

Processes I

CSE 351 Autumn 2022

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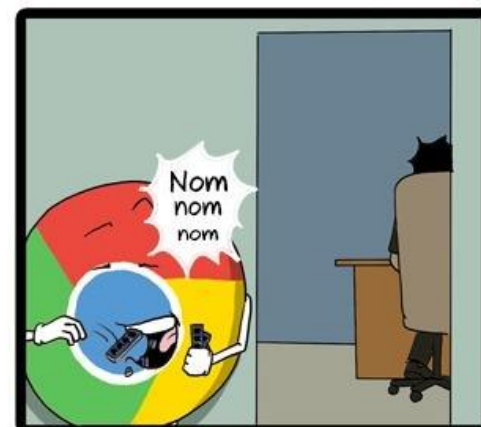
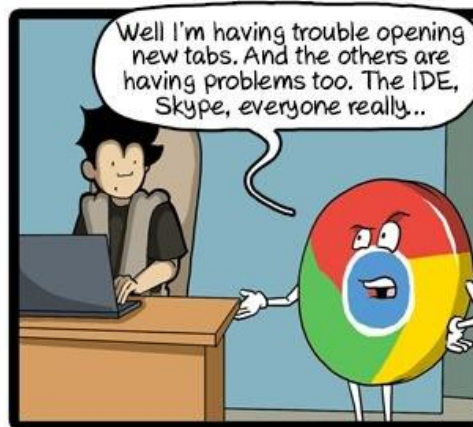
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Relevant Course Information

- ❖ hw17 due tonight
- ❖ hw19 due Friday (11/18)
 - Lab 4 preparation!
- ❖ hw20 due Monday (11/21)
- ❖ Lab 4 due Monday after Thanksgiving (11/28)

Mid-quarter Survey Debrief

- ❖ Pace is a little fast (lecture pace, lots of assignments)
- ❖ Readings are mostly good, but could be improved
 - Question explanations are good though could have more, text can be dense and difficult to understand
- ❖ HW: formatting is frustrating, questions can be vague, more explanations would be good
- ❖ Labs: difficult to start, having partners helps
- ❖ Midterm:
 - Stack question (Q6) was difficult, and GDB experience depended on comfort level
 - Love and hate for the design/explanation questions

AMAT, Revisited

- ❖ *Average Memory Access Time (AMAT)*: average time to access memory considering both hits and misses

$$\text{AMAT} = \text{Hit time} + \text{Miss rate} \times \text{Miss penalty}$$

$$\text{(abbreviated AMAT} = \text{HT} + \text{MR} \times \text{MP)}$$

- ❖ We called this a *cache performance metric*
 - This isn't the only metric we could have used!

Metrics in Computing

- ❖ Generally, folks care most about performance
 - Energy-efficiency is more important now since the plateau in 2004/2005
 - This is why we have so many specialized chips nowadays
- ❖ Really, this is just **efficiency** – making efficient use of the resources that we have
 - Performance: cycles/instruction, seconds/program
 - Energy efficiency: performance/watt
 - Memory: bytes/program, bytes/data structure

Metrics

- ❖ What do we do with metrics?
 - We tend to optimize along them!
 - Especially when jobs/funding depend on better performance along some metric
 - See all of Intel under “Moore’s Law”

- ❖ Sometimes, strange incentives emerge
 - “Minimize the number of bugs on our dashboard”
 - Does it count if we make the bugs invisible?
 - “Make this faster for our demo in a week”
 - Shortcuts might hurt performance at scale
 - “Minimize our average memory access time”
 - What if we add *more* memory accesses that we know will hit?

Metrics and Success

- ❖ Success is *defined along metrics*
 - This affects how we measure and optimize

- ❖ Let's say that we choose **performance/program** or **performance/program set** (*i.e.*, benchmarks):
 1. Measure existing performance
 2. Come up with a bunch of optimizations that would improve performance
 3. Select a few to build into the “next version”

Metrics and Success

- ❖ Success is *defined along metrics*
 - This affects how we measure and optimize
- ❖ Let's say that we choose **profit/year** or **stock price**:
 - Success means earning more profit than last year
 - Improvement or optimizations might include:
 - Reduce expenses, cut staff
 - Sell more things or fancier things (*e.g.*, in-app purchases)
 - Make people pay monthly for things they could get for free
 - Increase advertising revenue:

The New York Times

Whistle-Blower Says Facebook 'Chooses Profits Over Safety'

Frances Haugen, a Facebook product manager who left the company in May, revealed that she had provided internal documents to journalists and others.

Metrics and Success

- ❖ Success is *defined along metrics*
 - This affects how we measure and optimize
- ❖ Let's say that we choose **minoritized participation in computing**:
 - What does success/participation mean (and dangers)?
 - Women? BIPOC? All minoritized lumped together?
 - Might optimize for one group at the expense of others
 - Taking intro? Passing intro? Getting a degree? Getting a job?
 - Says nothing about retention or participation/decision-making level

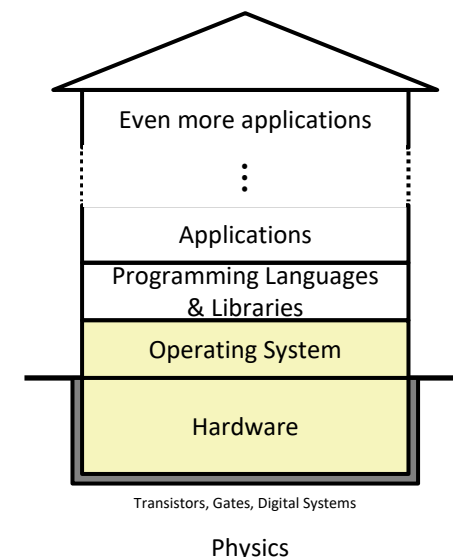
Design Considerations

- ❖ **Regardless of what we build, the way that we define success shapes the systems we build**
 - Choose your metrics carefully
 - There's more to choose from than performance (*e.g.*, usability, access, simplicity, agency)
- ❖ Metrics are a “heading” (in the navigational sense)
 - Best to reevaluate from time to time in case you're off course or your destination changes

The Hardware/Software Interface

❖ Topic Group 3: **Scale & Coherence**

- Caches, **Processes**, Virtual Memory, Memory Allocation



- ❖ How do we maintain logical consistency in the face of more data and more processes?
 - How do we support control flow both within many processes and things external to the computer?
 - How do we support data access, including dynamic requests, across multiple processes?

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

- ❖ Questions from the Reading?

Leading Up to Processes

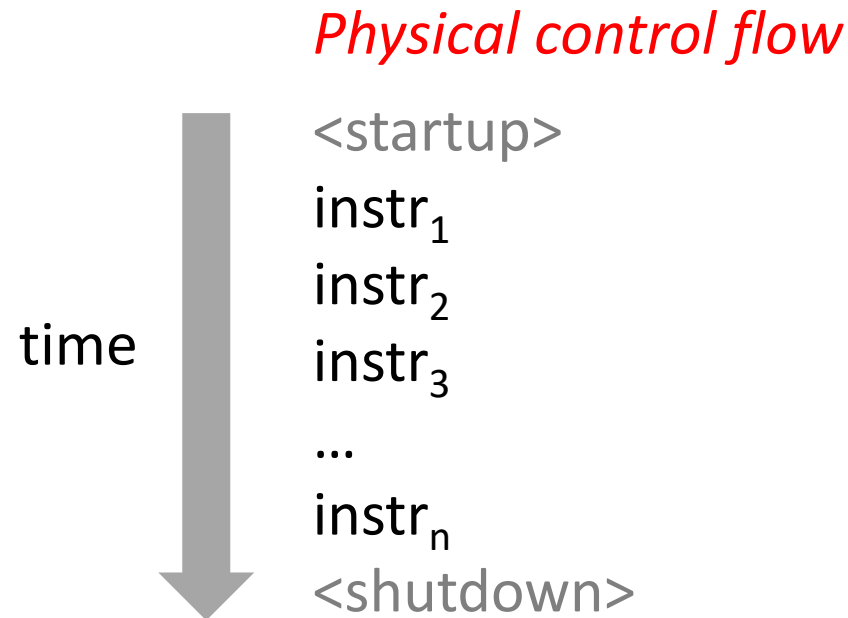
- ❖ System Control Flow
 - **Control flow**
 - **Exceptional control flow**
 - Asynchronous exceptions (interrupts)
 - Synchronous exceptions (traps & faults)

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*)



Altering the Control Flow

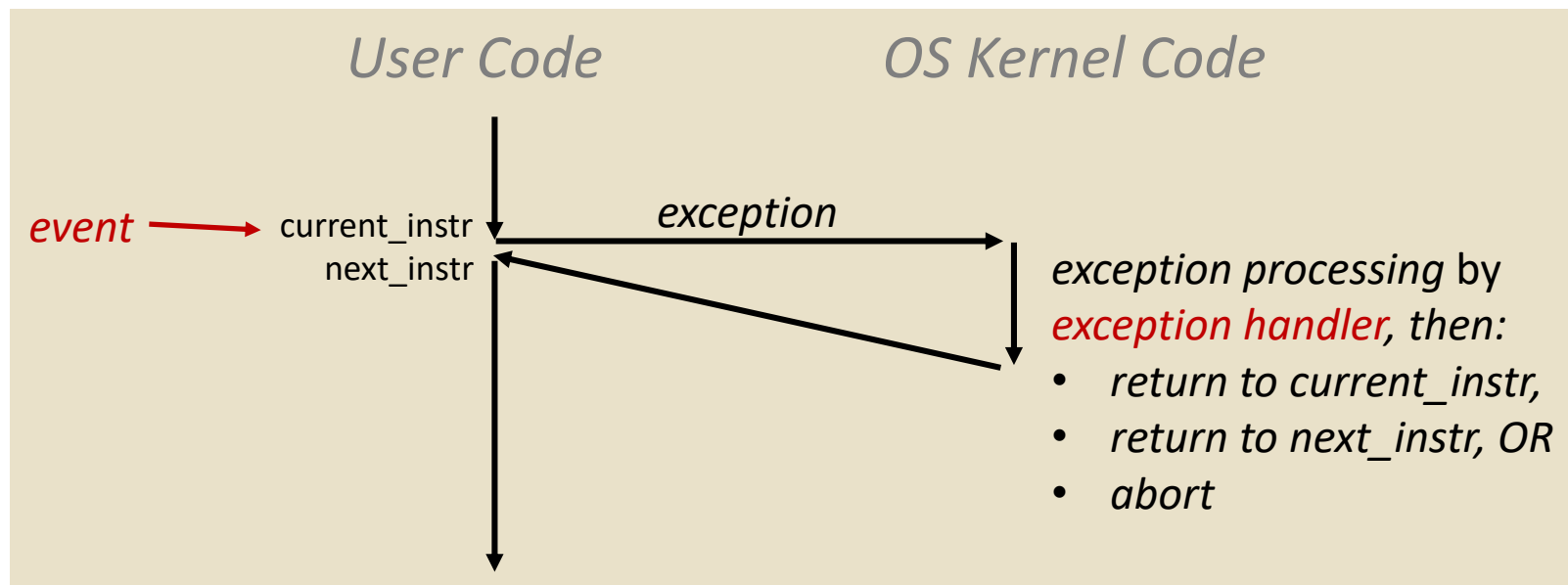
- ❖ Up to now, two ways to change control flow:
 - Jumps (conditional and unconditional)
 - Call and return
 - Both react to changes in *program state*
- ❖ Processor also needs to react to changes in *system state*
 - Unix/Linux user hits “Ctrl-C” at the keyboard
 - User clicks on a different application’s 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 EE/CSE474

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

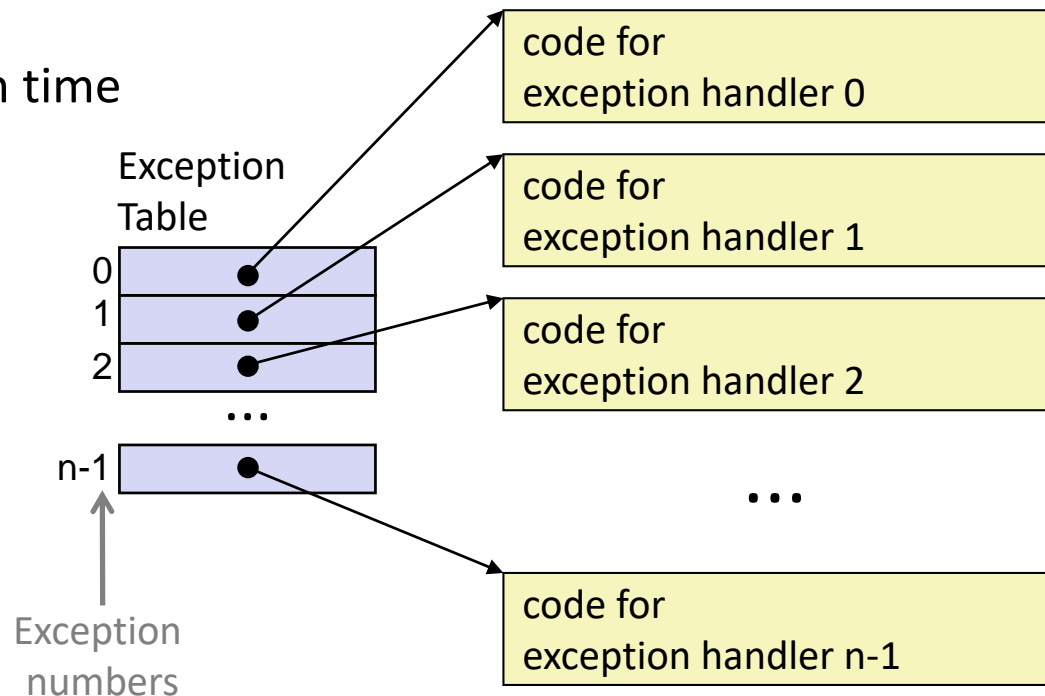


- ❖ *How does the system know where to jump to in the OS?*

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

<i>Exception Number</i>	<i>Description</i>	<i>Exception Class</i>
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 (Review)

- ❖ **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
 - **Faults**
 - **Unintentional** but possibly recoverable
 - Examples: *page faults*, segment protection faults, integer divide-by-zero exceptions
 - Either re-executes faulting (“current”) instruction or aborts
 - **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:

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

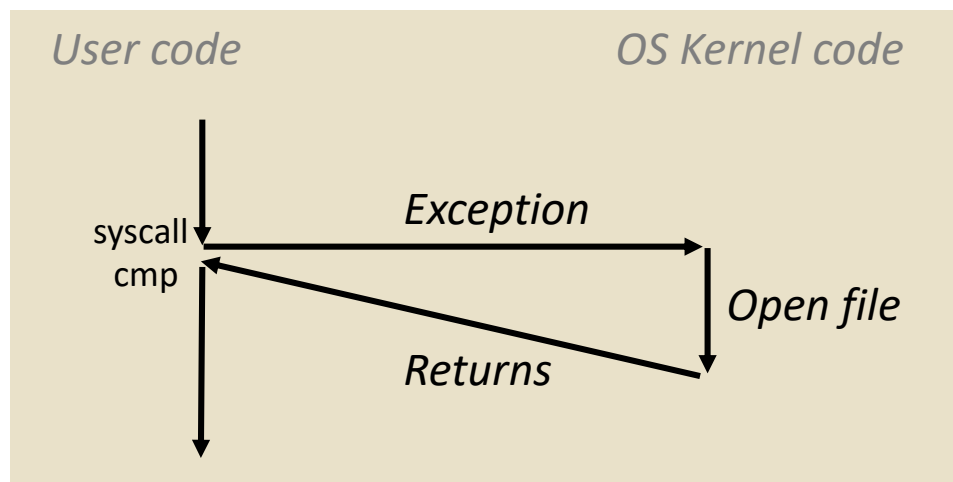
Traps Example: Opening File

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

```

000000000000e5d70 <__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  $0xffffffffffffffff001,%rax
...
e5dfa:  c3                retq

```



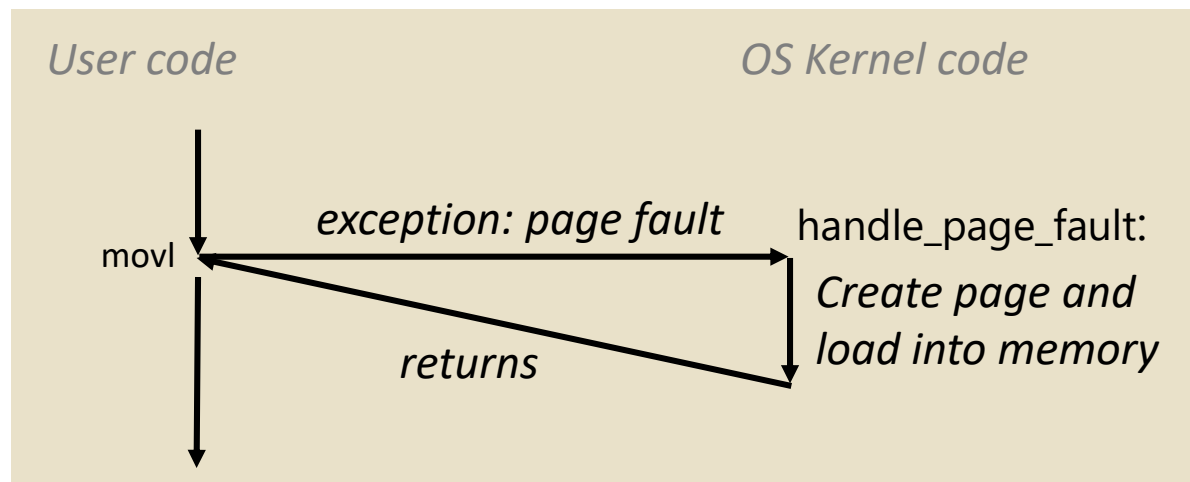
- `%rax` contains syscall number
- Other arguments in `%rdi`, `%rsi`, `%rdx`, `%r10`, `%r8`, `%r9`
- Return value in `%rax`
- Negative value is an error corresponding to negative `errno`

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
```

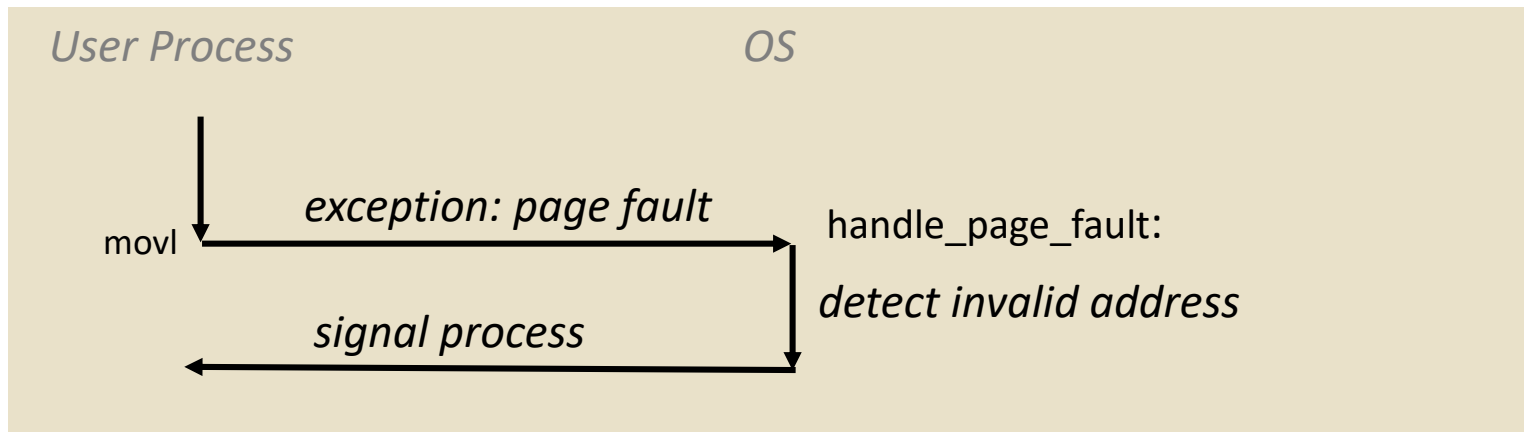


- ❖ Page fault handler must load page into physical memory
- ❖ Returns to faulting instruction: `mov` is executed again!
 - Successful on second try

Fault Example: Invalid Memory Reference

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

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



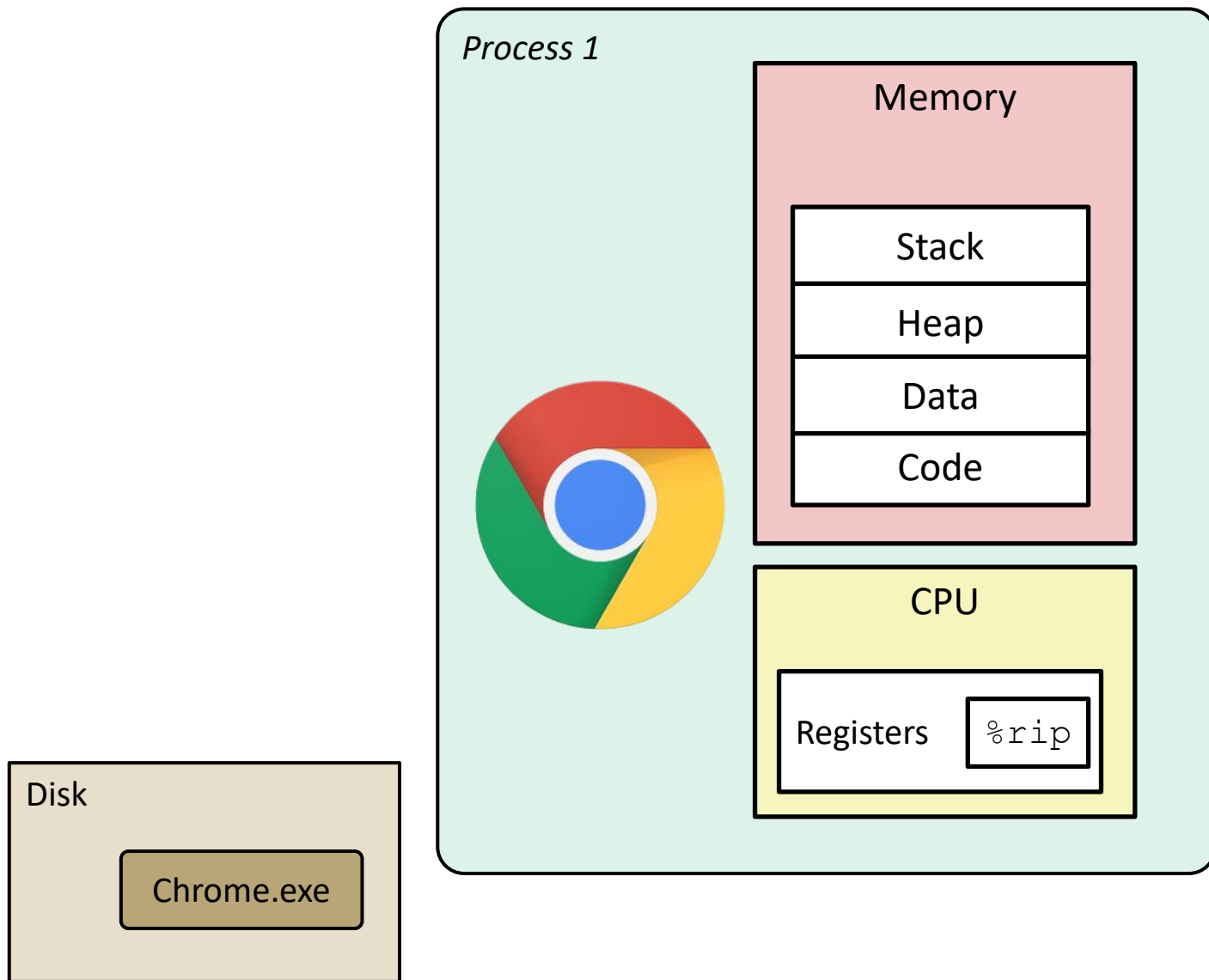
- ❖ Page fault handler detects invalid address
- ❖ Sends `SIGSEGV` signal to user process
- ❖ User process exits with “segmentation fault”

Processes

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

What is a process? (Review)

It's an *illusion!*

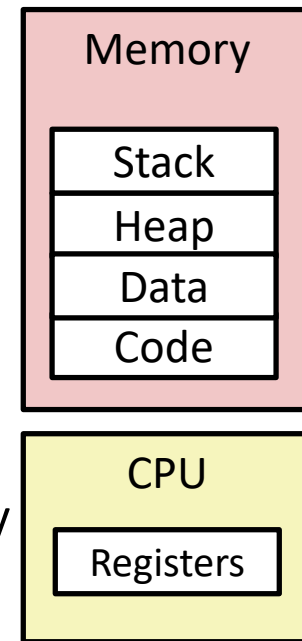


What is a process? (Review)

- ❖ 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?

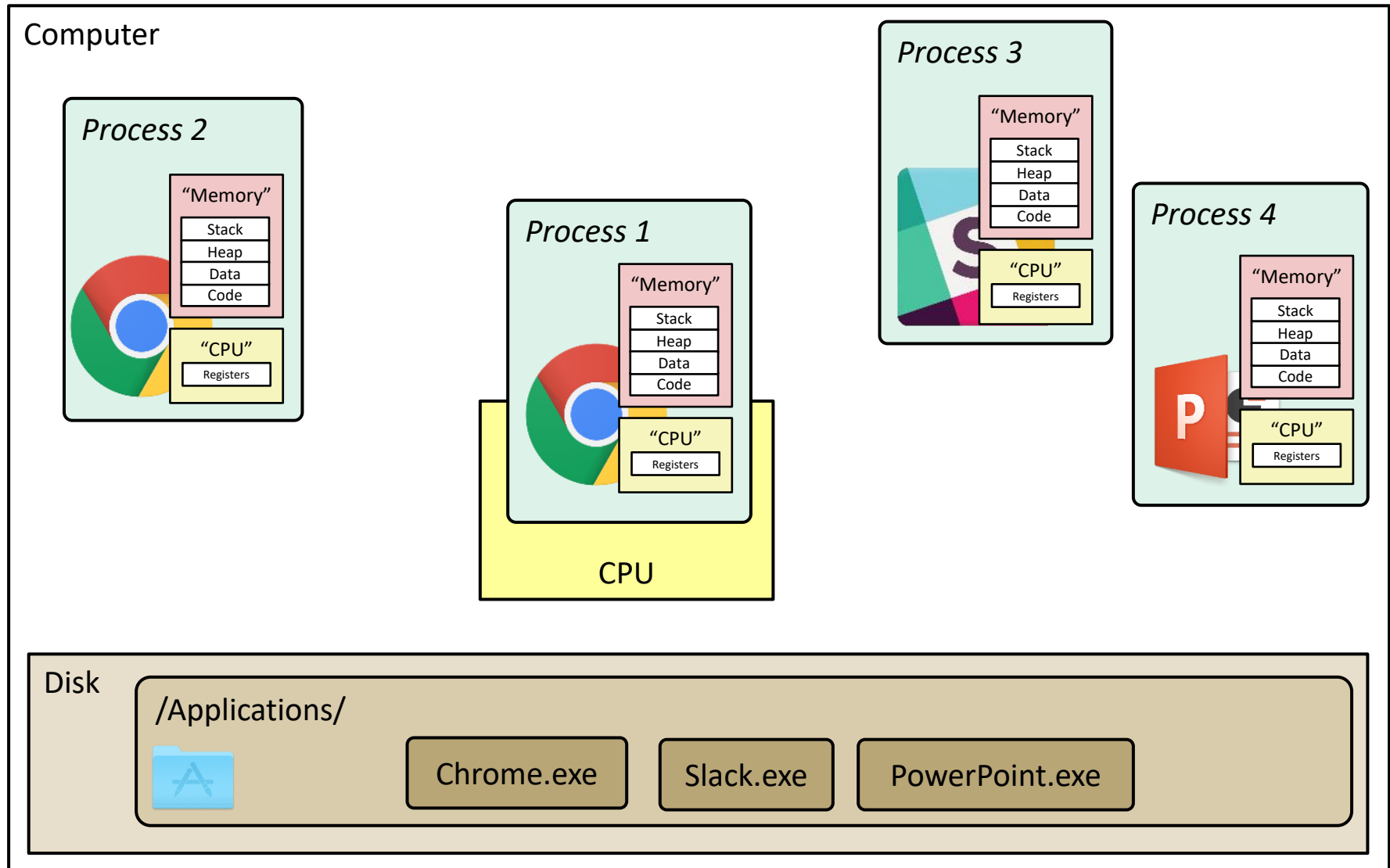
Processes (Review)

- ❖ 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**



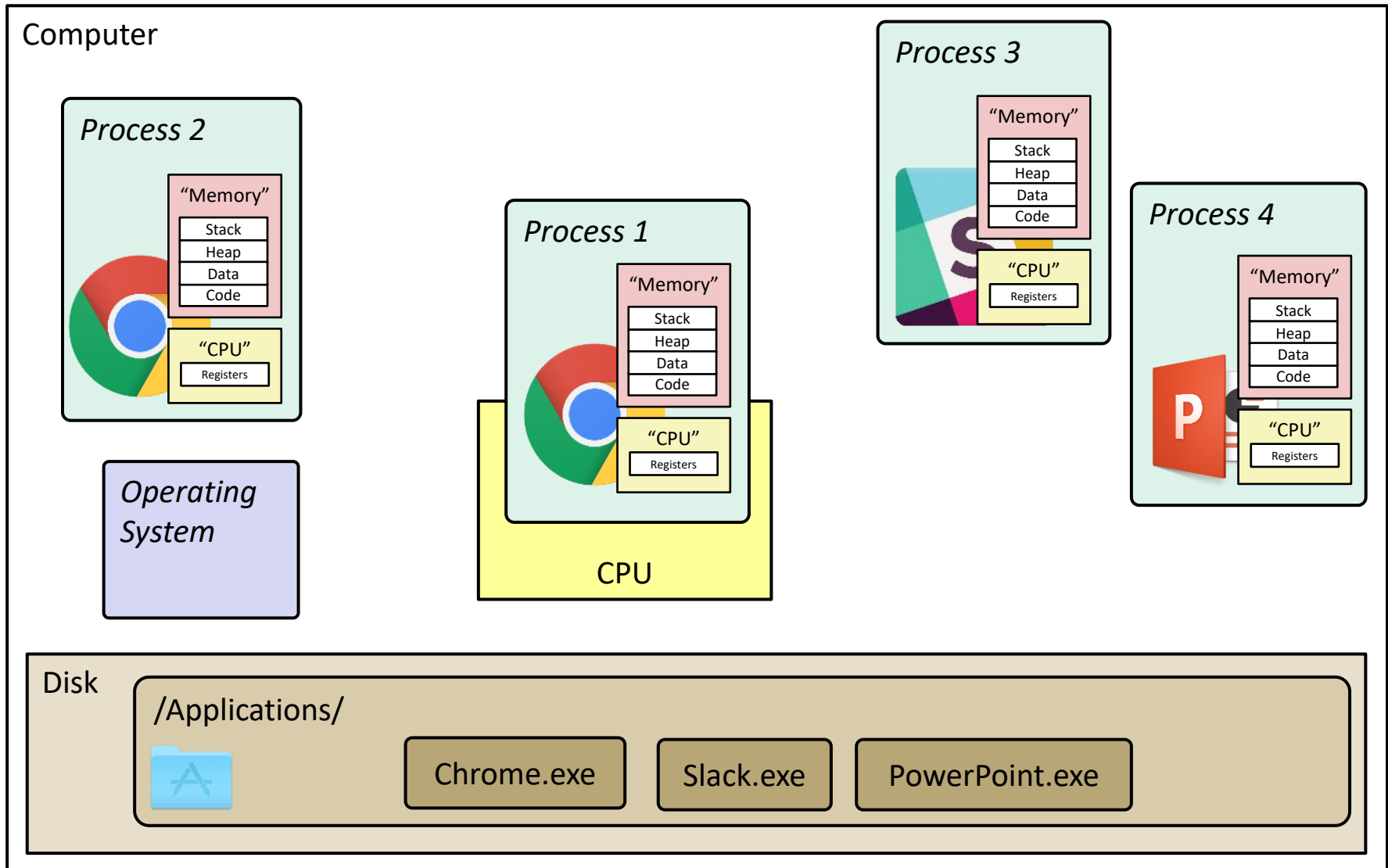
What is a process?

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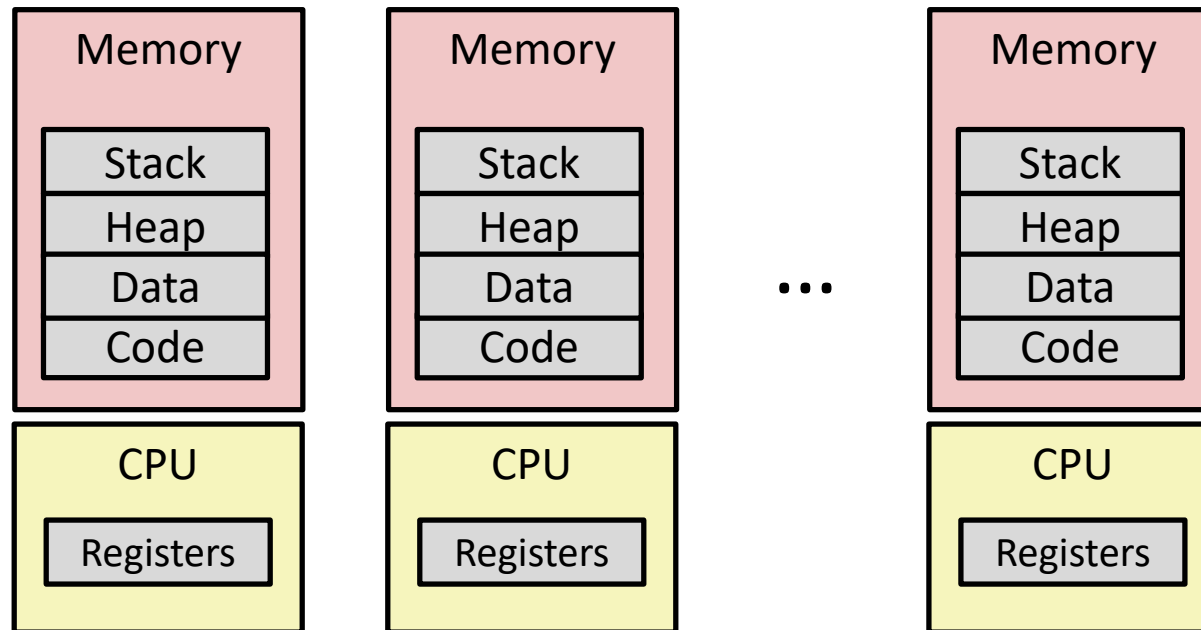


What is a process?

It's an *illusion!*

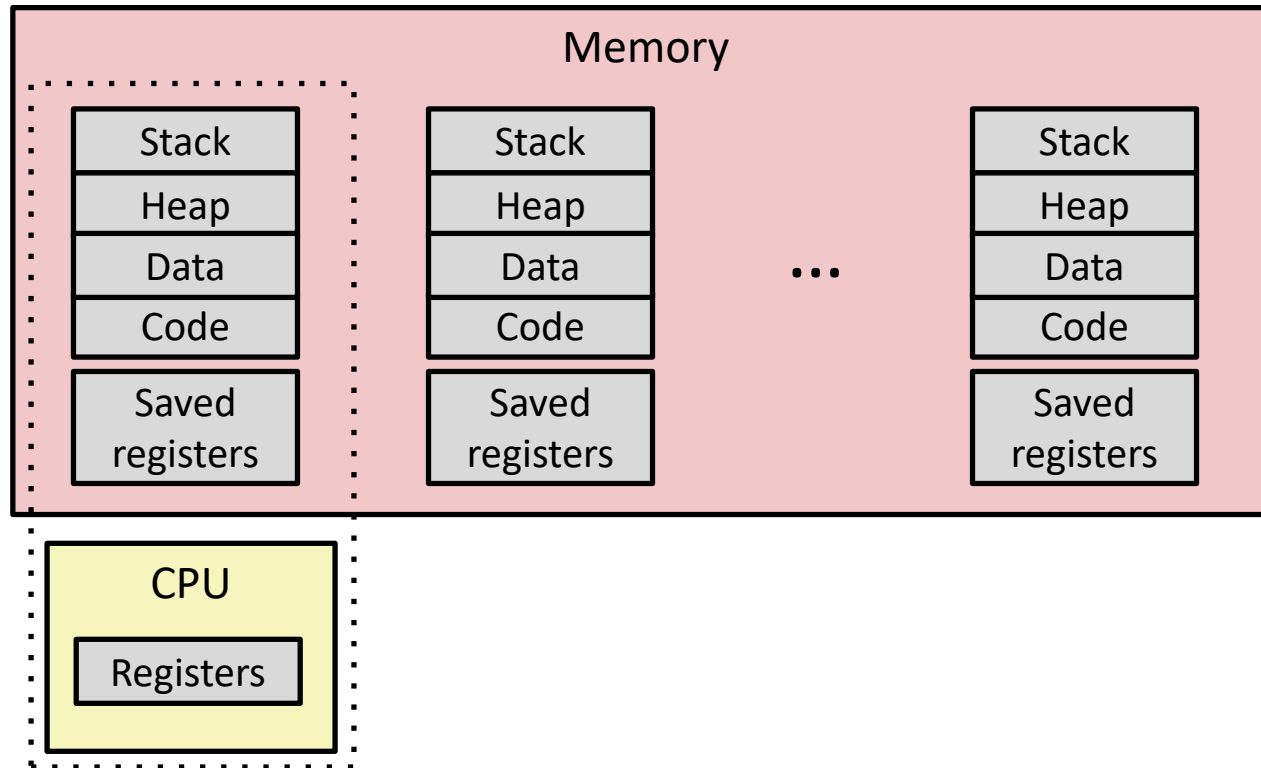


Multiprocessing: The Illusion



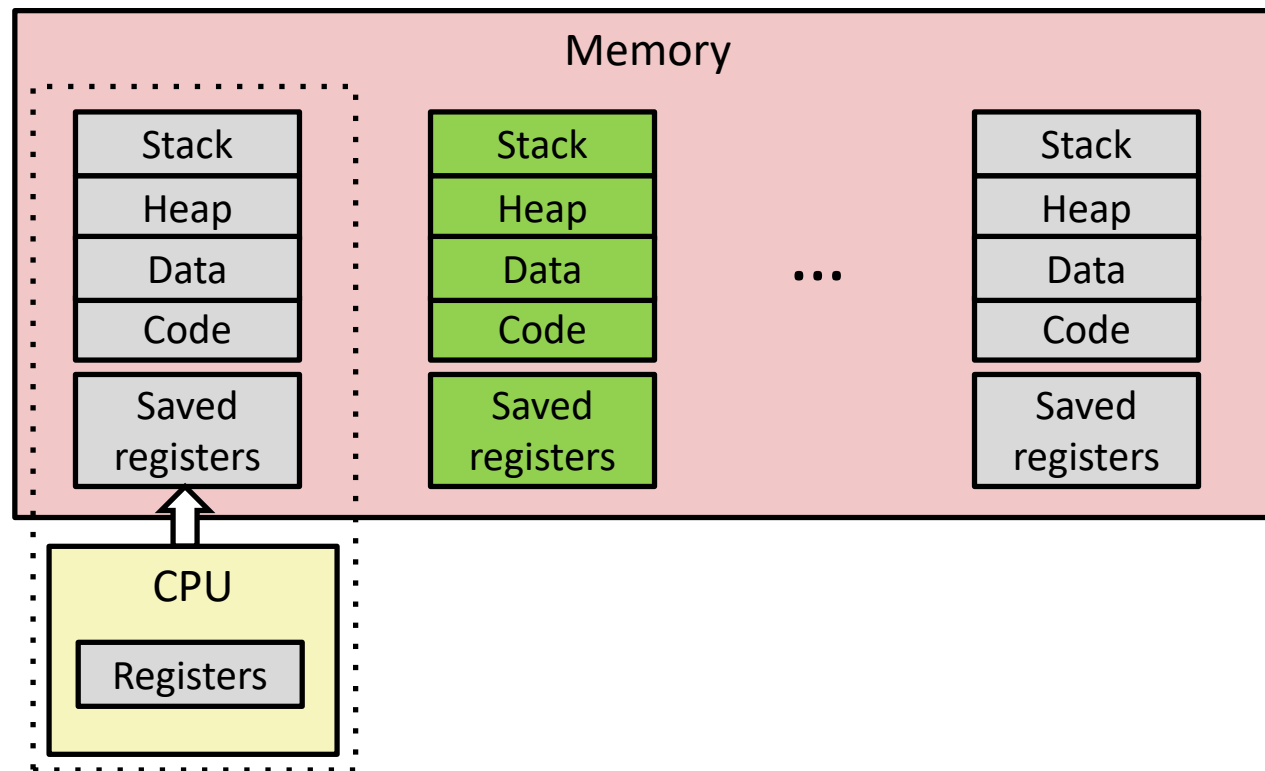
- ❖ Computer runs many processes simultaneously
 - Applications for one or more users
 - Web browsers, email clients, editors, ...
 - Background tasks
 - Monitoring network & I/O devices

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

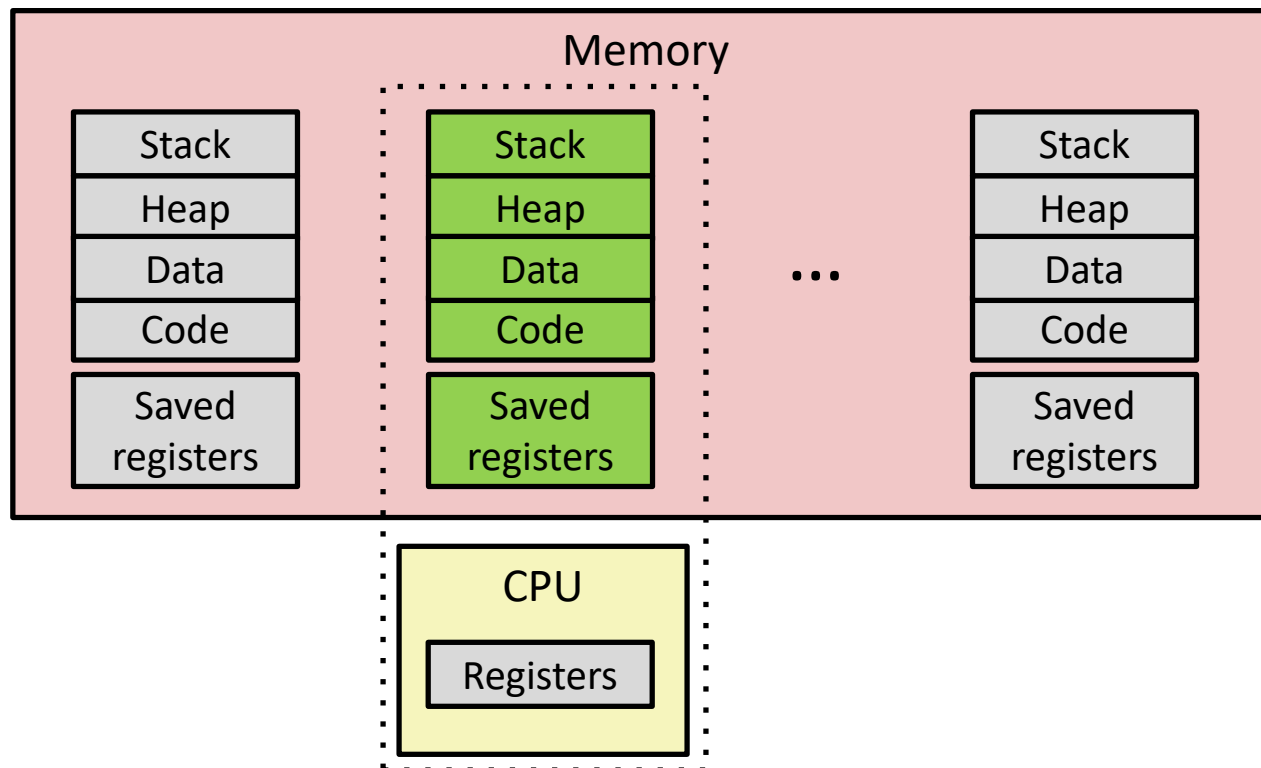
Multiprocessing (Review)



❖ Context switch

- 1) Save current registers in memory

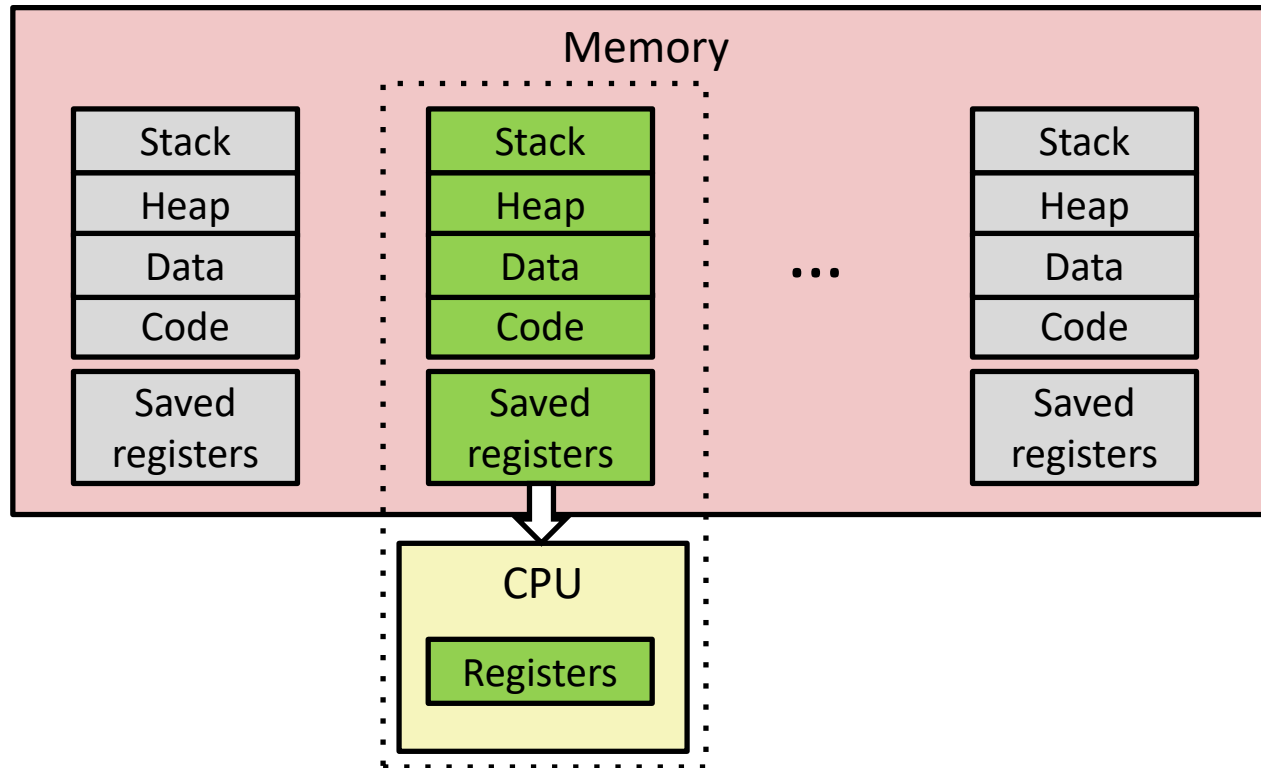
Multiprocessing (Review)



❖ Context switch

- 1) Save current registers in memory
- 2) **Schedule next process for execution**

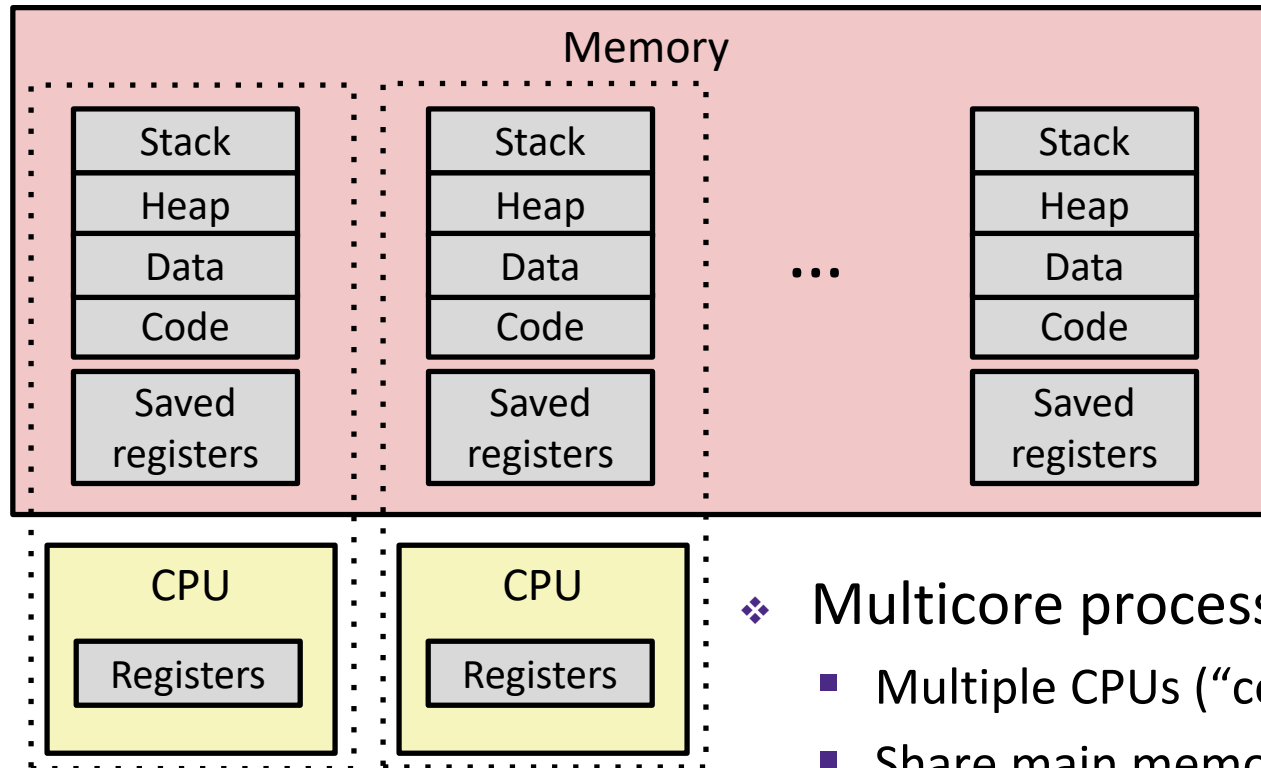
Multiprocessing (Review)



❖ 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

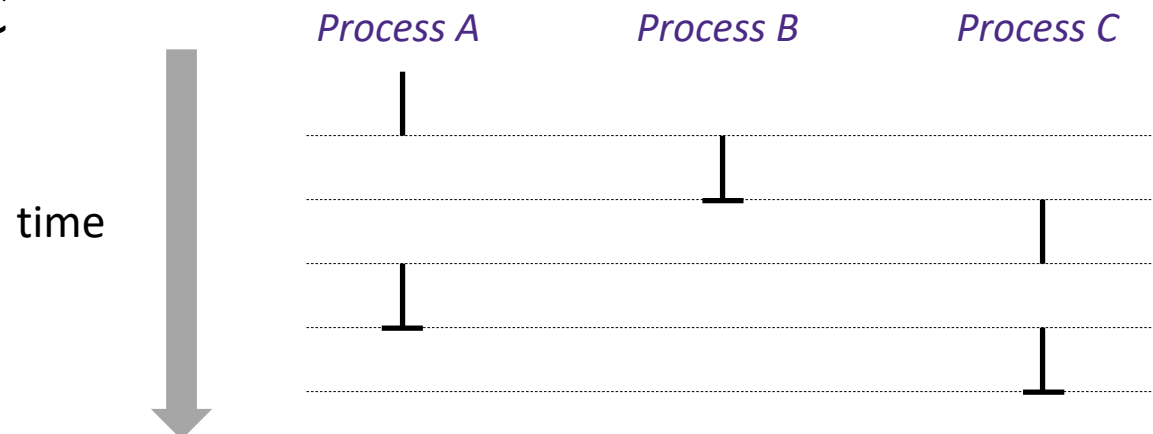


- ❖ **Multicore processors**
 - Multiple CPUs (“cores”) on single chip
 - Share main memory (and some of the caches)
 - Each can execute a separate process
 - Kernel schedules processes to cores
 - **Still constantly swapping processes**

Concurrent Processes

Assume only one CPU

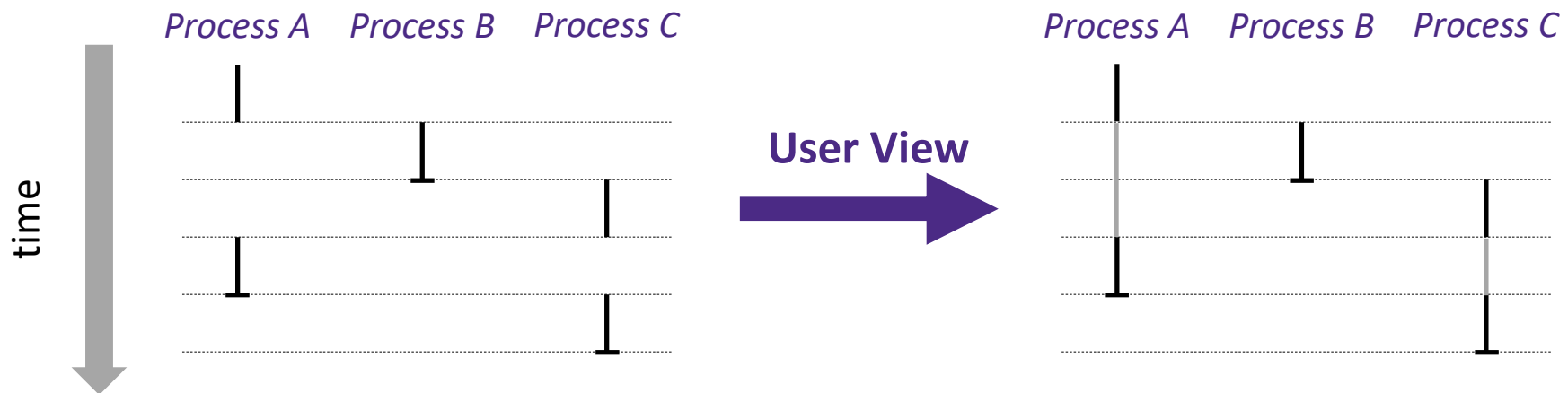
- ❖ Each process is a logical control flow
- ❖ Two processes *run concurrently* (are concurrent) if their instruction executions (flows) overlap in time
 - Otherwise, they are *sequential*
- ❖ Example: (running on single core)
 - Concurrent: A & B, A & C
 - Sequential: B & C



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*

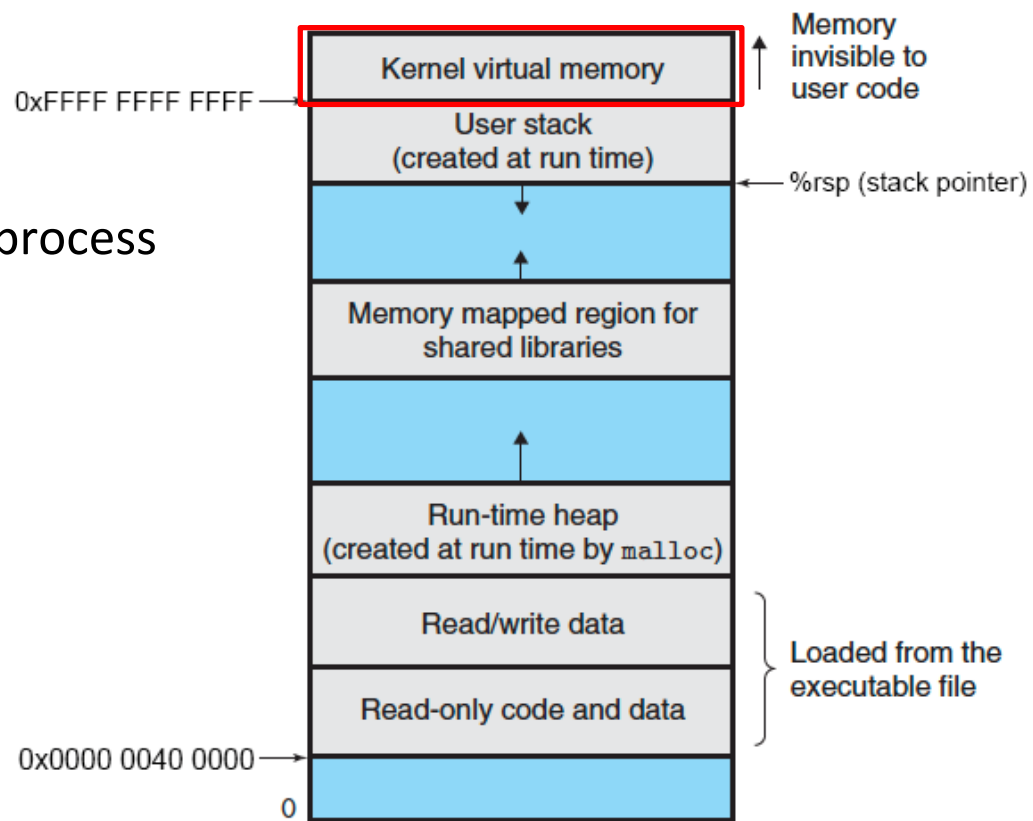


Context Switching

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

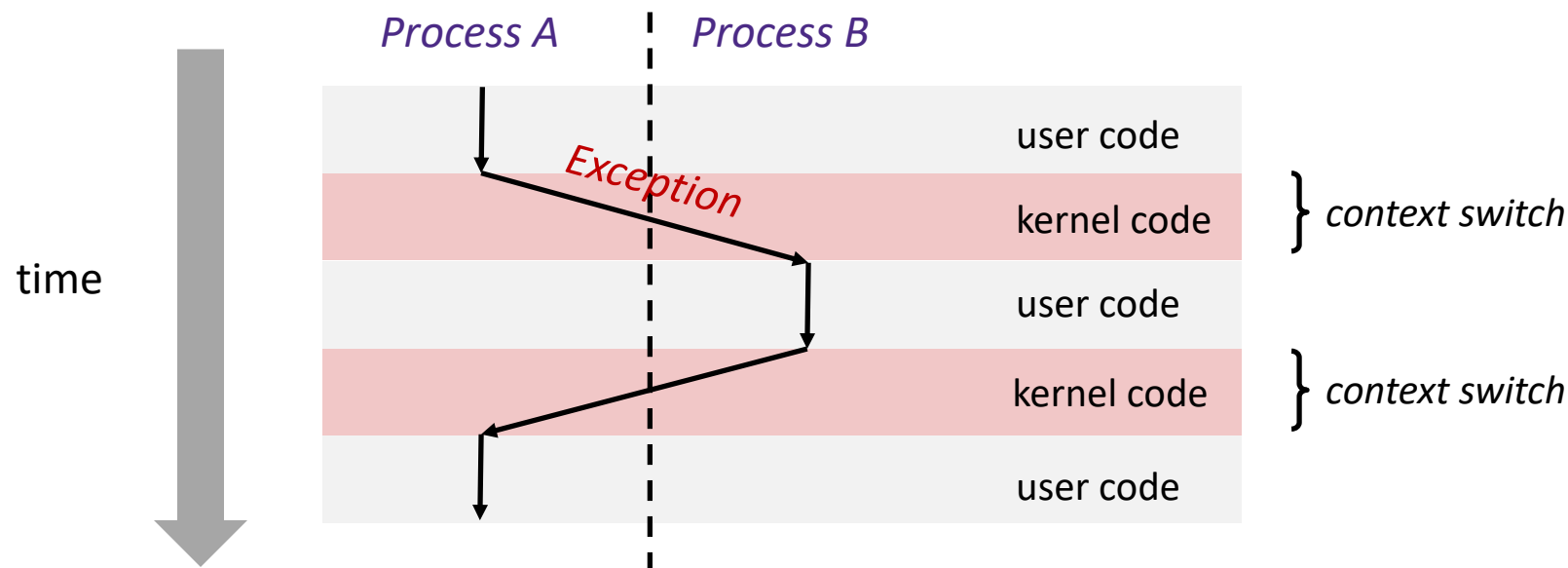
- ❖ In x86-64 Linux:
 - Same address in each process refers to same shared memory location



Context Switching (Review)

Assume only one CPU

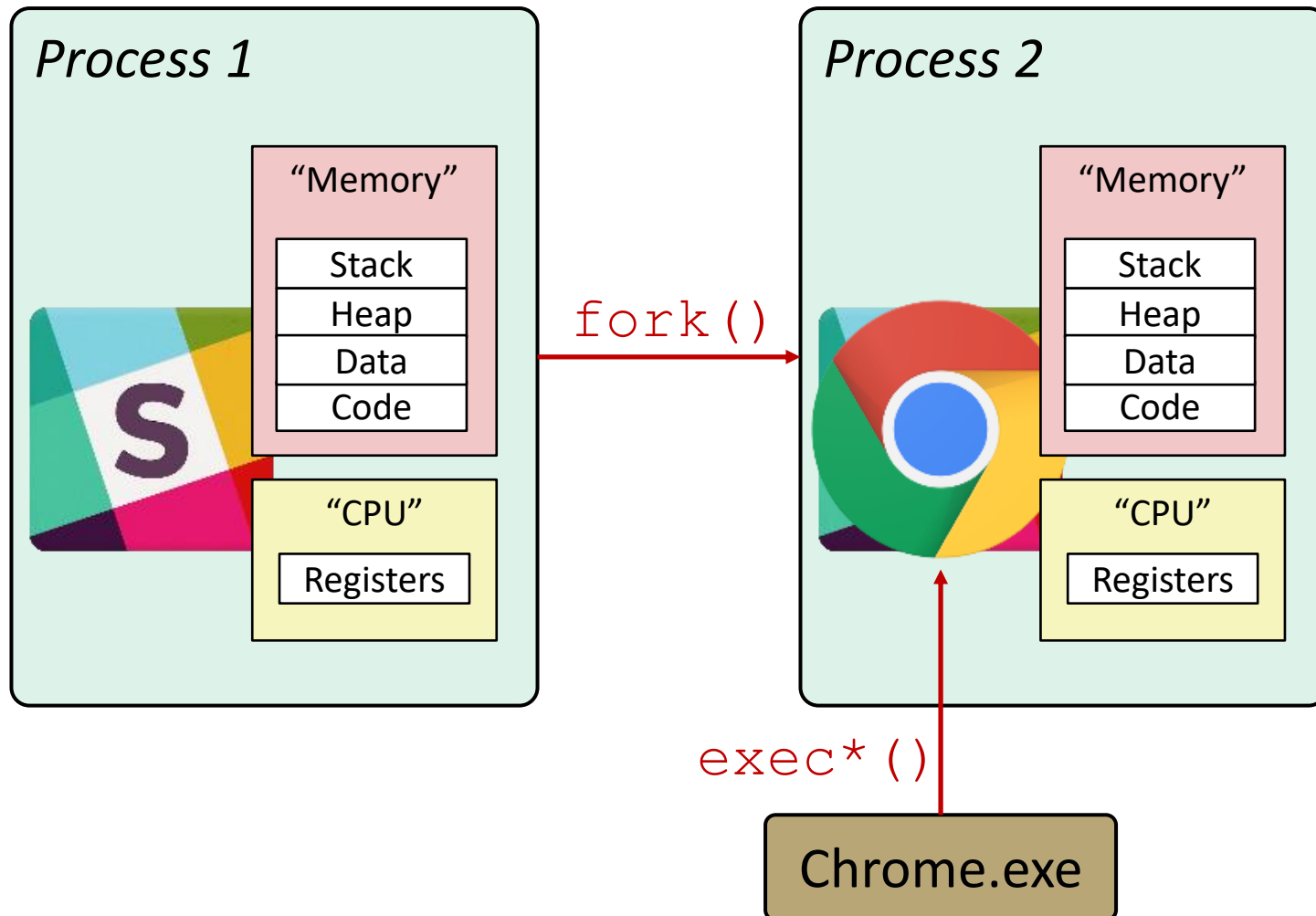
- ❖ Processes are managed by a *shared* chunk of OS code called the **kernel**
 - The kernel is not a separate process, but rather runs as part of a user process
- ❖ Context switch passes control flow from one process to another and is performed using kernel code



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*

- ❖ 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()`

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");  
}
```


Understanding `fork()`

Process X (parent; PID X)



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

fork ret = Y



```
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 = 0



```
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");
}
  
```

fork ret = Y

```

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

hello from **parent**

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 = 0

```

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

hello from **child**

Which one appears first?

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