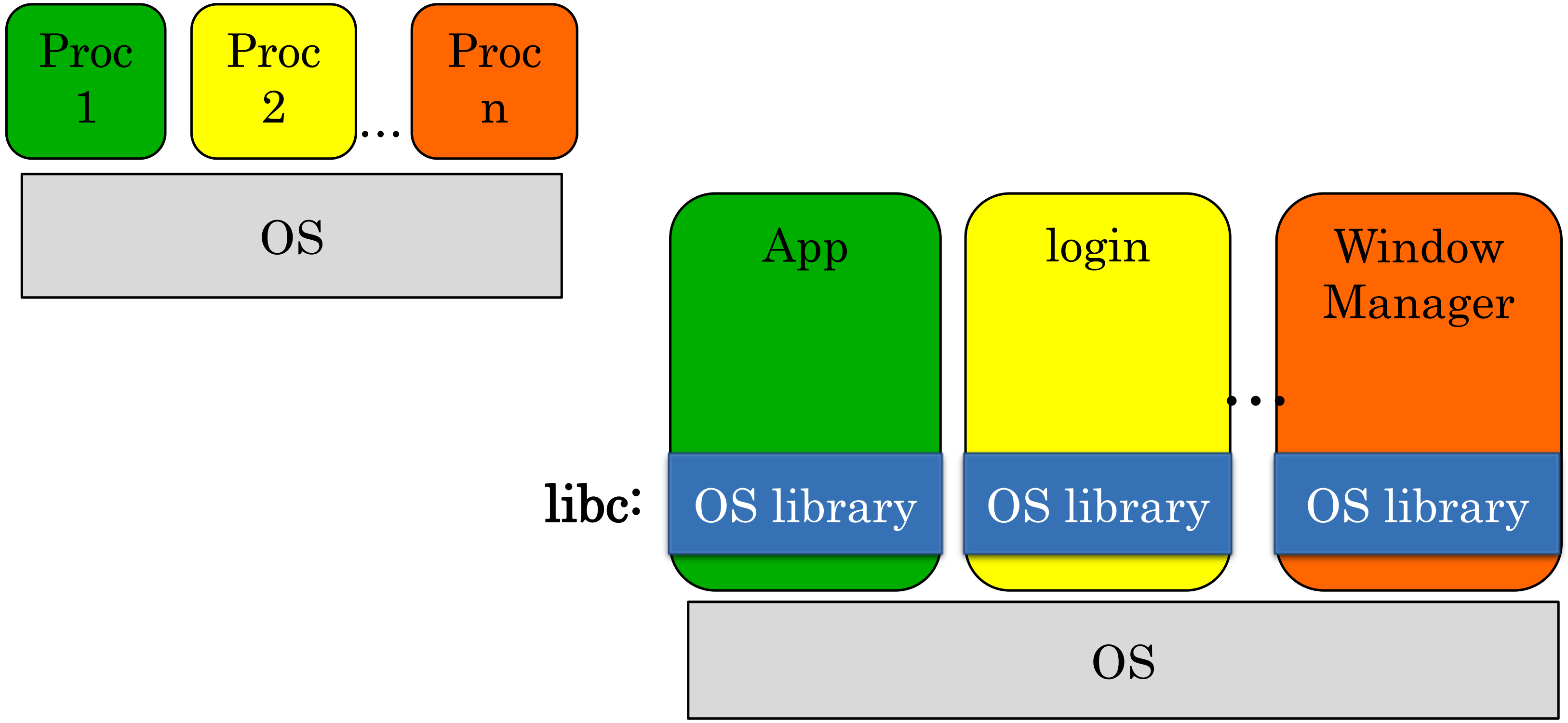
"But, I've never seen a syscall!"

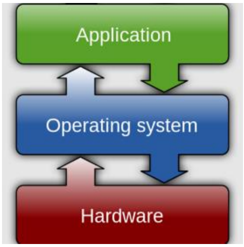
- OS library issues system call
- Language runtime uses OS library…





OS Library Issues Syscalls





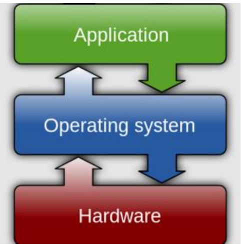
OS Library API for Threads: pthreads

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

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

  - `thread` is created executing `start_routine` with `arg` as its sole argument.
  - Attributes `attr` are often `NULL`
- `void pthread_exit(void* value_ptr);`
  - terminates the thread and makes `value_ptr` available to any successful join
  - Return of `start_routine` is implicit call to `pthread_exit`
- `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`.

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:

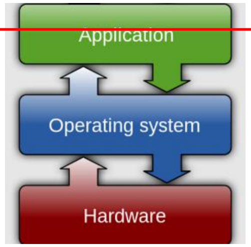
```
int pthread_create(…) {
    Do some work like a normal function…

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

Kernel:

```
get args from registers dispatch
to system function
Do the work to spawn the new thread
Store return value in %eax
```

```
    get return values from registers
    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;

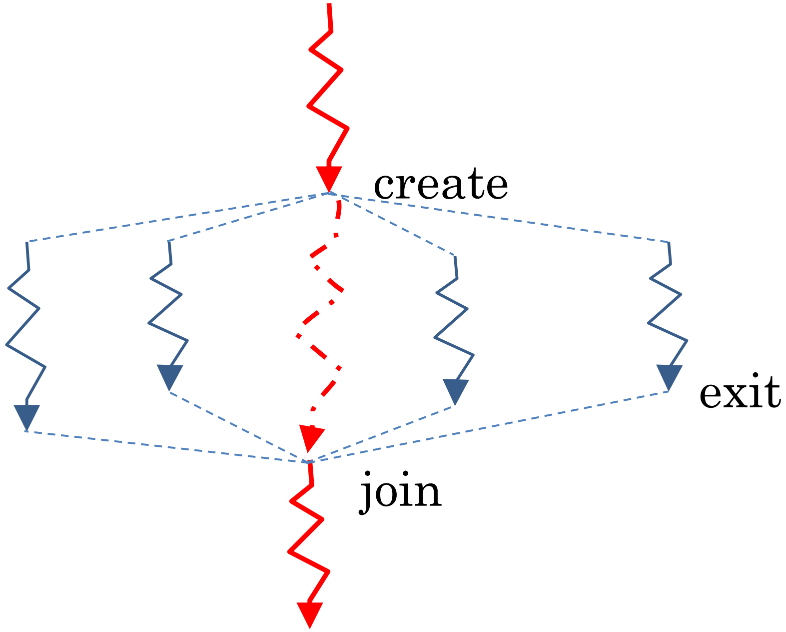
void *threadfun(void *threadid)
{
  long tid = (long)threadid;
  printf("Thread #%lx stack: %lx common: %lx (%d)\n", tid,
         (unsigned long) &tid, (unsigned long) &common, common++);
  pthread_exit(NULL);
}

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);
    }
  }

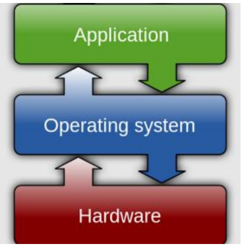
  for(t=0; t<nthreads; t++){
    pthread_join(threads[t], NULL);
  }
  pthread_exit(NULL);           /* last thing in the main thread  */
}
```

Fork-Join Pattern

- Main thread creates (forks) collection of sub-threads passing them arguments to work on…

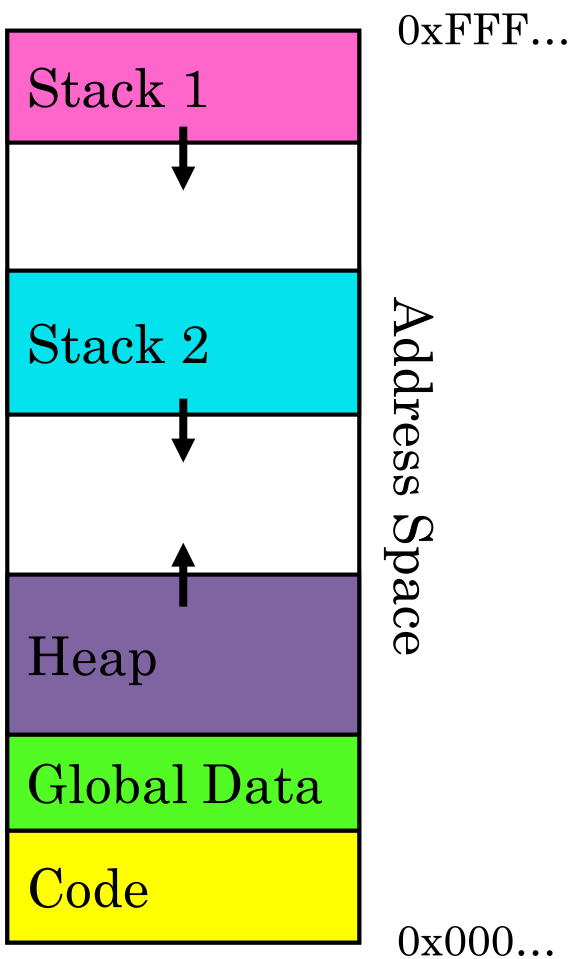


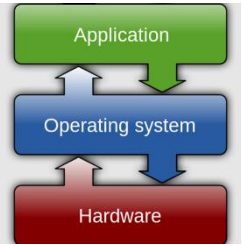
- … and then joins with them, collecting results.



Memory Layout with Two Threads

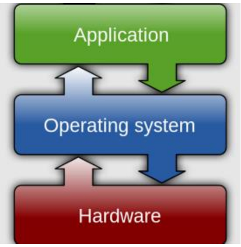
- Two sets of CPU registers
- Two sets of Stacks
- Issues:
  - How do we position stacks relative to each other?
  - What maximum size should we choose for the stacks?
  - What happens if threads violate this?
  - How might you catch violations?





Announcements

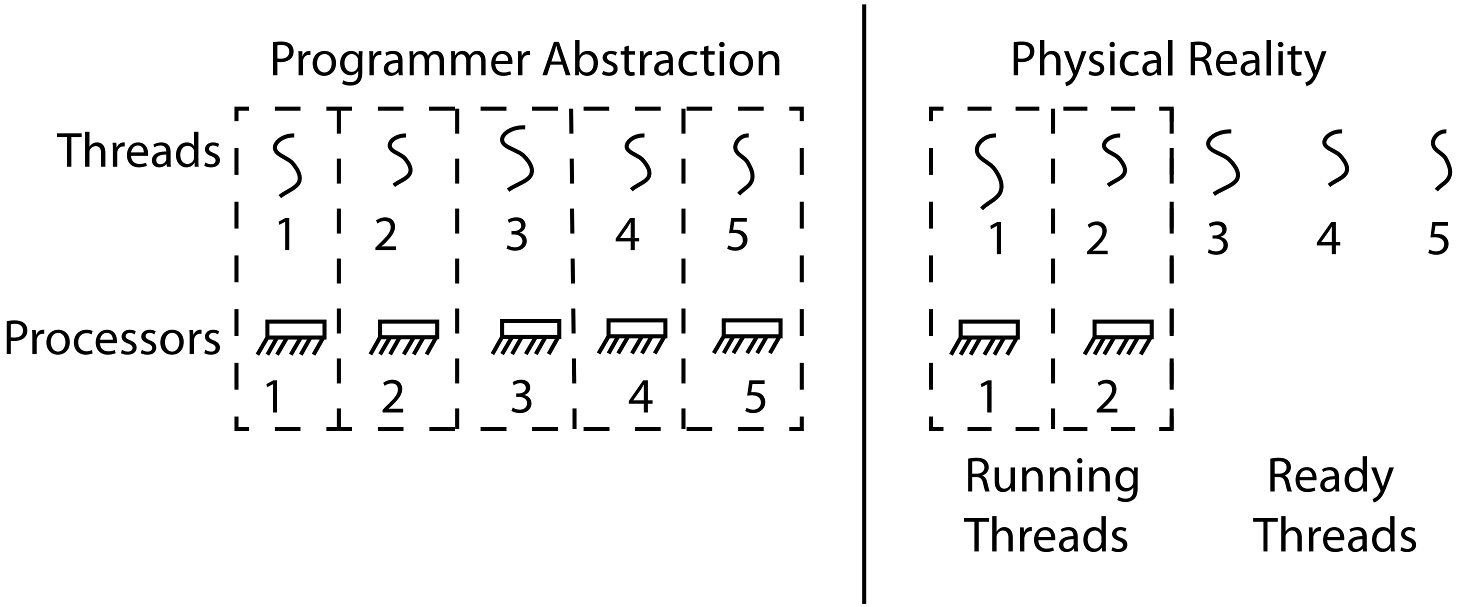
- Project 0 is due Monday, February 17
  - Attend next lecture for a walk through
  - Work through Study Guide: x86
- Assignment 1 was posted
  - Due Monday, February 24
- Project 1 will be posted soon
  - Groups have been assigned

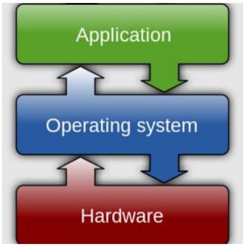


Interleaving and Nondeterminism

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

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

Possible Execution #1

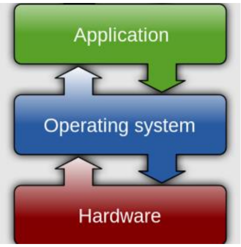
.
.
.
x = x + 1;
y = y + x;
z = x + 5y;
.
.
.

Possible Execution #2

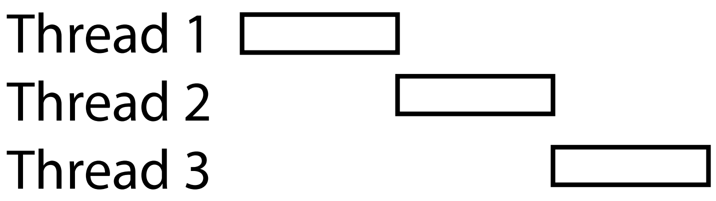
.
.
.
x = x + 1
....
thread is suspended
other thread(s) run
thread is resumed
....
y = y + x
z = x + 5y

Possible Execution #3

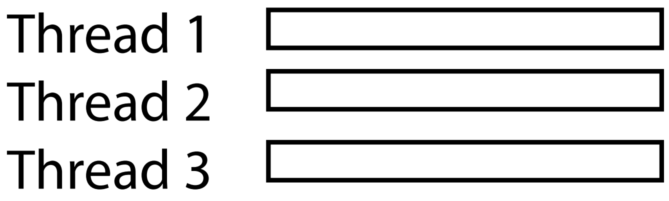
.
.
.
x = x + 1
y = y + x
....
thread is suspended
other thread(s) run
thread is resumed
....
z = x + 5y



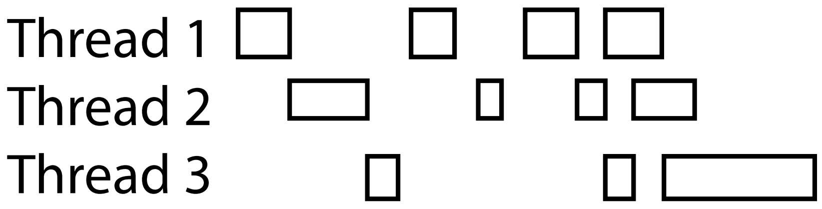
Possible Executions



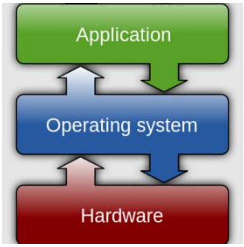
a) One execution



b) Another execution

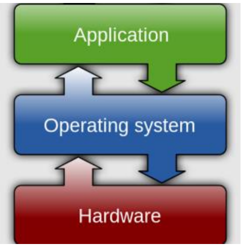


c) Another execution



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

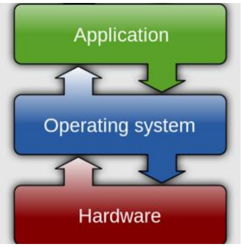


Race Conditions

- 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.

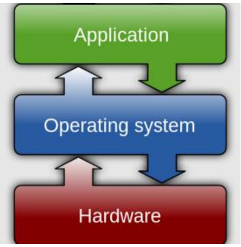


Race Conditions

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

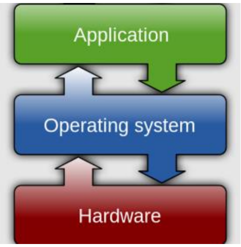
<u>Thread A</u>	<u>Thread B</u>
`x = y + 1;`	`y = 2;`
	`y = y * 2;`

- `1` or `3` or `5` (non-deterministic)
- Race Condition: Thread A races against Thread B



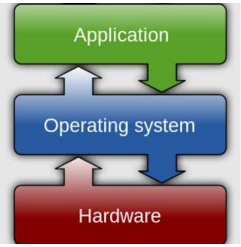
Relevant Definitions

- 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
  - Also called Mutex



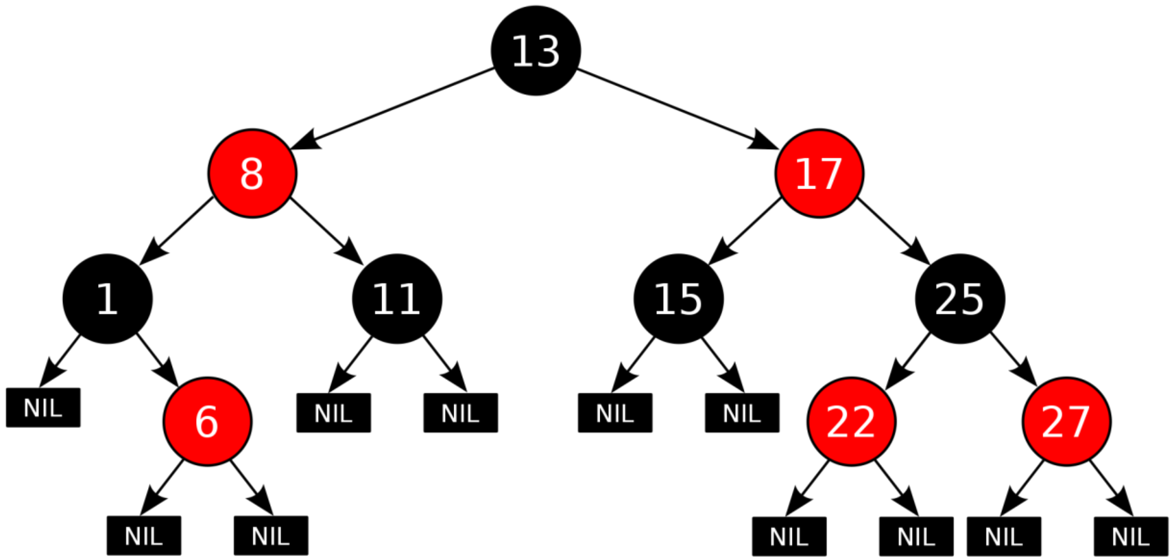
Locks (Mutexes)

- 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



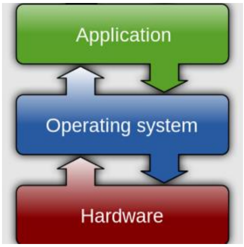
Example: Shared Data Structure

- Thread A
- Insert(3)



Tree-Based Set Data Structure

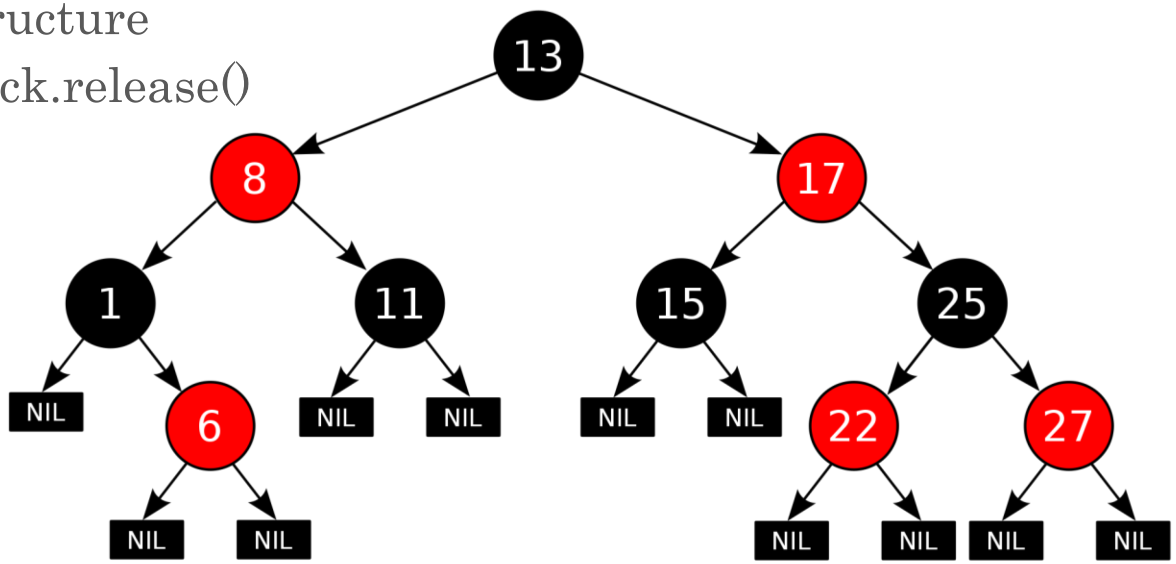
- Thread B
- Insert(4)
- Get(6)



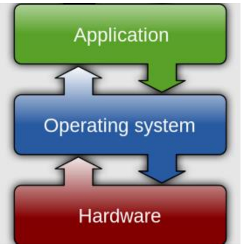
Example: Shared Data Structure

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

- Thread B
- Insert(4):
  - Lock.acquire()
  - Insert 4 into the data structure
  - Lock.release()
- Get(6):
  - Lock.acquire()
  - Check for membership
  - Lock.release()



Tree-Based Set Data Structure

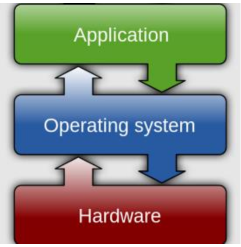


OS Library Locks: pthreads

- ```
  int pthread_mutex_init(
        pthread_mutex_t* mutex,
        pthread_mutexattr_t const* attr)
  ```
  - Attributes are most of the time NULL

- `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 Assignment 1


  ```

Our Example

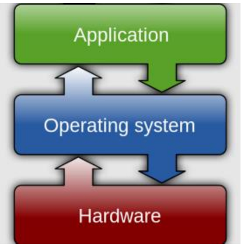
Critical section

```
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);

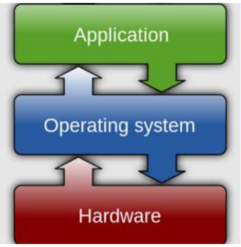
  printf("Thread #%lx stack: %lx common: %lx (%d)\n", tid,
         (unsigned long) &tid,
         (unsigned long) &common, my_common);
  pthread_exit(NULL);
}
```

Note: `pthread_mutex_init` was called once in main thread



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 an 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;

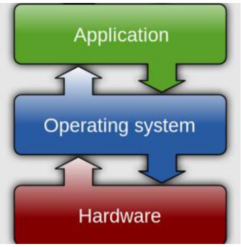
semaphore.down();
   // Critical section goes here
semaphore.up();
```

- Signaling other threads, e.g. ThreadJoin

```
initial value of semaphore = 0

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

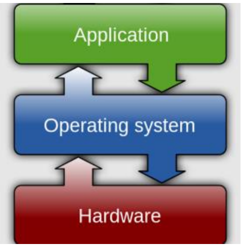
```
ThreadFinish {
    semaphore.up();
}
```



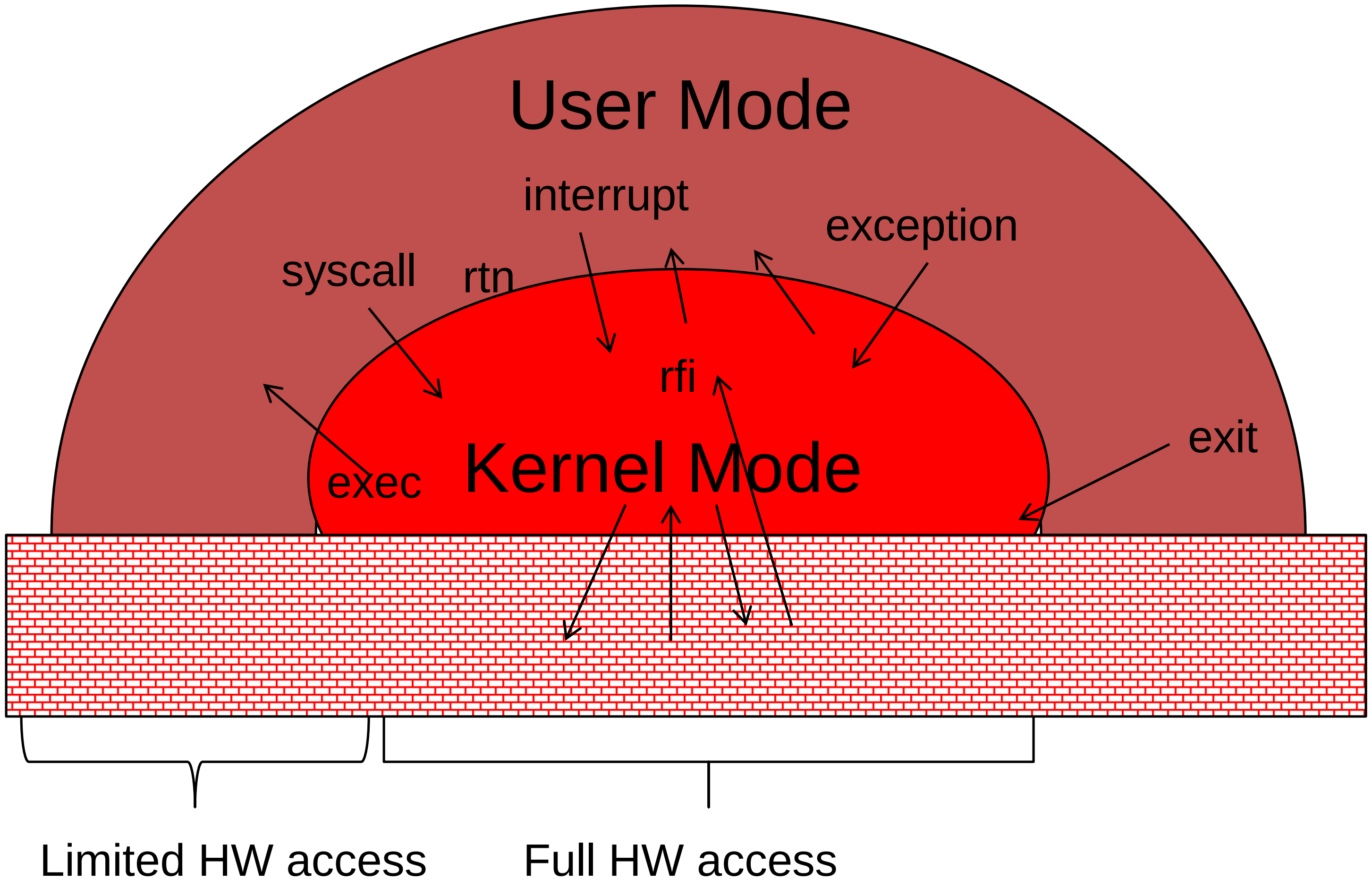
Processes

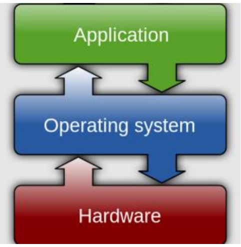
Recall: Process

- 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



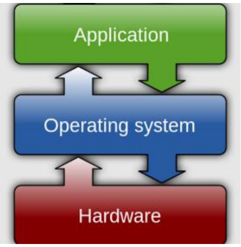
Recall: Life of a Process





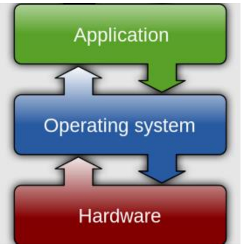
Processes

- 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! (Assignment 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
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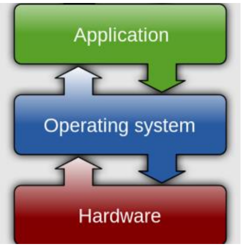
- `sigaction` – set handlers for signals



pid.c

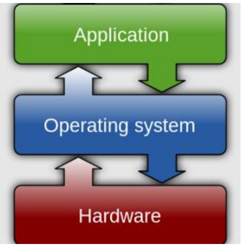
```
#include <stdlib.h>
#include <stdio.h>
#include <string.h>
#include <unistd.h>
#include <sys/types.h>

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: `entry.c`



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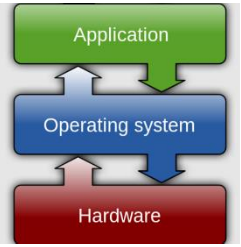
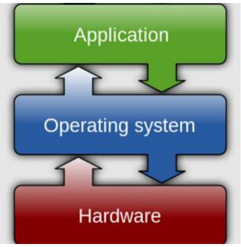


Creating Processes

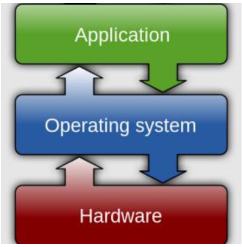
- `pid_t fork()` – copy the current process
  - New process has different `pid`
  - New process contains a single thread
- State of original process duplicated in both Parent and Child!
  - Address Space (Memory), File Descriptors (covered later), etc…
- Return value from `fork()`: `pid` (like an integer)
  - 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



fork1.c

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

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

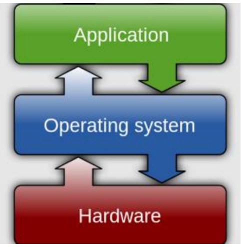


fork1.c

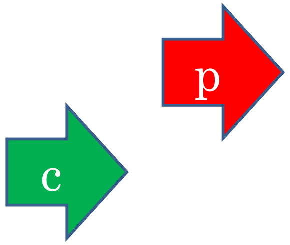
```c
#include <stdlib.h>
#include <stdio.h>
#include <unistd.h>
#include <sys/types.h>

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

p

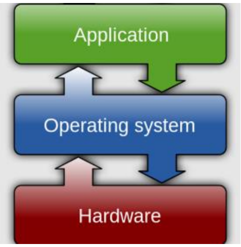


fork1.c




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

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



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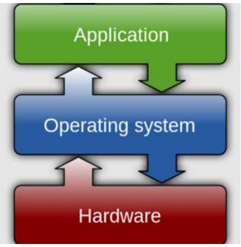
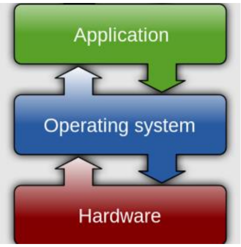


fork2.c – parent waits for child to finish

```
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);
}
…
```



Process Management API

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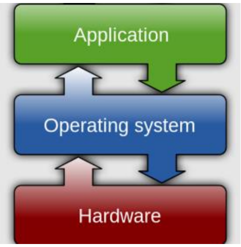
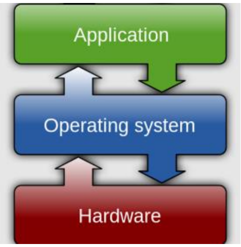


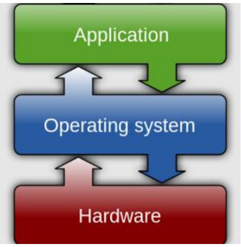
Running Another Program

- 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 (i.e. `fork` and `exec`)
- How can we do this?



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 failed");
  exit(1);
}
…
```



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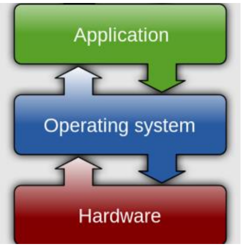
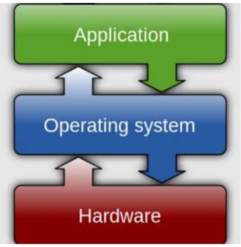


inf_loop.c

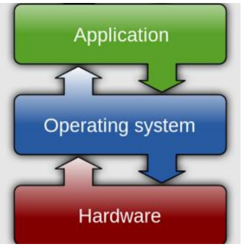
```c
#include <stdlib.h>
#include <stdio.h>
#include <sys/types.h>
#include <unistd.h>
#include <signal.h>

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



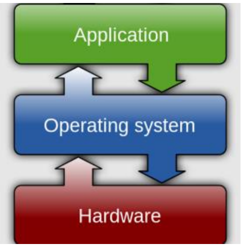
Common POSIX Signals

- `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?



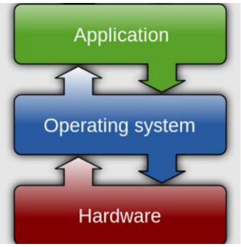
Shell

- 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 Assignment 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



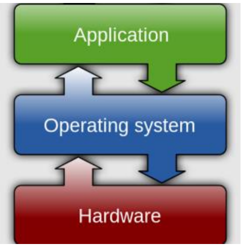
Process vs. Thread APIs

- 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



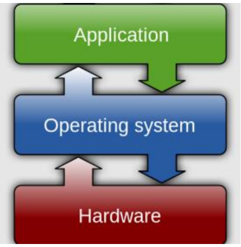
Threads vs. Processes

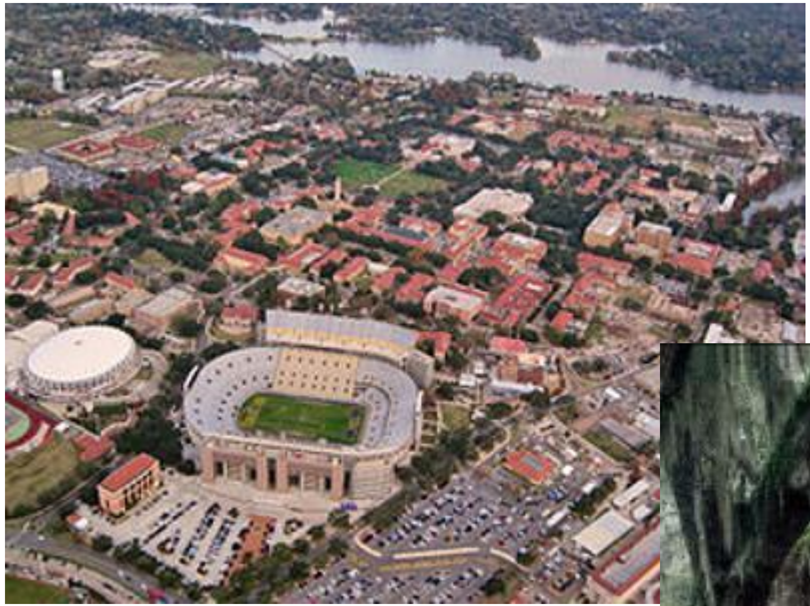
- If we have two tasks to run concurrently, do we run them in separate threads, or do we run them in separate processes?
- Depends on how much isolation we want
  - Threads are lighter weight [why?]
  - Processes are more strongly isolated



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





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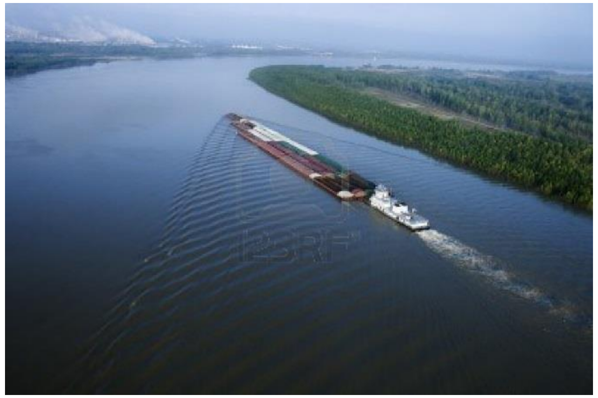

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