Processes

CSE 351 Autumn 2024

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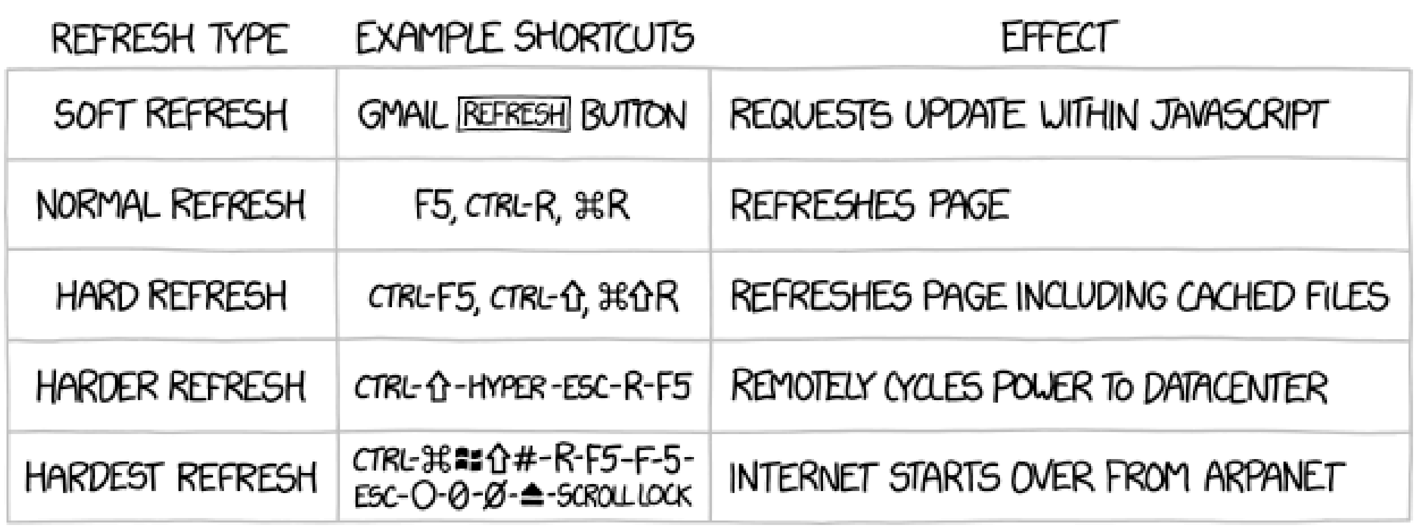


http://xkcd.com/1854/

Relevant Course Information

- HW21 due Tonight, Wednesday (11/20) @ 11:59 pm
- Lab 4 due Friday (11/22) @ 11:59 pm
  - Cache parameter puzzles and code optimizations
- HW22 due Friday (11/22) @ 11:59 pm
- HW23 due Monday (11/25) @ 11:59 pm
- Lab 5 (on Mem Alloc) coming soon!
  - The most significant amount of C programming you will do in this class – combines lots of topics from this class: pointers, bit manipulation, structs, examining memory
  - Understanding the concepts *first* and efficient *debugging* will save you lots of time
  - Light style grading

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

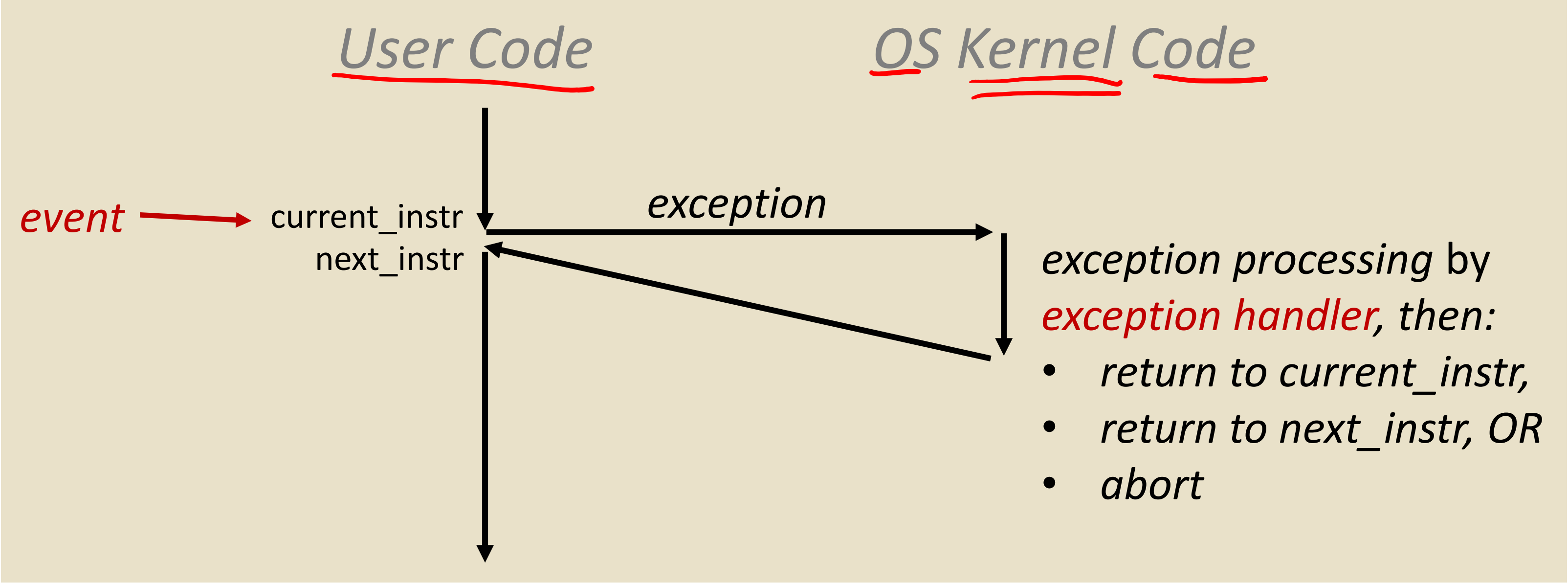
- Up to now, two ways to change control flow:
  - Jumps (conditional and unconditional)
  - Call and return
  - Both react to changes in *program state*
- Processor also needs to react to changes in *system state*
  - Unix/Linux user hits “Ctrl-C” at the keyboard
  - User clicks on a different application’s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



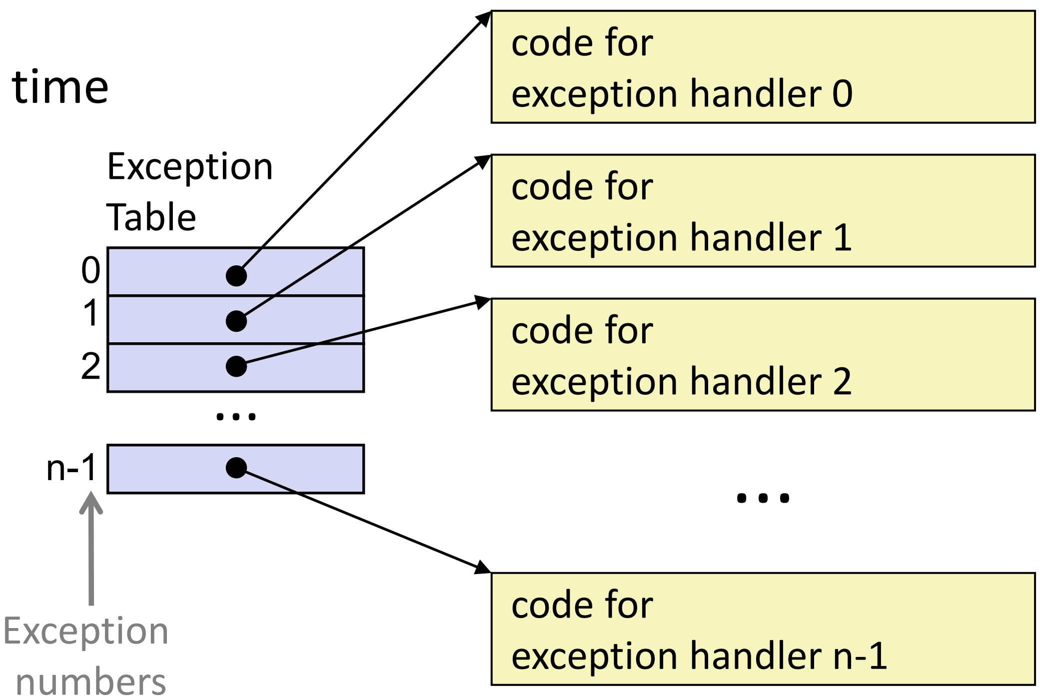
- *How does the system know where to jump to in the OS?*

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

like a jump table in a switch statement



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

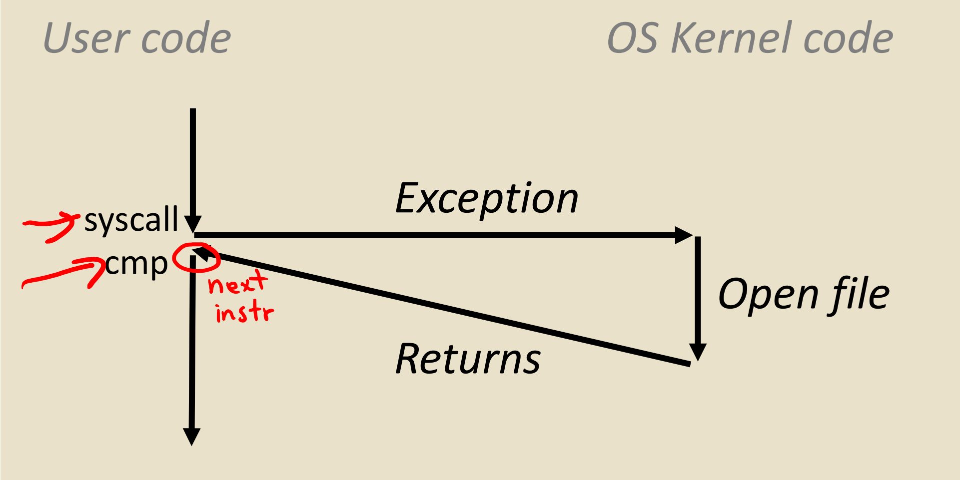
- Each system call has a unique ID number
- Examples for Linux on x86-64:

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`

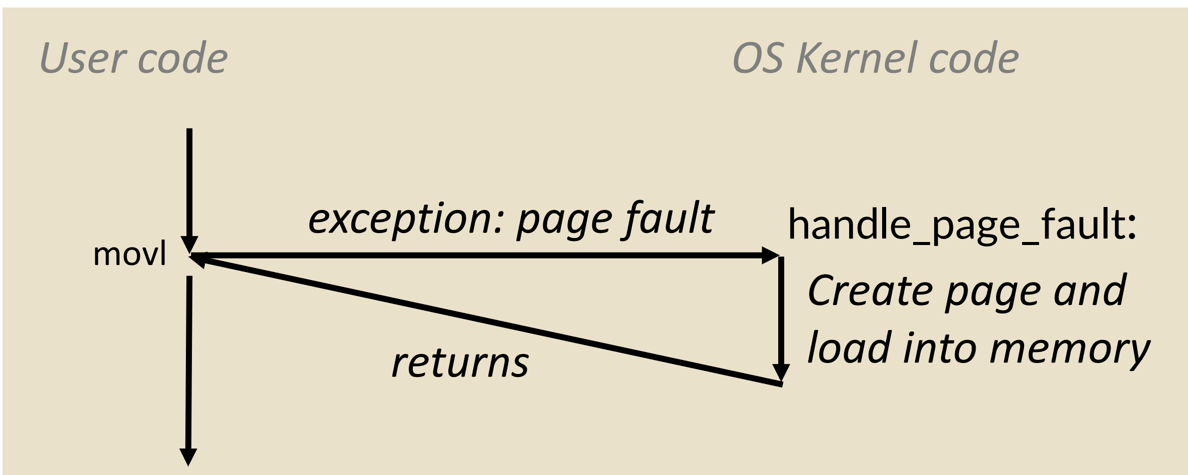
Fault Example: Page Fault

- 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

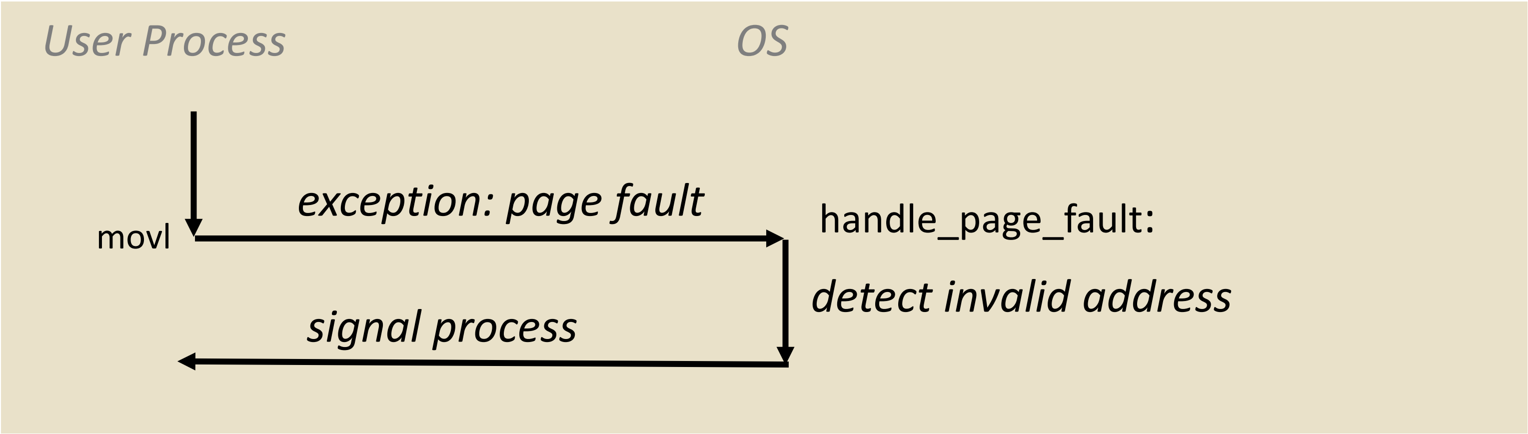


- Page fault handler must load page into physical memory
- Returns to faulting instruction: `mov` is executed again!
  - Successful on second try

Fault Example: Invalid Memory Reference

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

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



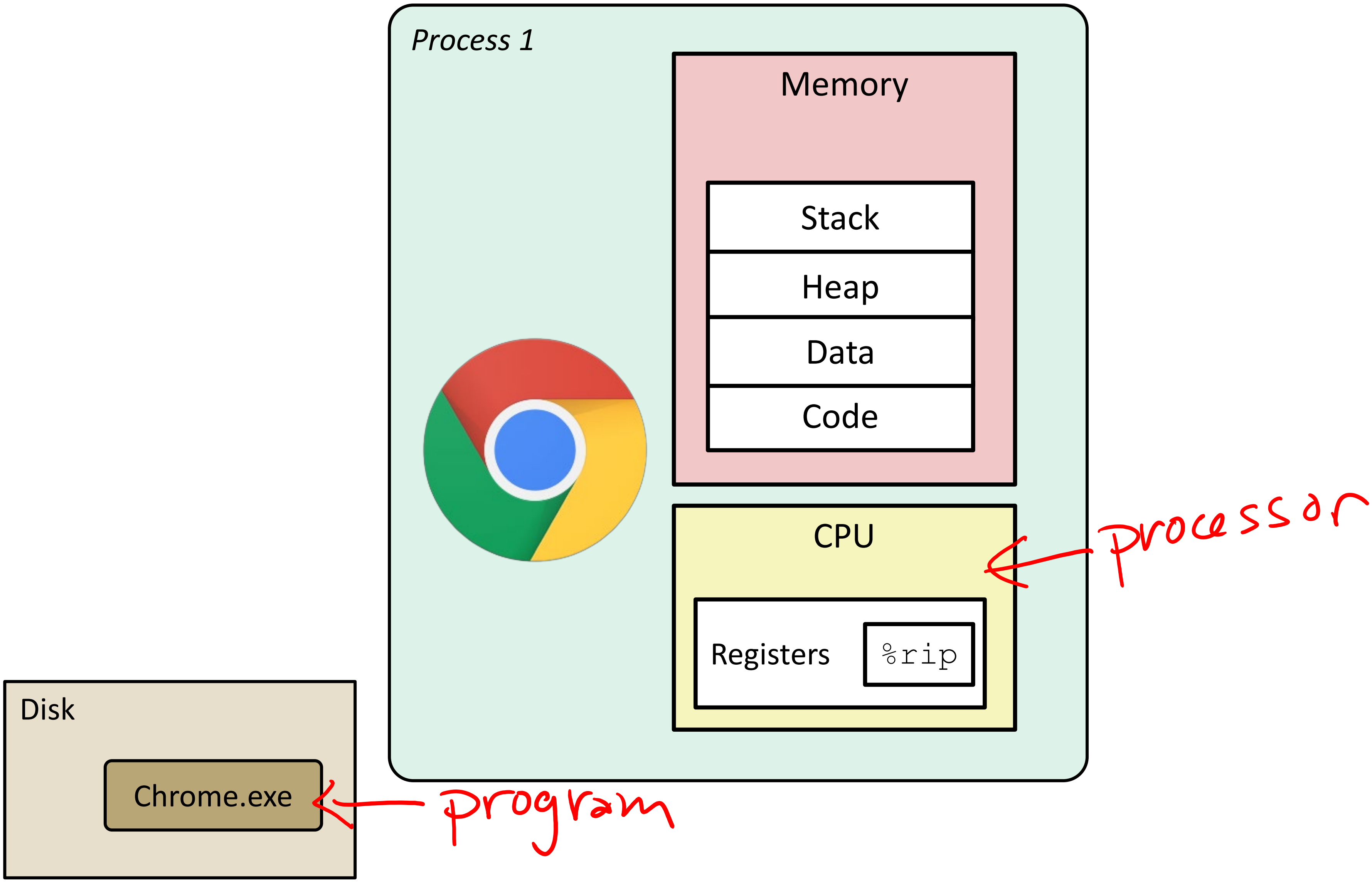
- Page fault handler detects invalid address
- Sends `SIGSEGV` signal to user process
- User process exits with “segmentation fault”

Processes

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

What is a process ? (Review)

It's an *illusion*!



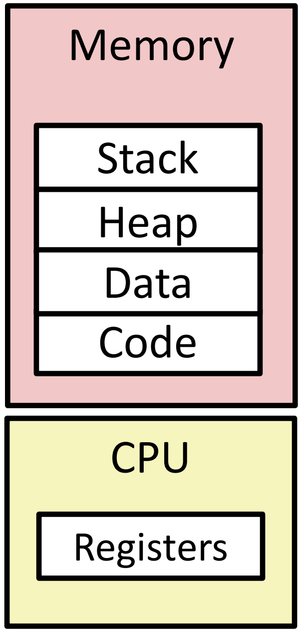
What is a process? (Review)

- 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)

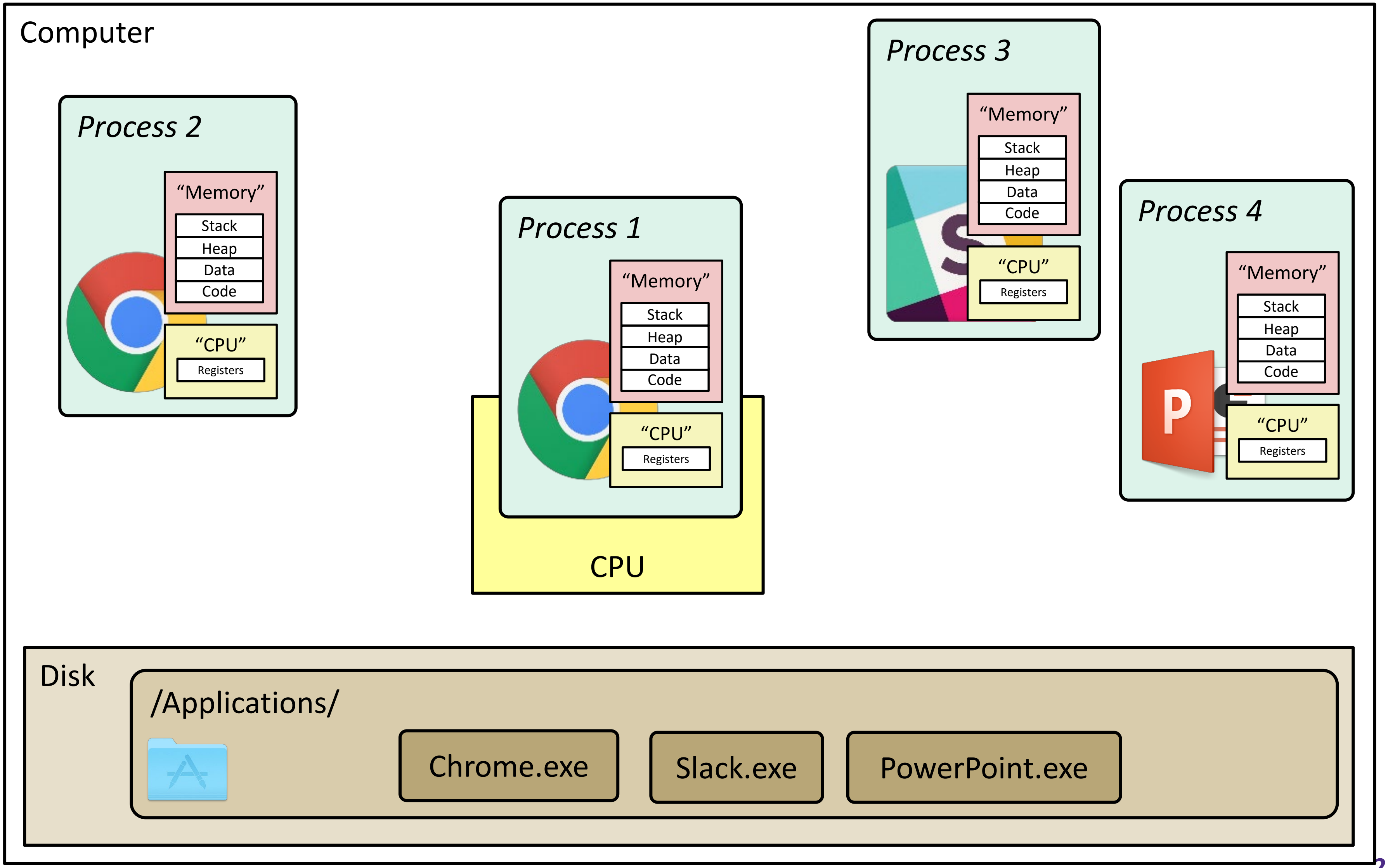
- A ***process*** is an instance of a running program
  - One of the most profound ideas in computer science

- 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***



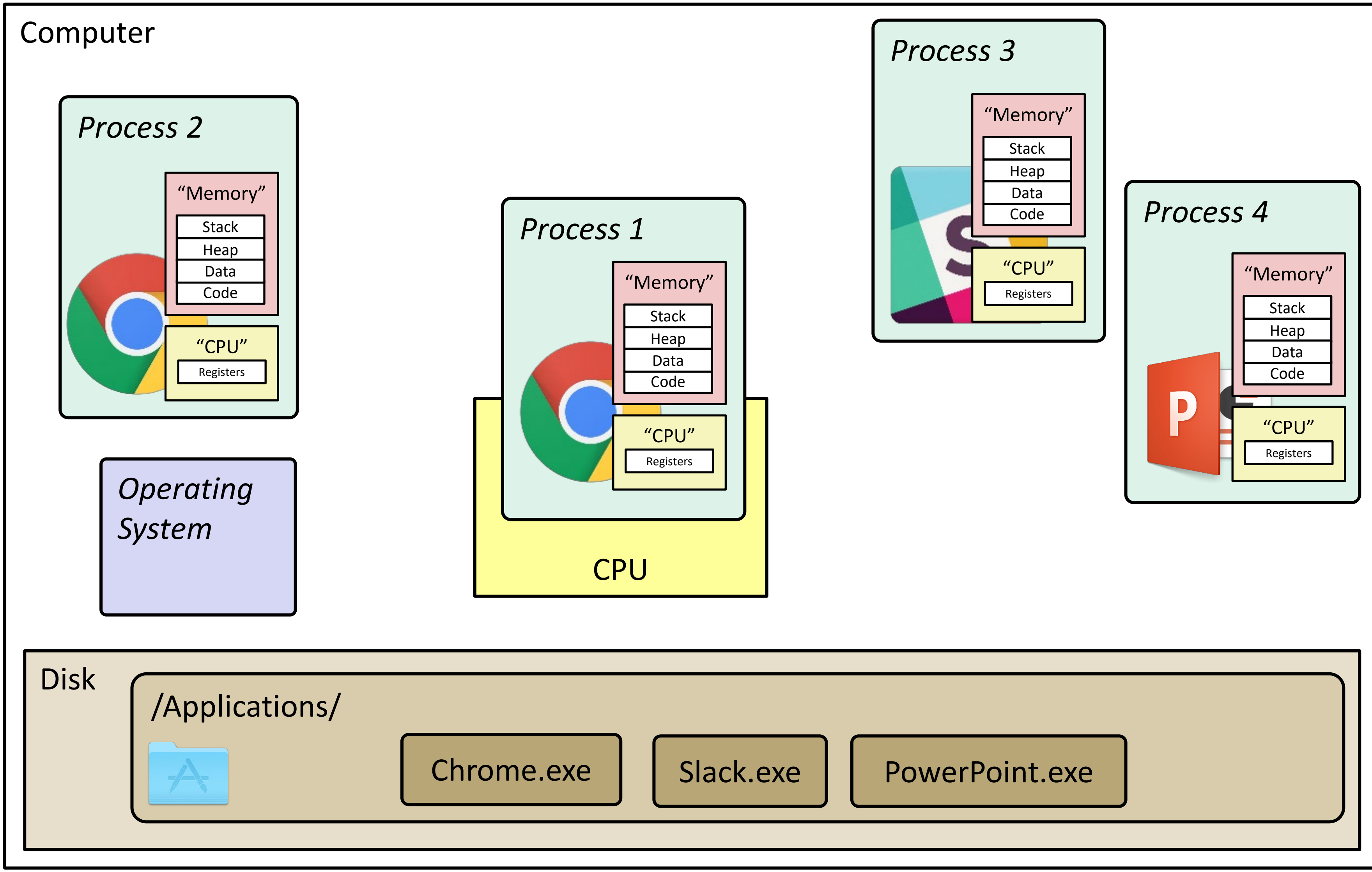
What is a process?

It's an *illusion*!

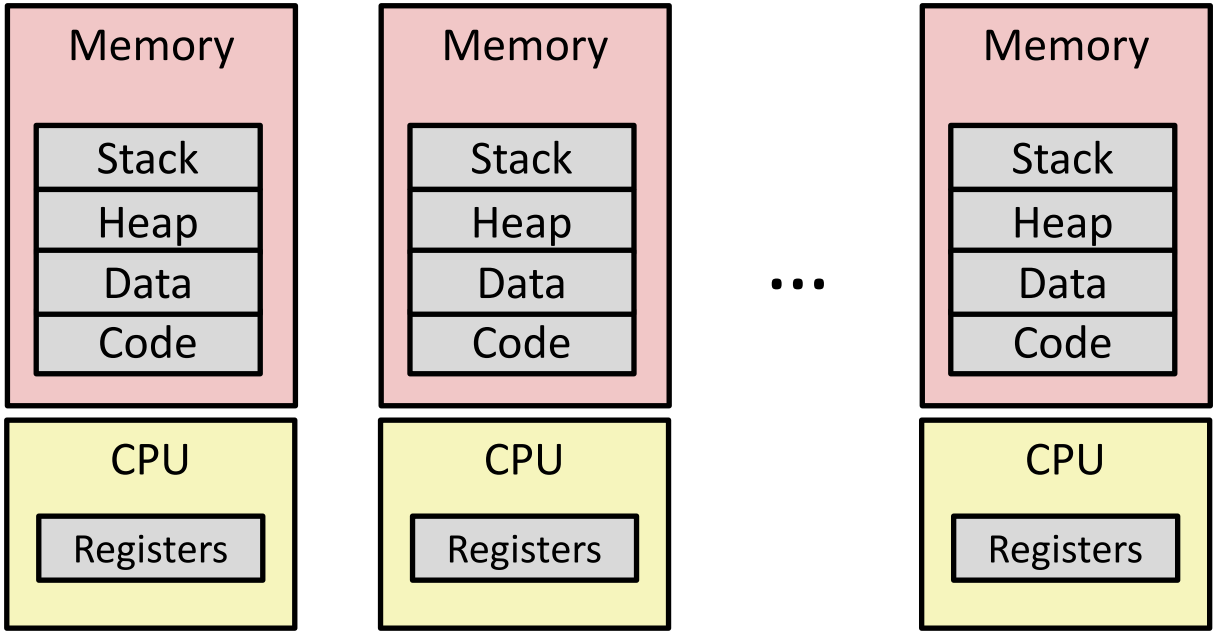


What is a process?

It's an *illusion*!



Multiprocessing: The Illusion

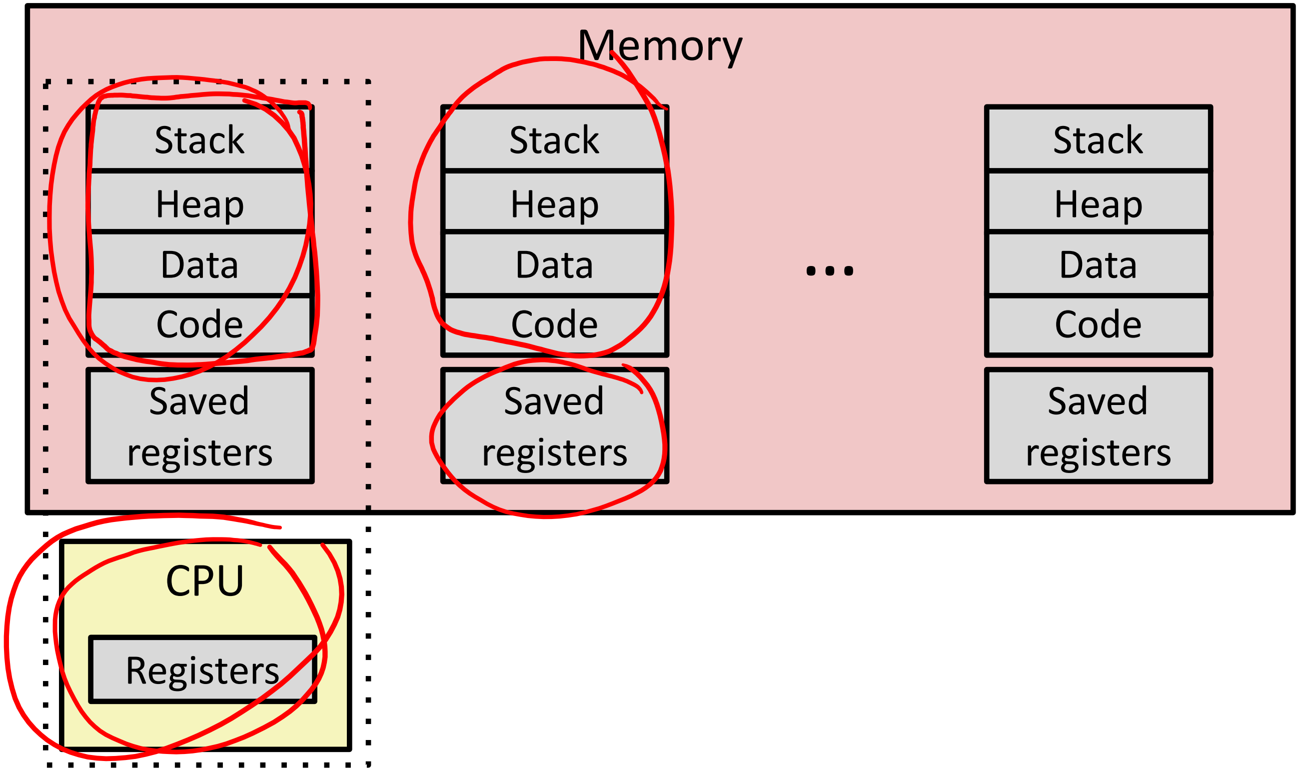


- Computer runs many processes simultaneously
  - Applications for one or more users
    - Web browsers, email clients, editors, …
  - Background tasks
    - Monitoring network & I/O devices

} user-level

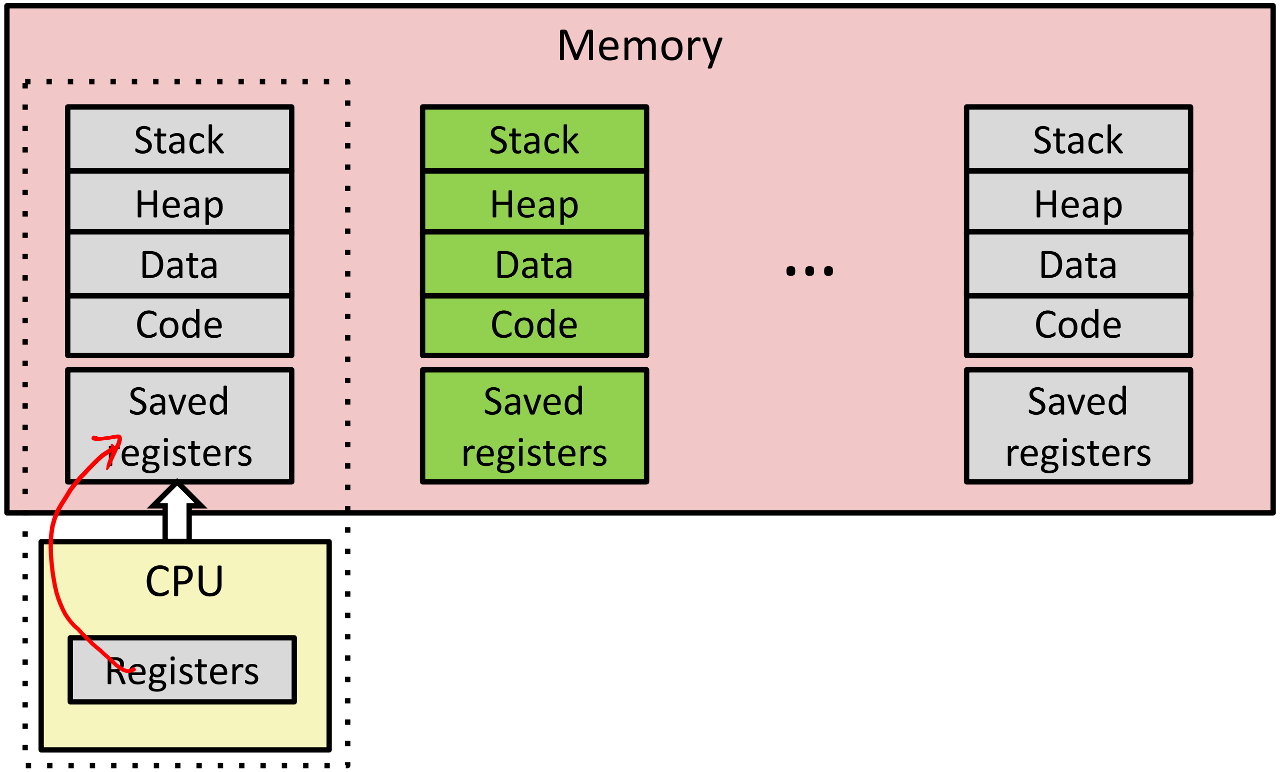
} mostly kernel/OS - level

Multiprocessing: The Reality



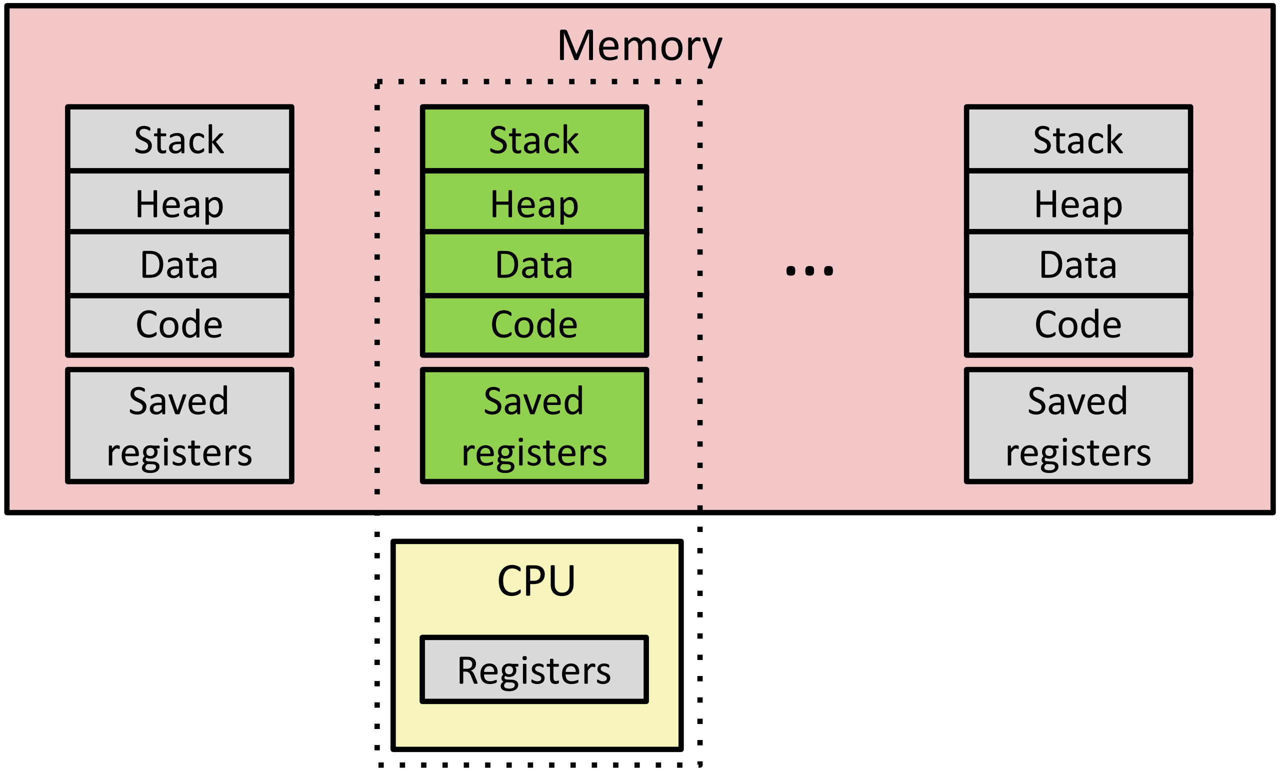
- Single processor executes multiple processes *concurrently*
  - Process executions interleaved, CPU runs *one at a time*
  - Address spaces managed by virtual memory system (later in course)
  - *Execution context* (register values, stack, …) for other processes saved in memory

Multiprocessing (Review)



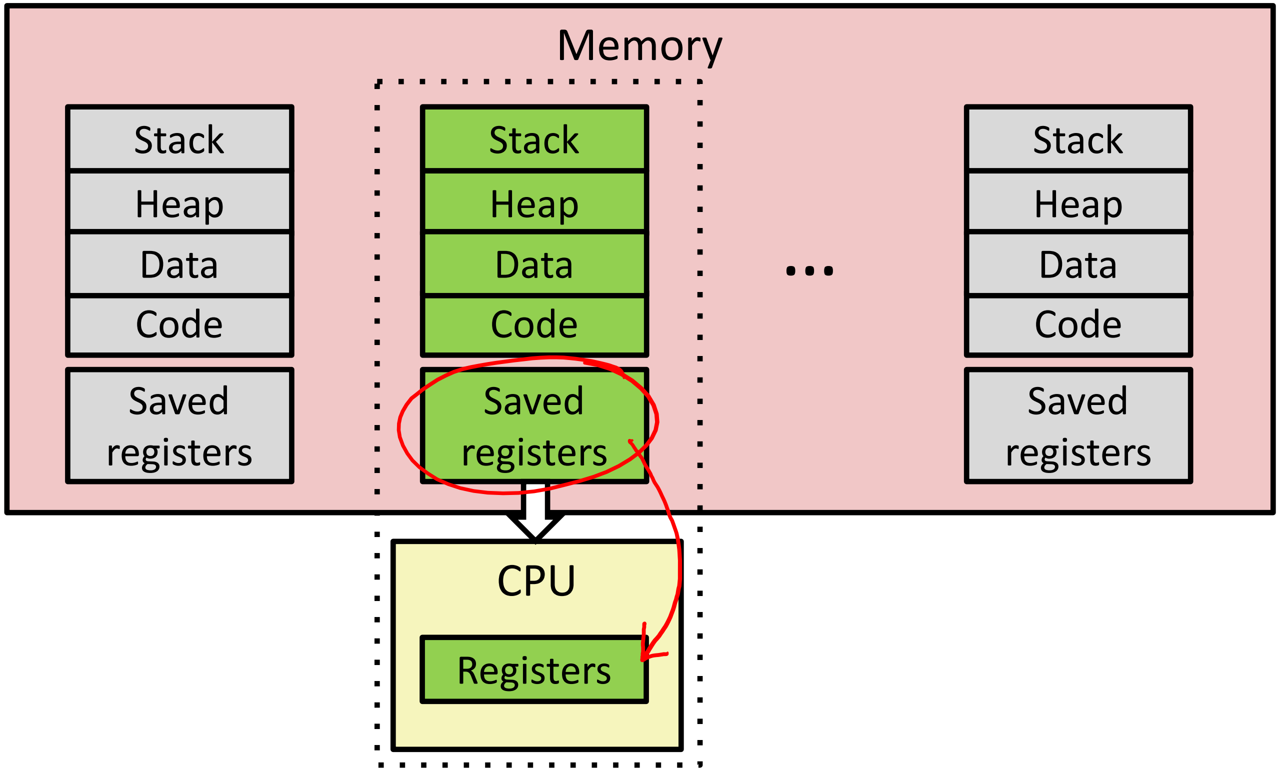
- Context switch
  1) Save current registers in memory

Multiprocessing (Review)



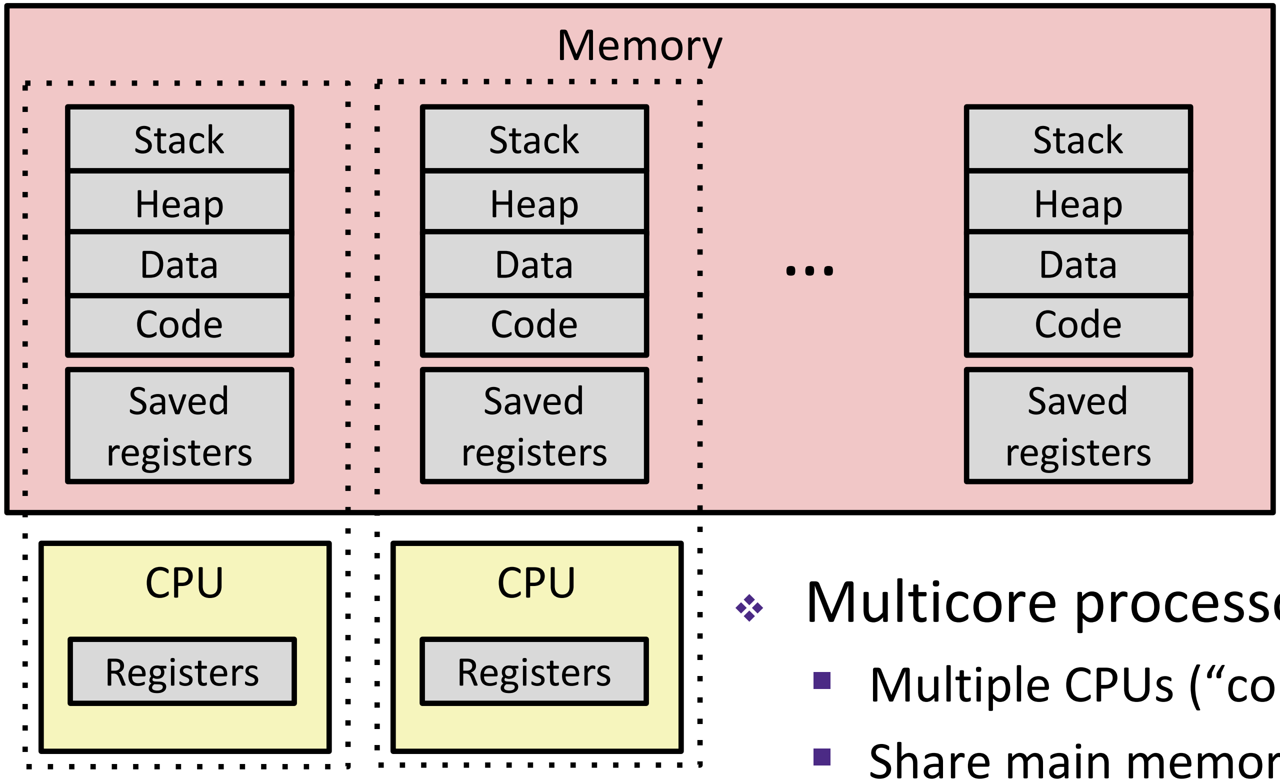
- Context switch
  1) Save current registers in memory
  2) **Schedule next process for execution** (OS decides)

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

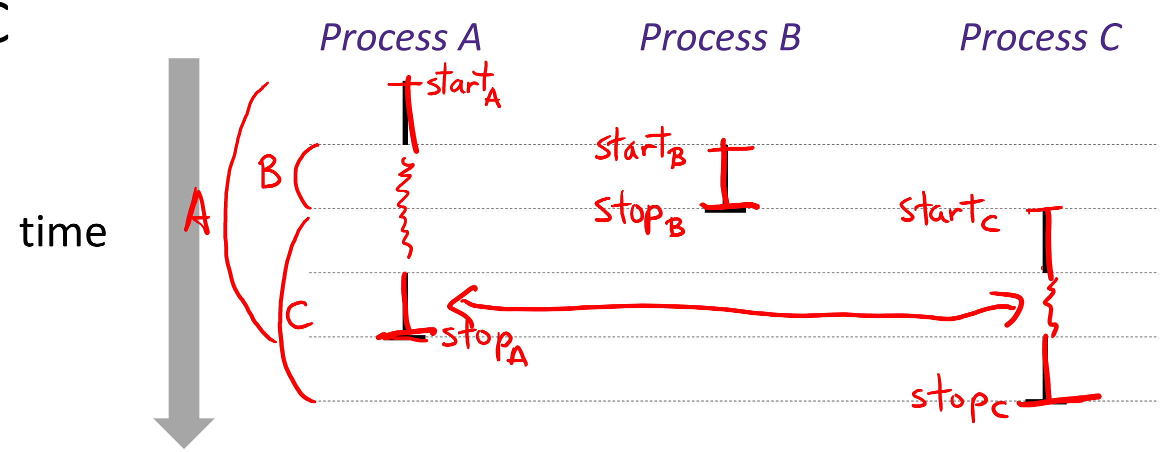


- Multicore processors
  - Multiple CPUs ("cores") on single chip
  - Share main memory (and some of the caches)
  - Each can execute a separate process
    - Kernel schedules processes to cores
    - ***Still* constantly swapping processes**

Concurrent Processes

Assume only one CPU

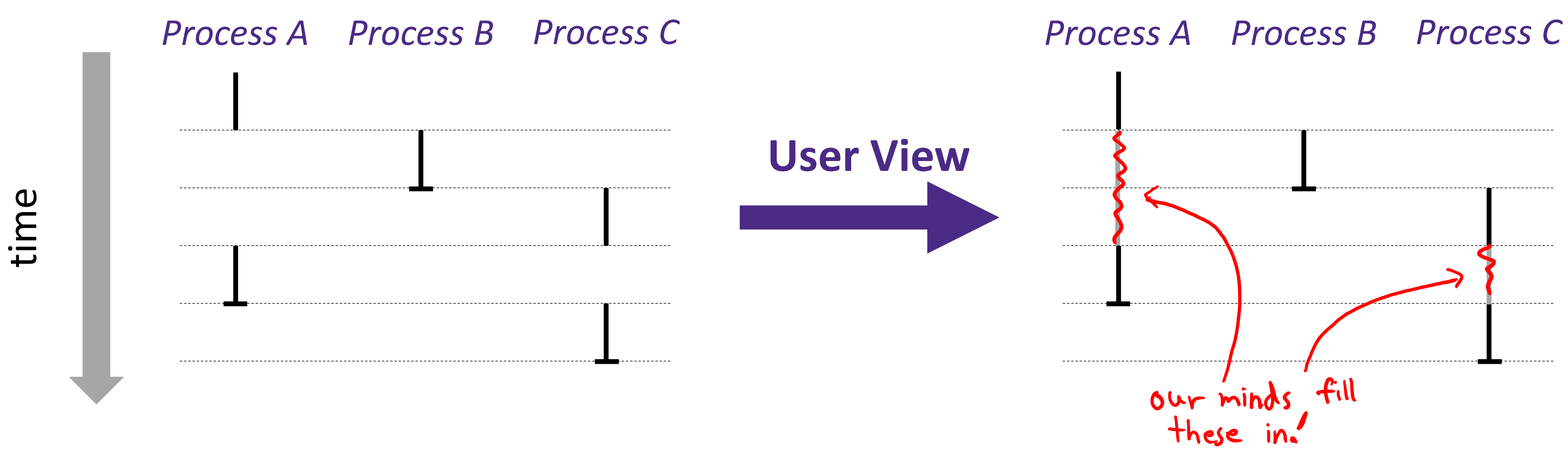
- Each process is a logical control flow
- Two processes *run concurrently* (are concurrent) if their instruction executions (flows) overlap in time
  - Otherwise, they are *sequential*
- Example: (running on single core)
  - Concurrent: A & B, A & C
  - Sequential: B & C



User's View of Concurrency

Assume only one CPU

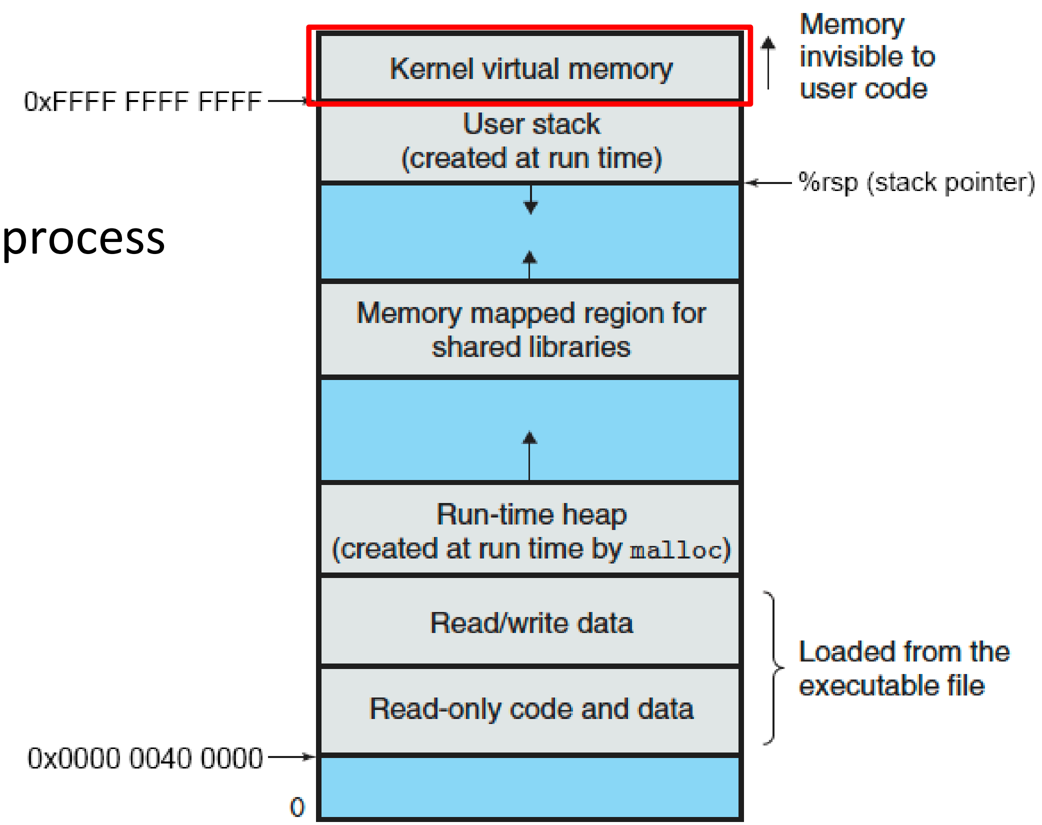
- Control flows for concurrent processes are physically disjoint in time
  - CPU only executes instructions for one process at a time
- However, the user can *think of* concurrent processes as executing at the same time, in *parallel*



Context Switching

Assume only one CPU

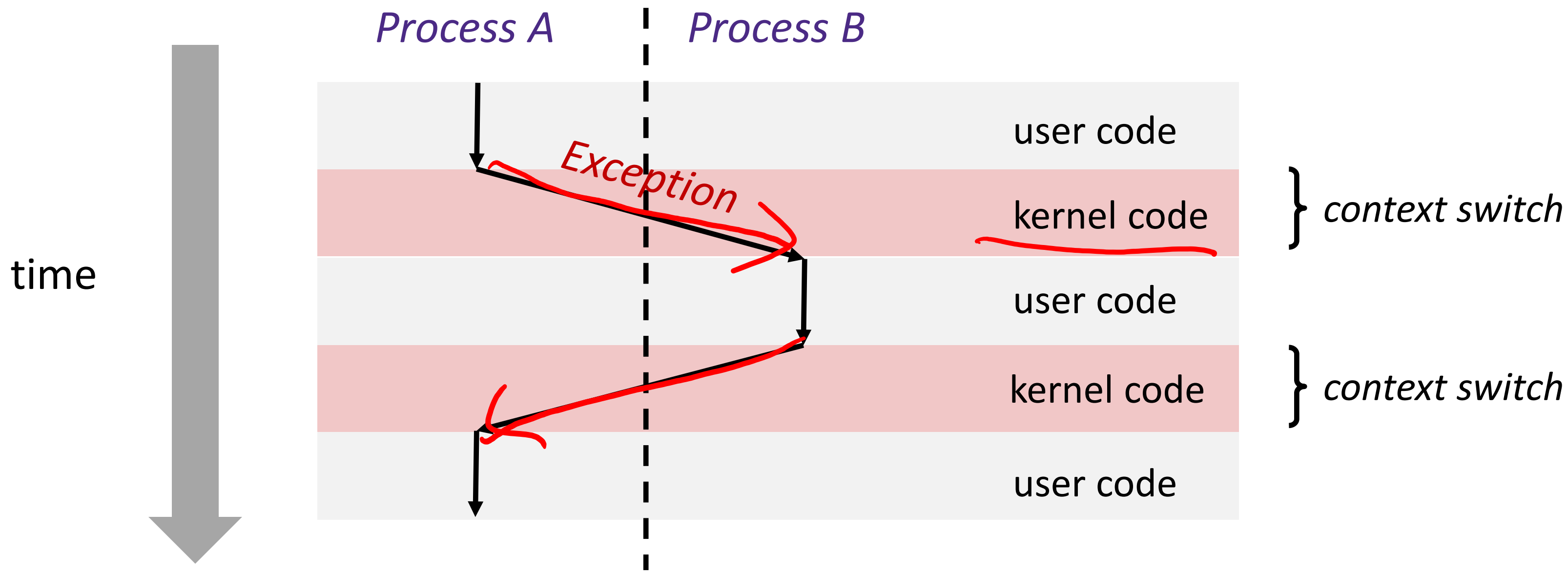
- Processes are managed by a *shared* chunk of OS code called the kernel
  - The kernel is not a separate process, but rather runs as part of a user process
- In x86-64 Linux:
  - Same address in each process refers to same shared memory location



Context Switching (Review)

Assume only one CPU

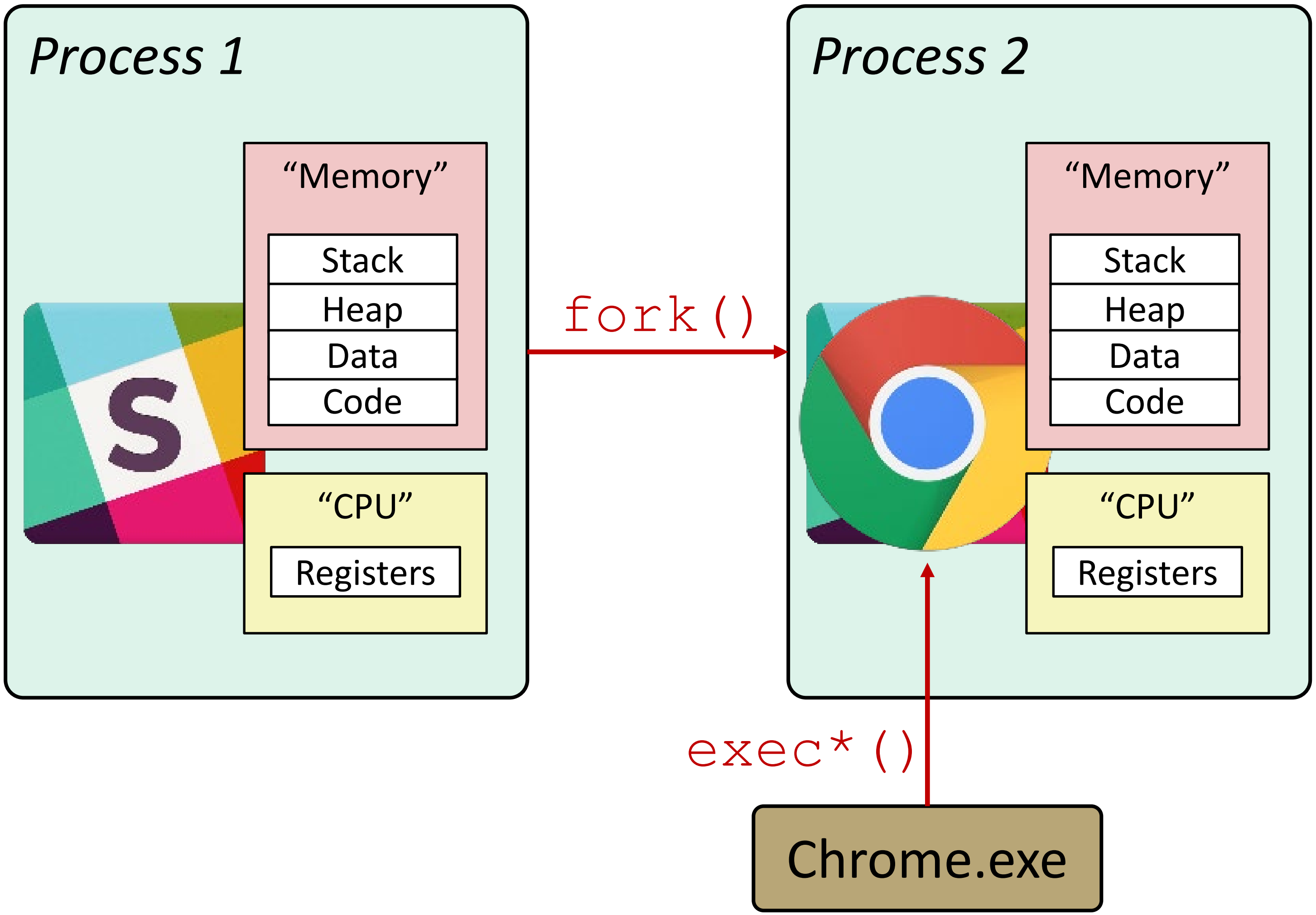
- Processes are managed by a *shared* chunk of OS code called the kernel
  - The kernel is not a separate process, but rather runs as part of a user process
- Context switch passes control flow from one process to another and is performed using kernel code



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

returns a PID

parent child

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

parent gets child's PID

child gets 0

- `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");
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```

Understanding `fork()`

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`fork_ret` = Y

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`fork_ret` = 0

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`fork_ret = Y`

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`fork_ret = 0`

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

`hello from parent`

`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