VIRTUALIZATION: THE CPU

Andrea Arpaci-Dusseau

CS 537, Fall 2019

ADMINISTRIVIA

- Project 1 is out! Due Monday, 9/16 before midnight
  - Solo, but later ones will involve project partners
  - Handin directories and test cases available
- Discussion sections on Wednesday
  - Can attend others if room (last two have most space)
- Sign up for Piazza
- Lecture recordings
- Still on waitlist? Sign attendance sheet at end of lecture
- Lecture ends at 12:15pm
- Microphone: Let me know if you can't hear

AGENDA / OUTCOMES

Abstraction for CPU

- What is a Process? What is its lifecycle?

Mechanism

- How does a process interact with the OS?
- How does the OS switch between processes?

REVIEW

What is an Operating System?

- Software that converts hardware into a useful form for applications

What abstraction does the OS provide for the CPU?

- Process or thread

For memory?

- Virtual address space

What are some advantages of OS providing resource management?

- Protect applications from one another
- Provide fair and efficient access to resources (cost, time, energy)

VIRTUALIZING THE CPU

High-level Goal:

Give each "process" impression it alone is actively using CPU

Resources can be shared in **time** and/or **space**

Assume single uniprocessor

- Time-sharing (multi-processors: advanced issue with space-sharing)

Memory?

- Space-sharing (later)

Disk?

- Space-sharing (later)

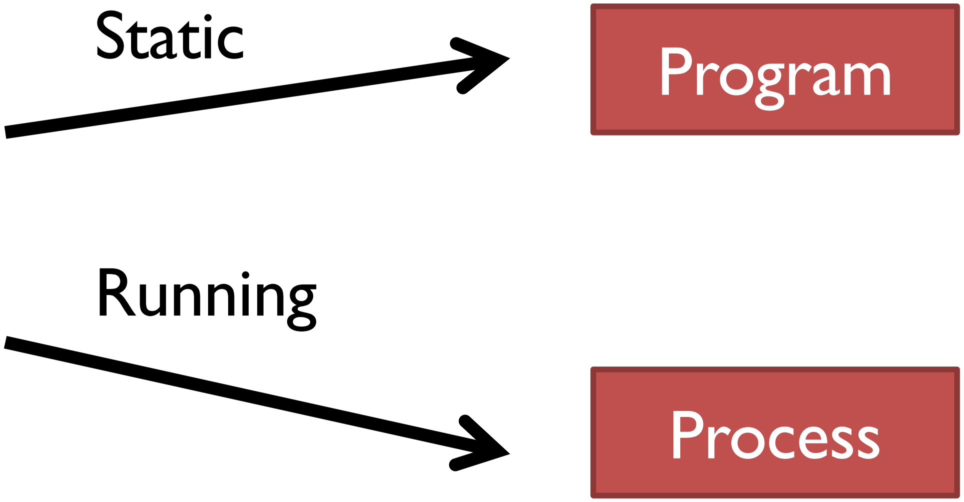
ABSTRACTION: PROCESS

PROGRAM VS PROCESS

```
#include <stdio.h>
#include <stdlib.h>
#include "common.h"

int main(int argc, char *argv[]) {
    char *str = argv[1];

    while (1) {
      printf("%s\n", str);
      Spin(1);
    }
    return 0;
}
```



Static

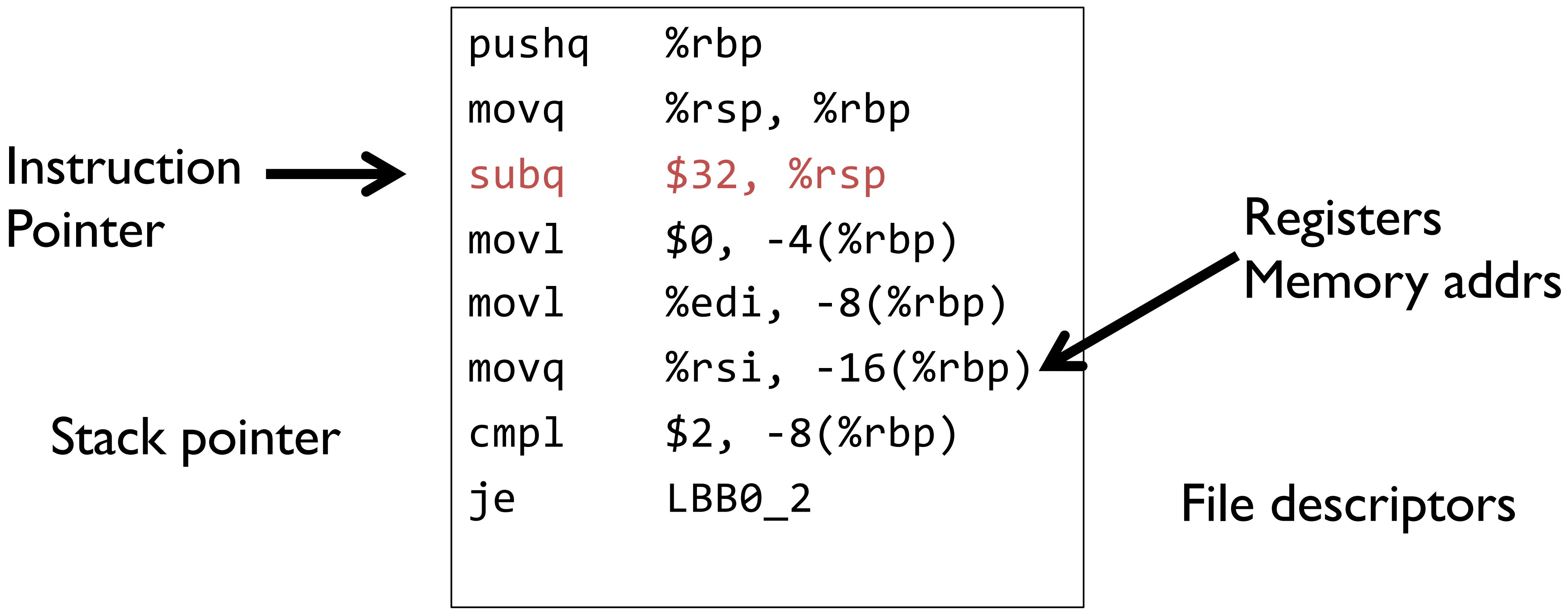
Program

Running

Process

WHAT IS A PROCESS?

Stream of executing instructions and their “context” in address space



```
pushq    %rbp
movq     %rsp, %rbp
subq     $32, %rsp
movl     $0, -4(%rbp)
movl     %edi, -8(%rbp)
movq     %rsi, -16(%rbp)
cmpl     $2, -8(%rbp)
je       LBB0_2
```

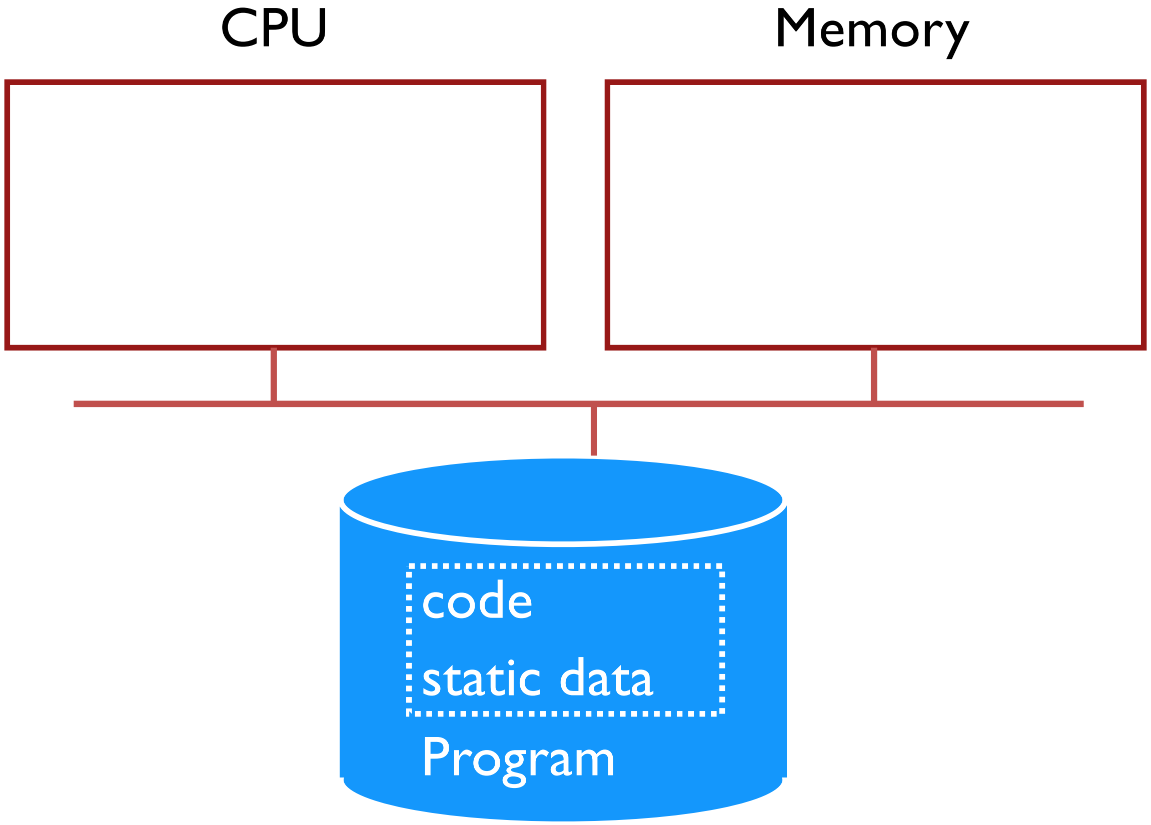
Instruction Pointer

Stack pointer

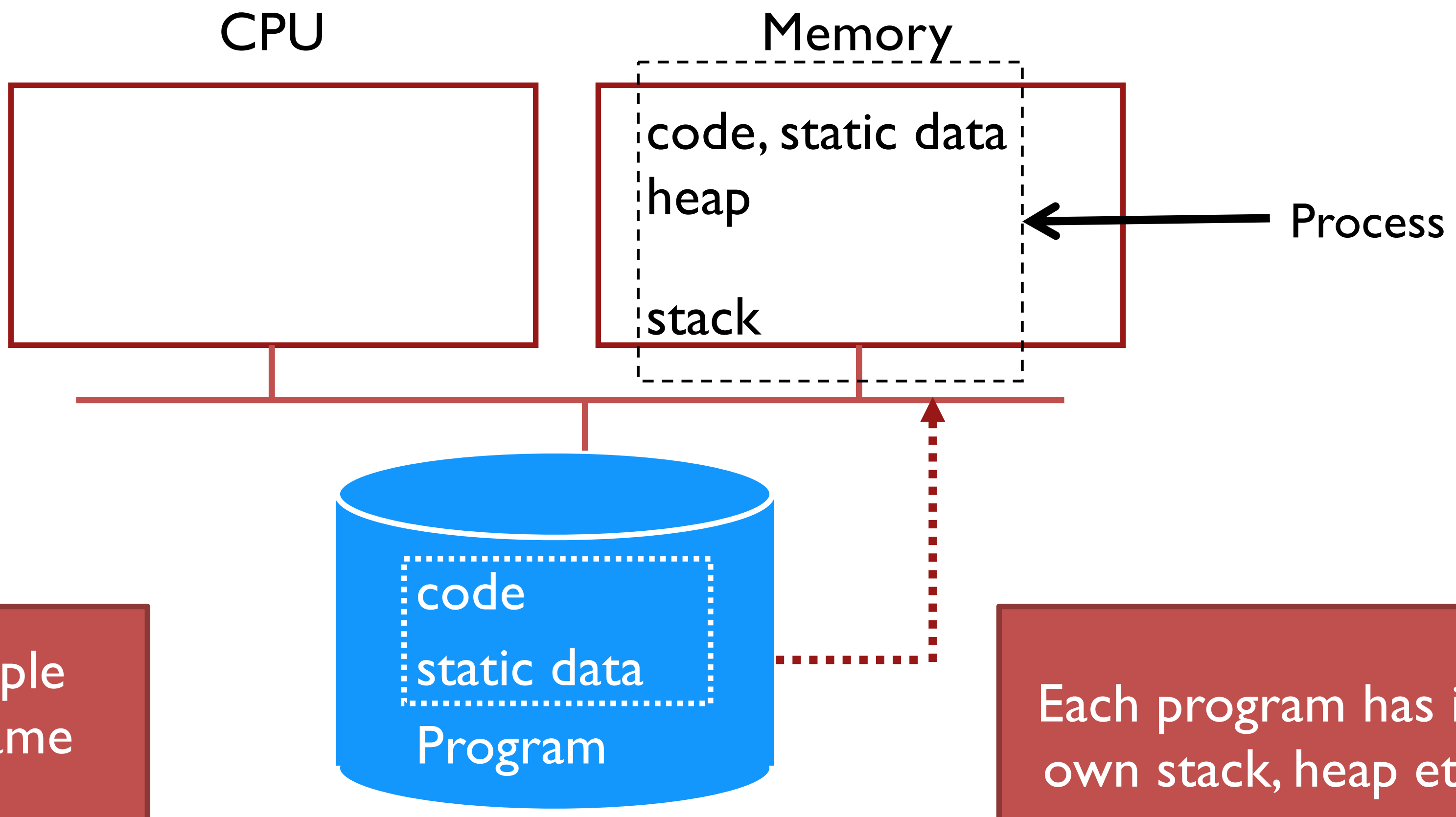
Registers
Memory addrs

File descriptors

PROCESS CREATION



PROCESS CREATION



Can run multiple instances of same program

Each program has its own stack, heap etc.

PROCESS VS THREAD DEMO

- Two **processes** examining same memory address see **different** values (I.e., different contents)
  - Different isolated address spaces

- Two **threads** examining memory address see **same** value (I.e., same contents)
  - Share same address space

PROCESS VS THREAD

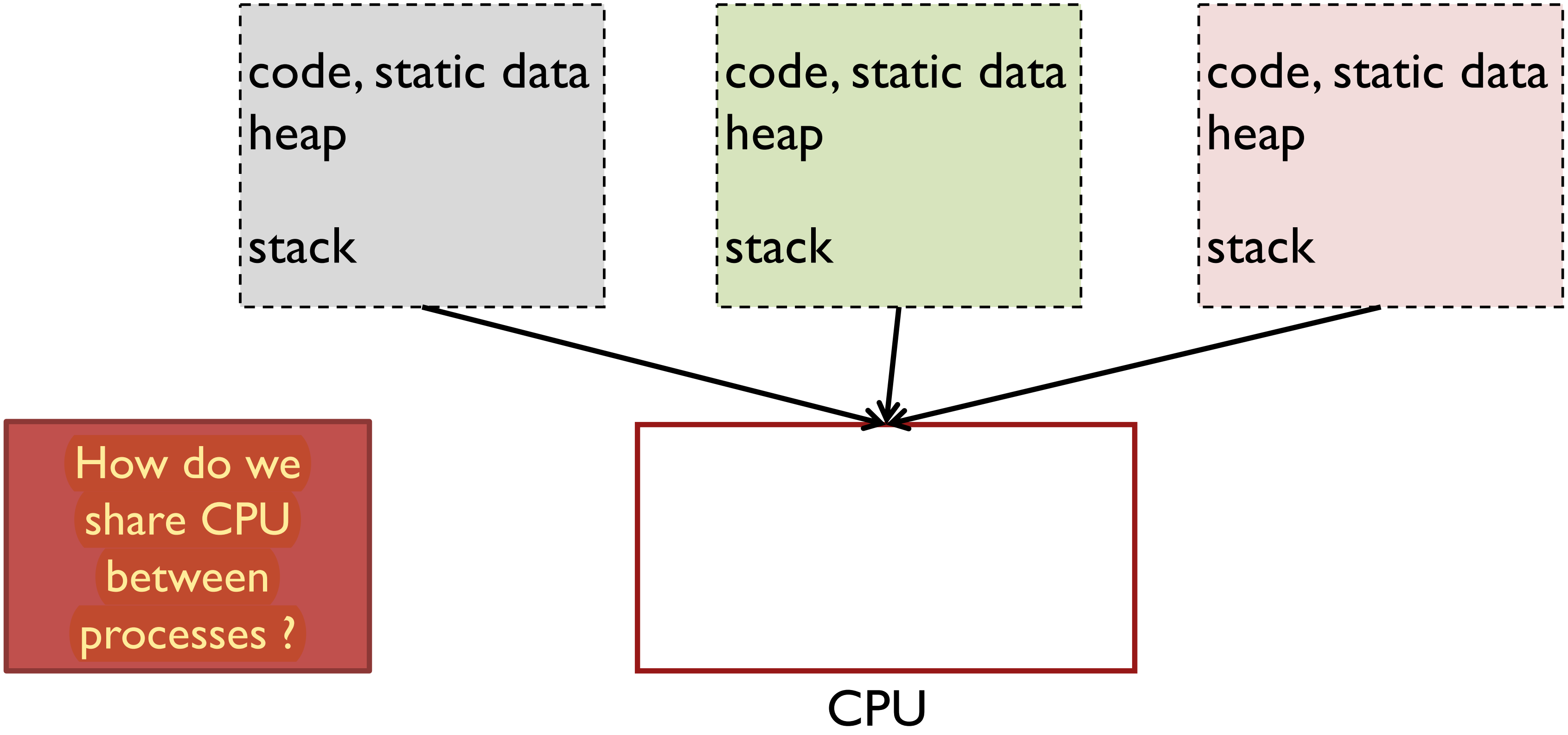
Threads: “Lightweight process”

Execution streams that share an address space
Can directly read / write same memory

Can have multiple threads within a single process

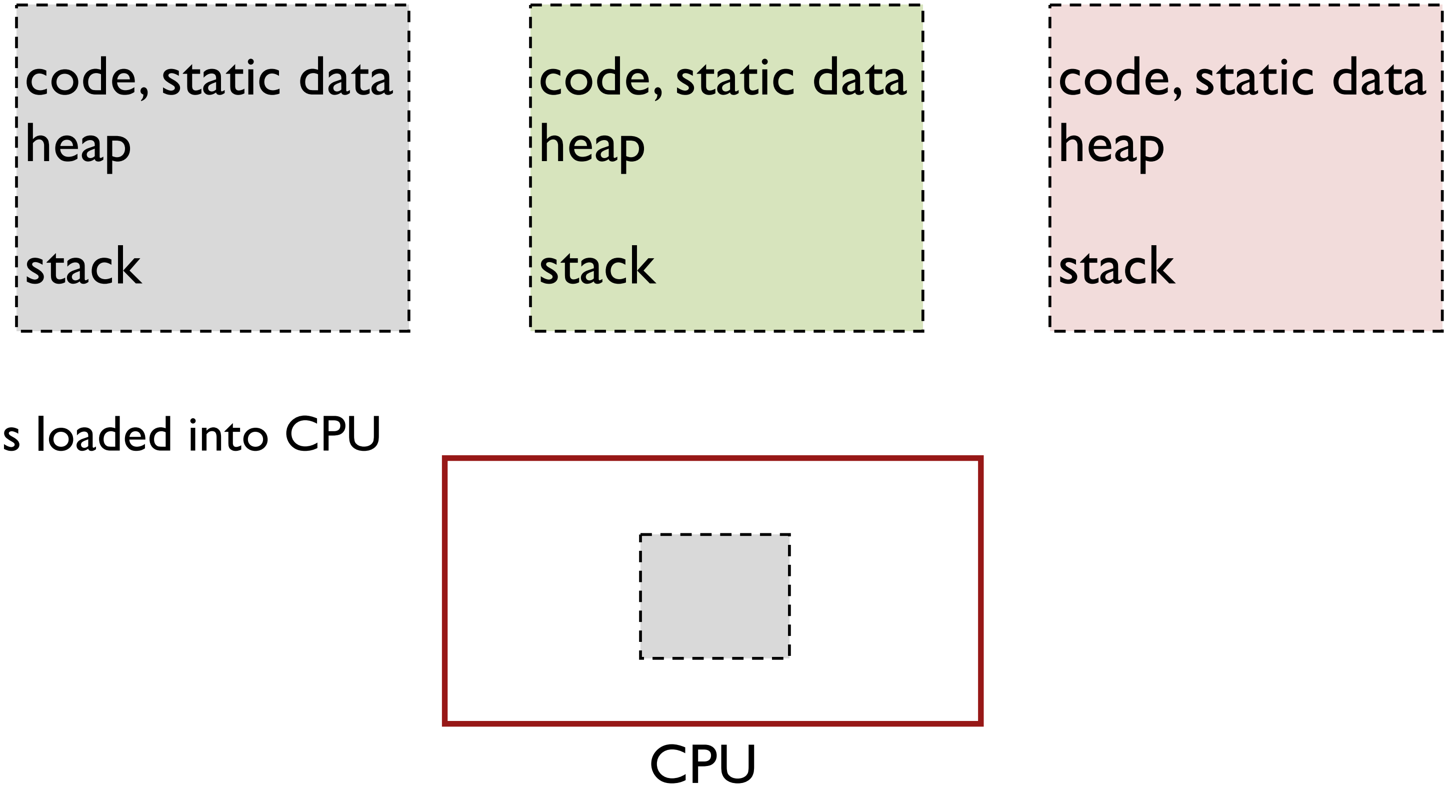
WHY DO WE NEED PROCESSES ?

SHARING CPU



How do we share CPU between processes ?

TIME SHARING



code, static data
heap
stack

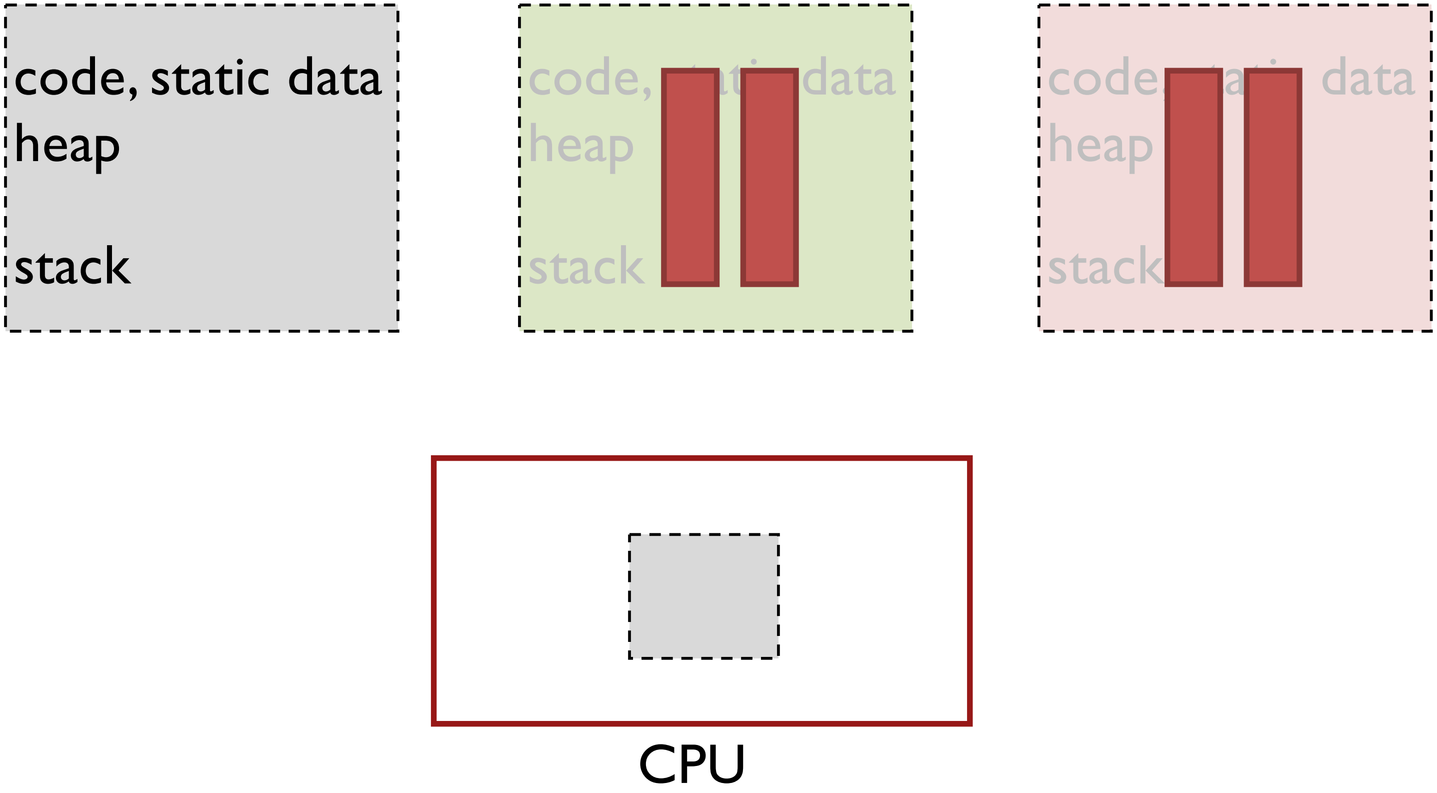
code, static data
heap
stack

code, static data
heap
stack

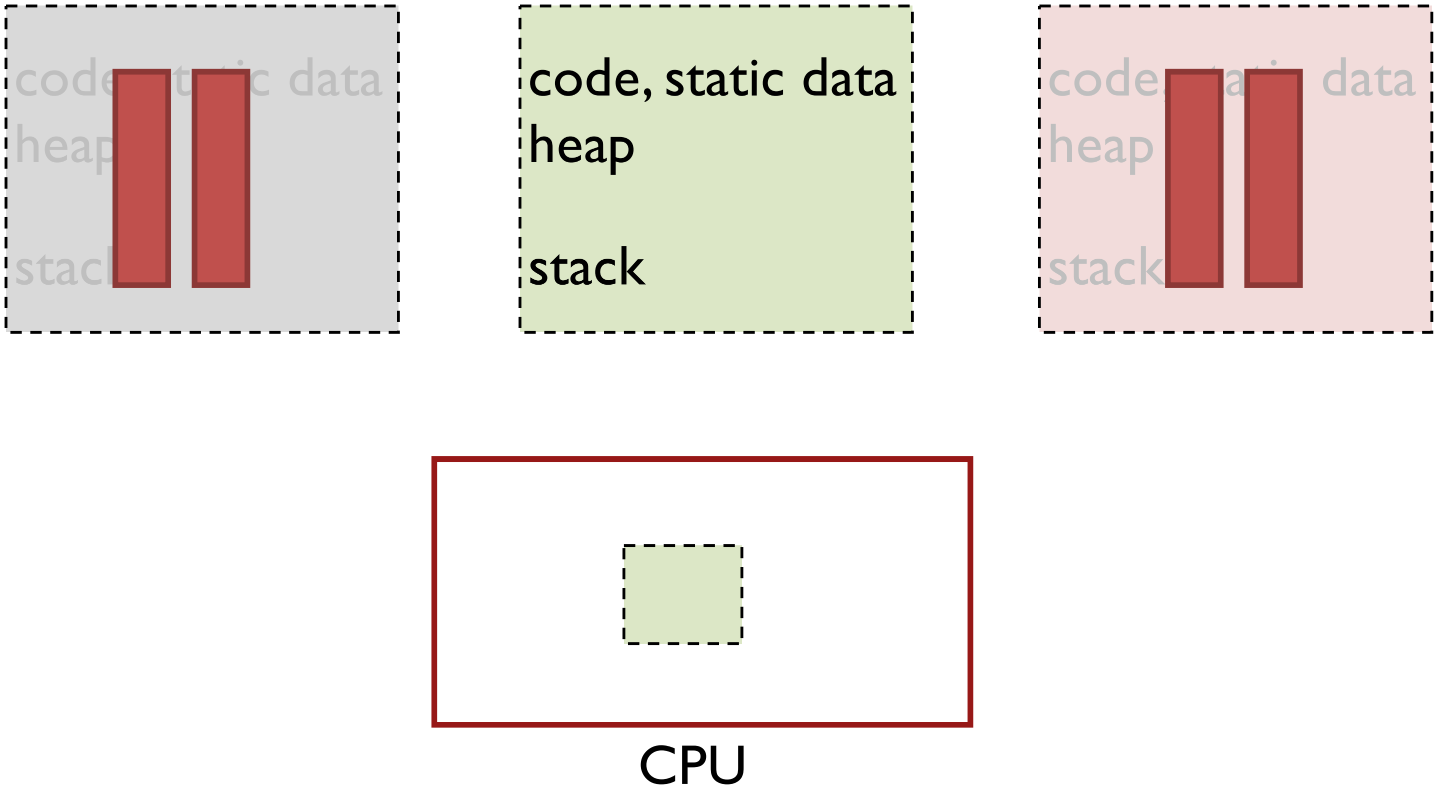
CPU

Context is loaded into CPU

TIME SHARING



TIME SHARING



code, static data
heap

stack

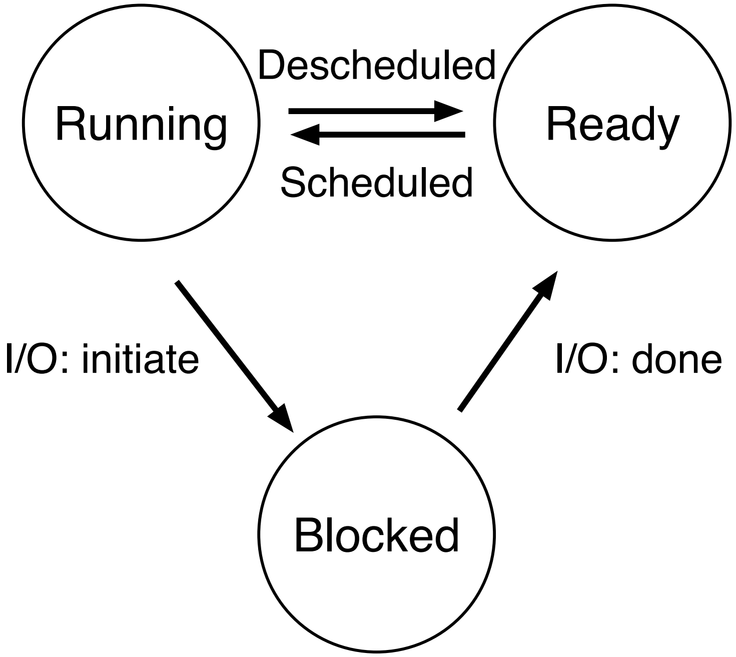
CPU

WHAT TO DO WITH PROCESSES THAT ARE NOT RUNNING ?

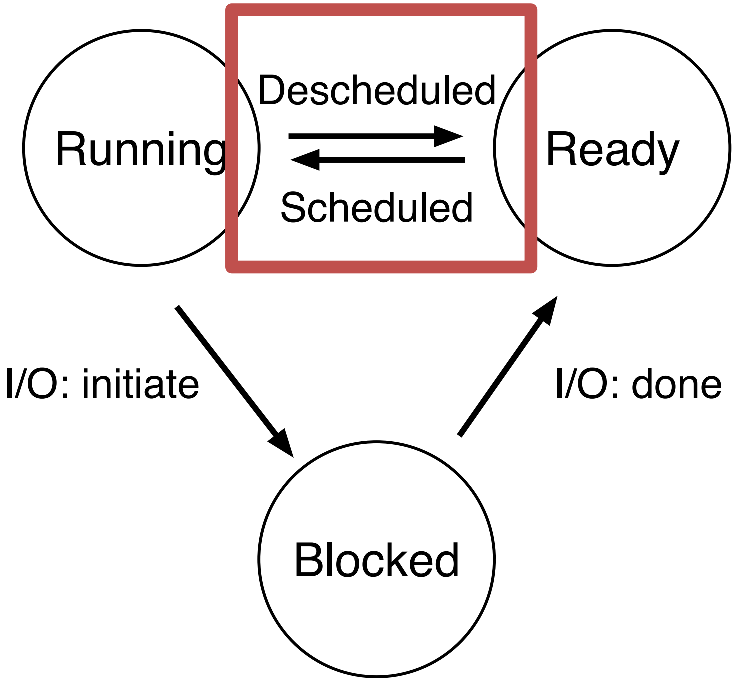
OS Scheduler

- Save context when process is paused
- Restore context on resumption

STATE TRANSITIONS



STATE TRANSITIONS



ASIDE: OSTEP HOMEWORKS!

- Optional homeworks corresponding to each chapter in book
- Little simulators to help you understand
- Can generate problems and solutions!

http://pages.cs.wisc.edu/~remzi/OSTEP/Homework/homework.html

PROCESS HW

Run ./process_run.py –l 2:100,2:0

QUIZ

```
≥ ./process-run.py -l 3:50,3:40
Process 0
  io
  io
  cpu

Process 1
  cpu
  io
  io
```

CPU TIME SHARING

Mechanism goals: Be able to run processes

- Efficiency: Time sharing should not add overhead
- Control: OS should be able to intervene when required

Policy goals: Pick the "best" process to schedule

- Reschedule process for fairness? efficiency ?

Separate mechanism from policy for clean OS design

How to have efficient mechanism??

EFFICIENT EXECUTION

Simple answer !?: Direct Execution

Allow user process to run directly

Create process and transfer control to main()

Challenges

1) What if the process wants to do something restricted ? Access disk ?

2) What if the process runs forever ? Buggy ? Malicious ?

Solution: Limited Direct Execution (LDE)

CHALLENGE 1: RESTRICTED OPS

How can we ensure user process can’t harm others?

Solution: privilege levels supported by hardware (bit of status)

User processes run in user mode (restricted mode)

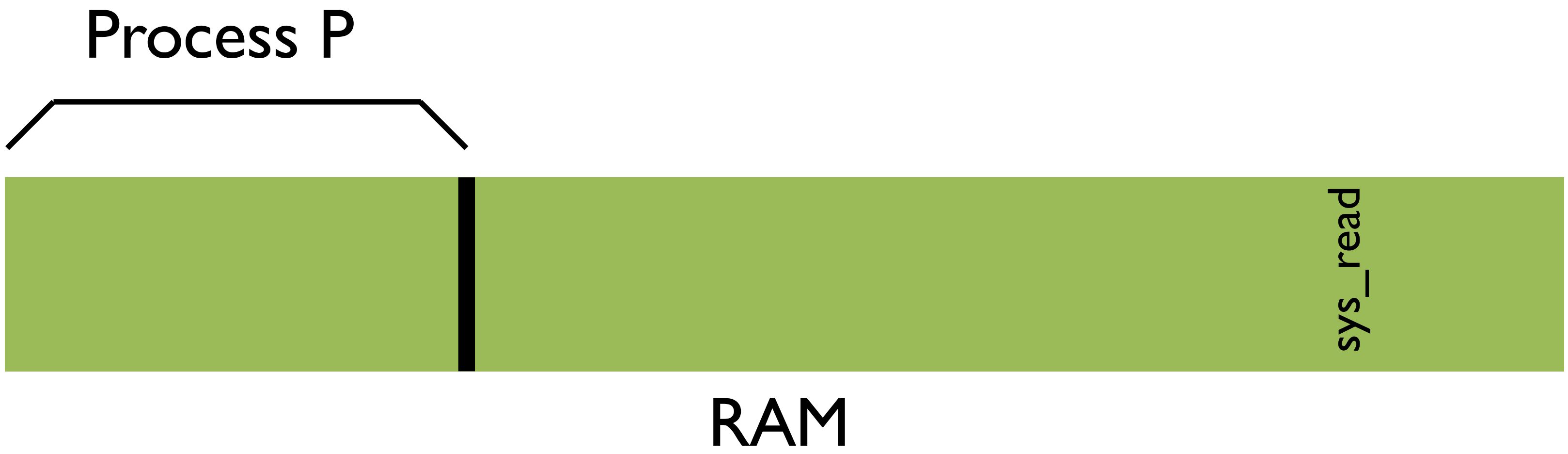
OS runs in kernel mode (not restricted)

How can process access devices?

System calls (function call implemented by OS)

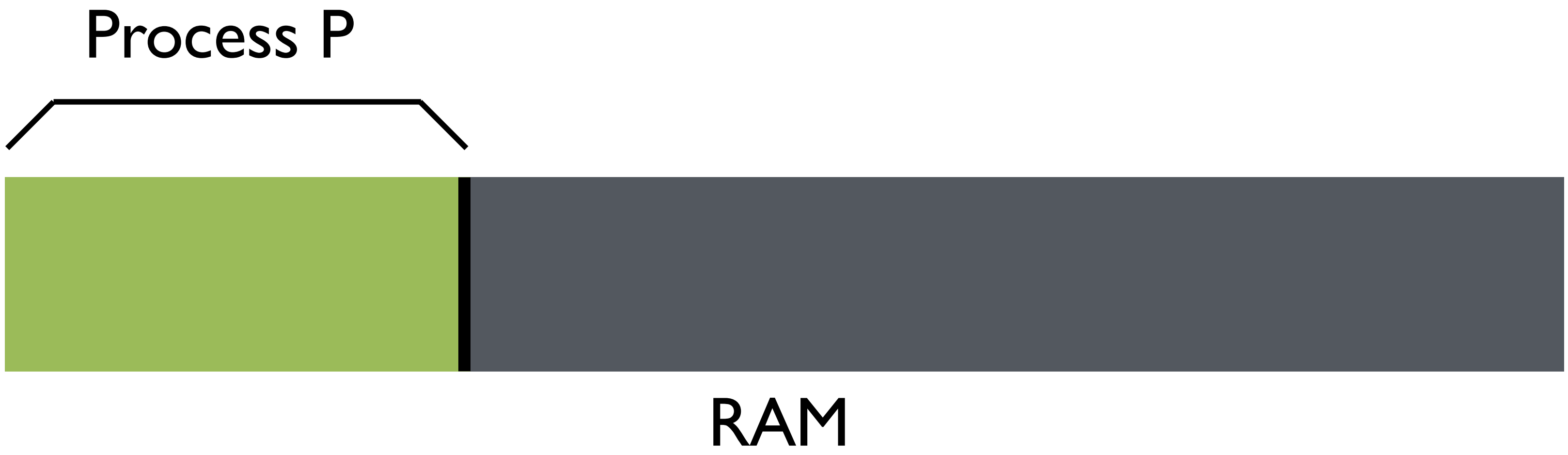
SYSTEM CALL

SYSTEM CALL



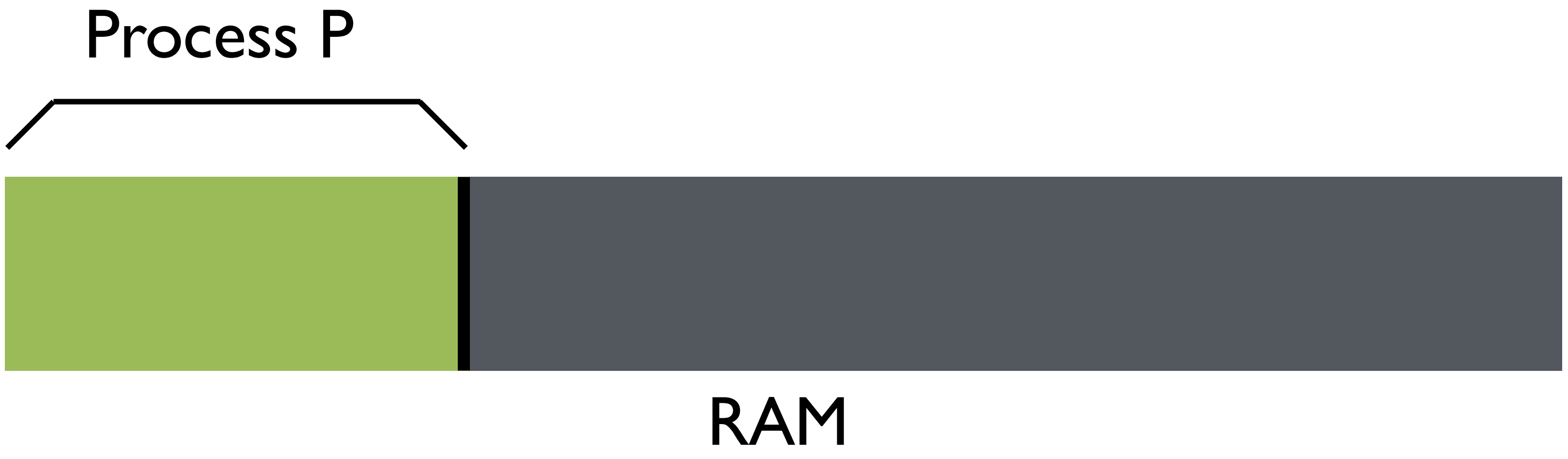
P wants to call read()

SYSTEM CALL



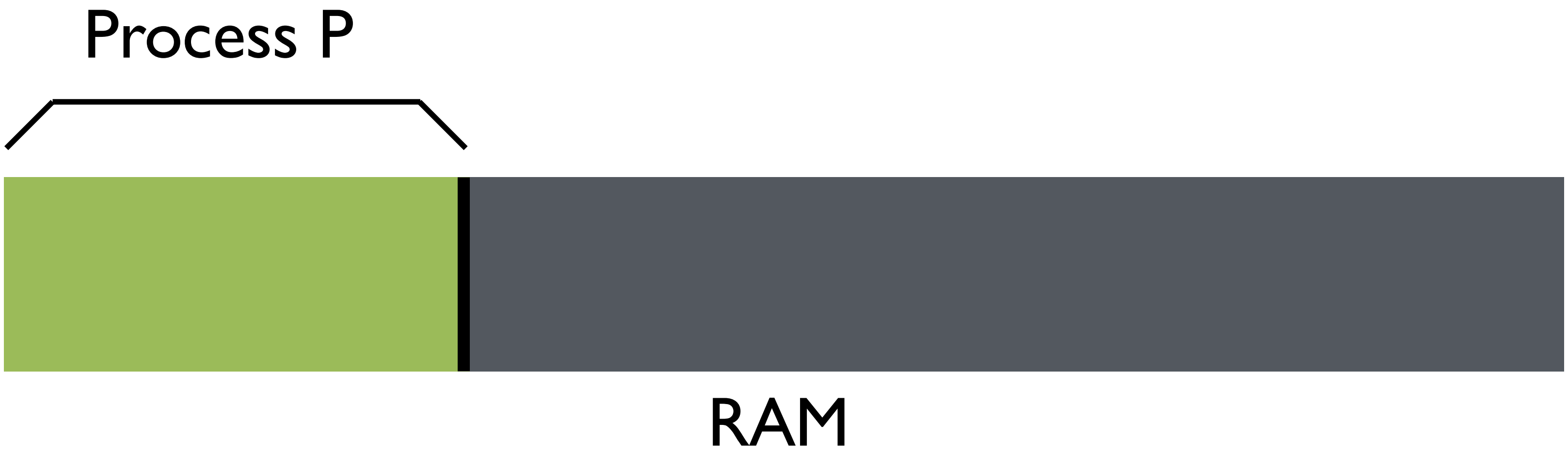
P can only see its own memory because of **user mode**
(other areas, including kernel, are hidden)

SYSTEM CALL



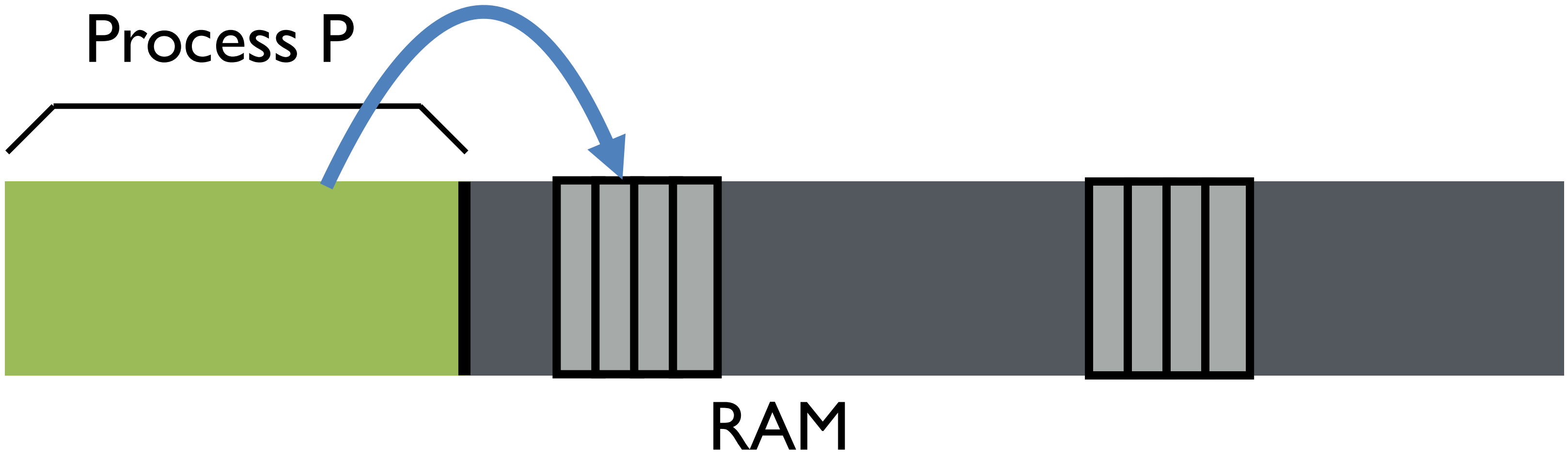
P wants to call read() but no way to call it directly

SYSTEM CALL



```
movl $6, %eax;   int $64
```

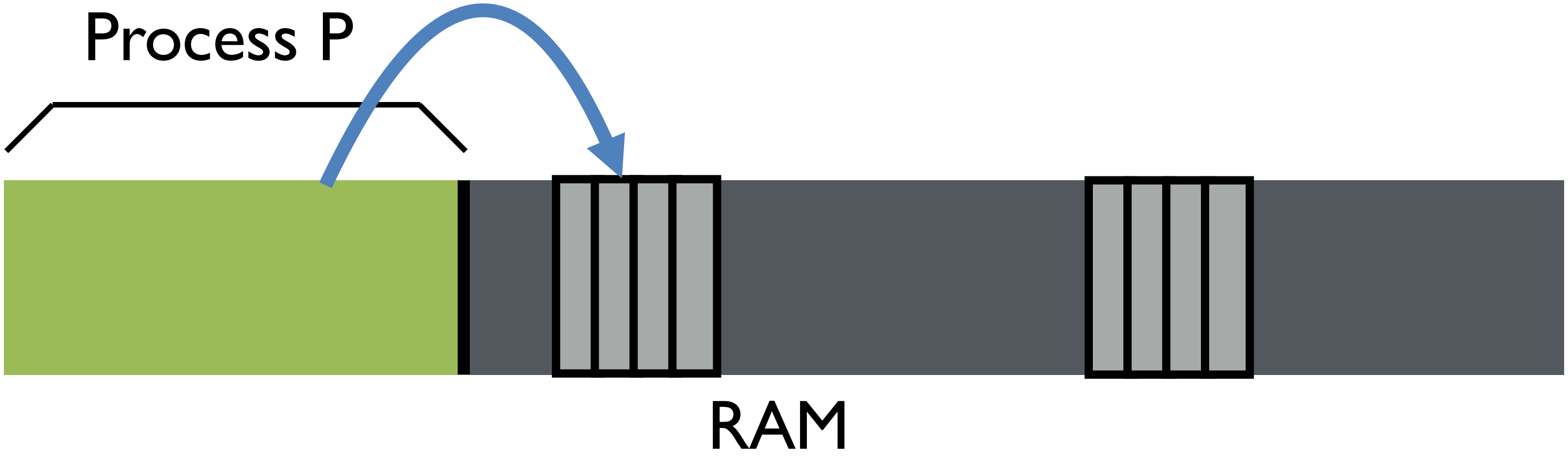
SYSTEM CALL



```
movl $6, %eax;    int $64
```

Trap table index

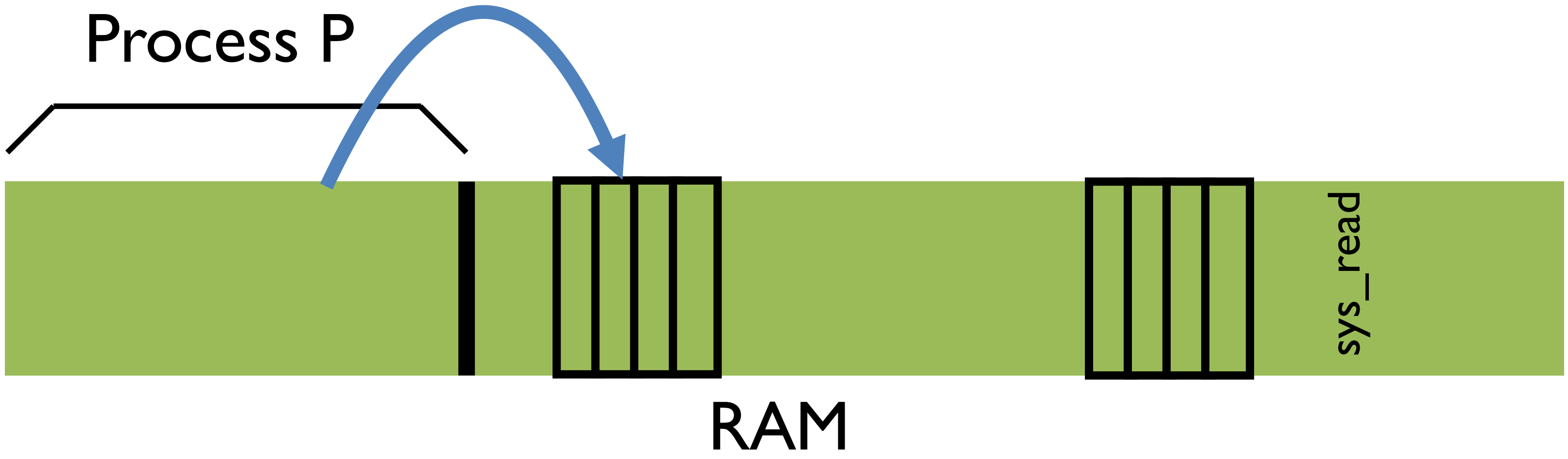
SYSTEM CALL



Syscall table index

```
movl $6, %eax;    int $64
```

SYSTEM CALL

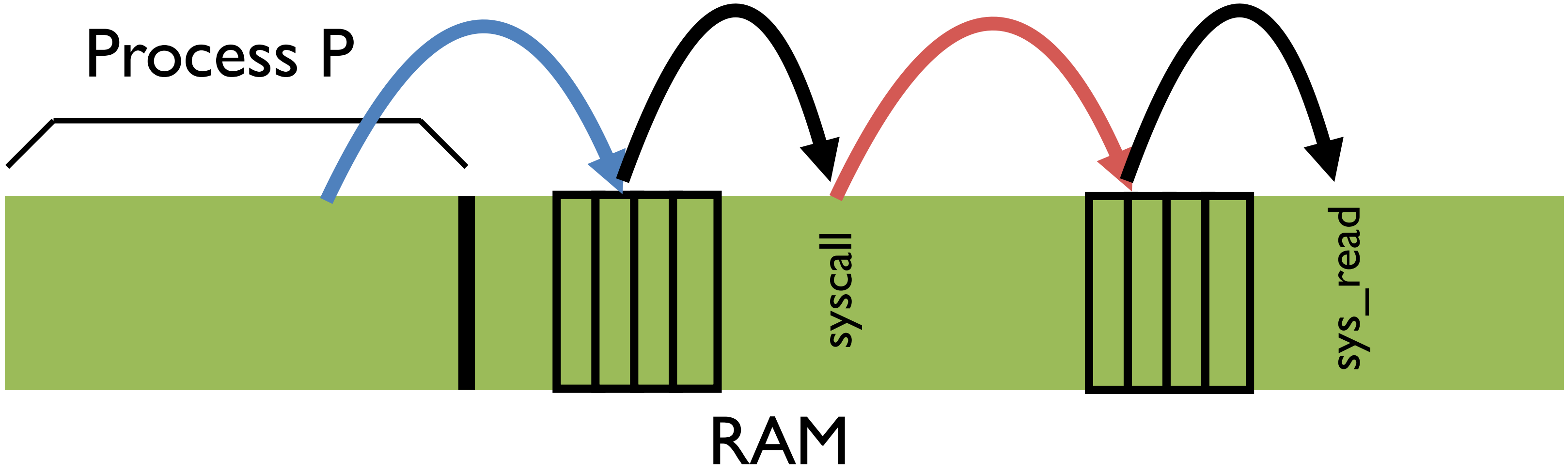


Syscall table index

```
movl $6, %eax;   int $64
```

Trap table index

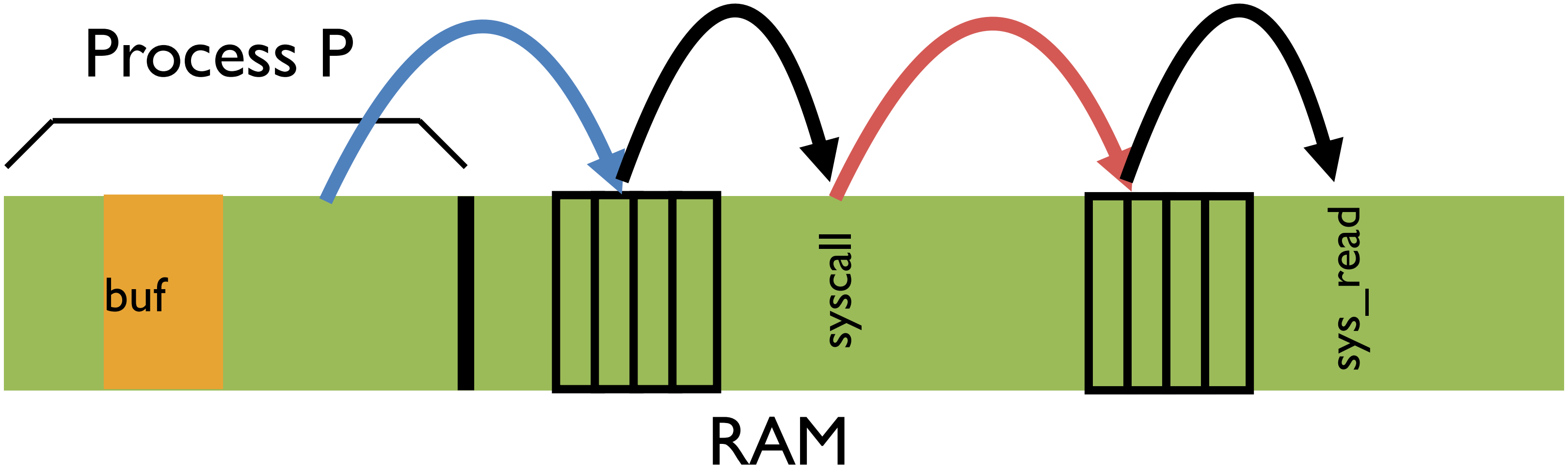
SYSTEM CALL



```
movl $6, %eax;   int $64
```

Follow entries to correct system call code

SYSTEM CALL



Kernel can access user memory to fill in user buffer
return-from-trap at end to return to Process P

SYSCALL SUMMMARY

Separate user-mode from kernel mode for security

Syscall: call kernel mode functions

- Transfer from user-mode to kernel-mode (trap)
- Return from kernel-mode to user-mode (return-from-trap)

5 MINUTE BREAK!

Talk with at least two neighbors

- What has been your favorite course in CS? What did you like most about it?
- Favorite course outside of CS? Why?

REPEAT: EFFICIENT EXECUTION

Simple answer !?: Direct Execution

- Allow user process to run directly
- Create process and transfer control to main()

Challenges

1) What if the process wants to do something restricted ? Access disk ?
2) What if the process runs forever ? Buggy ? Malicious ?

Solution: Limited Direct Execution (LDE)

CHALLENGE 2: HOW TO TAKE CPU AWAY

Policy

- To decide which process to schedule when
- Decision-maker to optimize some workload performance metric

Mechanism

- To switch between processes
- Low-level code that implements the decision

Separation of policy and mechanism: Recurring theme in OS

DISPATCH MECHANISM

OS runs dispatch loop

```
while (1) {
     run process A for some time-slice
     stop process A and save its context
     load context of another process B
}
```

Context-switch

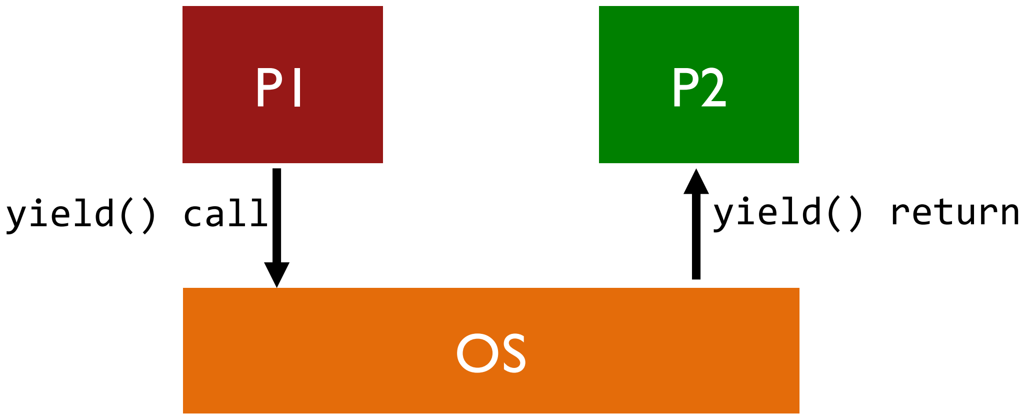
Question 1: How does dispatcher gain control?

Question 2: What must be saved and restored?

HOW DOES DISPATCHER GET CONTROL?

Option 1: Cooperative Multi-tasking: Trust process to relinquish CPU through traps

- Examples: System call, page fault (access page not in main memory), or error (illegal instruction or divide by zero)
- Provide special `yield()` system call



PROBLEMS WITH COOPERATIVE ?

Disadvantages: Processes can misbehave

By avoiding all traps and performing no I/O, can take over entire machine

Only solution: Reboot!

Not performed in modern operating systems

TIMER-BASED INTERRUPTS

Option 2: Timer-based Multi-tasking (True multi-tasking)

Guarantee OS can obtain control periodically

Enter OS by enabling periodic alarm clock

- Hardware generates timer interrupt (CPU or separate chip) Example: Every 10ms
- User must not be able to mask timer interrupt

Operating System

Hardware

Program

Process A

Operating System	Hardware	Program
		Process A
	timer interrupt save regs(A) to k-stack(A) move to kernel mode jump to trap handler for timer	

Operating System	Hardware	Program
		Process A
	timer interrupt	
	save regs(A) to k-stack(A)	
	move to kernel mode	
	jump to trap handler for timer	
Handle the trap for timer		
Call switch() routine		
save regs(A) to proc-struct(A)		
restore regs(B) from proc-struct(B)		
switch to k-stack(B)		
return-from-trap (into B)		

Operating System	Hardware	Program
		Process A
	timer interrupt save regs(A) to k-stack(A) move to kernel mode jump to trap handler for timer	
Handle the trap for timer Call switch() routine save regs(A) to proc-struct(A) restore regs(B) from proc-struct(B) switch to k-stack(B) return-from-trap (into B)		
	restore regs(B) from k-stack(B) move to user mode jump to B’s IP	

Operating System	Hardware	Program
		Process A
	timer interrupt save regs(A) to k-stack(A) move to kernel mode jump to trap handler for timer	
Handle the trap for timer Call switch() routine save regs(A) to proc-struct(A) restore regs(B) from proc-struct(B) switch to k-stack(B) return-from-trap (into B)		
	restore regs(B) from k-stack(B) move to user mode jump to B’s IP	
		Process B

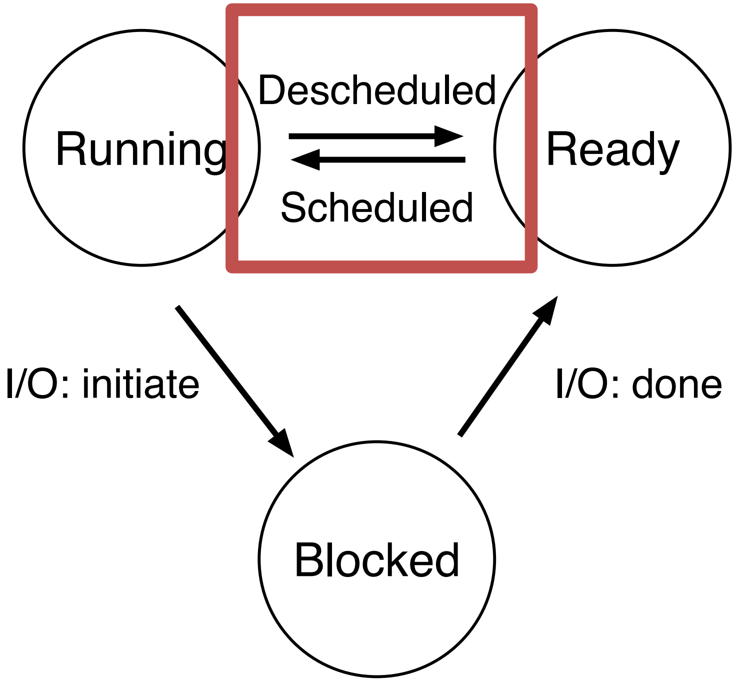
SUMMARY

Process: Abstraction to virtualize CPU

Use time-sharing in OS to switch between processes

Key aspects

- Use system calls to run access devices etc. from user mode
- Context-switch using interrupts for multi-tasking



POLICY ?

NEXT CLASS!

ADMINISTRIVIA

- Lecture ends at 12:15pm
- Project 1 is out! Due Monday, 9/16 before midnight
  - Handin directories and test cases available
- Discussion sections on Wednesday
  - Can attend others if room (last two have most space)
- Sign up for Piazza
- Still on waitlist? Sign attendance sheet at end of lecture