Processes

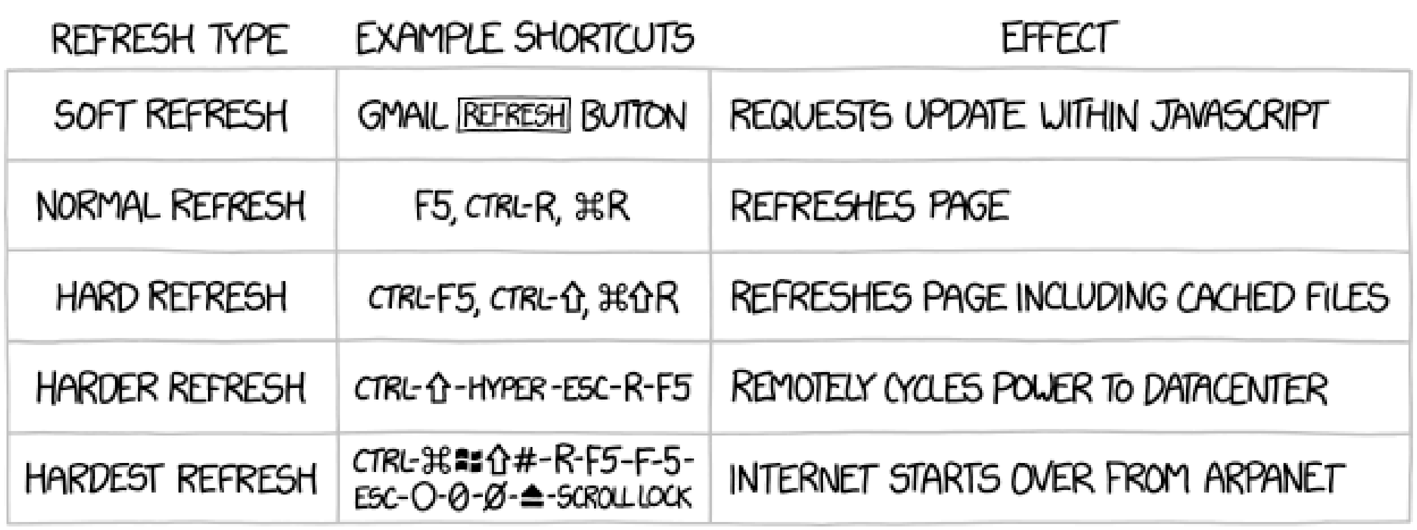
CSE 351 Spring 2022

Instructor:

Ruth Anderson

Teaching Assistants:

Melissa Birchfield, Jacob Christy, Alena Dickmann, Kyrie Dowling, Ellis Haker, Maggie Jiang, Diya Joy, Anirudh Kumar, Jim Limprasert, Armin Magness, Hamsa Shankar, Dara Stotland, Jeffery Tian, Assaf Vayner, Tom Wu, Angela Xu, Effie Zheng



REFRESH TYPE	EXAMPLE SHORTCUTS	EFFECT
SOFT REFRESH	GMAIL [REFRESH] BUTTON	REQUESTS UPDATE WITHIN JAVASCRIPT
NORMAL REFRESH	F5, CTRL-R, ⌘R	REFRESHES PAGE
HARD REFRESH	CTRL-F5, CTRL-⇧, ⌘⇧R	REFRESHES PAGE INCLUDING CACHED FILES
HARDER REFRESH	CTRL-⇧-HYPER-ESC-R-F5	REMOTELY CYCLES POWER TO DATACENTER
HARDEST REFRESH	CTRL-⌘⊞⇧#-R-F5-F-5-ESC-O-0-Ø-⏏-SCROLL LOCK	INTERNET STARTS OVER FROM ARPANET

http://xkcd.com/1854/

Relevant Course Information

- Lab 3 due Wednesday (5/11)
- hw17 due Friday (5/13)
  - Don't wait too long, this is a BIG hw
- hw19 due Monday (5/16)
  - Lab 4 preparation
- Lab 4 due Friday (5/20) - coming soon!
  - Cache parameter puzzles and code optimizations

Roadmap

C:

```c
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```java
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
    c.getMPG();
```

Assembly language:

```
get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

Machine code:

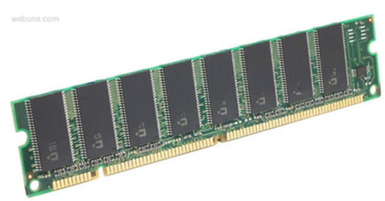
```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:

Windows 10

OS X Yosemite

Computer system:



- Memory & data
- Integers & floats
- x86 assembly
- Procedures & stacks
- Executables
- Arrays & structs
- Memory & caches
- Processes
- Virtual memory
- Memory allocation
- Java vs. C

Reading Review

- Terminology:
  - Exceptional control flow, event handlers
  - Operating system kernel
  - Exceptions: interrupts, traps, faults, aborts
  - Processes: concurrency, context switching, fork-exec model, process ID

Leading Up to Processes

- System Control Flow
  - **Control flow**
  - **Exceptional control flow**
  - Asynchronous exceptions (interrupts)
  - Synchronous exceptions (traps & faults)

Control Flow

- **So far:** we've seen how the flow of control changes as a *single program* executes
- **Reality:** multiple programs running *concurrently*
  - How does control flow across the many components of the system?
  - In particular: More programs running than CPUs
- *Exceptional* control flow is basic mechanism used for:
  - Transferring control between *processes* and OS
  - Handling *I/O* and *virtual memory* within the OS
  - Implementing multi-process apps like shells and web servers
  - Implementing concurrency

Control Flow

- Processors do only one thing:
  - From startup to shutdown, a CPU simply reads and executes (interprets) a sequence of instructions, one at a time
  - This sequence is the CPU's *control flow* (or *flow of control*)

Physical control flow

time

<startup>
instr_1
instr_2
instr_3
…
instr_n
<shutdown>

Altering the Control Flow

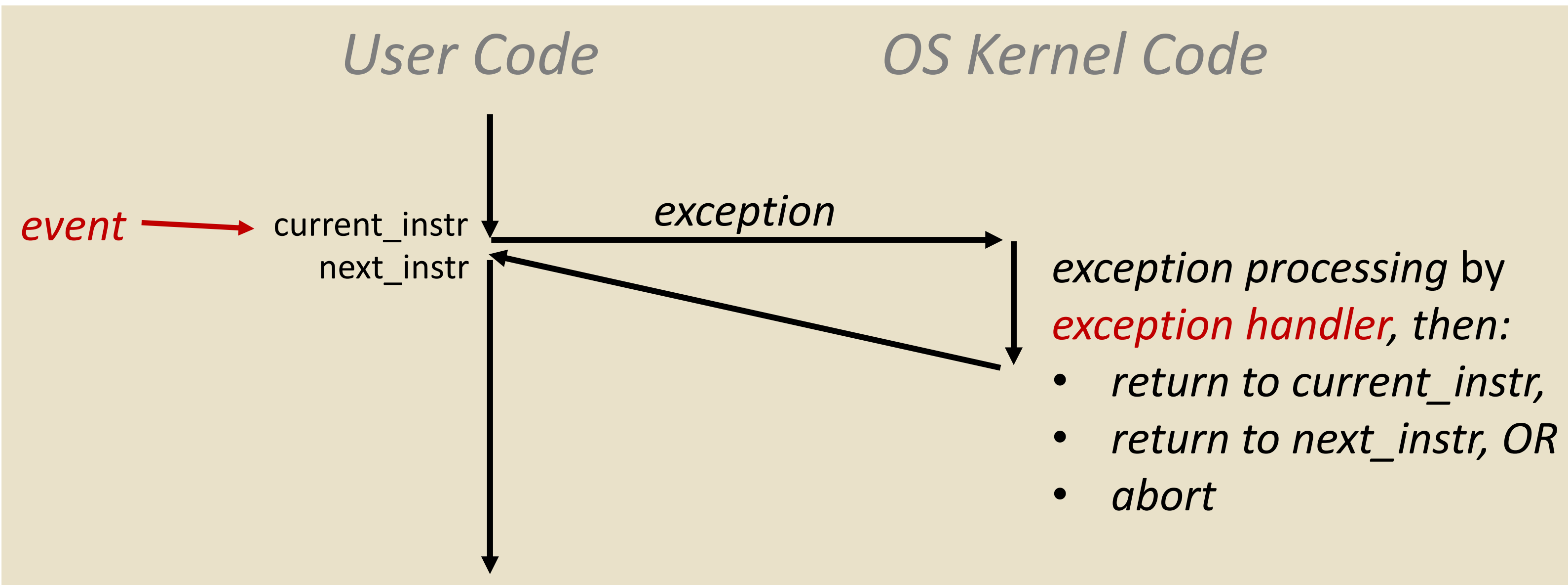
- Up to now, two ways to change control flow:
  - Jumps (conditional and unconditional)
  - Call and return
  - Both react to changes in *program state*
- Processor also needs to react to changes in *system state*
  - Unix/Linux user hits "Ctrl-C" at the keyboard
  - User clicks on a different application's window on the screen
  - Data arrives from a disk or a network adapter
  - Instruction divides by zero
  - System timer expires
- Can jumps and procedure calls achieve this?
  - No – the system needs mechanisms for *"exceptional"* control flow!

Exceptional Control Flow

- Exists at all levels of a computer system
- Low level mechanisms
  - **Exceptions**
    - Change in processor's control flow in response to a system event (*i.e.* change in system state, user-generated interrupt)
    - Implemented using a combination of hardware and OS software
- Higher level mechanisms
  - **Process context switch**
    - Implemented by OS software and hardware timer
  - **Signals**
    - Implemented by OS software
    - We won't cover these – see CSE451 and CSE/EE474

Exceptions (Review)

- An *exception* is transfer of control to the operating system (OS) kernel in response to some *event* (*i.e.* change in processor state)
  - Kernel is the memory-resident part of the OS
  - Examples: division by 0, page fault, I/O request completes, Ctrl-C

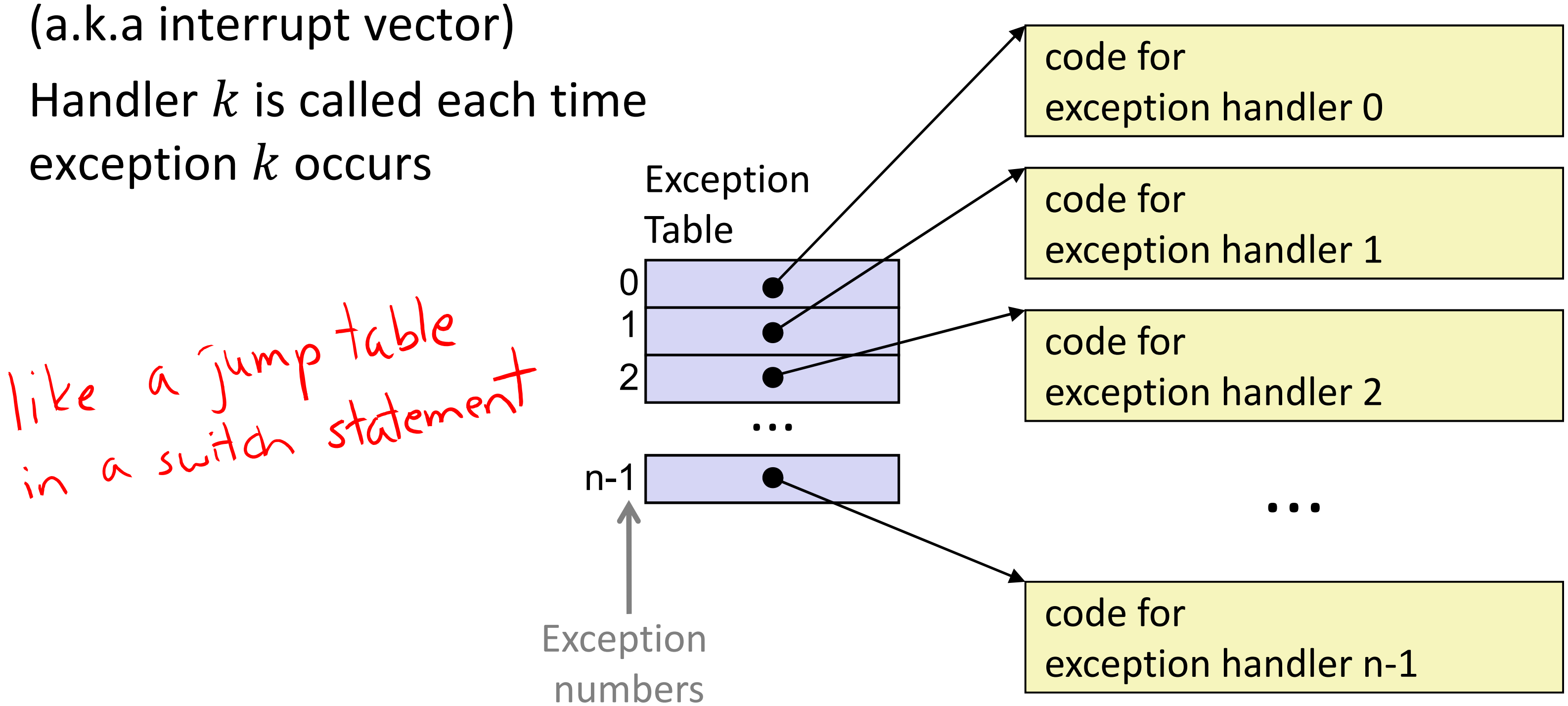


- *How does the system know where to jump to in the OS?*

Exception Table

This is extra (non-testable) material

- A jump table for exceptions (also called *Interrupt Vector Table*)
  - Each type of event has a unique exception number k
  - k = index into exception table (a.k.a interrupt vector)
  - Handler k is called each time exception k occurs



Exception Table (Excerpt)

This is extra (non-testable) material

Exception Number	*Description*	*Exception Class*
0	Divide error	Fault
13	General protection fault	Fault
14	Page fault	Fault
18	Machine check	Abort
32-255	OS-defined	Interrupt or trap

Leading Up to Processes

- System Control Flow
  - Control flow
  - Exceptional control flow
  - **Asynchronous exceptions (interrupts)**
  - **Synchronous exceptions (traps & faults)**

Asynchronous Exceptions (Interrupts)

- Caused by events external to the processor
  - Indicated by setting the processor's interrupt pin(s) (wire into CPU)
  - After interrupt handler runs, the handler returns to "next" instruction

- Examples:
  - I/O interrupts
    - Hitting Ctrl-C on the keyboard
    - Clicking a mouse button or tapping a touchscreen
    - Arrival of a packet from a network
    - Arrival of data from a disk
  - Timer interrupt
    - Every few milliseconds, an external timer chip triggers an interrupt
    - Used by the OS kernel to take back control from user programs

Synchronous Exceptions (Review)

- Caused by events that occur as a result of executing an instruction:
  - ***Traps***
    - **Intentional**: transfer control to OS to perform some function
    - Examples: *system calls*, breakpoint traps, special instructions
    - Returns control to "next" instruction ("current" instr did what it was supposed to)
  - ***Faults***
    - **Unintentional** but possibly recoverable
    - Examples: *page faults*, segment protection faults, integer divide-by-zero exceptions
    - Either re-executes faulting ("current") instruction or aborts
      - ↑ if recoverable ... ↑ if not recoverable
  - ***Aborts***
    - **Unintentional** and unrecoverable
    - Examples: parity error, machine check (hardware failure detected)
    - Aborts current program

System Calls

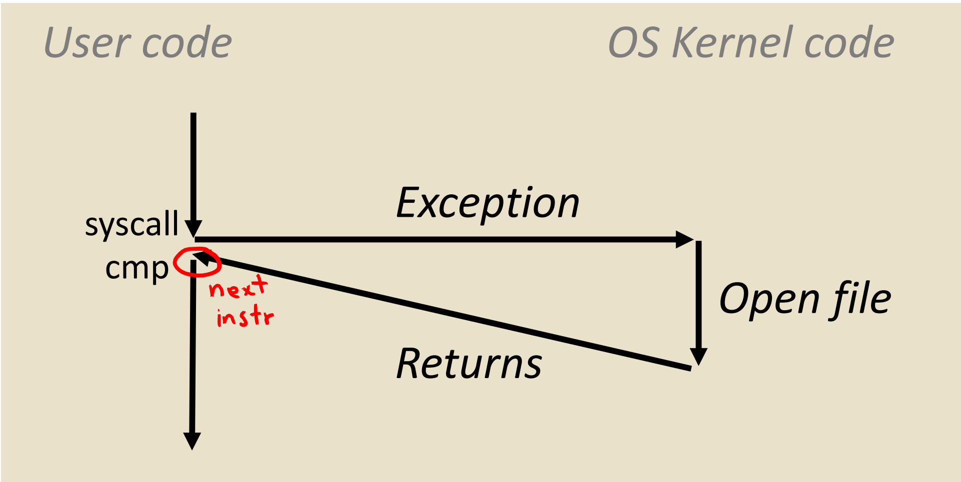
- Each system call has a unique ID number
- Examples for Linux on x86-64:

Number	***Name***	***Description***
0	`read`	Read file
1	`write`	Write file
2	`open`	Open file
3	`close`	Close file
4	`stat`	Get info about file
57	`fork`	Create process
59	`execve`	Execute a program
60	`_exit`	Terminate process
62	`kill`	Send signal to process

Traps Example: Opening File

- User calls `open(filename, options)`
- Calls `__open` function, which invokes system call instruction `syscall`

```
0000000000e5d70 <__open>:
...
e5d79:   b8 02 00 00 00      mov   $0x2,%eax  # open is syscall 2
e5d7e:   0f 05               syscall          # return value in %rax
e5d80:   48 3d 01 f0 ff ff   cmp   $0xfffffffffffff001,%rax
...
e5dfa:   c3                  retq
```



- `%rax` contains syscall number
- Other arguments in `%rdi`, `%rsi`, `%rdx`, `%r10`, `%r8`, `%r9`
- Return value in `%rax`
- Negative value is an error corresponding to negative `errno`

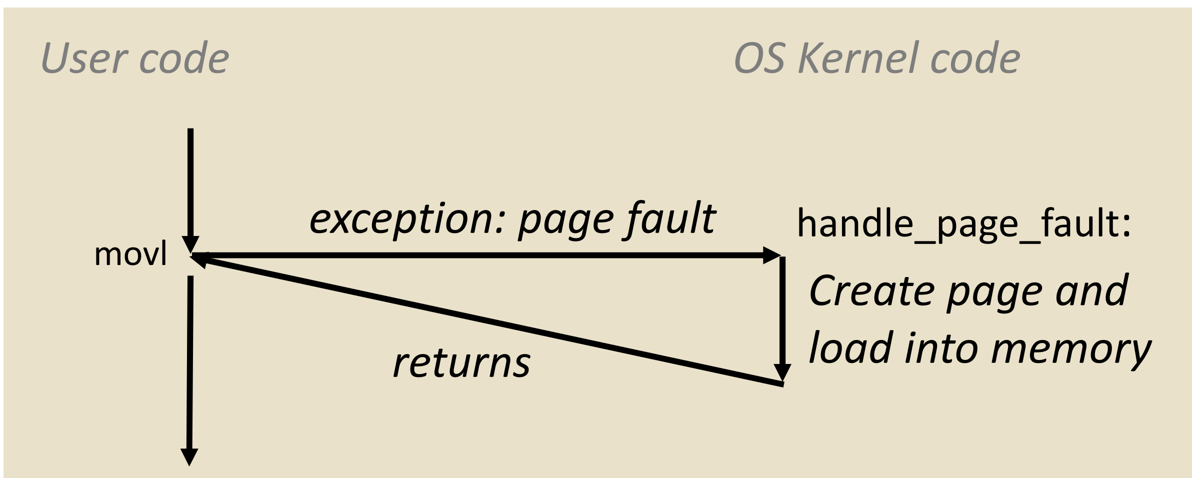
Fault Example: Page Fault

- User writes to memory location
- That portion (page) of user's memory is currently on disk

```
int a[1000];
int main () {
  a[500] = 13;
}
```

```
80483b7:        c7 05 10 9d 04 08 0d    movl    $0xd,0x8049d10
```

normal mov, but address not currently in memory

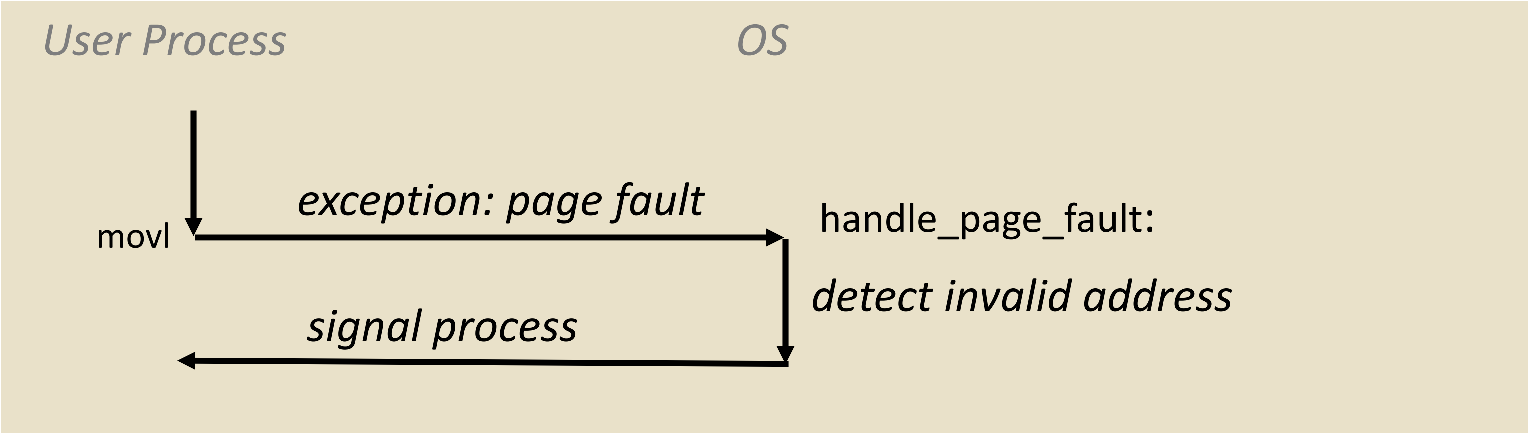


- Page fault handler must load page into physical memory
- Returns to faulting instruction: `mov` is executed again!
  - Successful on second try

Fault Example: Invalid Memory Reference

```
int a[1000];
int main() {
  a[5000] = 13;
}
```

```
80483b7:    c7 05 60 e3 04 08 0d    movl    $0xd,0x804e360
```



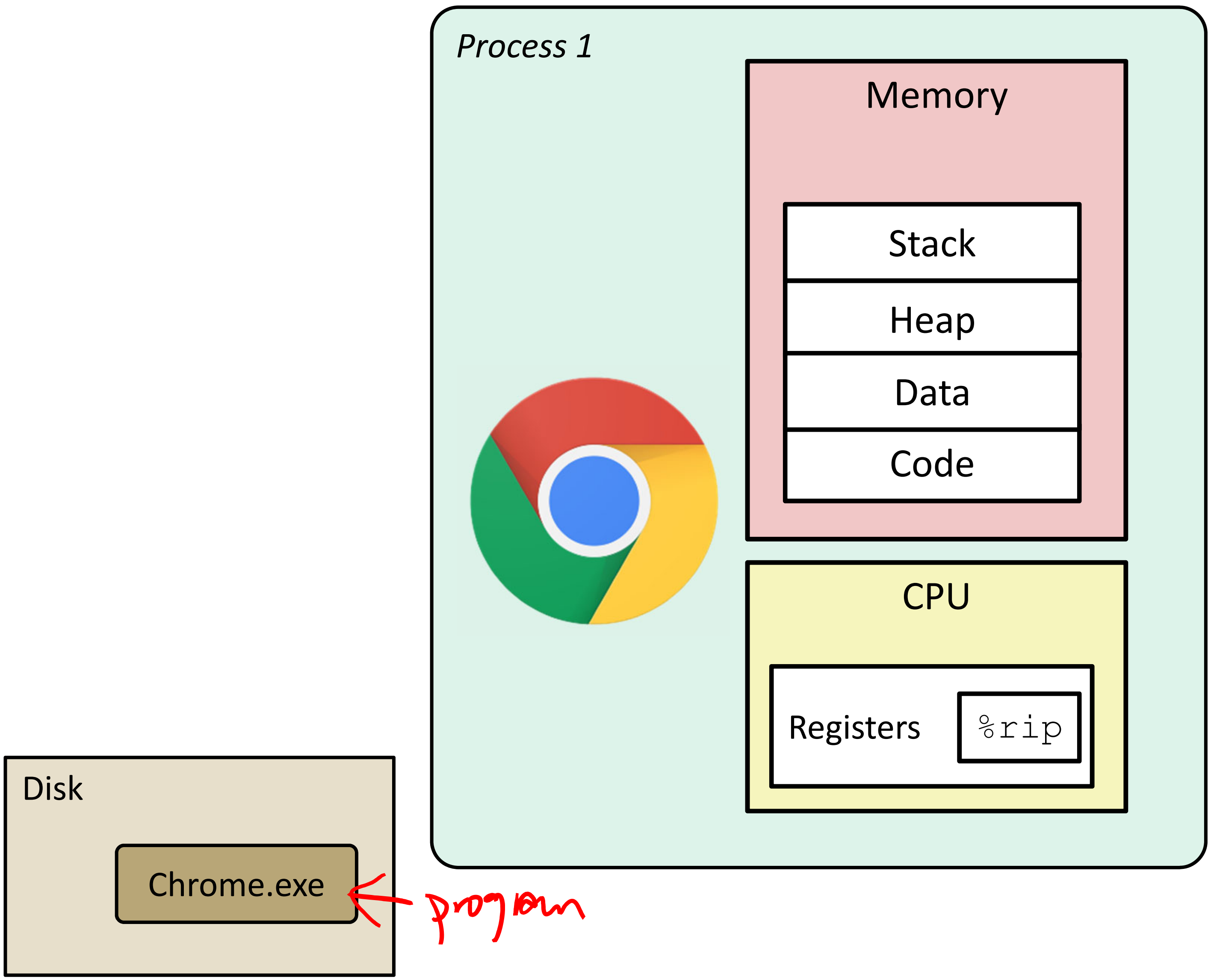
- Page fault handler detects invalid address
- Sends `SIGSEGV` signal to user process
- User process exits with "segmentation fault"

Processes

- **Processes and context switching**
- Creating new processes
  - `fork()`, `exec*()`, and `wait()`
- Zombies

What is a process ? (Review)

It's an *illusion*!



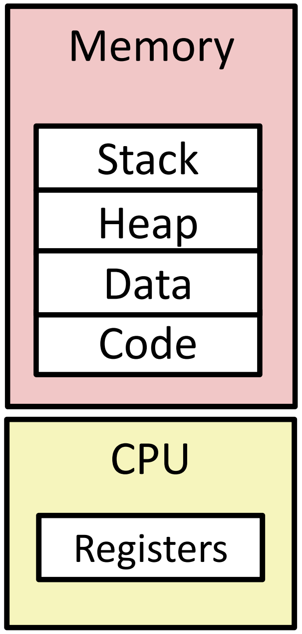
What is a process? (Review)

- Another *abstraction* in our computer system
  - Provided by the OS
  - OS uses a data structure to represent each process
  - Maintains the ***interface*** between the program and the underlying hardware (CPU + memory)
- What do *processes* have to do with *exceptional control flow*?
  - Exceptional control flow is the *mechanism* the OS uses to enable **multiple processes** to run on the same system
- What is the difference between:
  - A processor? A program? A process?

Processes (Review)

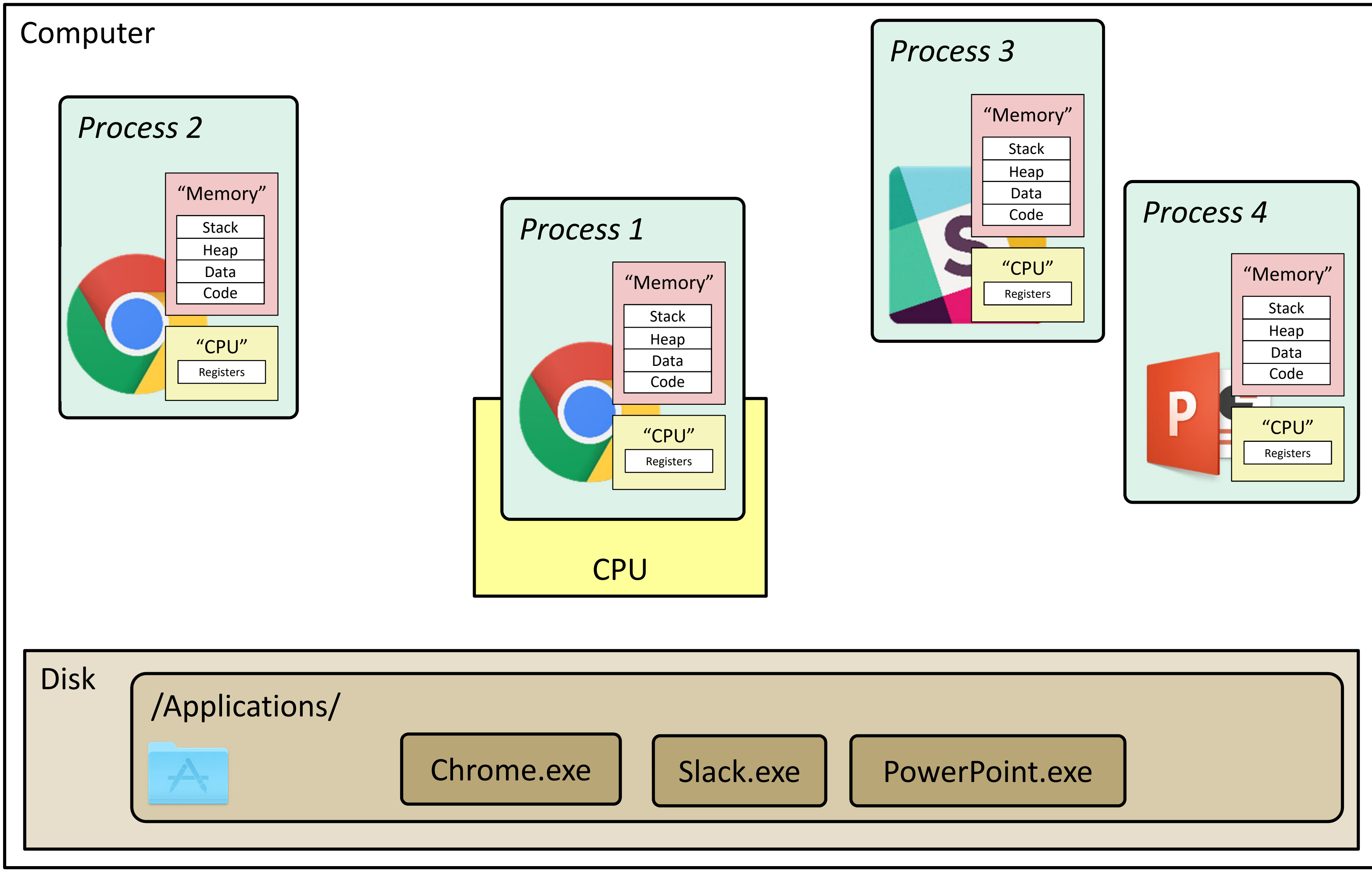
- A ***process*** is an instance of a running program
  - One of the most profound ideas in computer science

- Process provides each program with two key abstractions:
  - *Logical control flow*
    - Each program seems to have exclusive use of the CPU
    - Provided by kernel mechanism called ***context switching***
  - *Private address space*
    - Each program seems to have exclusive use of main memory
    - Provided by kernel mechanism called ***virtual memory***



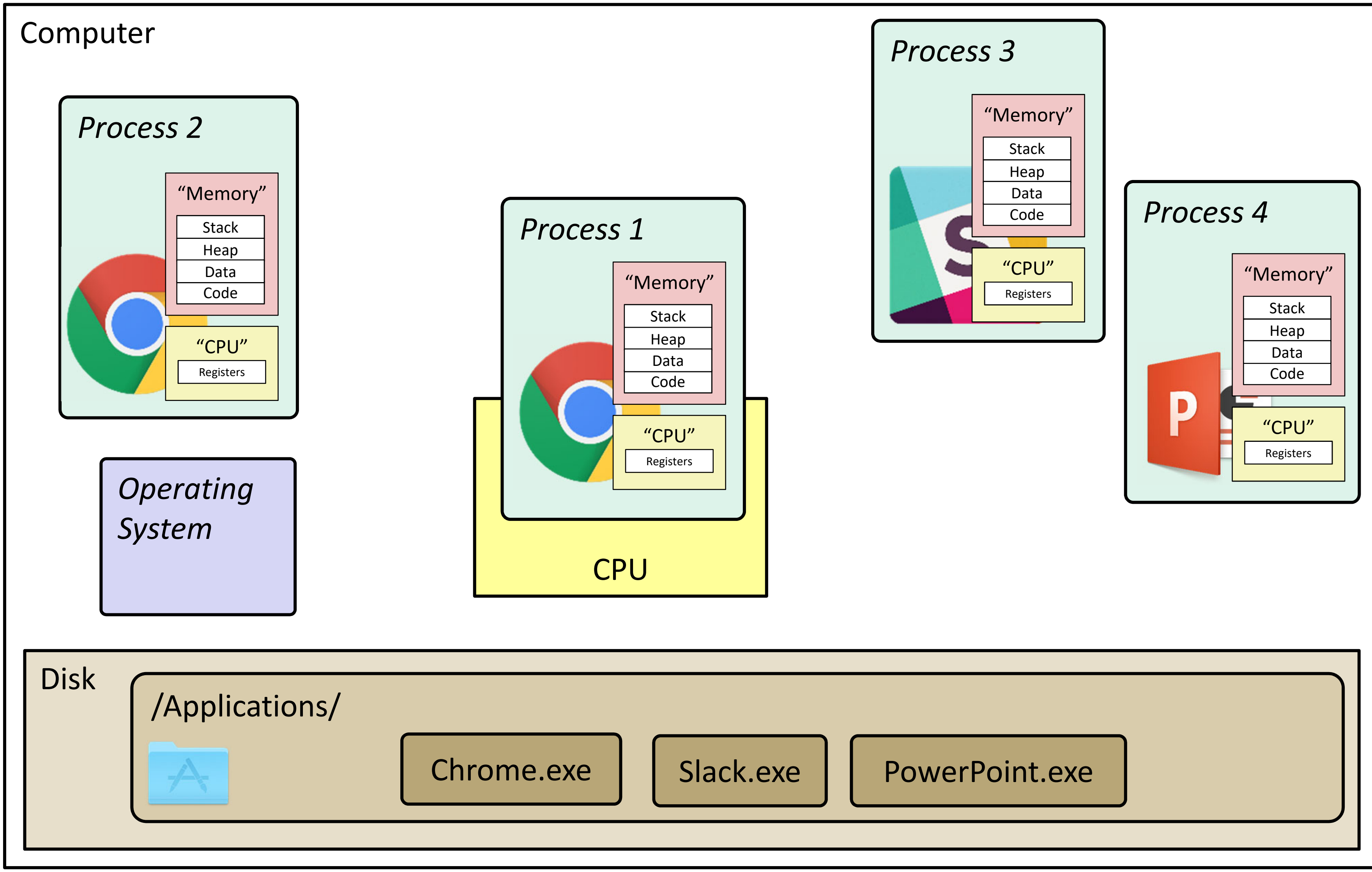
What is a process?

It's an *illusion*!

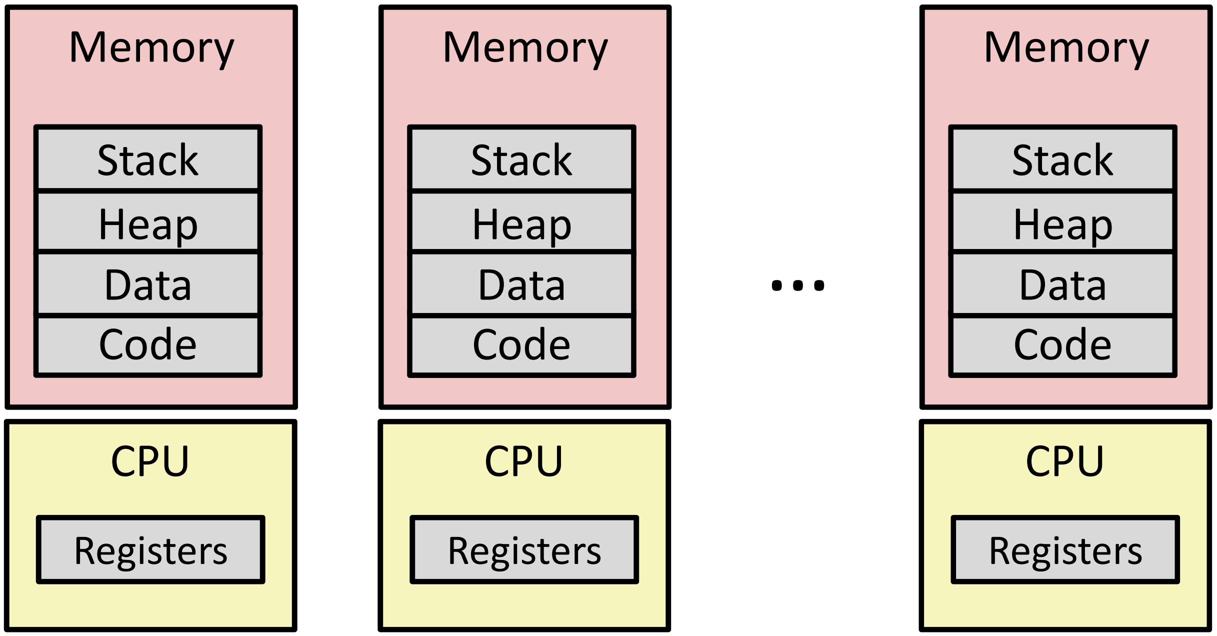


What is a process?

It's an *illusion*!



Multiprocessing: The Illusion

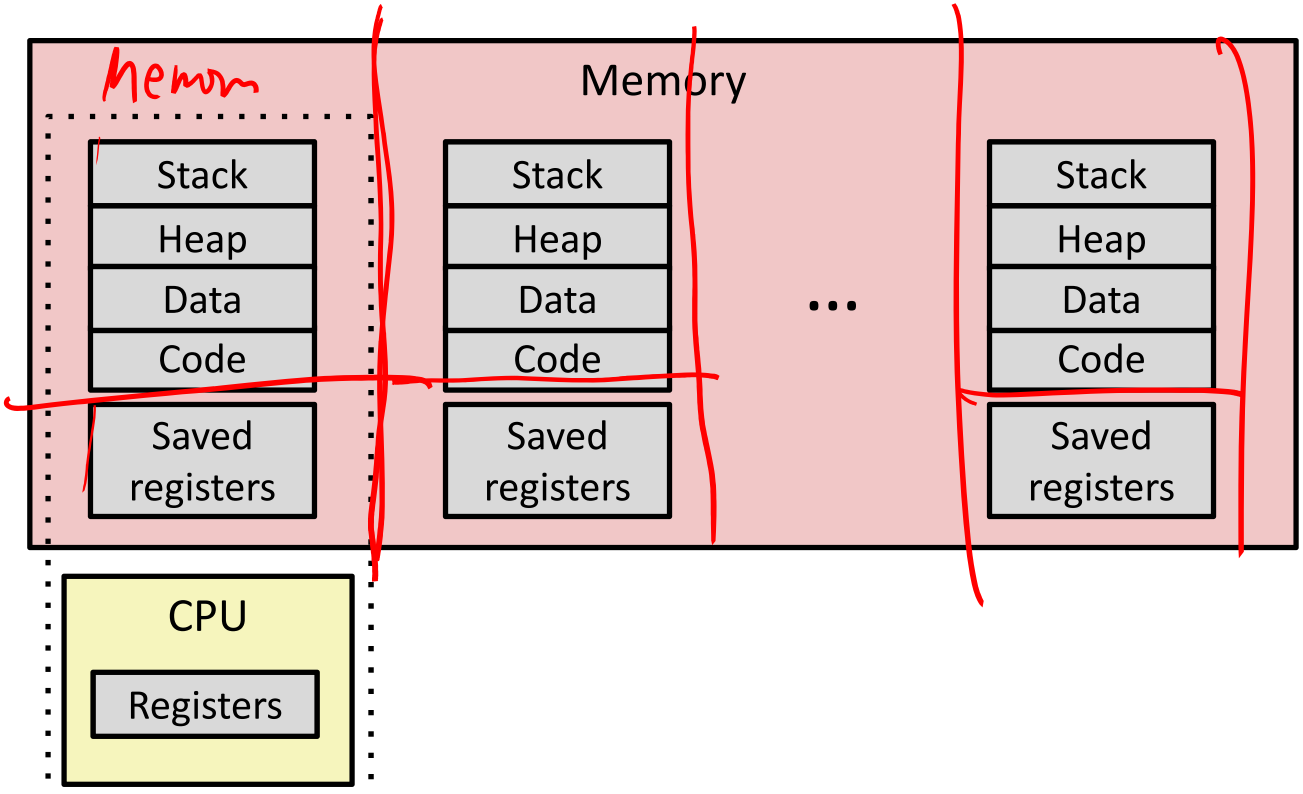


- Computer runs many processes simultaneously
  - Applications for one or more users
    - Web browsers, email clients, editors, …
  - Background tasks
    - Monitoring network & I/O devices

user-level

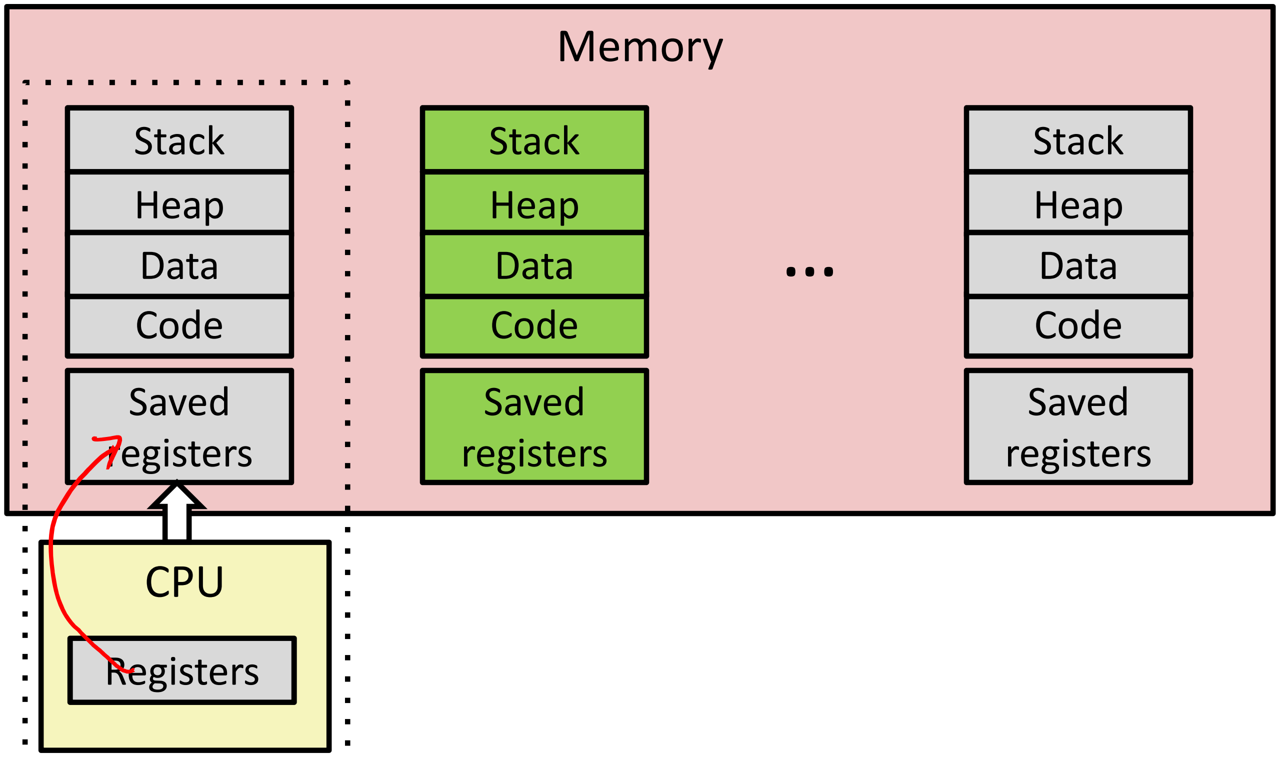
mostly kernel/OS-level

Multiprocessing: The Reality



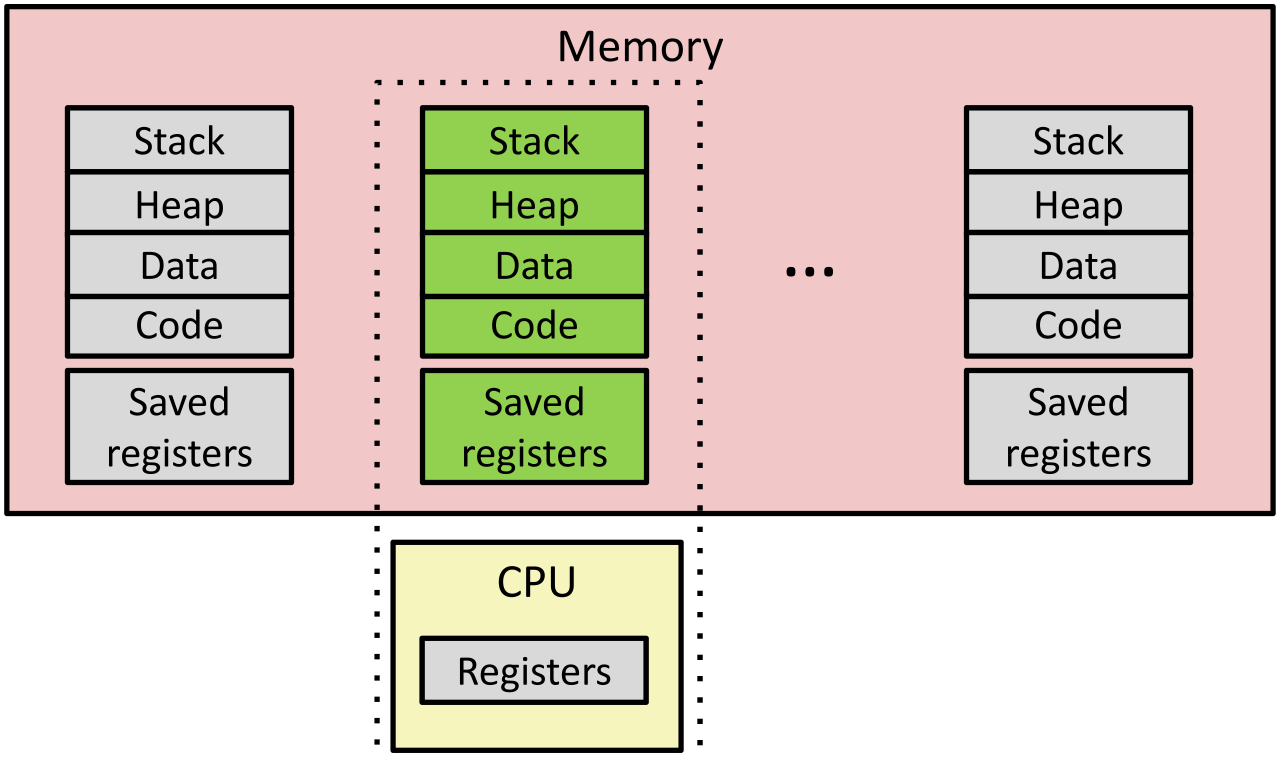
- Single processor executes multiple processes *concurrently*
  - Process executions interleaved, CPU runs *one at a time*
  - Address spaces managed by virtual memory system (later in course)
  - *Execution context* (register values, stack, …) for other processes saved in memory

Multiprocessing (Review)



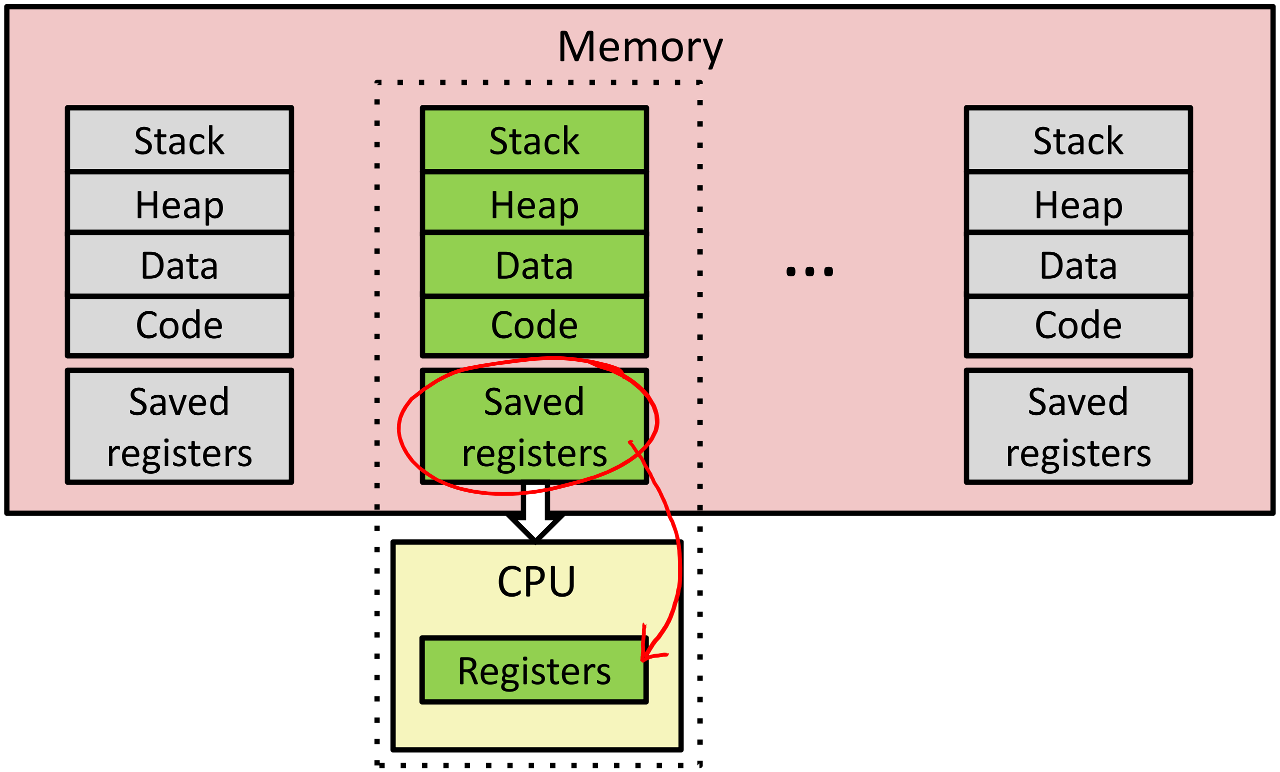
- Context switch
  1) **Save current registers in memory**

Multiprocessing (Review)



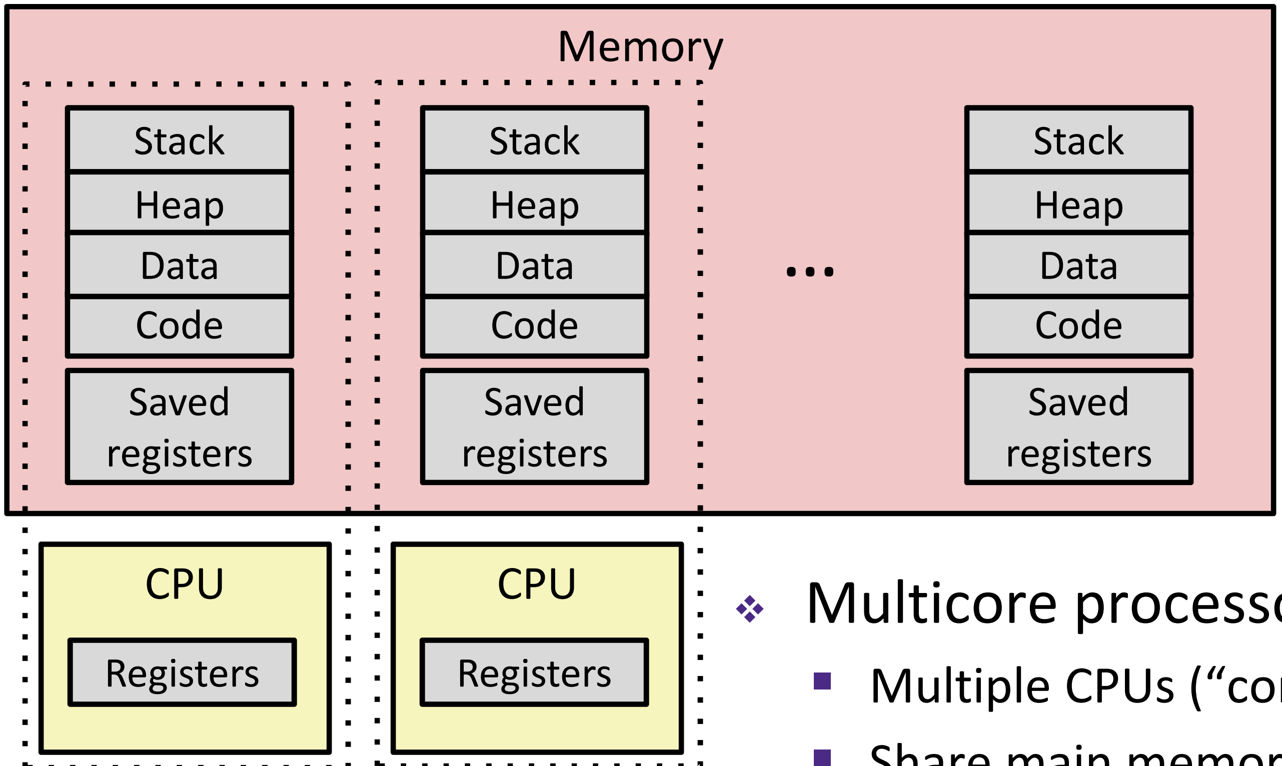
- Context switch
  1) Save current registers in memory
  2) **Schedule next process for execution** (OS decides)

Multiprocessing (Review)



- Context switch
  1) Save current registers in memory
  2) Schedule next process for execution
  3) **Load saved registers and switch address space**

Multiprocessing: The (Modern) Reality

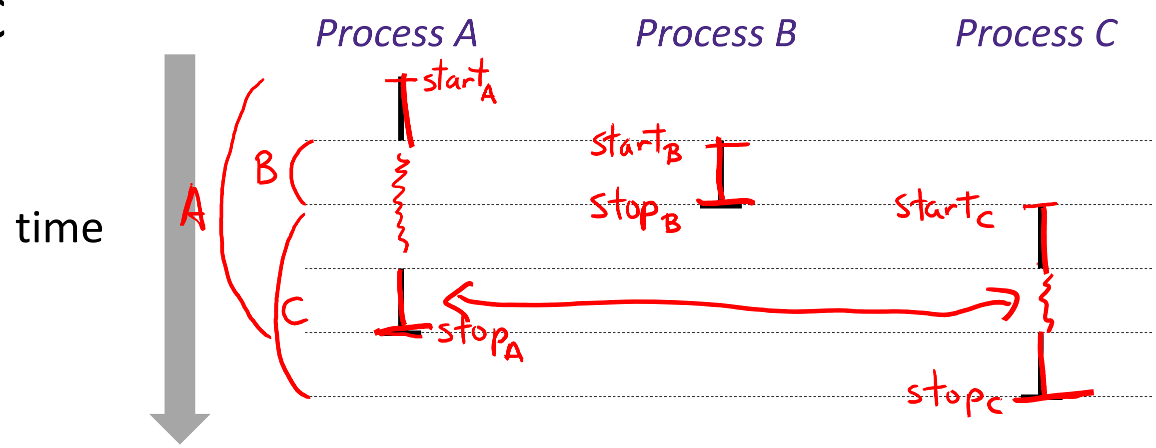


- Multicore processors
  - Multiple CPUs (“cores”) on single chip
  - Share main memory (and some of the caches)
  - Each can execute a separate process
    - Kernel schedules processes to cores
    - ***Still* constantly swapping processes**

Concurrent Processes

Assume only one CPU

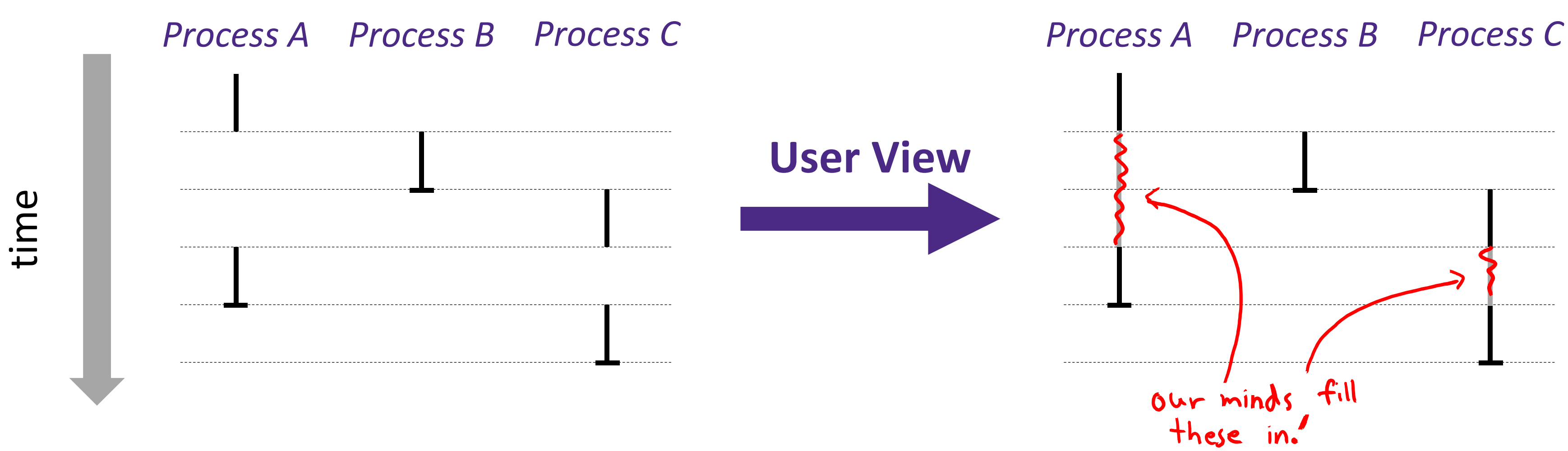
- Each process is a logical control flow
- Two processes *run concurrently* (are concurrent) if their instruction executions (flows) overlap in time
  - Otherwise, they are *sequential*
- Example: (running on single core)
  - Concurrent: A & B, A & C
  - Sequential: B & C



User's View of Concurrency

Assume only one CPU

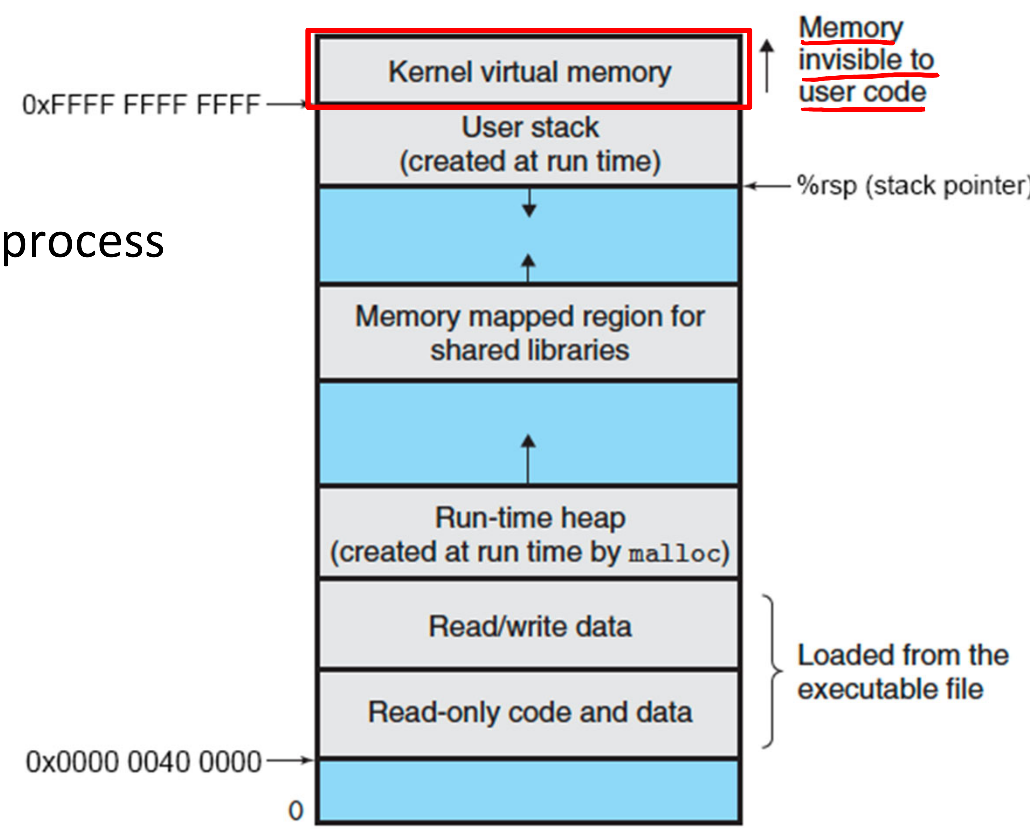
- Control flows for concurrent processes are physically disjoint in time
  - CPU only executes instructions for one process at a time
- However, the user can *think of* concurrent processes as executing at the same time, in *parallel*



Context Switching

Assume only one CPU

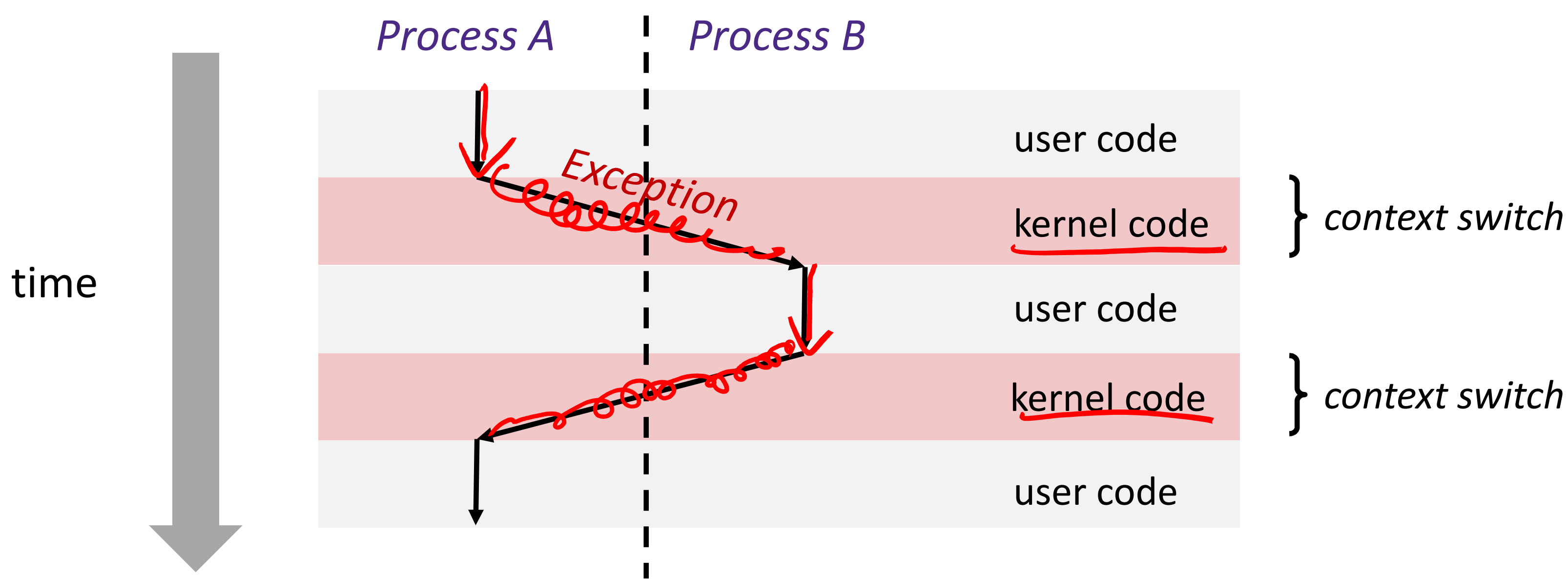
- Processes are managed by a *shared* chunk of OS code called the kernel
  - The kernel is not a separate process, but rather runs as part of a user process
- In x86-64 Linux:
  - Same address in each process refers to same shared memory location



Context Switching (Review)

Assume only one CPU

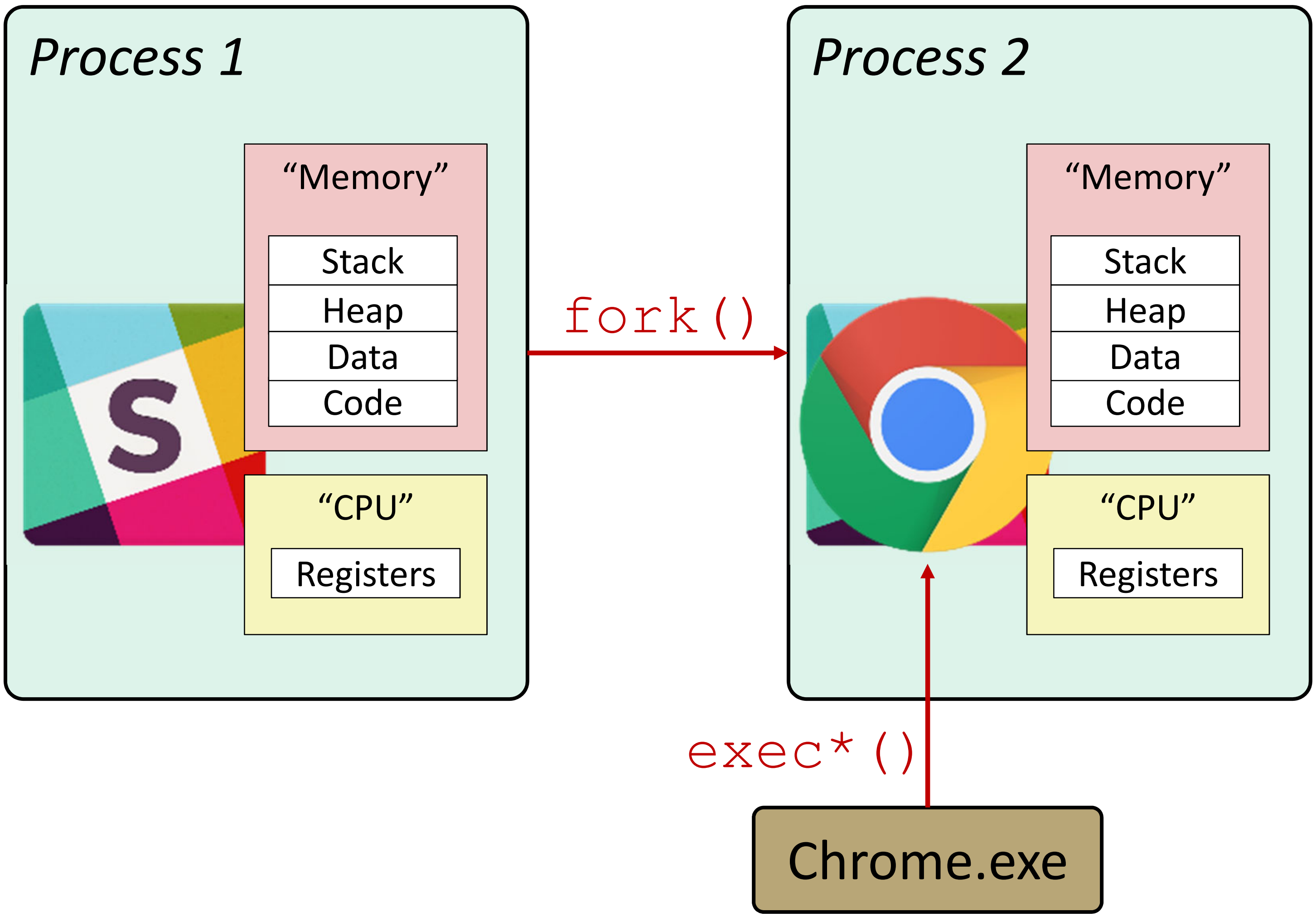
- Processes are managed by a *shared* chunk of OS code called the kernel
  - The kernel is not a separate process, but rather runs as part of a user process
- Context switch passes control flow from one process to another and is performed using kernel code



Processes

- Processes and context switching
- **Creating new processes**
  - **`fork()` and `exec*()`**
- Ending a process
  - `exit()`, `wait()`, `waitpid()`
  - Zombies

Creating New Processes & Programs



Creating New Processes & Programs

- fork-exec model (Linux):
  - `fork()` creates a copy of the current process
  - `exec*()` replaces the current process' code and address space with the code for a different program
    - Family: `execv`, `execl`, `execve`, `execle`, `execvp`, `execlp`
  - `fork()` and `execve()` are *system calls*

↳ intentional, synchronous exceptions ⇒ traps

- Other system calls for process management:
  - `getpid()`
  - `exit()`
  - `wait()`, `waitpid()`

`fork`: Creating New Processes

- `pid_t fork(void)`
  - Creates a new "child" process that is *identical* to the calling "parent" process, including all state (memory, registers, etc.)
  - Returns 0 to the child process
  - Returns child's process ID (PID) to the parent process
- Child is *almost* identical to parent:
  - Child gets an identical (but separate) copy of the parent's virtual address space
  - Child has a different PID than the parent

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

- `fork` is unique (and often confusing) because it is called once but returns "twice"

Understanding `fork()`

fork_ret = Y

Process X (parent; PID X)

```
pid_t fork_ret = fork();
if (fork_ret == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

fork →

fork_ret = 0

Process Y (child; PID Y)

```
pid_t fork_ret = fork();
if (fork_ret == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

Understanding `fork()`

Process X (parent; PID X)

```
pid_t fork_ret = fork();
if (fork_ret == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

Process Y (child; PID Y)

```
pid_t fork_ret = fork();
if (fork_ret == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

`fork_ret = Y`

```
pid_t fork_ret = fork();
if (fork_ret == 0) {
   printf("hello from child\n");
} else { //parent
   printf("hello from parent\n");
}
```

`fork_ret = 0`

```
pid_t fork_ret = fork();
if (fork_ret == 0) { //child
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

Understanding `fork()`

Process X (parent; PID X)

```
pid_t fork_ret = fork();
if (fork_ret == 0) {
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} else {
   printf("hello from parent\n");
}
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Process Y (child; PID Y)

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pid_t fork_ret = fork();
if (fork_ret == 0) {
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fork_ret = Y

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}
```

fork_ret = 0

```
pid_t fork_ret = fork();
if (fork_ret == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

hello from parent

hello from child

Which one appears first?

non-deterministic!

Summary

- Exceptions
  - Events that require non-standard control flow
  - Generated asynchronously (interrupts) or synchronously (traps and faults)
  - After an exception is handled, either:
    - Re-execute the current instruction
    - Resume execution with the next instruction
    - Abort the process that caused the exception
- Processes
  - Only one of many active processes executes at a time on a CPU, but each appears to have total control of the processor
  - OS periodically "context switches" between active processes