System Control Flow & Processes

CSE 351 Spring 2024

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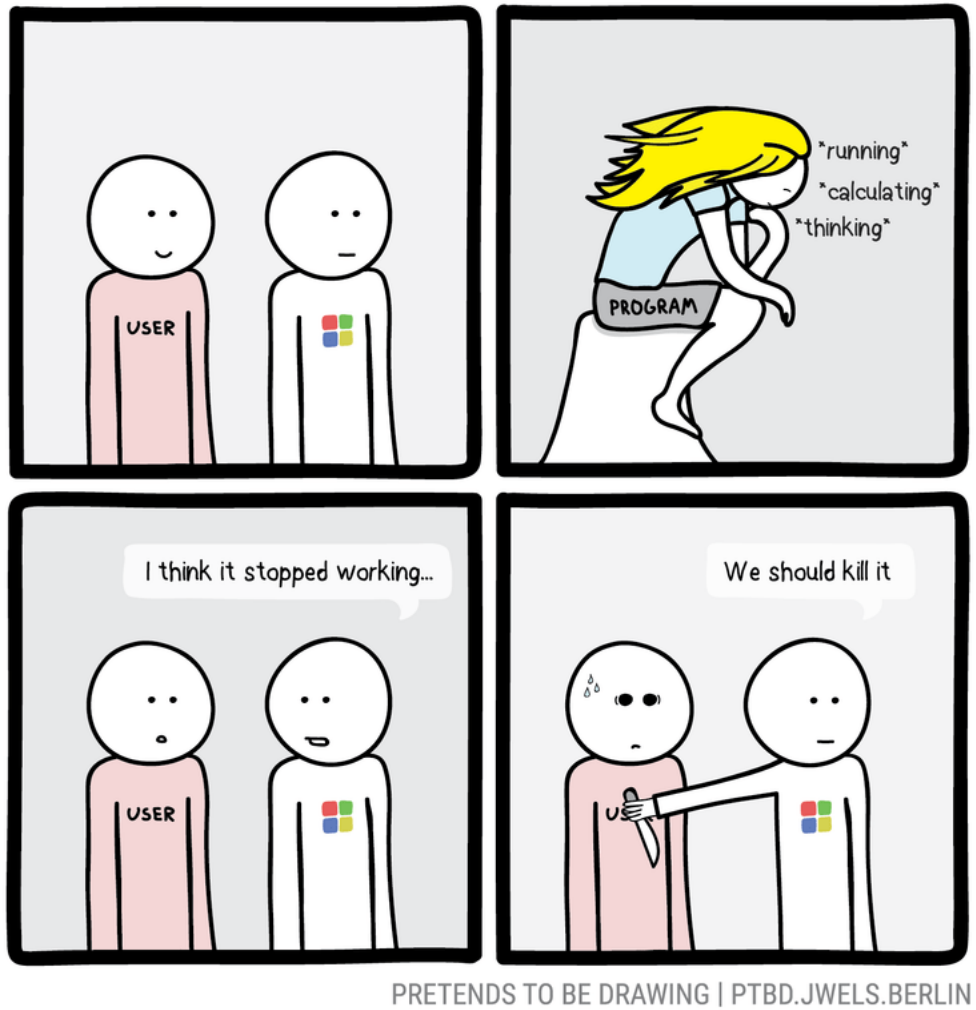


Playlist: CSE 351 24Sp Lecture Tunes!

Announcements, Reminders

- HW19 due tonight!
  - HW20 due Wednesday (15 May)
  - HW21 due Friday (17 May)
  - HW22 due Monday (20 May)
- Lab 4 due Friday
  - Use any late days left on Lab 4!
- Lab 5 releasing Friday!
- Guest lectures by Prof. Kelly Shaw on Wednesday & Friday 😎

Midterm Grades: A Reminder

Your **success in life** is not defined by grades.

You are not defined by grades.

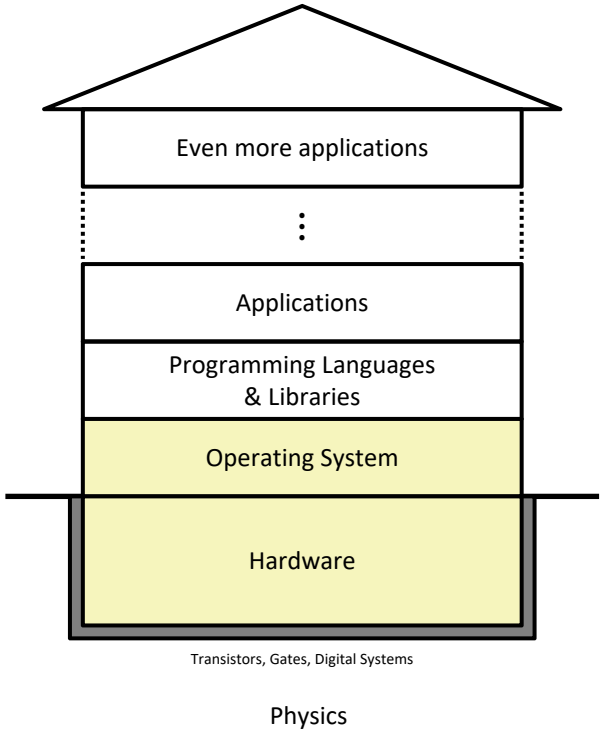
- We know all of this seems critically important right now, but we promise, the numbers on a transcript will fade with time. I (Elba) personally got both the highest and lowest midterm grades in my classes at some point in my college career.

- **We'll release grades later this week!**
  - Regrade requests will be open for a week – please let us know if anything looks amiss!

The Hardware/Software Interface

- Topic Group 3: **Scale & Coherence**
  - Caches, **Processes**, Virtual Memory, Memory Allocation

So far we've been viewing concepts from the perspective of a single program…



- 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? (Hint: Virtual memory next time!)

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

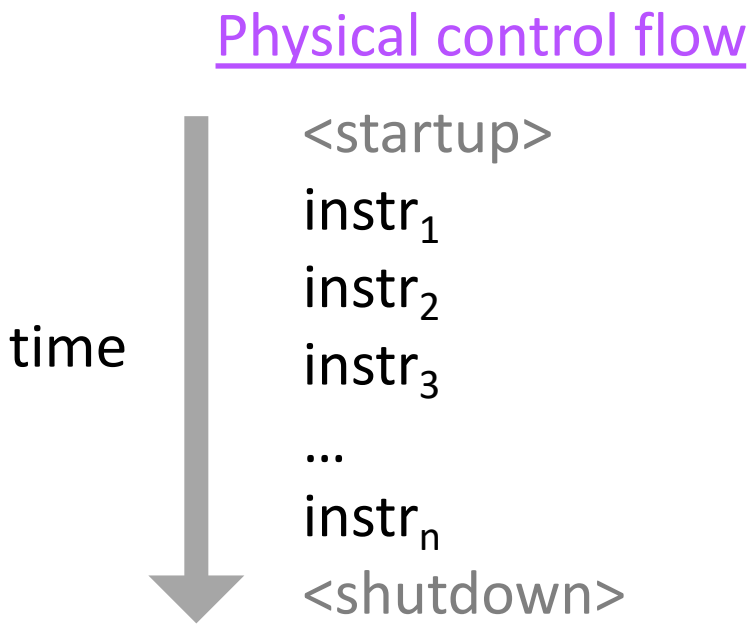
- System Control Flow
  - **Control flow**
  - **Exceptional control flow**
  - Asynchronous exceptions (interrupts)
  - Synchronous exceptions (traps & faults)

Control Flow

- **So far:** we've seen how the flow of control changes as a single program executes, mainly within the program.
- **Reality:** multiple programs running concurrently
  - How does control flow across the many components of the system?
  - In particular: We usually have 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**



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 (important later!)
- Can jumps and procedure calls achieve this?
  - No – the system needs mechanisms for *"exceptional"* control flow!

Before, we've been operating in a world where everything comes from within a program, but now we have to think about what happens outside the program.

Exceptional Control Flow

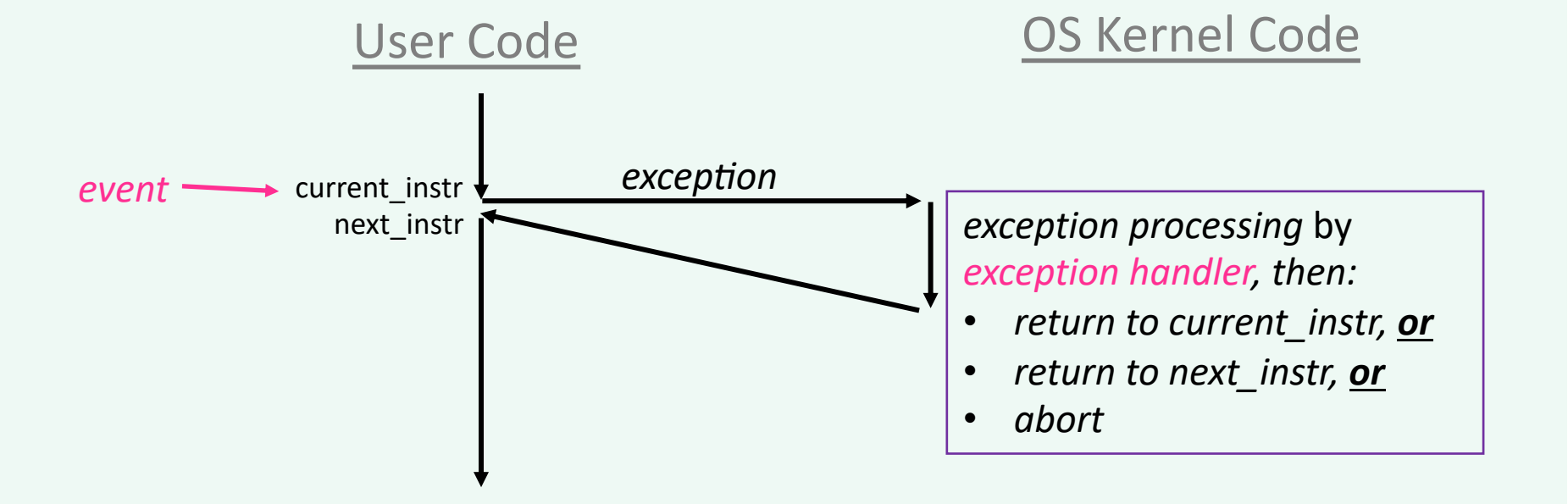
🚨 These are unrelated to Java's exceptions. 🚨

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 in detail—see CSE 451 and EE/CSE 474

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 operating system code that **lives in memory, very VIP**
  - Examples: division by 0, page fault, I/O request completes, Ctrl-C

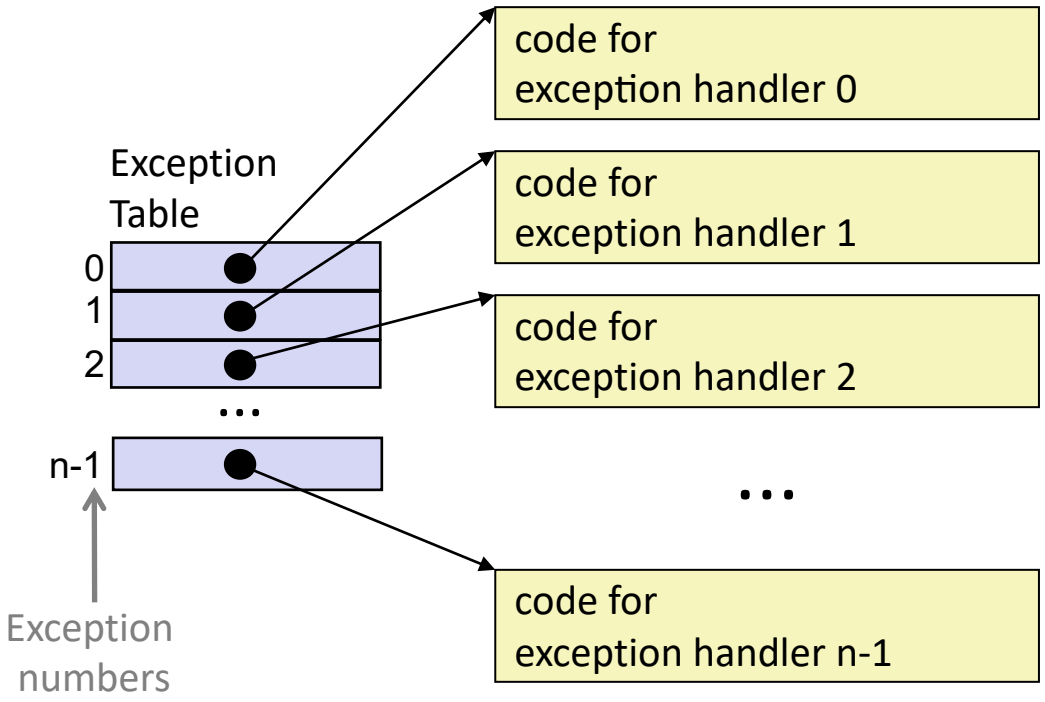


- How does the system know where to jump to in the OS?

This is extra (non-testable) material

Exception Table

- 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 (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** *(why is it called this?)*
    - **Intentional**: transfer control to OS to perform some function
    - Examples: *system calls*, breakpoint traps, special instructions
    - Returns control to "next" instruction, because we wanted it to happen ❤️
  - **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 the current program

System Calls

These are **not** the same as exception numbers!

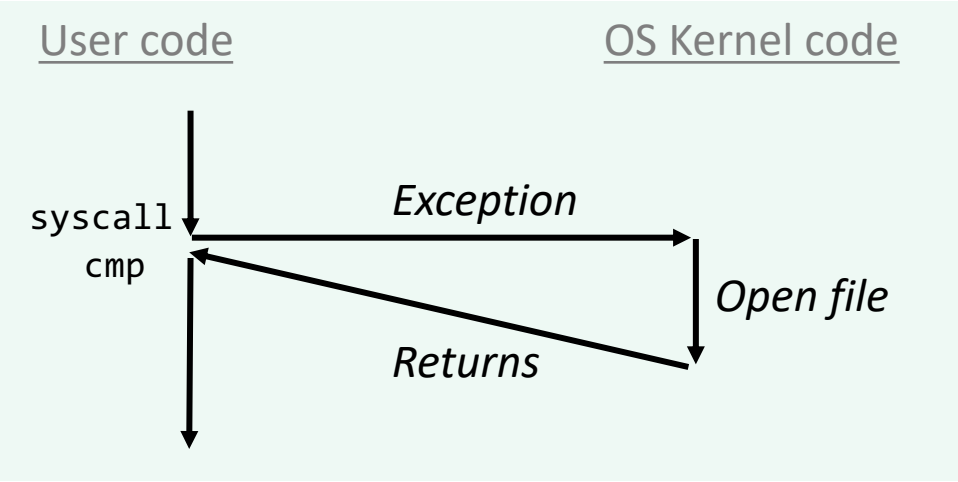
- Each system call has a unique ID number
- Examples for Linux on x86-64:

	Number	Name	Description
Files	0	`read`	Read file
	1	`write`	Write file
	2	`open`	Open file
	3	`close`	Close file
	4	`stat`	Get info about file
Processes	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`

```
00000000000e5d70 <__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
```



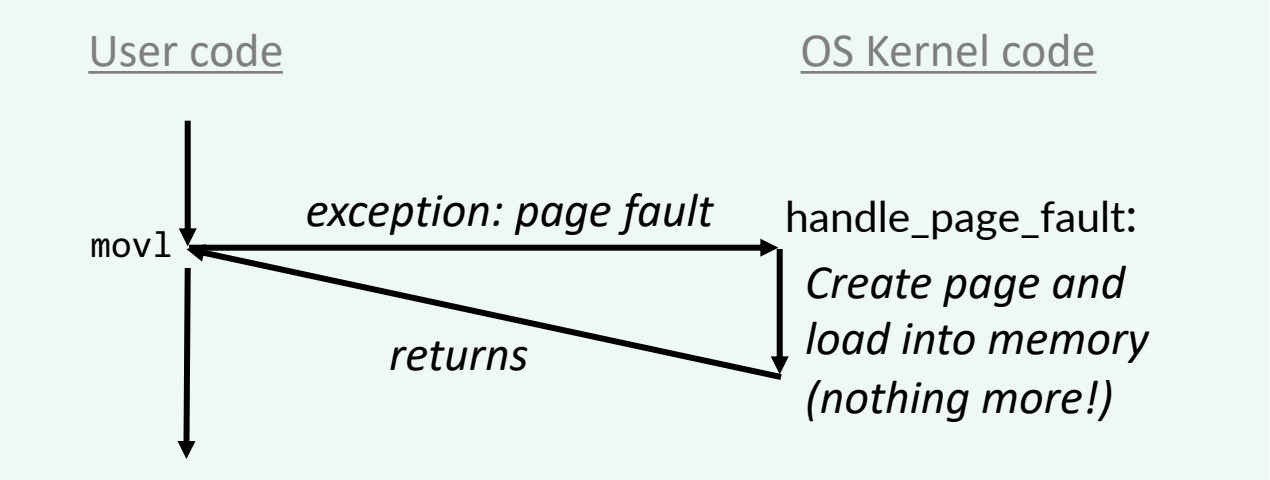
- `%(r|e)ax` contains syscall number (weird…)
- Other arguments in `%rdi`, `%rsi`, `%rdx`, `%r10`, `%r8`, `%r9`
- Return value in `%rax`
- Negative value is an error corresponding to negative `errno`

Fault Example: Page Fault

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

- User writes to memory location
- That portion (page) of user's memory is currently on disk and not in memory

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

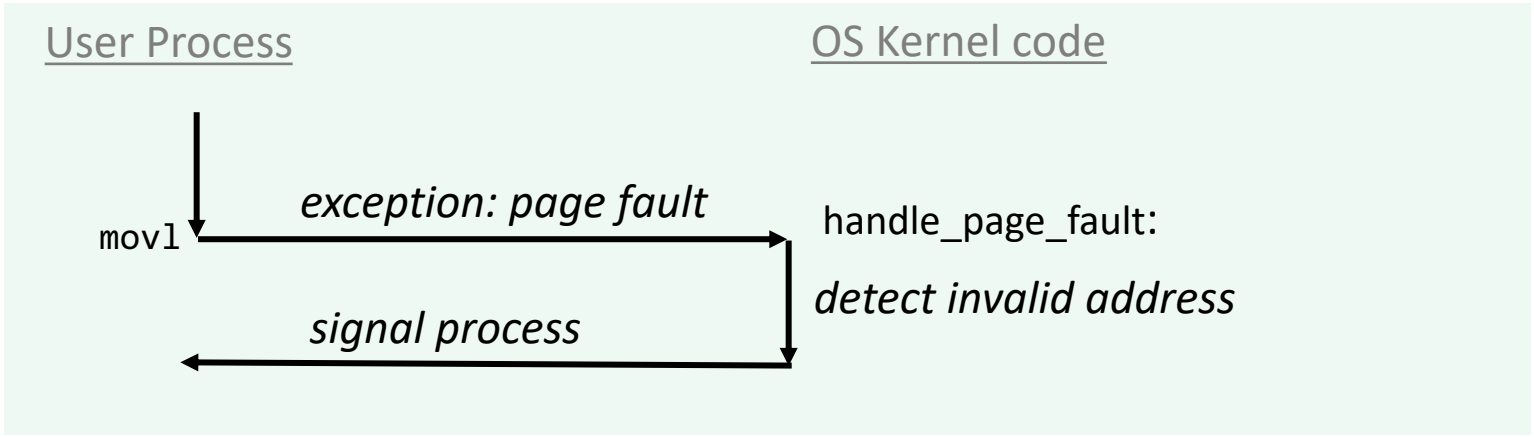


- Page fault handler must load page into physical memory
- Returns to faulting instruction: `mov` **is executed again**!
  - Successful on second try

Abort Example: Invalid Memory Reference

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

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

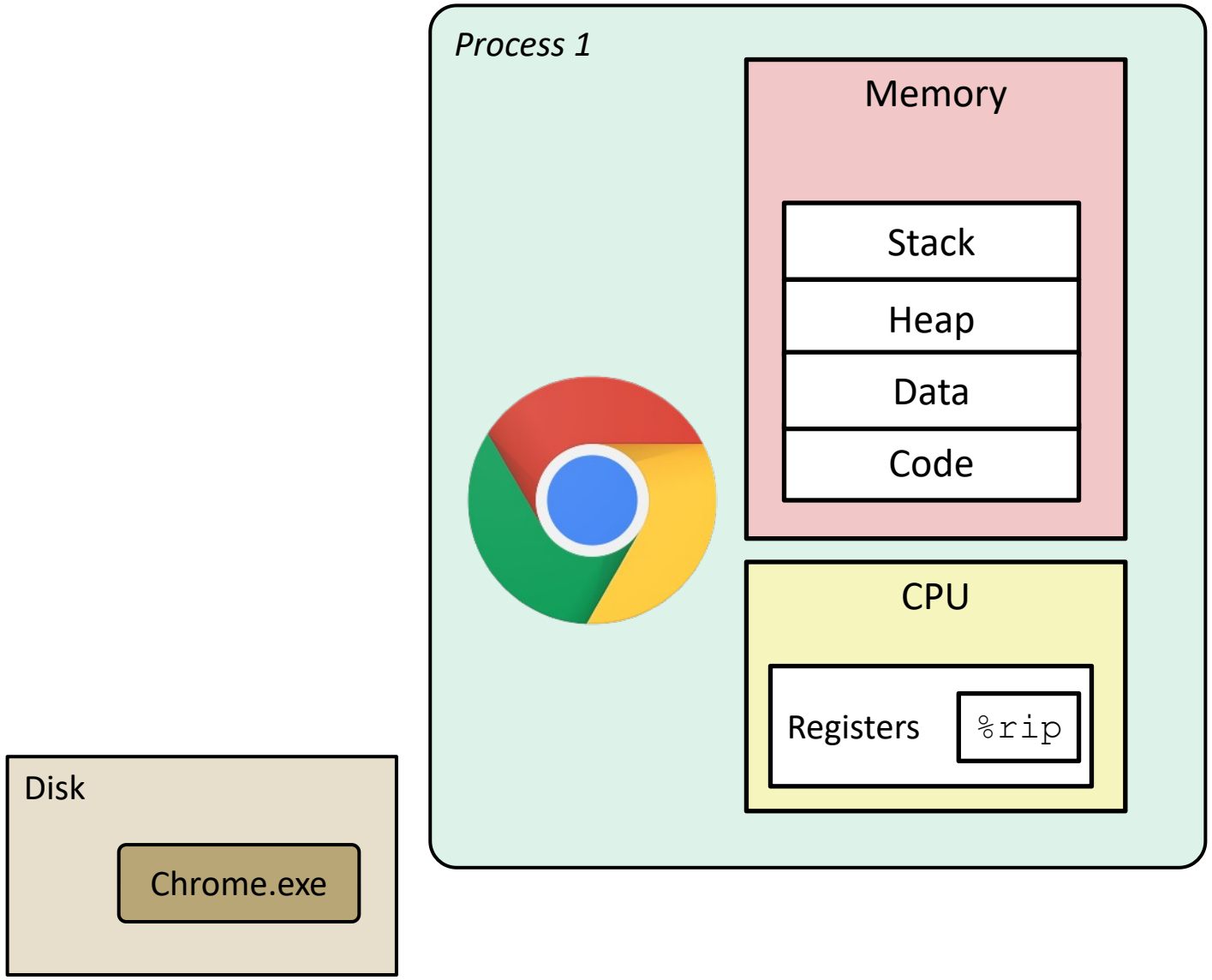


- Page fault handler detects invalid address
- Sends `SIGSEGV` signal to user process
- User process exits with "segmentation fault"

Processes

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

What is a process? (Review)



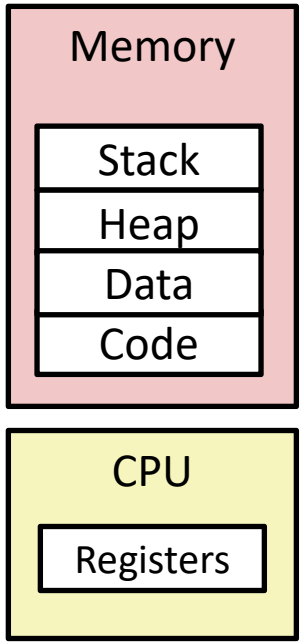
It's an illusion, though!

What is a process? (Review)

- A **process** is an **instance of a running program**
  - One of the most profound ideas in computer science
- Another abstraction in our computer
  - Provided by the OS
  - OS uses a data structure to represent each process (contains process ID (PID), etc.)
  - Maintains the **interface** between the program and the underlying hardware (CPU + memory)
- What is the difference between:
  - A processor? A program? A process?

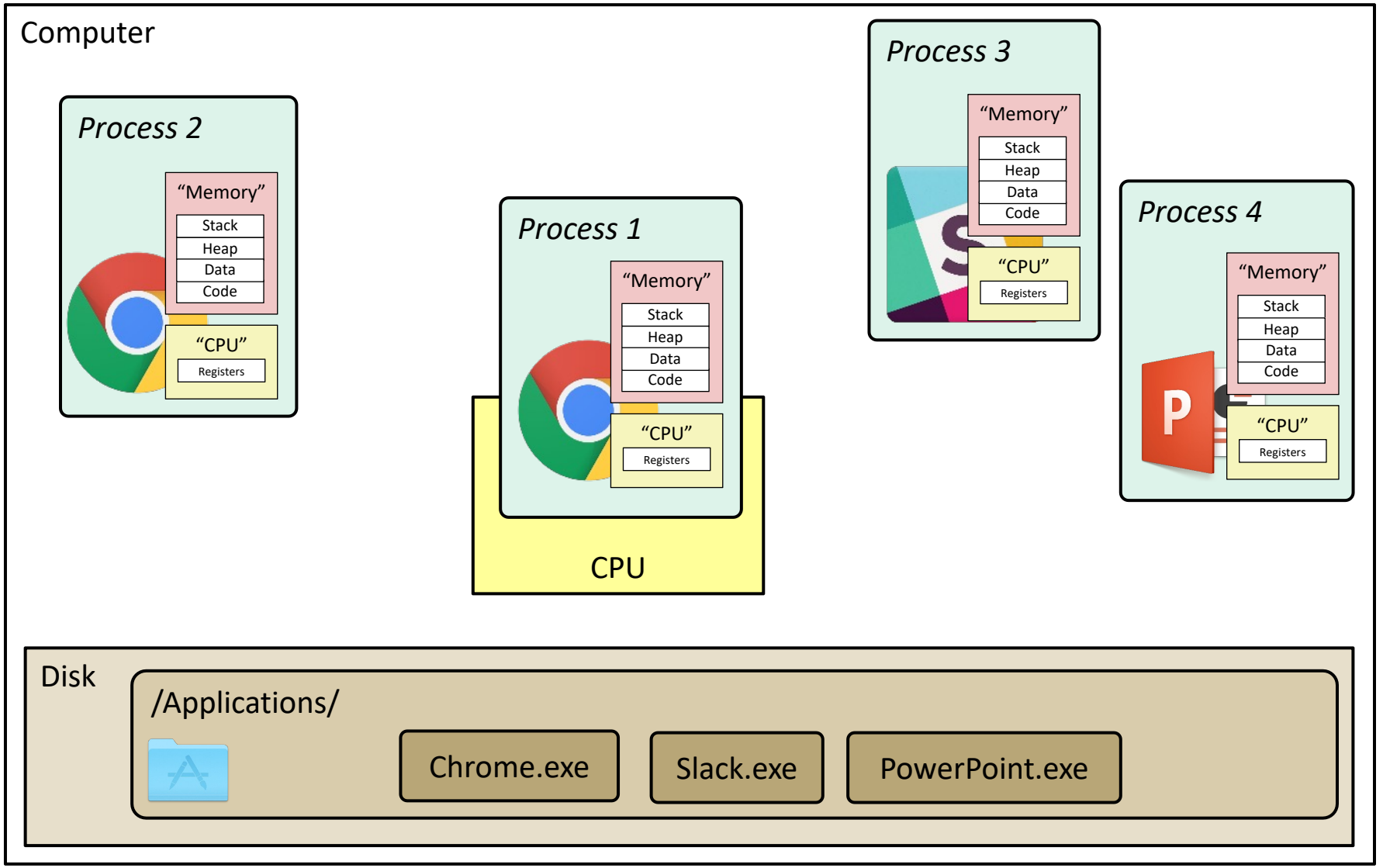
Processes (Review)

- 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 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



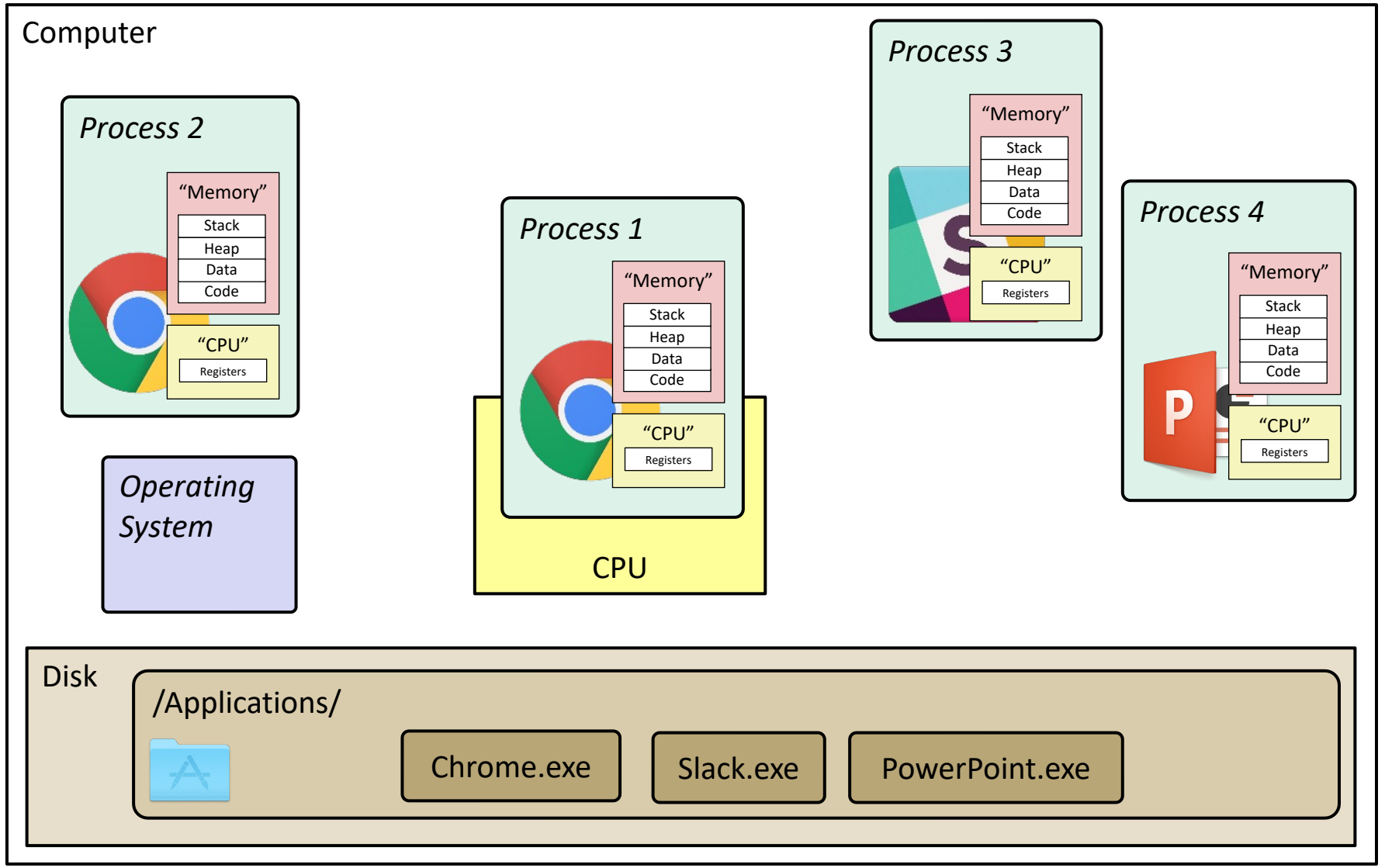
What is a process?

It's an *illusion*!

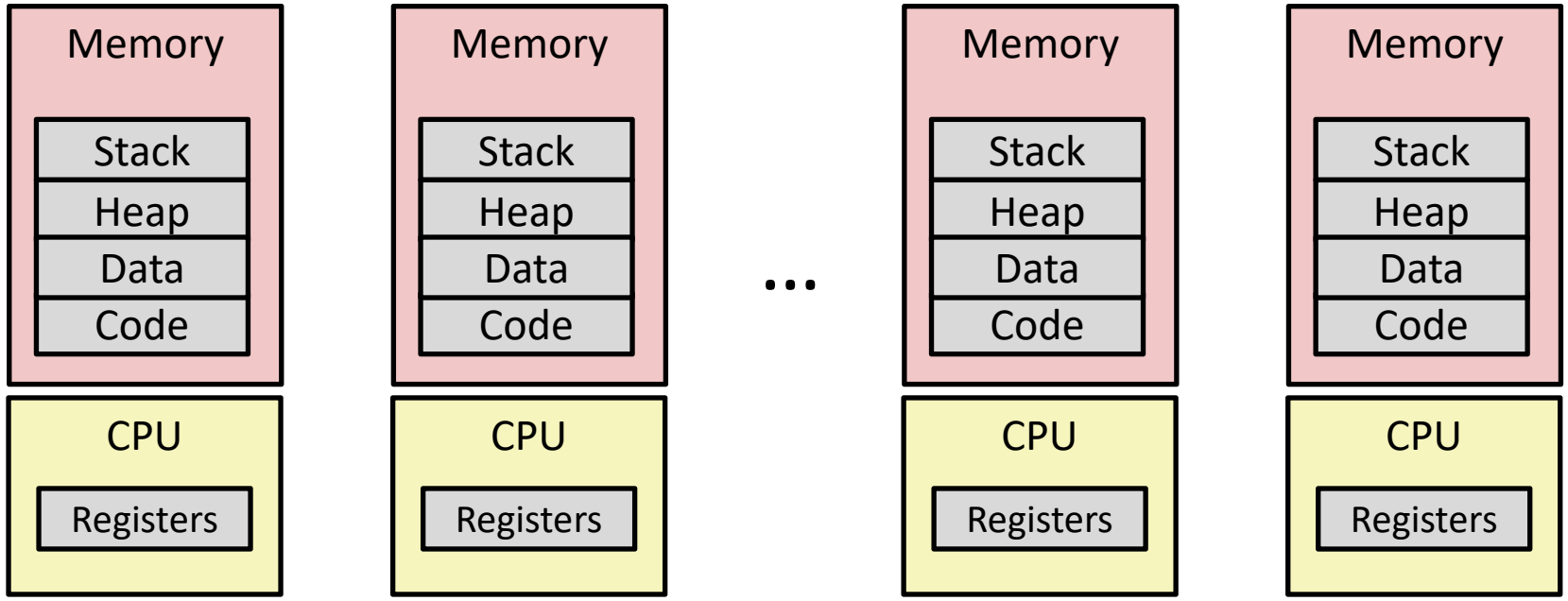


What is a process?

It's an *illusion*!

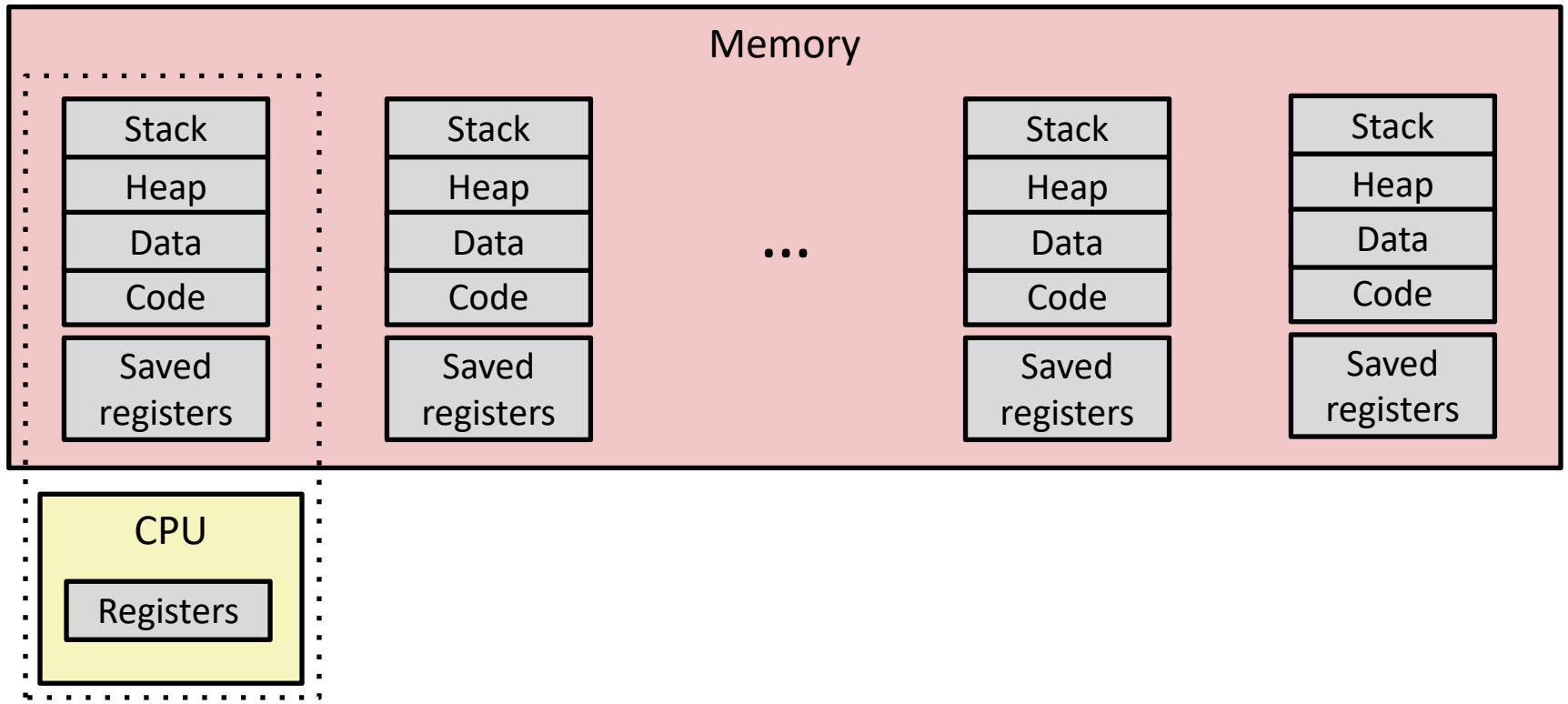


Multiprocessing: The Illusion



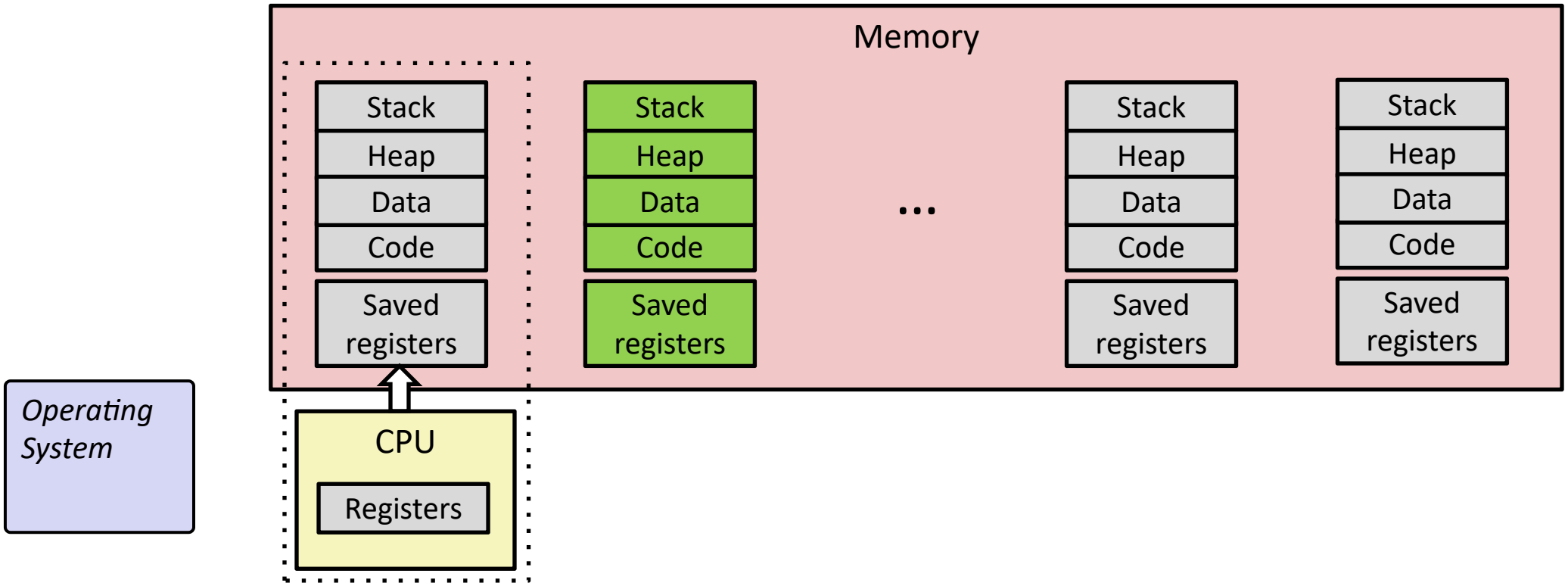
- Computer runs many processes simultaneously
  - Applications for one or more users
    - Web browsers, email clients, editors, …
  - Background tasks
    - Monitoring network & I/O devices

Multiprocessing: The Reality



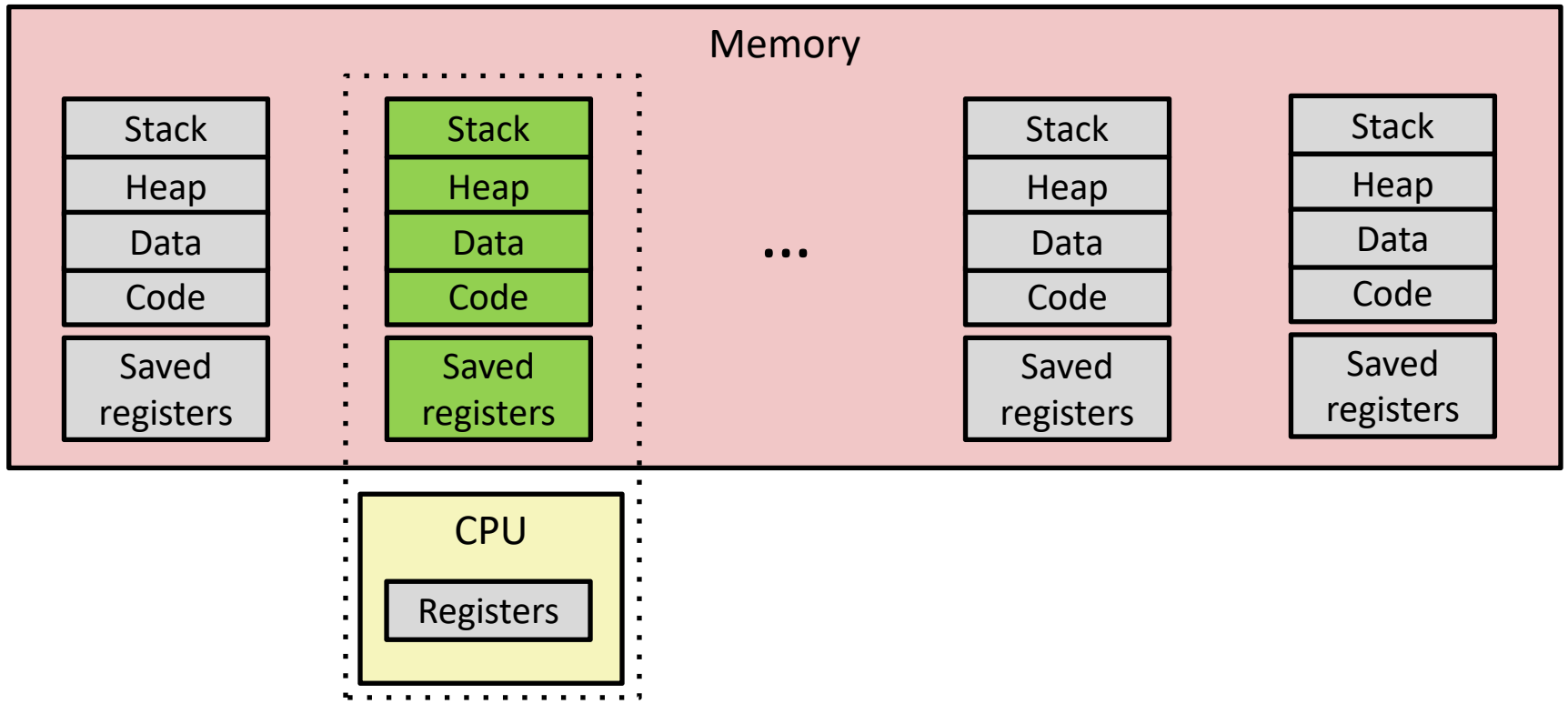
- Single processor executes multiple processes concurrently
  - Process executions interleaved, CPU runs *one at a time*
  - Address spaces managed by virtual memory system (we'll get to it!)
  - **Execution context** (register values, stack, …) for other processes saved in memory

Multiprocessing (Review)



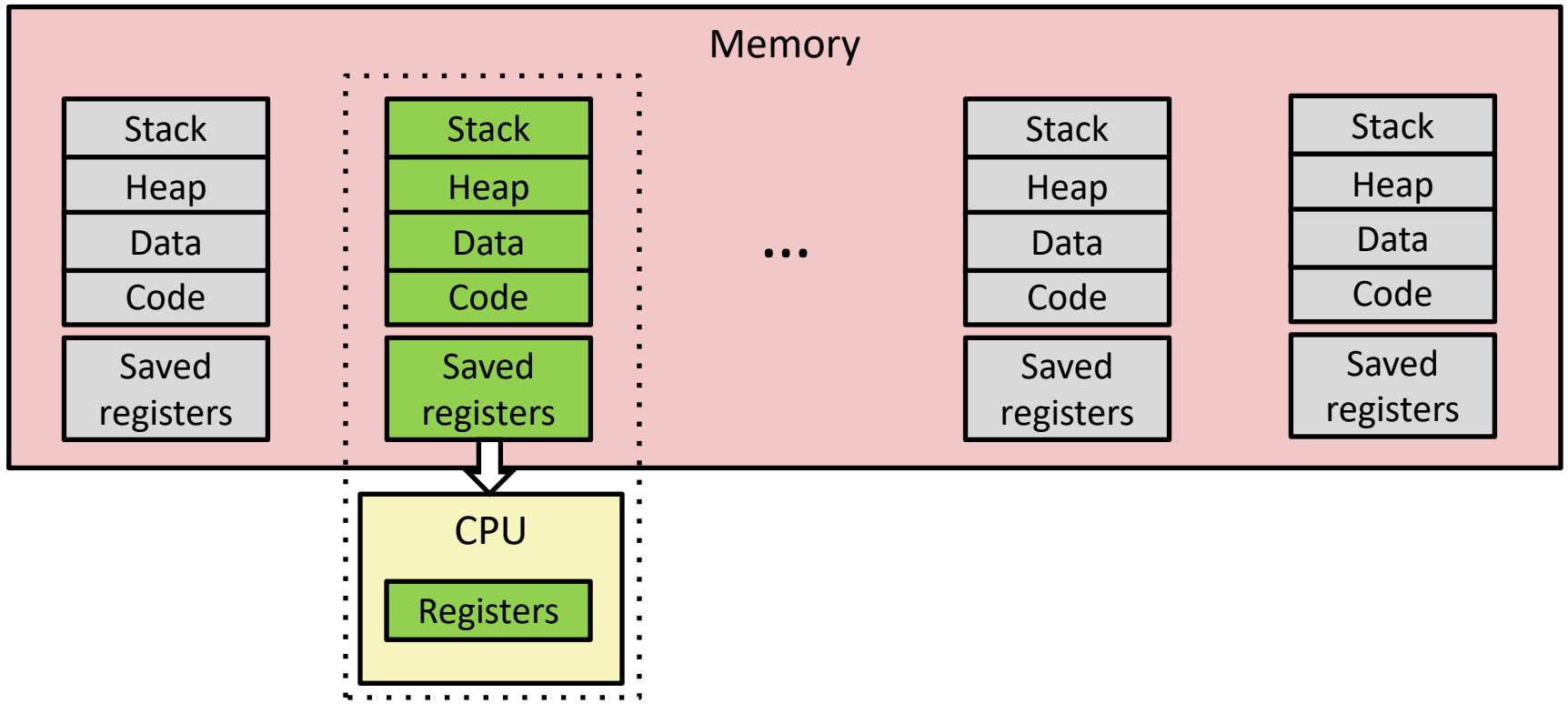
- Context switch
  1) **Save current registers in memory**

Multiprocessing (Review)



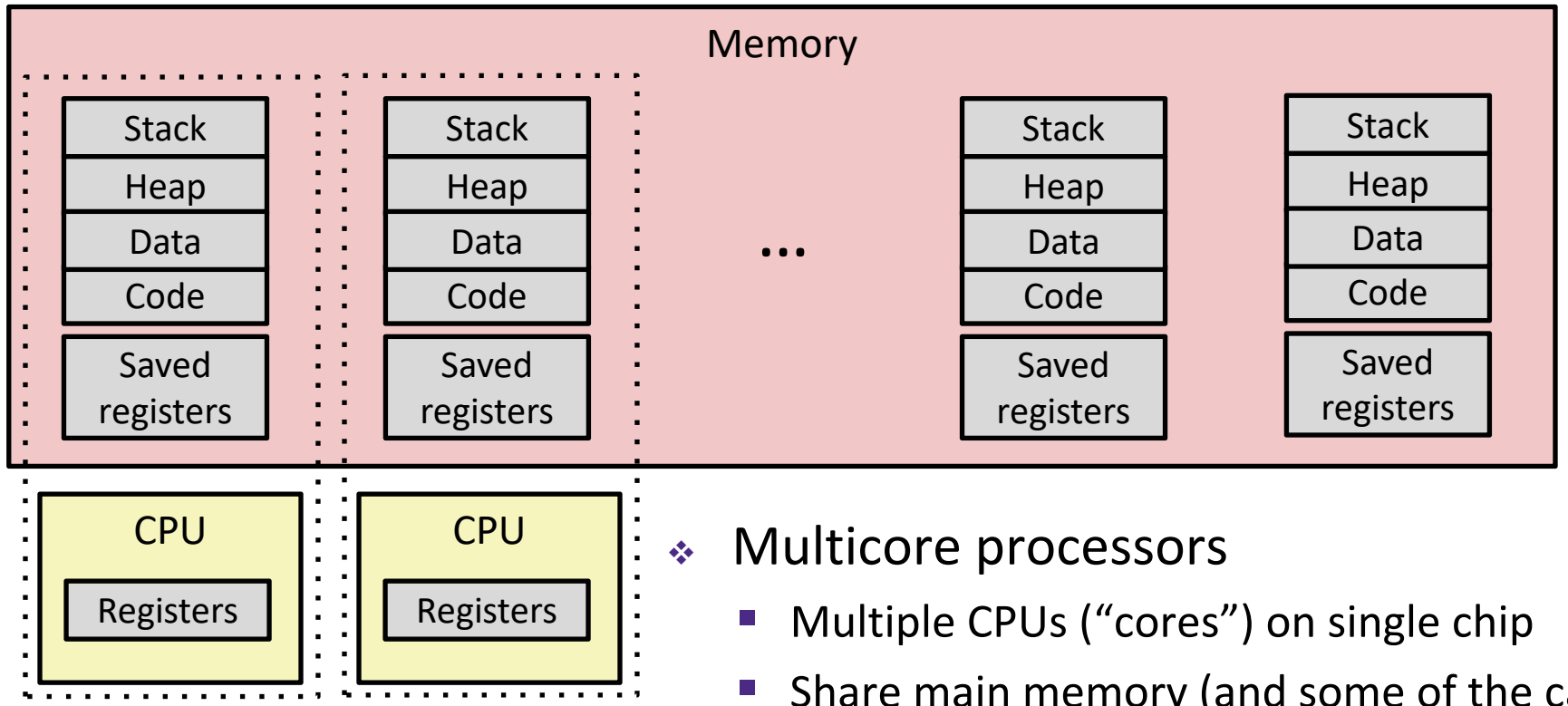
- Context switch
  1) Save current registers in memory
  2) **Schedule next process for execution**

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

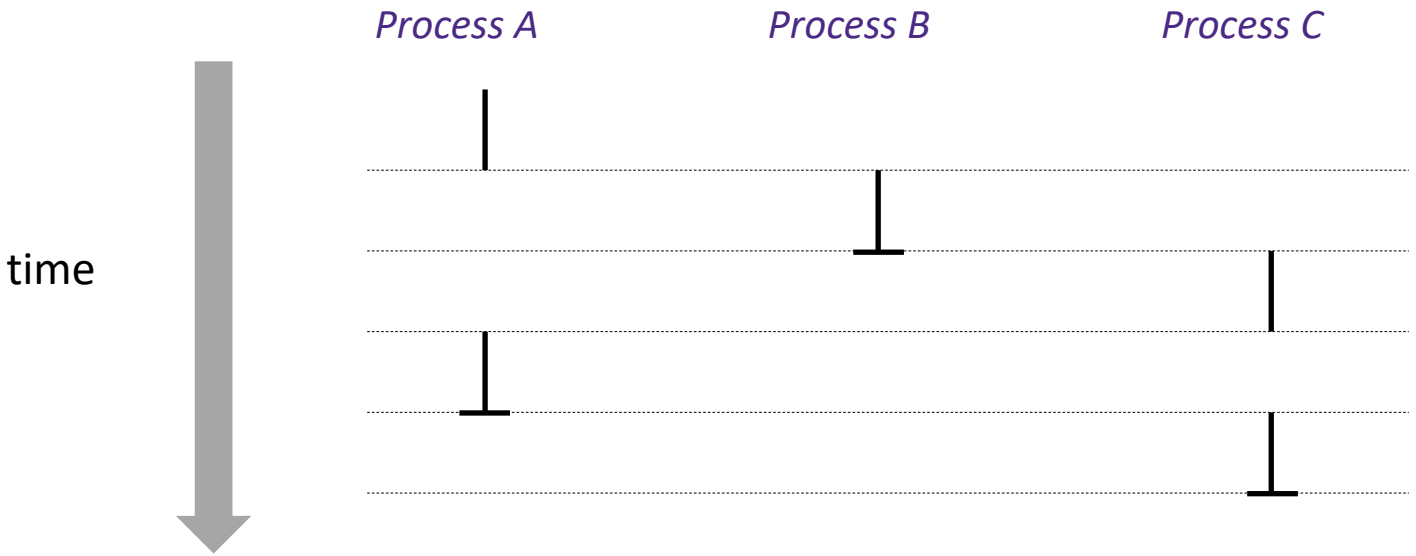


- Multicore processors
  - Multiple CPUs ("cores") on single chip
  - Share main memory (and some of the caches)
  - Each can execute a separate process
    - Kernel schedules processes to cores
    - **Still constantly swapping processes**

Concurrent Processes

Assume only one CPU core

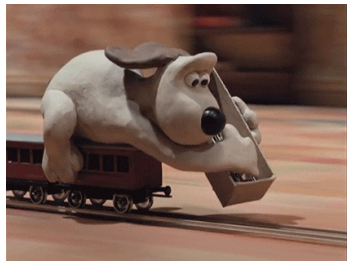
- Each process is a logical control flow
- Two processes run **concurrently** (are concurrent) if their instruction executions/flows overlap in time
  - Otherwise, they are **sequential**
- **Example**: (running on single core)
  - Concurrent: A & B, A & C
  - Sequential: B & C



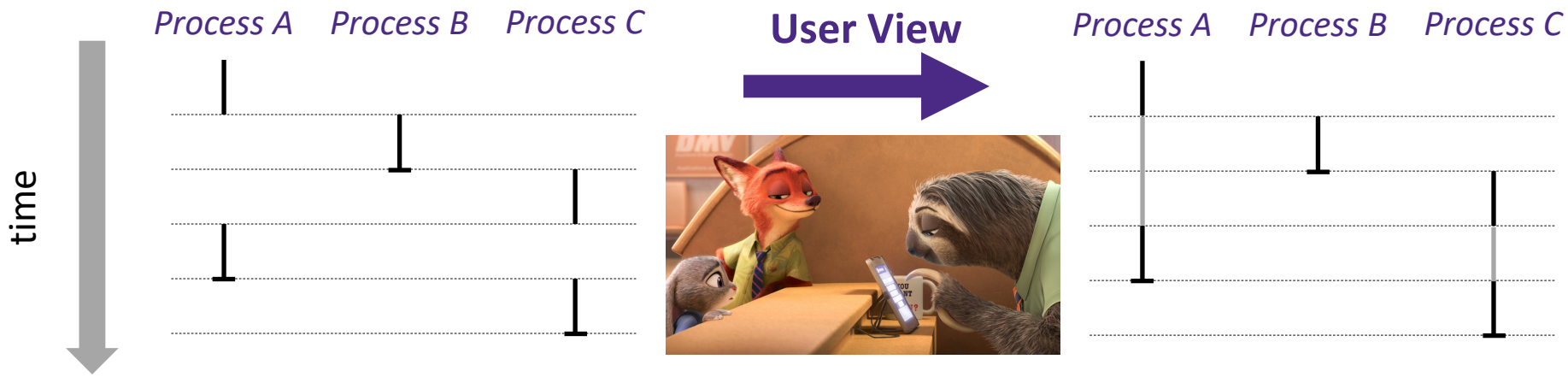
User's View of Concurrency

Assume only one CPU core

- 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

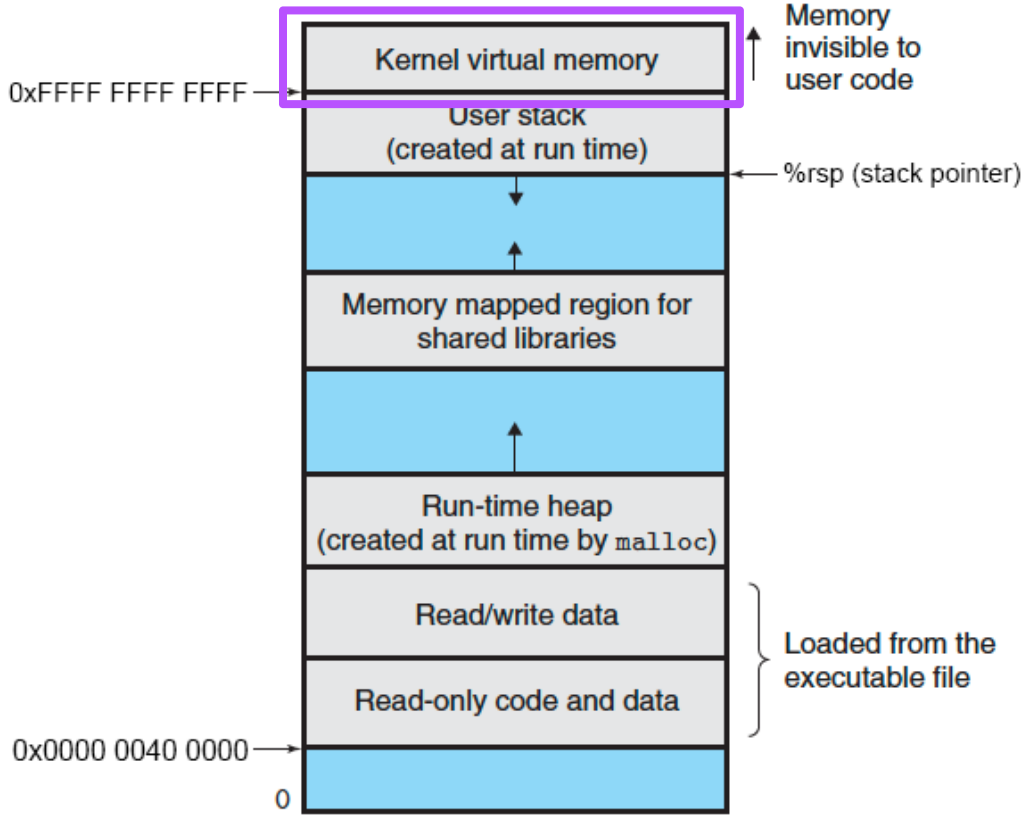


Context Switching

Assume only one CPU core

- 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*

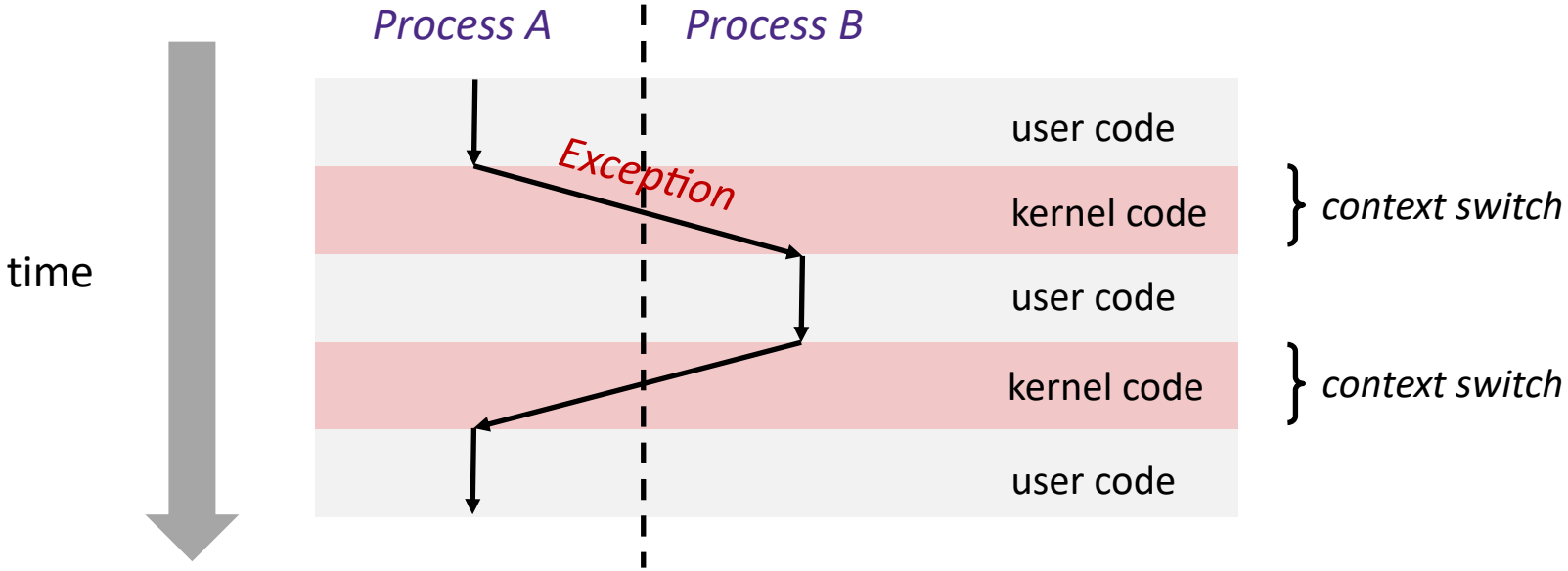


* sort of, the story here became more complicated after Meltdown and Spectre…

Context Switching (Review)

Assume only one CPU core

- 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



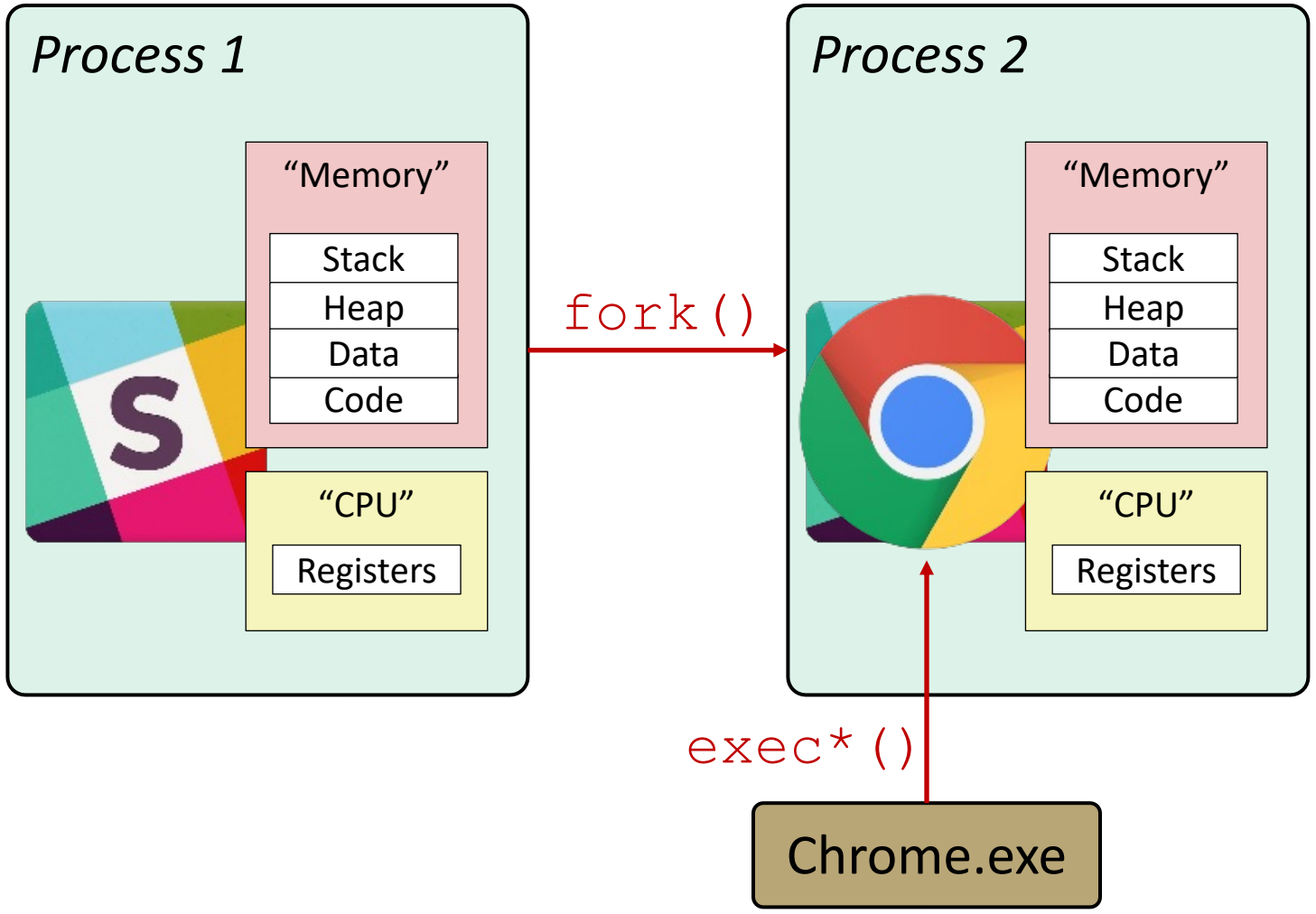
Processes & Context Switching Summary

- 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

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"

Summary

- Exceptions
  - Events that require non-standard control flow
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