CPU Virtualization

Virtualization: The CPU

Questions answered in this lecture:

- What is a process? (Chapter 4-5)
- Why is limited direct execution a good approach for virtualizing the CPU? (Chapter 6)
- What execution state must be saved for a process? (Chapter 6)
- What 3 modes could a process in? (Chapter 6)

What is a Process?

Process: An execution stream in the context of a process state

What is an execution stream?

- Stream of executing instructions
- Running piece of code
- “thread of control”

What is process state?

- Everything that the running code can affect or be affected by
- Registers
  - General purpose, floating point, status, program counter, stack pointer
- Address space
  - Heap, stack, and code
- Open files

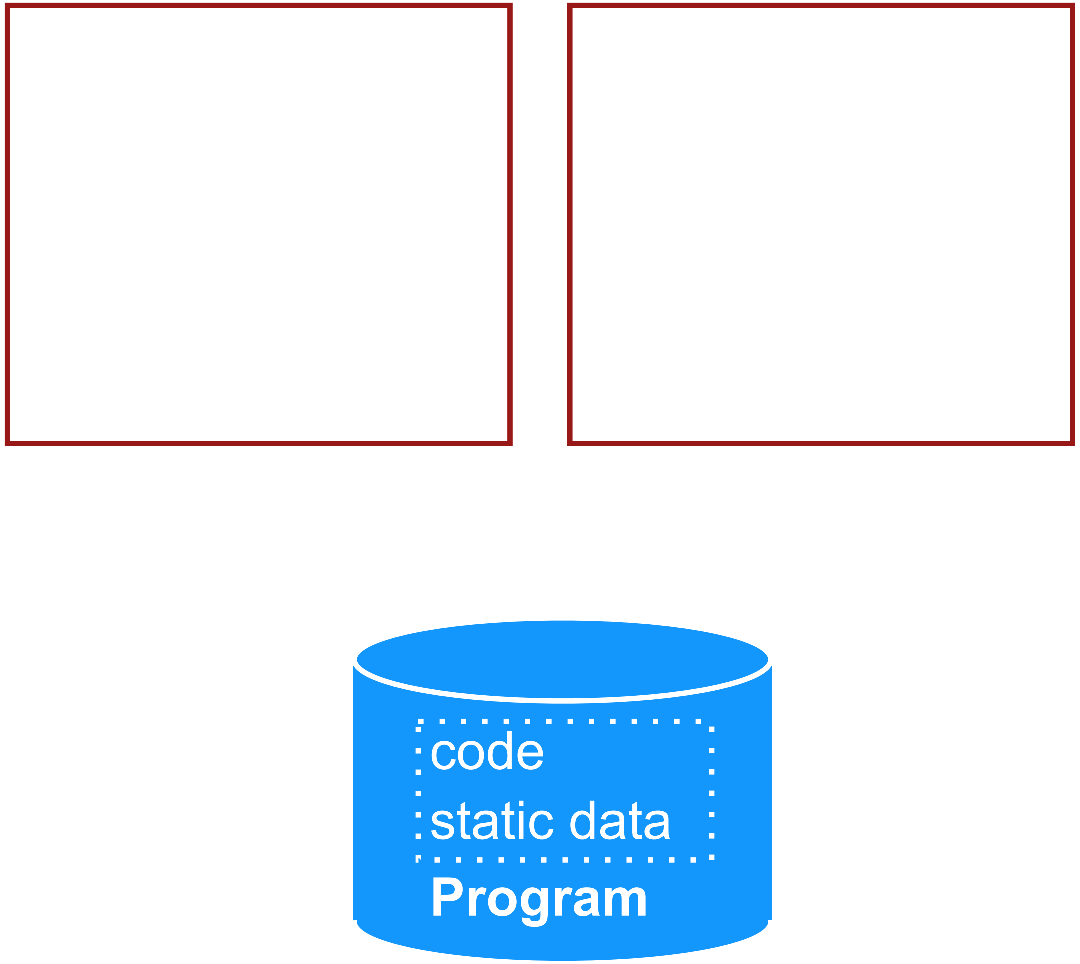
Processes vs. Programs

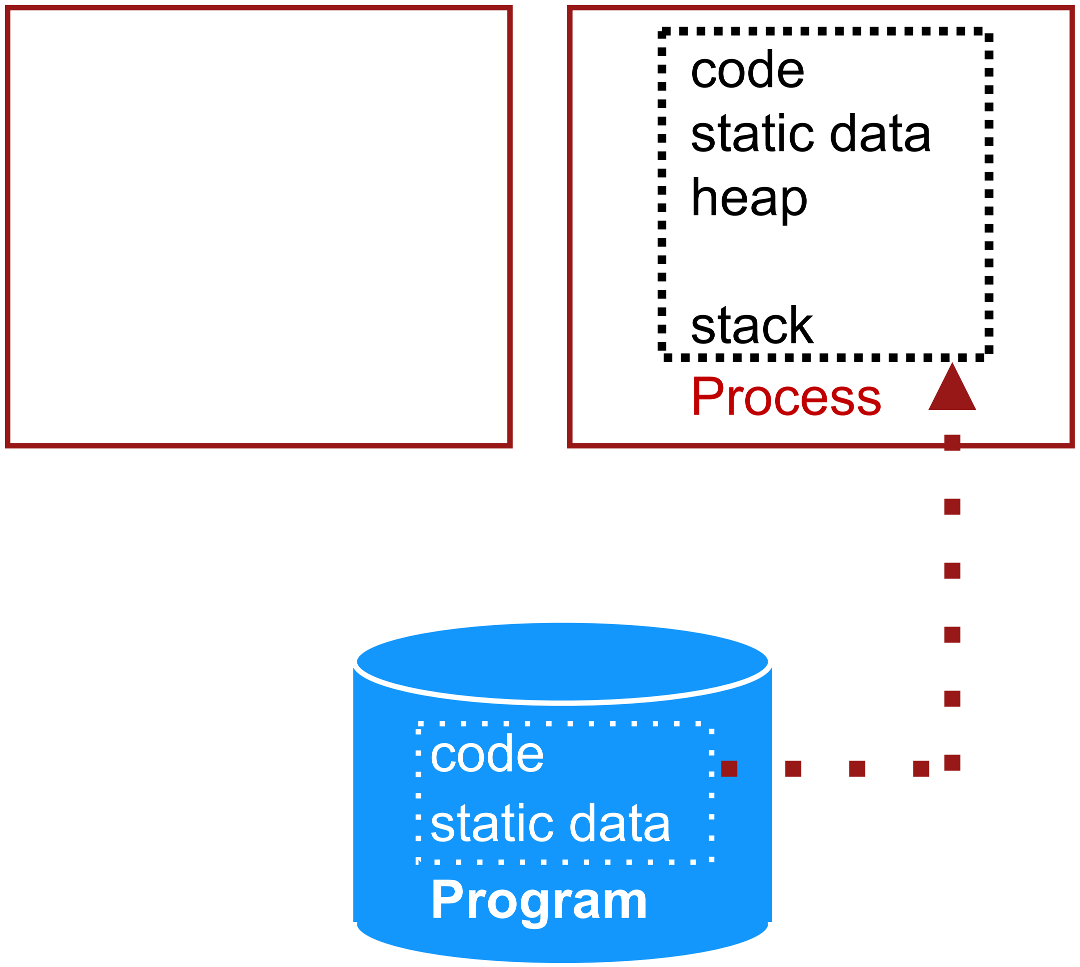
A process is different than a program

- Program: Static code and static data
- Process: Dynamic instance of code and data

Can have multiple process instances of same program

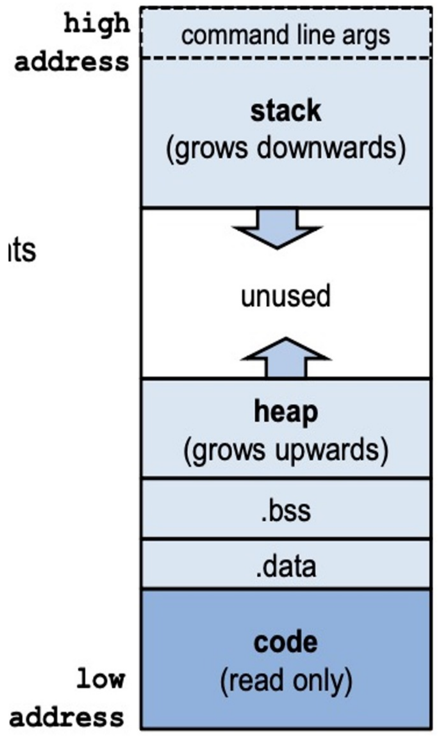
- Example: many users can run “ls” at the same time


code
static data
Program


code
static data
heap
stack
Process
code
static data
Program

Recall: Process Memory Segments

- The OS allocates memory for each process - ie. a running program – for data and code
- This memory consists of different segments
- Stack - for local variables – incl. command line arguments and environment variables
- Heap - for dynamic memory
- Data segment for – global uninitialised variables (.bss) – global initialised variables (.data)
- Code segment typically read-only



Processes vs. Threads

- A process is different than a thread
- Thread: “Lightweight process” (LWP)
  - An execution stream that shares an address space
  - Multiple threads within a single process
- Example:
  - Two **processes** examining same memory address 0xffe84264
    see **different** values (I.e., different contents)
  - Two **threads** examining memory address 0xffe84264
    see **same** value (I.e., same contents)

Goal: Give each process the impression that it alone is actively using the CPU

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

Assume single uniprocessor

- **Time-sharing** (today's multi-processors: more nuanced)

But while sharing, processes

- should not perform restricted operations
- should not run forever or make the entire system slow

One possibility: let the OS inspect each process instruction before running

- The problem? Performance

How to Provide Good CPU Performance?

Direct execution

- Allow user process to run directly on hardware
- OS creates process and transfers control to starting point (i.e., main())

Problems with direct execution?

1. Process could do something restricted

   Could read/write other process data (disk or memory)

2. Process could run forever (slow, buggy, or malicious)

   OS needs to be able to switch between processes

3. Process could do something slow (like I/O)

   OS wants to use resources efficiently and switch CPU to other process

Solution: **Limited direct execution:**

OS *and the hardware* maintain some control

Problem 1: Restricted Ops

How can we ensure user process can't unilaterally perform restricted operations?

Solution: privilege levels/separation provided by hardware (status bit on a register)

- OS runs in kernel mode (not restricted)
  - Instructions for interacting with devices enabled
  - Could have many privilege levels (advanced topic)
- User processes run in user mode (restricted mode)
  - Interacting with devices directly will trap (software interrupt)
  - Pre-set routines that run when privileged/restricted instructions run

How can a process legitimately access a device?

- System calls (function call implemented by OS)
- Change privilege level through system call (trap)

Legitimate use: System Call

syscall(SYS_call, arg1, arg2, …);

System Call Example

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

int main(void) {

        long ID1, ID2;
        /*-----------------------------*/
        /* direct system call          */
        /* SYS getpid (func no. is 20) */
        /*-----------------------------*/
        ID1 = syscall(SYS_getpid);
        printf ("syscall(SYS_getpid)=%ld\n", ID1);

        /*-----------------------------*/
        /* "libc" wrapped system call  */
        /* SYS getpid (Func No. is 20) */
        /*-----------------------------*/
        ID2 = getpid();
        printf ("getpid()=%ld\n", ID2);

        return(0);
}
```

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

List of Linux System Calls

http://www.cheat-sheets.org/saved-copy/Linux_Syscall_quickref.pdf

System Call

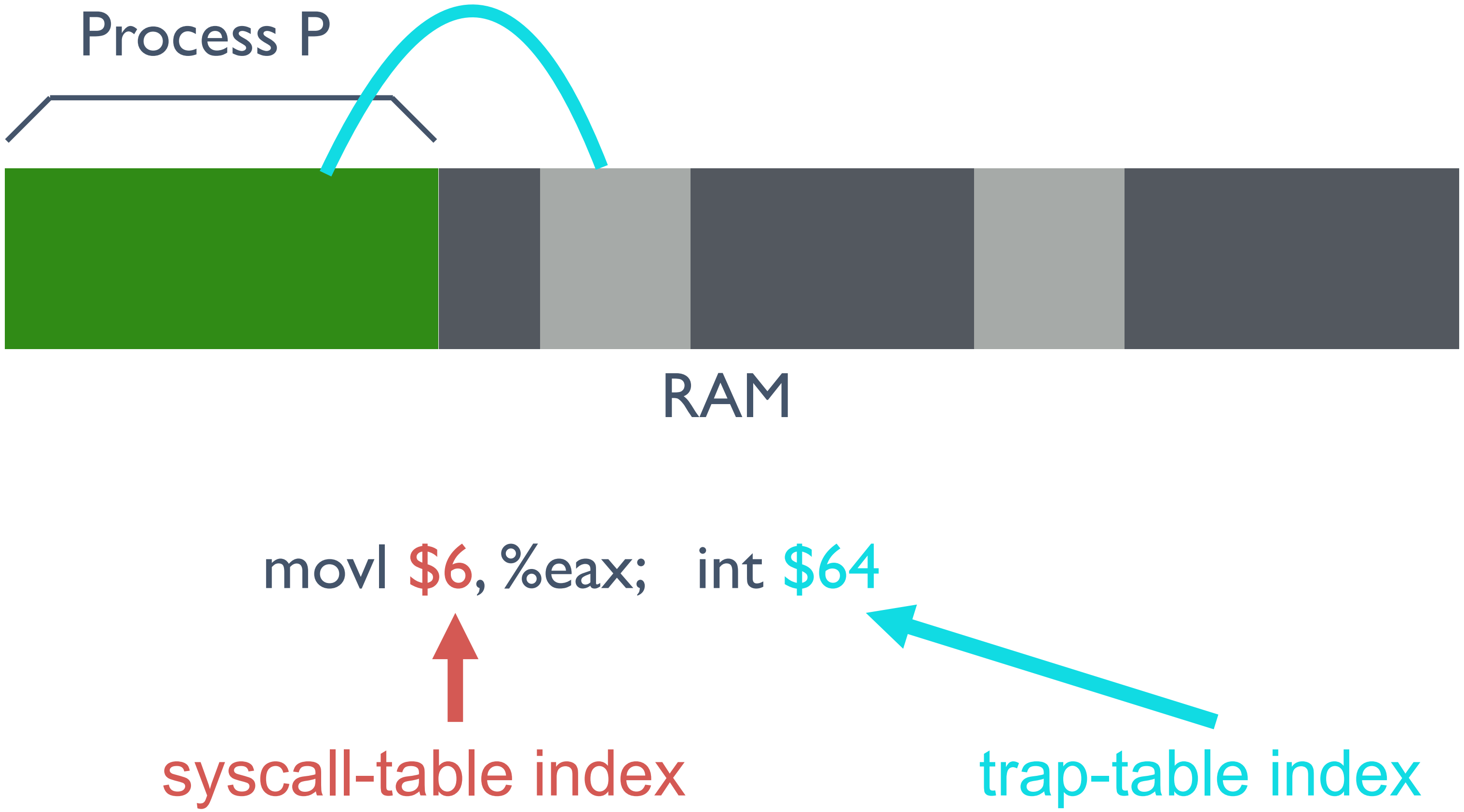
read():

movl $6, %eax;   int $64

Assembly convention: movl %eax, …

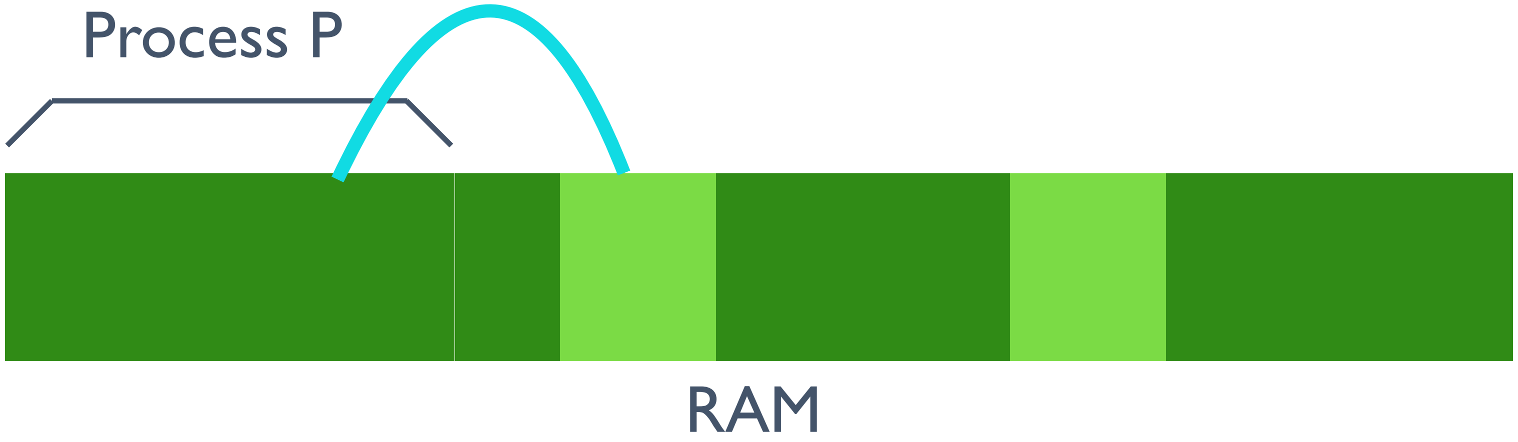
- CPU uses contents of EAX register as source operand

System Call



Process P
RAM
movl $6, %eax;   int $64
syscall-table index
trap-table index

System Call



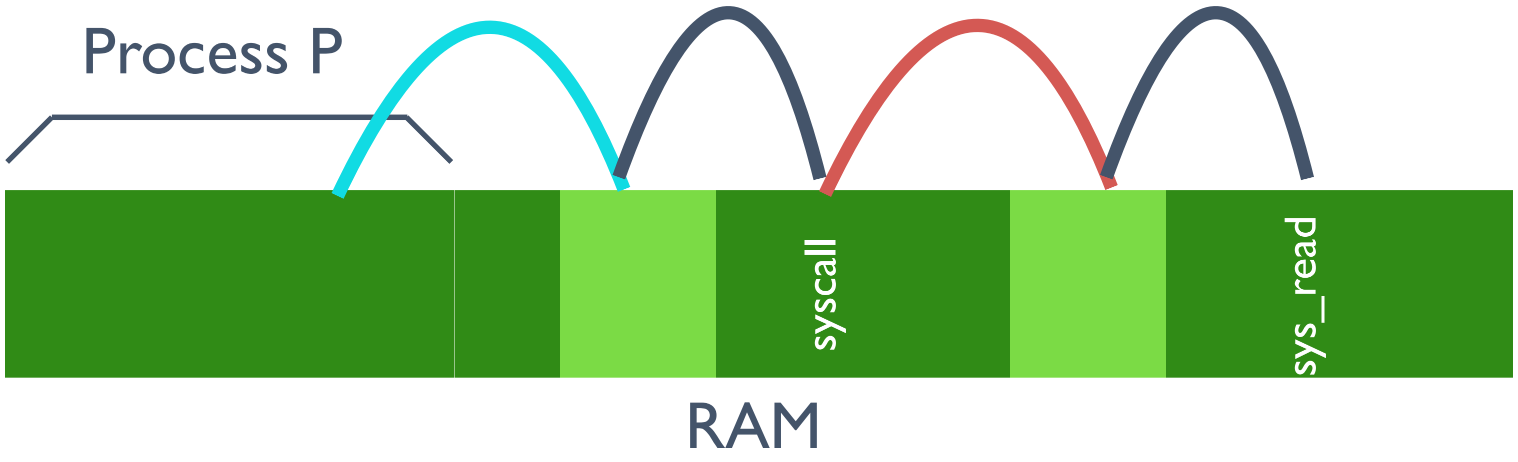
movl $6, %eax;   int $64

syscall-table index

trap-table index

Kernel mode: we can do anything!

System Call



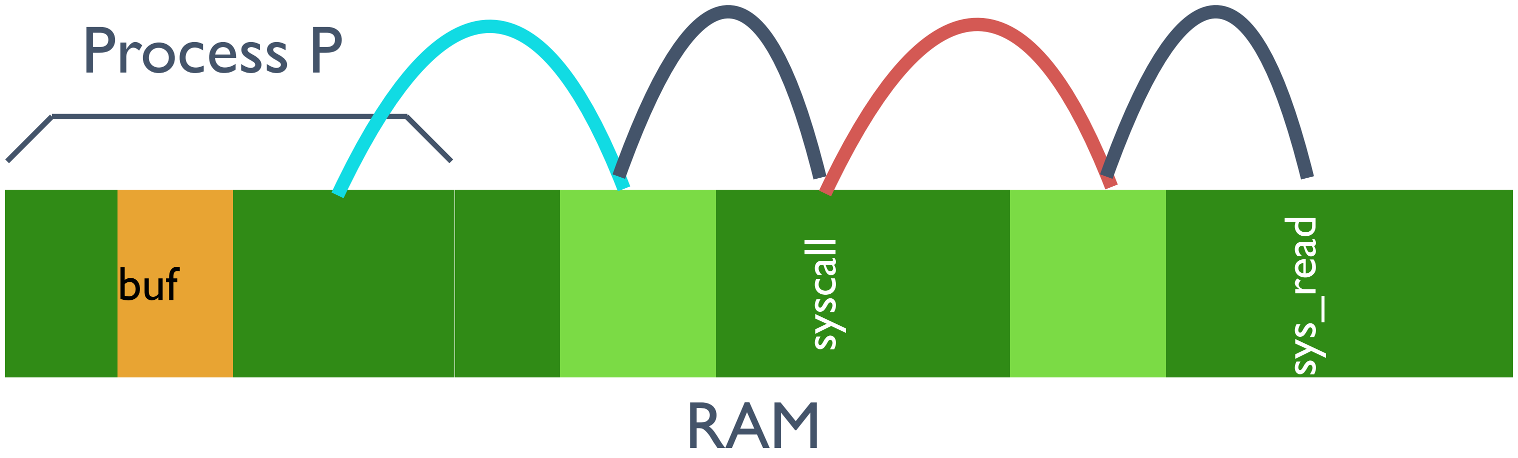
movl $6, %eax;   int $64

syscall-table index

trap-table index

Follow entries to correct system call code

System Call



movl $6, %eax;   int $64

syscall-table index

trap-table index

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

System Call

App

System Call movl $6, %eax; int $64

H/W-level Trap Table

$63	illegal access
$64	system call
$65	Device Interrupt

OS

```
Syscall() {
  sysnum = %eax
  sys_handle= get_fn_table(sysnum)
  sys_handle ();
}
```

Syscall table

Num	Function
6	sys_read
7	sys_write

User processes are not allowed to directly perform:

- Arbitrary memory access
- Disk I/O
- Special x86 instructions like `lidt`

What if a process tries to do something privileged/restricted on its own?

Typical response: trap (hardware); OS kills process

Problem 2: How to take the CPU away?

OS requirements for **multiprogramming** (or multitasking)

- Mechanism: To switch between processes
- Policy: To decide which process to run at what time

Separation of policy and mechanism

- Recurring theme in OS design
- Policy: Decision-maker to optimize some workload performance metric
  - Which process to run when?
  - Process **Scheduler**: next lecture
- Mechanism: Low-level code that implements the decision
  - "How”?
  - Process **Dispatcher**: Today’s lecture

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

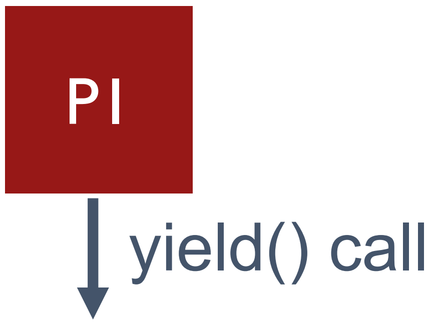
Question 1: How does dispatcher regain control after the time slice?

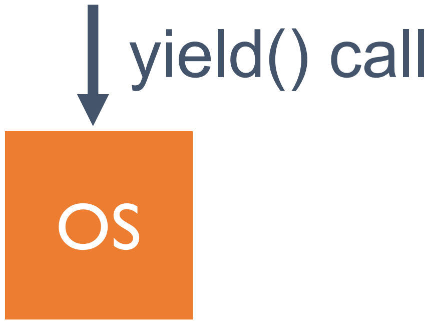
Question 2: What execution context must be saved and restored?

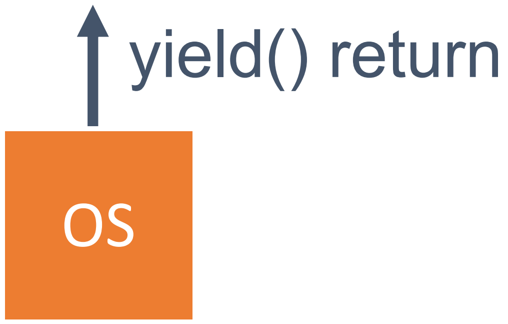
Q1: How does Dispatcher regain control?

Option 1: Cooperative Multi-tasking

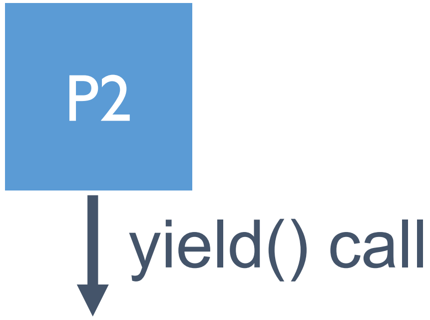
- Trust process to relinquish CPU to OS through traps
  - Examples: System call, page fault (access page not in main memory), or error (illegal instruction or divide by zero)
  - Provide special `yield()` system call


PI
yield() call


yield() call
OS


yield() return
OS


P2
yield() return


P2
yield() call

Q1: How Does Dispatcher regain control?

- Problem with cooperative approach?
- 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

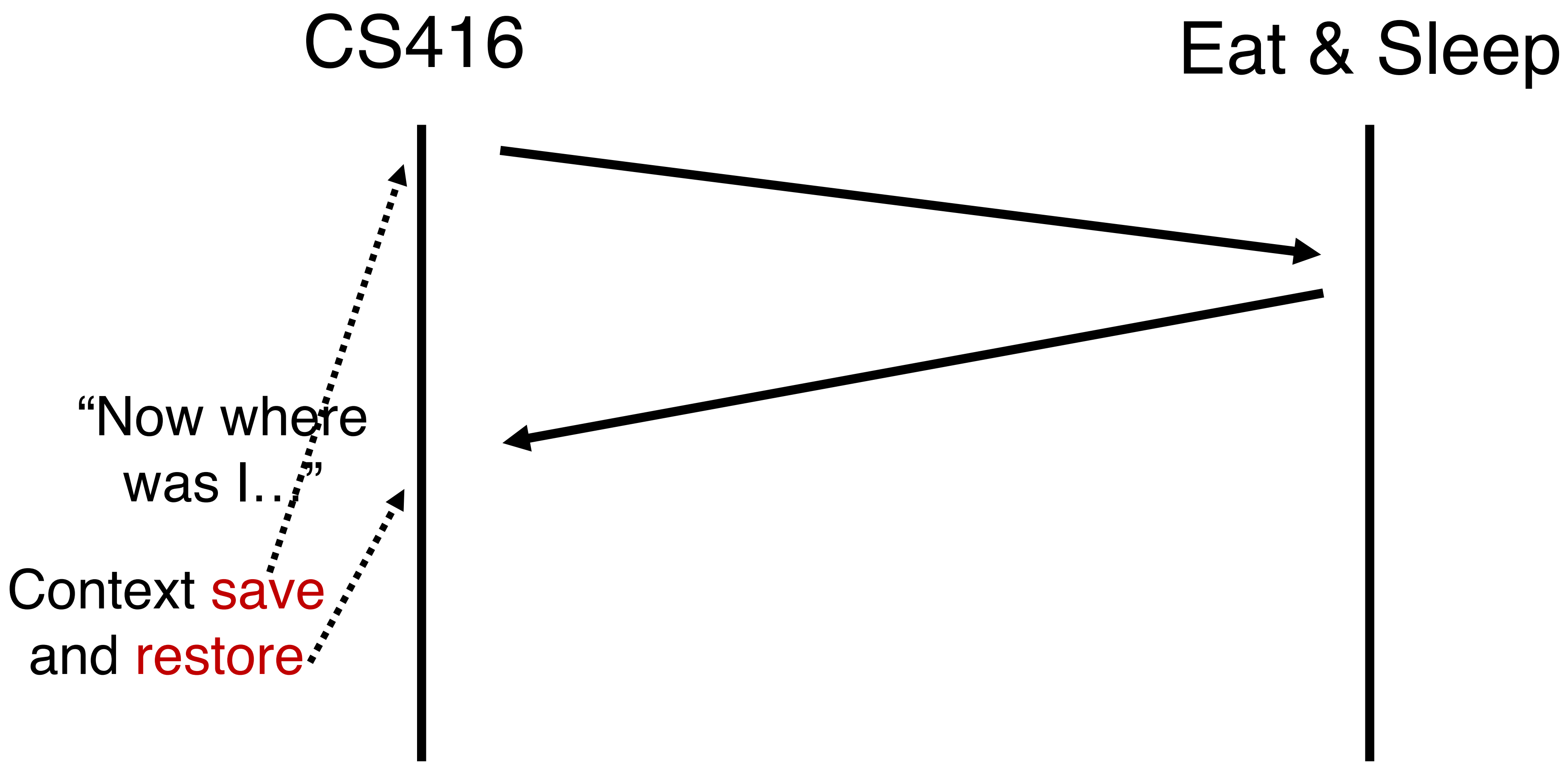
Q1: How does Dispatcher regain control?

Option 2: Regain control without cooperation

- Guarantee OS can obtain control periodically. How?
- 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 (privileged operation)
- Dispatcher counts interrupts between context switches
  - Example: Waiting 20 timer ticks gives 200 ms time slice
  - Common time slices range from 10 ms to 200 ms
  - Research systems today: ~5 microseconds

Use hardware mechanisms (timer, traps) to regain control

Q2: What Context must be Saved?



Q2: What Context must be Saved?

Dispatcher must save the context of the process when it's not running

- Save it in process control block (PCB) (or process descriptor)
- PCB is a structure maintained for each process in the OS

What information is stored in PCB?

- PID
- Process state (I.e., running, ready, or blocked)
- **Execution state (all registers, PC, stack pointer) -- *Context***
- Scheduling priority
- Accounting information (parent and child processes)
- Credentials (which resources can be accessed, owner)
- Pointers to other allocated resources (e.g., open files)

Requires special hardware support. Why?

- Hardware saves process PC and PSR on interrupts

Q3: What's inside a PCB?

```
// the information xv6 tracks about each process
// including its register context and state
struct proc {
    char *mem;                    // Start of process memory
    uint sz;                      // Size of process memory
    char *kstack;                 // Bottom of kernel stack
                                  // for this process
    enum proc_state state;        // Process state
    int pid;                      // Process ID
    struct proc *parent;          // Parent process
    int killed;                   // If non-zero, have been killed
    struct file *ofile[NOFILE]; // Open files
    struct inode *cwd;            // Current directory
    struct context context;       // Switch here to run process
    struct trapframe *tf;         // Trap frame for the
                                  // current interrupt
};
```

Conceptually: Separate kernel thread of execution per process

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

Operating System | Hardware | Program

Process A

…

timer interrupt
save regs(A) to k-stack(A)
move to kernel mode
jump to trap handler

Handle the trap
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)

Must have been saved the last time OS switched B out

Operating System

Hardware

Program

Process A

…

timer interrupt
save regs(A) to k-stack(A)
move to kernel mode
jump to trap handler

Handle the trap
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	
Handle the trap 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 …

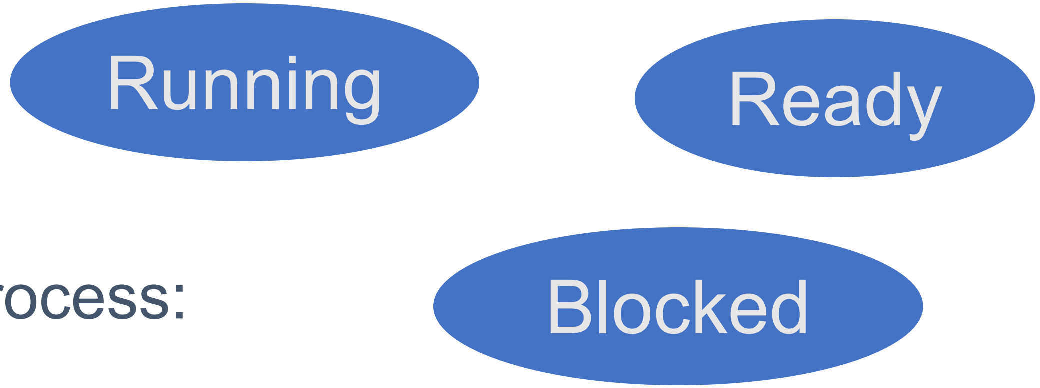
Q4: What Context must be Saved?

```
// the registers will save and restore
// to stop and subsequently restart a process
struct context {
    int eip;  // Index pointer register
    int esp;  // Stack pointer register
    int ebx; // Called the base register
    int ecx; // Called the counter register
    int edx; // Called the data register
    int esi;  // Source index register
    int edi;  // Destination index register
    int ebp; // Stack base pointer register
};

// the different states a process can be in
enum proc_state { UNUSED, EMBRYO, SLEEPING,
                  RUNNABLE, RUNNING, ZOMBIE };
```

Problem 3: Slow Ops such as I/O?

When running process performs op that does not use CPU, OS switches to process that needs CPU (policy issues)



Transitions?

OS must track state of each process:

- Running:
    - On the CPU (only one on a uniprocessor)
- Ready:
    - Waiting for the CPU
- Blocked
    - Asleep: Waiting for I/O or synchronization to complete

Problem 3: Slow Ops such as I/O?

OS must track every process in system

- Each process identified by unique Process ID (PID)

OS maintains queues of all processes

- Ready queue: Contains all ready processes
- Event queue: One logical queue per event
  - e.g., disk I/O and locks
  - Contains all processes waiting for that event to complete

Next Lecture: Policy for determining which **ready** process to run

Virtualization: Context switching gives each process impression it has its own CPU

Direct execution makes processes fast

Limited execution at key points ensures OS retains control

Hardware is crucial for limited direct execution

- Privilege separation: user vs kernel mode
- Timer interrupts
- Automatic register saves and restores

Process Creation

Two ways to create a process

- Build a new empty process from scratch
- Copy an existing process and change it appropriately

Option 1: New process from scratch

- Steps
  - Load specified code and data into memory; Create empty call stack
  - Create and initialize PCB (make it look like context-switch)
  - Put process on ready list
- Advantages: No wasted work (compared to option 2)
- Disadvantages: Difficult to express all possible options for setup, complex
  - Process permissions, where to write I/O, environment variables
  - Example: WindowsNT has call with 10 arguments

Process Creation

Option 2: Clone an existing process and change it

- Example: Unix fork() and exec()
  - Fork(): Clones the calling process
  - Exec(char *file): Overlays file image on calling process
- Fork()
  - Stop current process and save its state
  - Make copy of code, data, stack, and PCB
  - Add new PCB to ready list
  - Any changes needed to child process? Yes!
- Exec(char *file)
  - Replace current data and code segments with those in specified file
- Advantages: Flexible, clean, simple
- Disadvantages: Wasteful to perform copy and then overwrite of memory

Unix Process Creation

Fork/exec crucial to how the user's shell is implemented!

```
While (1) {
  Char *cmd = getcmd();
  Int retval = fork();
  If (retval == 0) {
       // This is the child process
       // Setup the child's process environment here
       // E.g., where is standard I/O, how to handle signals?
       exec(cmd);
       // exec does not return if it succeeds
       printf("ERROR: Could not execute %s\n", cmd);
       exit(1);
  } else {
       // This is the parent process; Wait for child to finish
       int pid = retval;
       wait(pid);
  }
}
```