# The Hardware/Software Interface

## Processes I

No handout today

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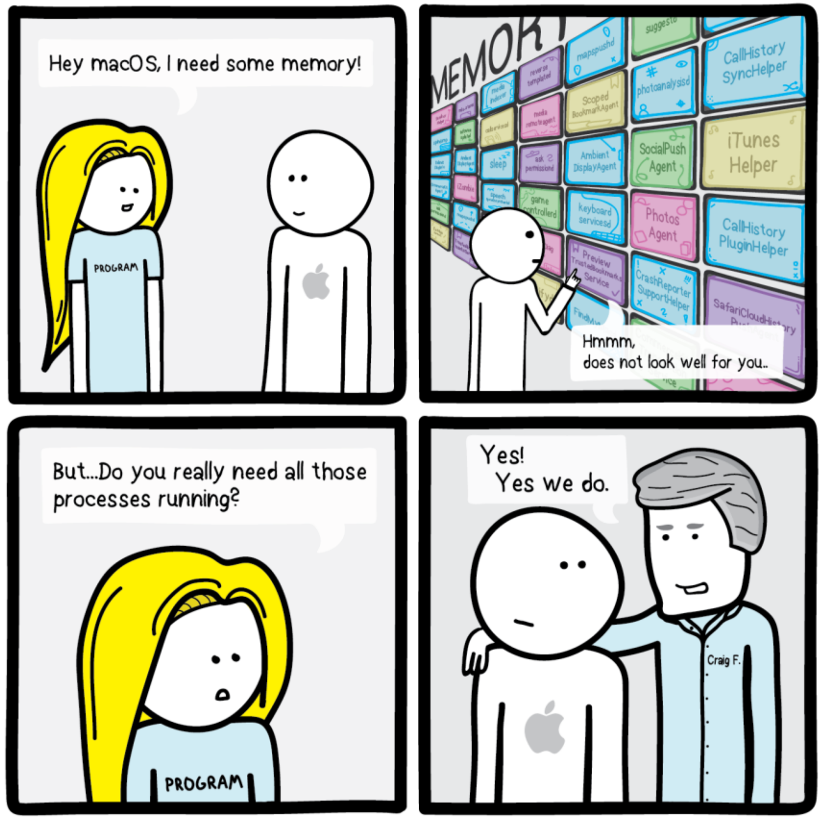


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# Relevant Course Information

- HW 22 due Friday (11/21)
- HW 23 due Monday (11/24)
- Lab 4 due Friday (11/21)
- Lab 5 due 12/4

- Section on Memory Allocation/Lab 5 tomorrow

- Final review session 12/5 (Fri)
- Final 12/10 (Wed)

# Lecture Outline (1/3)

- **System Control Flow**
- Processes
- Process Management (x86-64 Linux)

# 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

many applications open at once:
browser, text editor, music, file explorer, etc.

- *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

# CPU 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>
$instr_1$ mov
$instr_2$ add
$instr_3$ jmp
…
$instr_n$ call
<shutdown>

# Altering the Control Flow

- Up to now, two ways to change control flow (caused by changes in *program state*):
  - Jumps (conditional and unconditional)
  - Procedures: `call` and `ret`
- Processor also needs to react to changes in *system state*
  - *e.g.*, 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

kills active process

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

# Exceptional Control Flow

- Mechanisms exist at all levels of a computer system
  - **Exceptions** (low-level) are changes in processor's control flow in response to a system event (*e.g.*, change in system state, user-generated interrupt)
    - Implemented using a combination of hardware and OS software
  - **Process context switches** (higher-level) pass execution on the CPU from one process to another
    - Implemented by OS software and hardware timer
  - **Signals** (higher-level) are standardized inter-process messages to trigger specific behavior
    - Implemented by OS software
    - We won't cover these in detail – see CSE 451 and EE/CSE 474

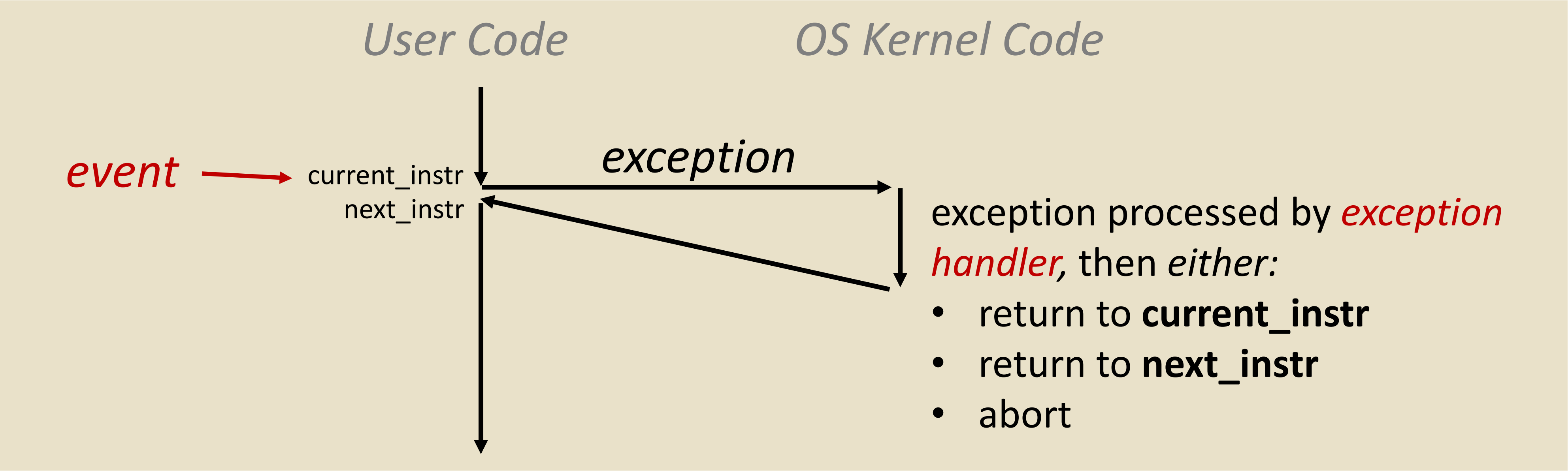
# Aside: Java Exceptions (Review)

This is extra (non-testable) material

- Java has exceptions, but they're *something different*
  - *e.g.*, `NullPointerException`, `MyBadThingHappenedException`
  - `throw` statements
  - `try`/`catch` statements
- Java exceptions are for reacting to (unexpected) program state
  - Can be implemented with stack operations and conditional jumps
  - A mechanism for "many call-stack returns at once"
  - Requires additions to the calling convention, but no additional CPU features
- System-state changes on previous slide are mostly of a different sort (asynchronous/external except for divide-by-zero) and implemented very differently

# 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**
  - *e.g.*, division by 0, page fault, I/O request completes, Ctrl-C

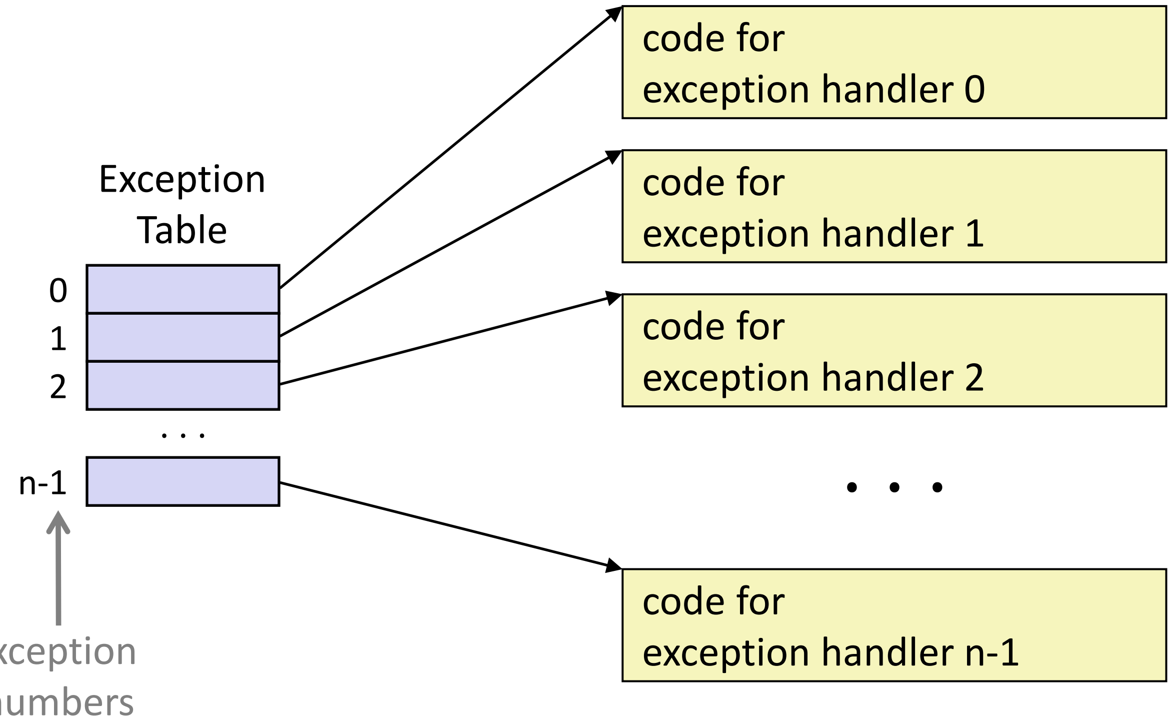



- *How does the system know where to jump to in the OS?*

# 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 |

Different on Windows vs. Linux, etc.

# *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: an external timer chip triggers an interrupt every few milliseconds
    - Used by the OS kernel to take back control from user programs

Context switches depend upon timer interrupts

# *Synchronous* Exceptions (Review)

- Caused by events that occur **because 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 sometimes
    - 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

# Traps: System Calls

- Each system call has a unique ID number
  - NOT the same as exception numbers!
- Examples for x86-64 Linux :

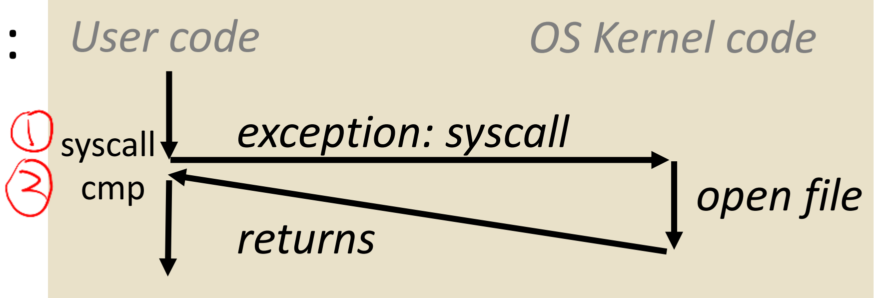
| Number | Name | Description |
|---|---|---|
| 0 | `read` | Read file |
| 1 | `write` | Write file |
| 2 | `open` | Open file |
| 3 | `close` | Close file |
| 4 | `stat` | Get info about file |
| 57 | `fork` | Create process |
| 59 | `execve` | Execute a program |
| 60 | `_exit` | Terminate process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

# Trap 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 indicates an error
  - Execution resumes at next instruction:



# Fault Example: Page Fault

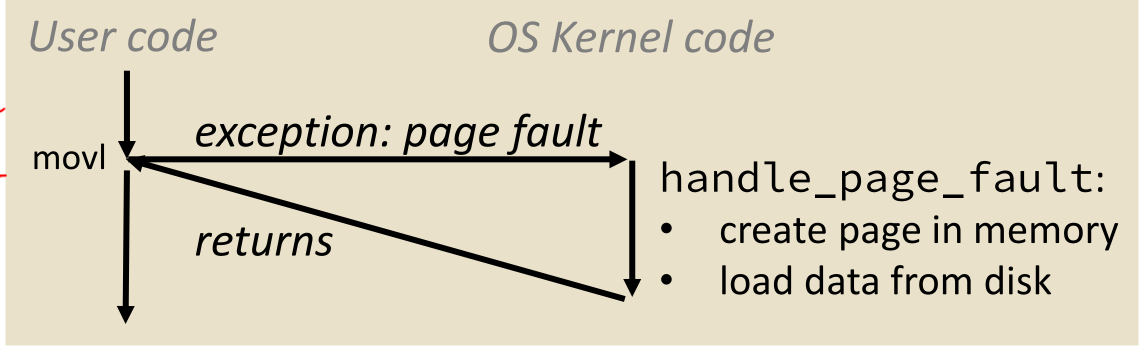
- User writes to memory location:

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

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

  - That location happens to be currently on disk (not in memory)
    - Page fault handler must load page into physical memory
  - Execution returns to faulting instruction: (mov is executed again)
    - Successful on second try

1st try = fault
2nd try = success



# Fault Example: Invalid Memory Reference

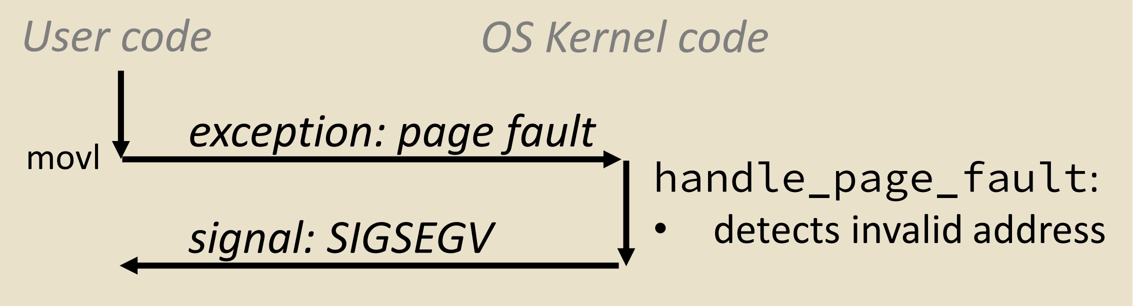
- User writes to memory location:

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

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

- That location is past allocated memory in an invalid region
  - Page fault handler detects invalid address
- `SIGSEGV` signal sent to user process:
  - User process exits with "segmentation fault"

Signal Segment Violation



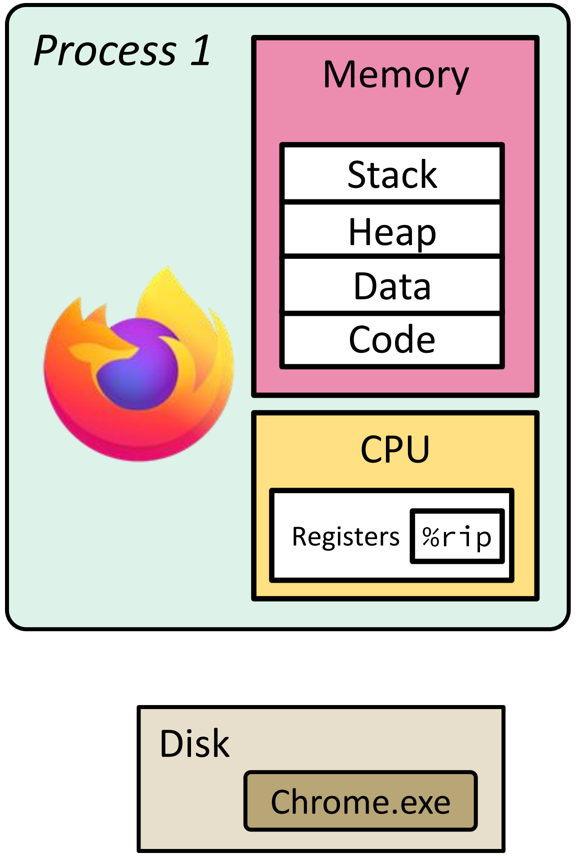
# Lecture Outline (2/3)

- System Control Flow
- **Processes**
- Process Management (x86-64 Linux)

# What is a Process?

- **It's an *illusion/abstraction*!**
  - The OS uses a data structure to represent each process
  - Maintains the *interface* between the program and the underlying hardware (CPU + memory)

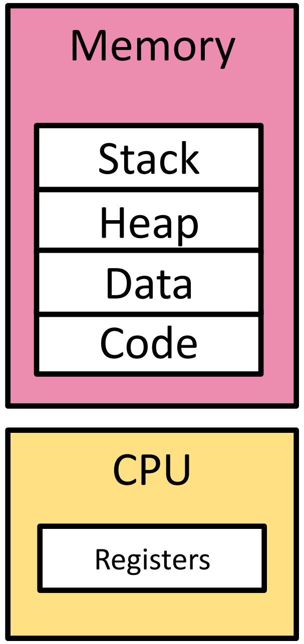
- Exceptional control flow is the *mechanism* the OS uses to enable **multiple processes** to run on the same system



# Processes (Review)

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

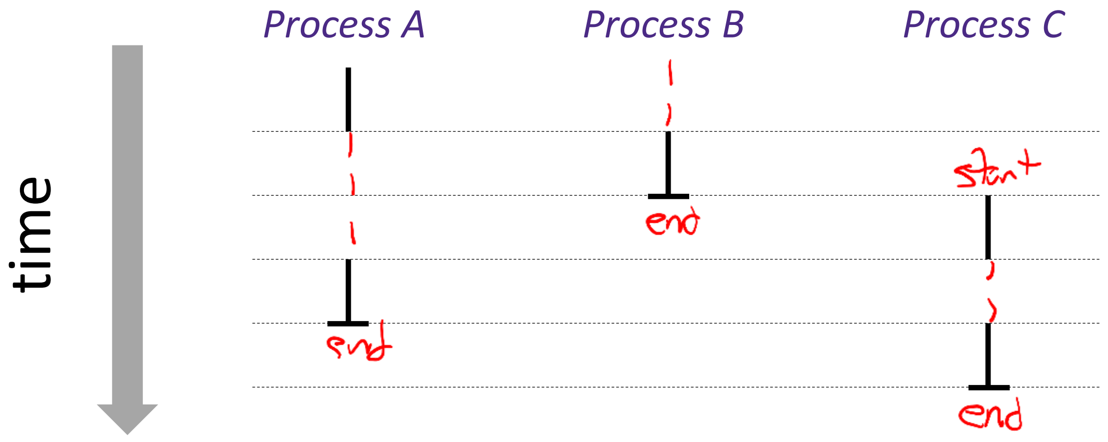
- Process provides each program with two key abstractions:
  - *Logical control flow*
    - Each program *seems to* have exclusive use of the CPU
    - Provided by kernel mechanism called ***context switching***
  - *Private address space*
    - Each program *seems to* have exclusive use of main memory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



# Concurrent Processes (Review)

Assume only one CPU

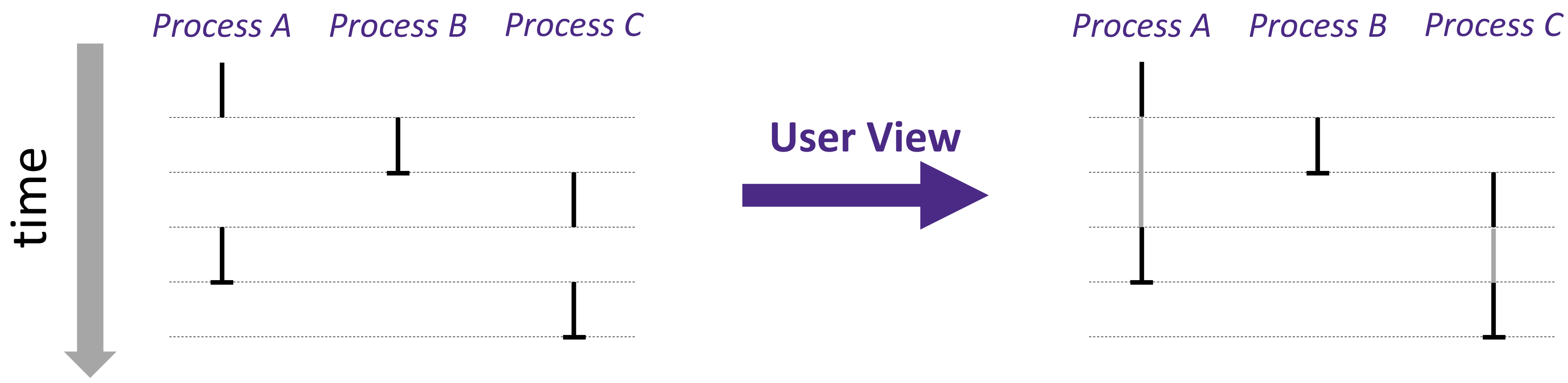
- Each process is a logical control flow
- Two processes *run concurrently* (are concurrent) if their instruction executions (flows) overlap in time
  - Otherwise, they are *sequential*
- Example: (running on single core)
  - Concurrent: A & B, A & C
  - Sequential: B & C



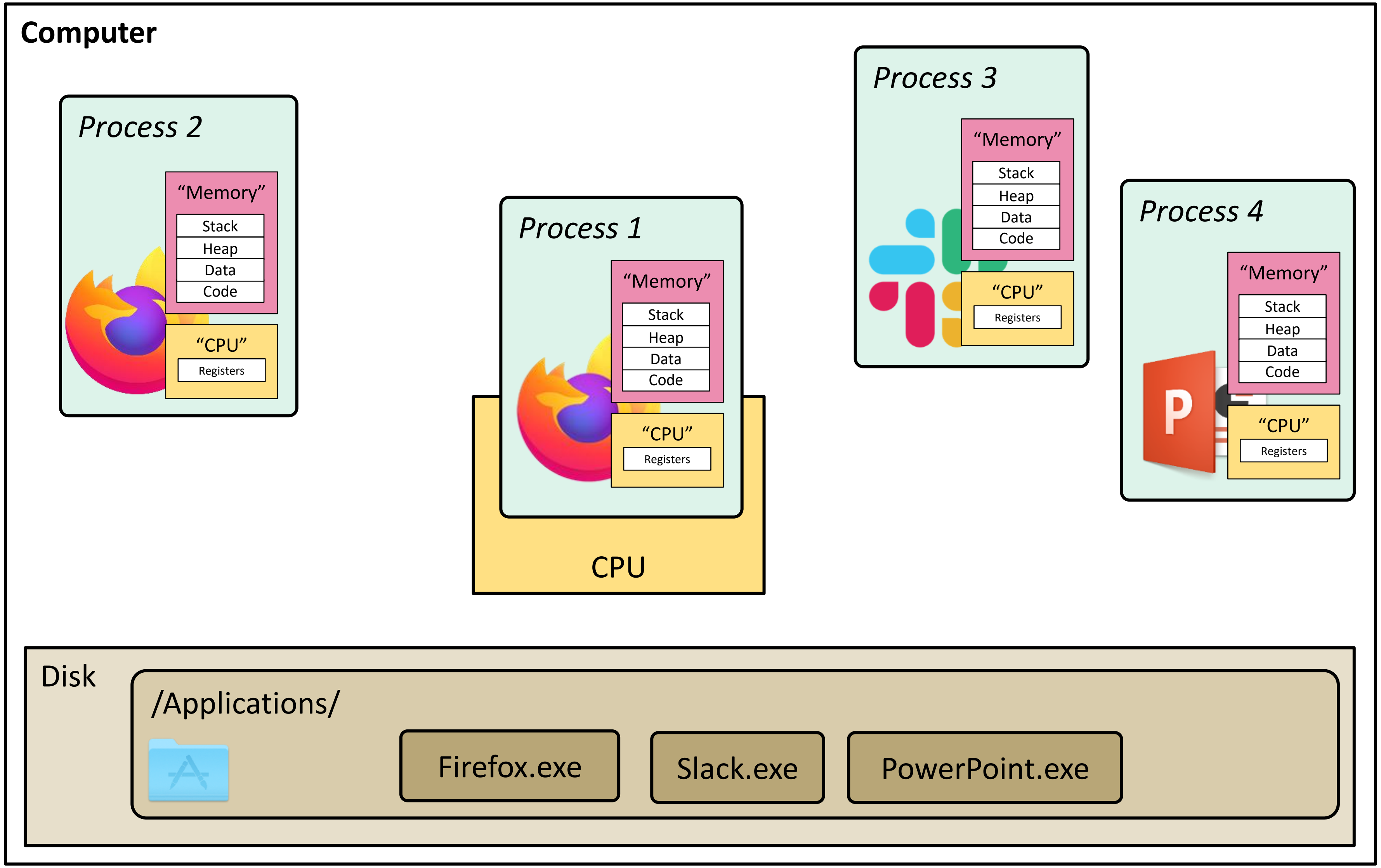
# User's View of Concurrency

Assume only <u>one</u> CPU

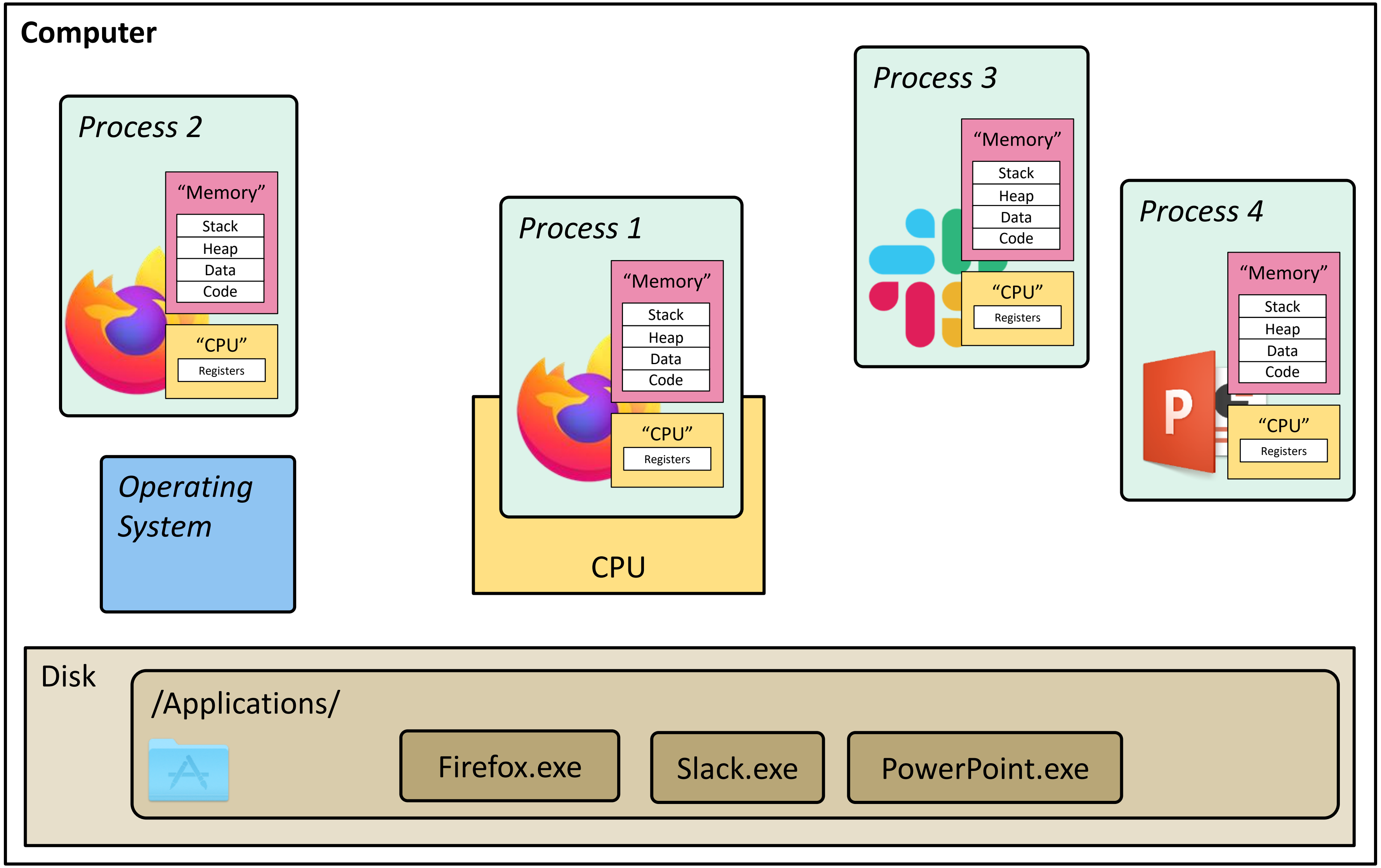
- Control flows for concurrent processes are physically disjoint in time
  - CPU only executes instructions for one process at a time
- However, the user can *think of* concurrent processes as executing at the same time, in *parallel*



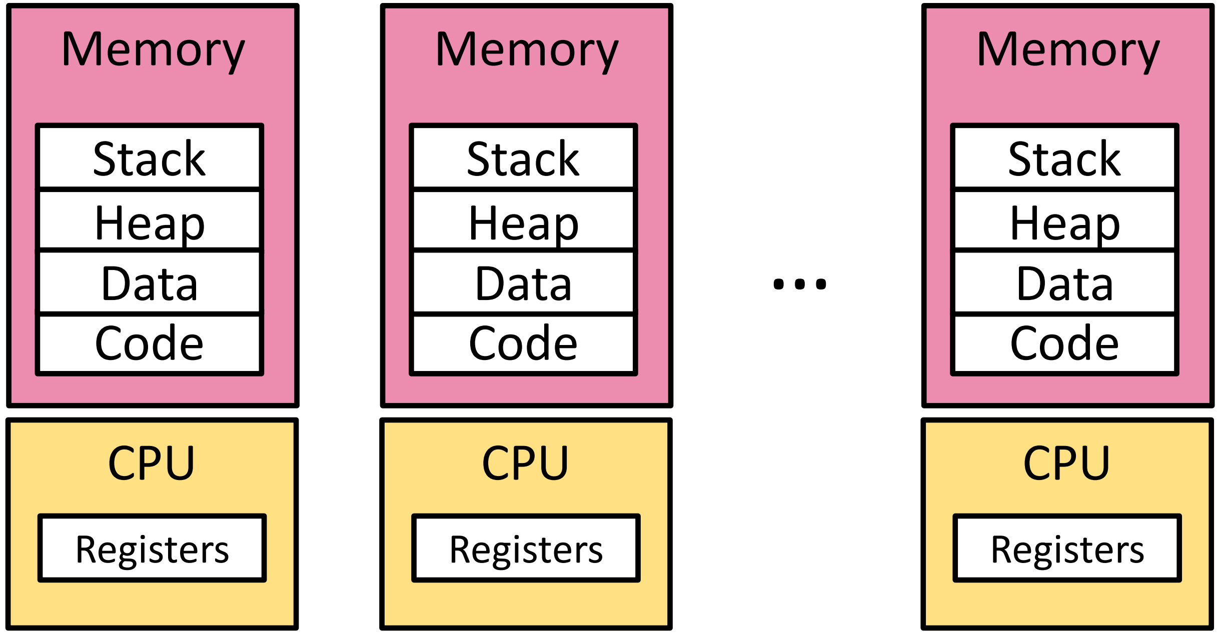
# Multiple Processes



# Multiple Processes: Context Switching

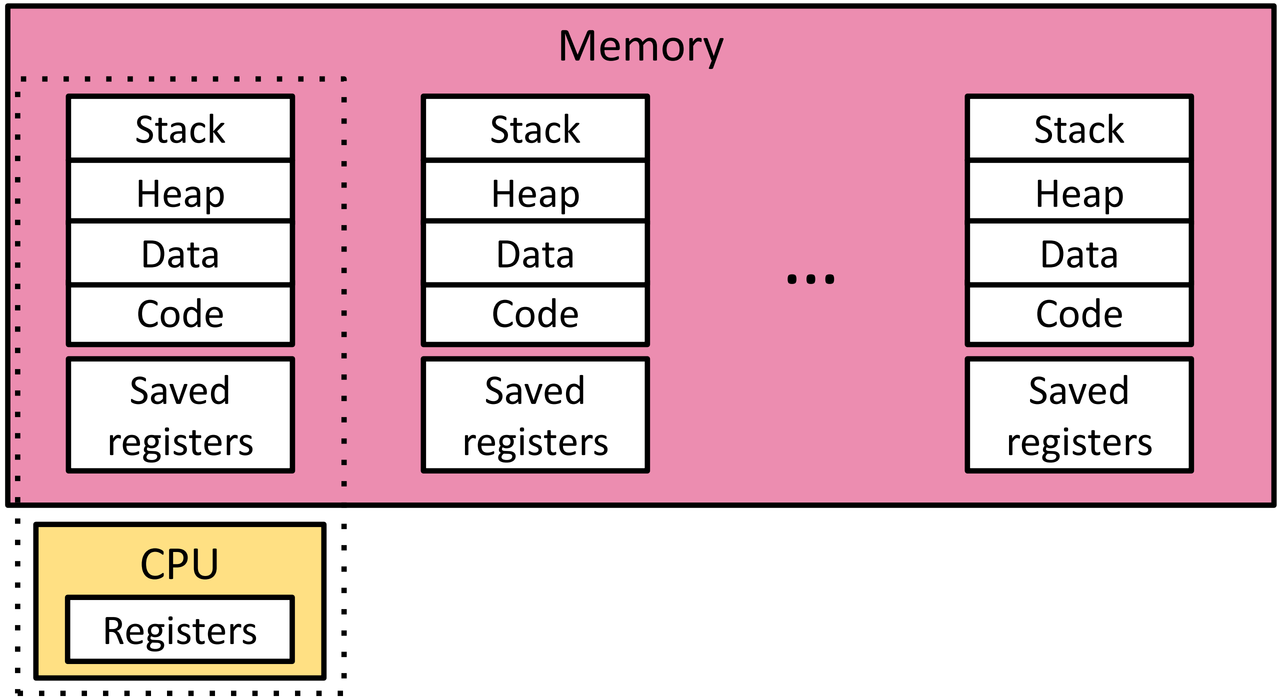


# Multiprocessing: The Illusion



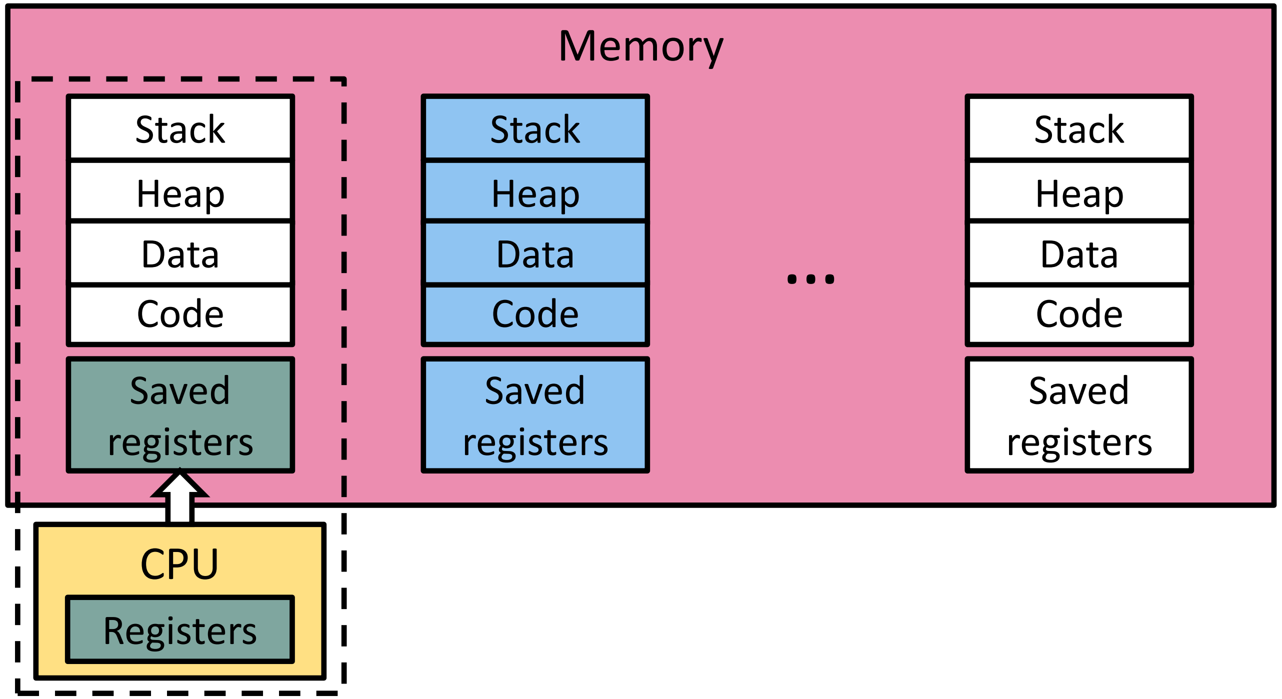

- A computer runs many processes simultaneously
  - Applications for one or more users (*e.g.*, web browsers, email clients, text editors)
  - Background tasks (*e.g.*, monitoring network & I/O devices)

# Multiprocessing: The Reality



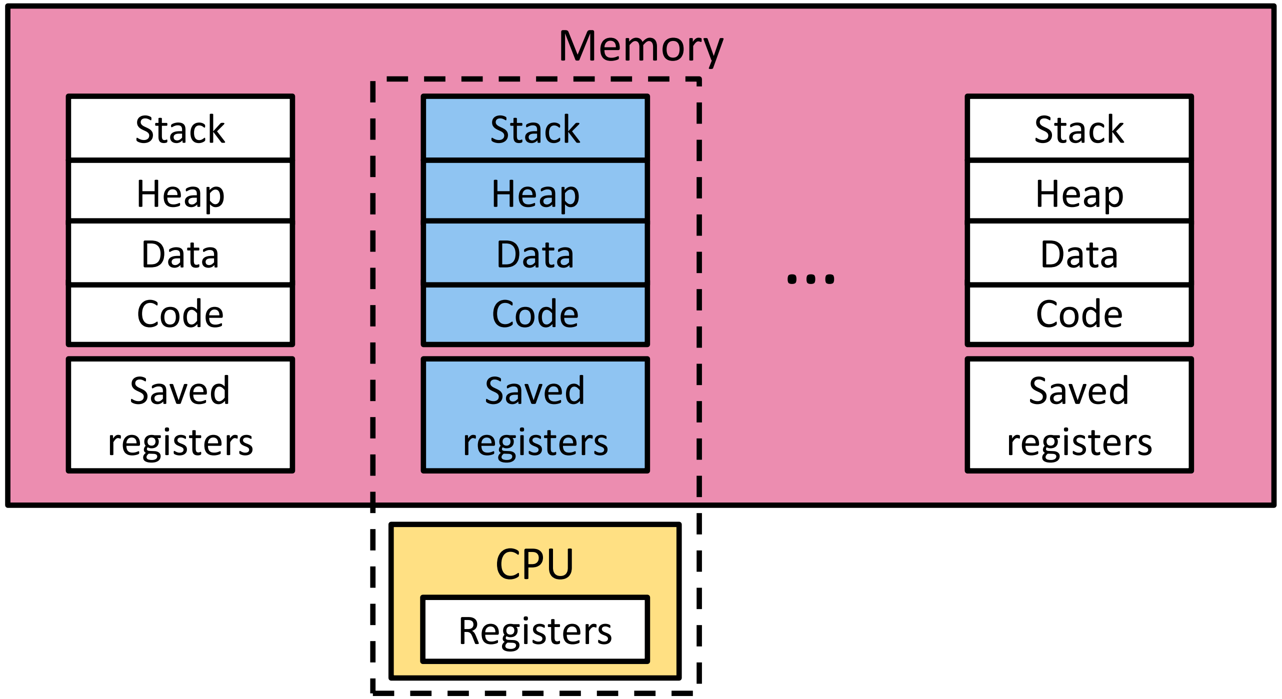

- Single processor executes multiple processes *concurrently*
  - Process executions are interleaved – CPU only runs *one at a time*
  - Address spaces managed by virtual memory system (we'll get to it!)
  - *Execution context* (register values, stack, …) for other processes saved in memory

# Multiprocessing: Context Switching (Review, 1/3)



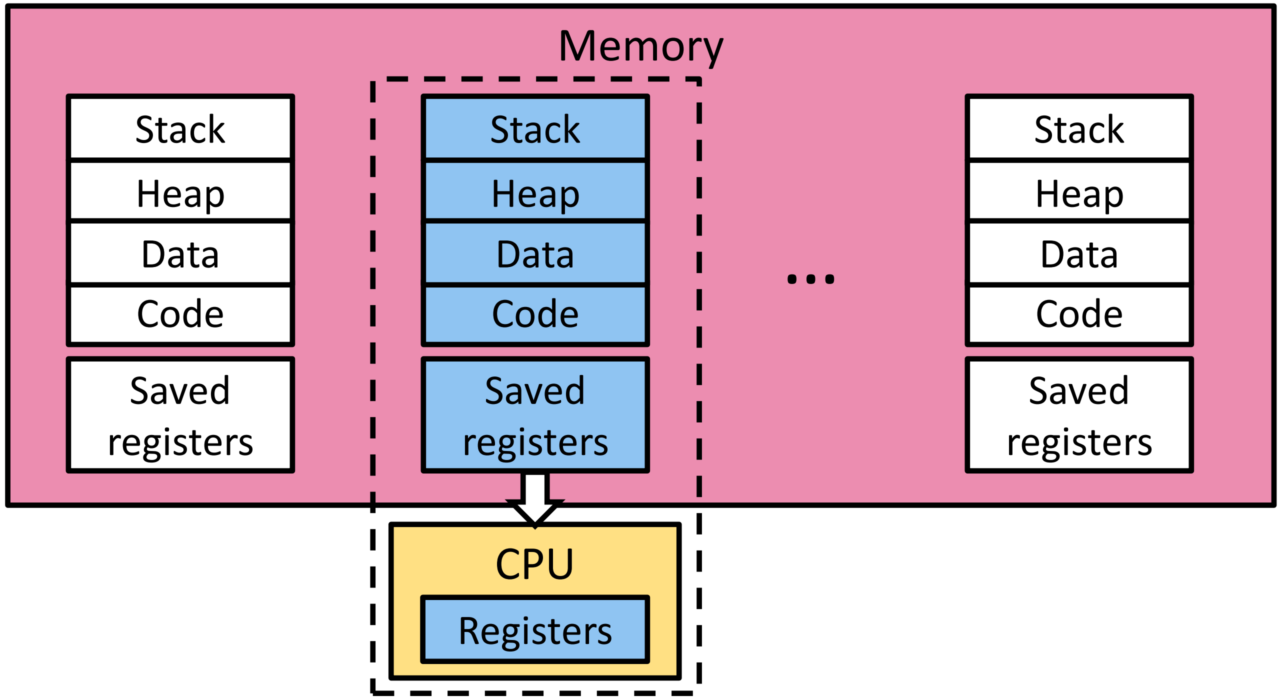

- Context switch
  1) **Save current registers in memory**

# Multiprocessing: Context Switching (Review, 2/3)



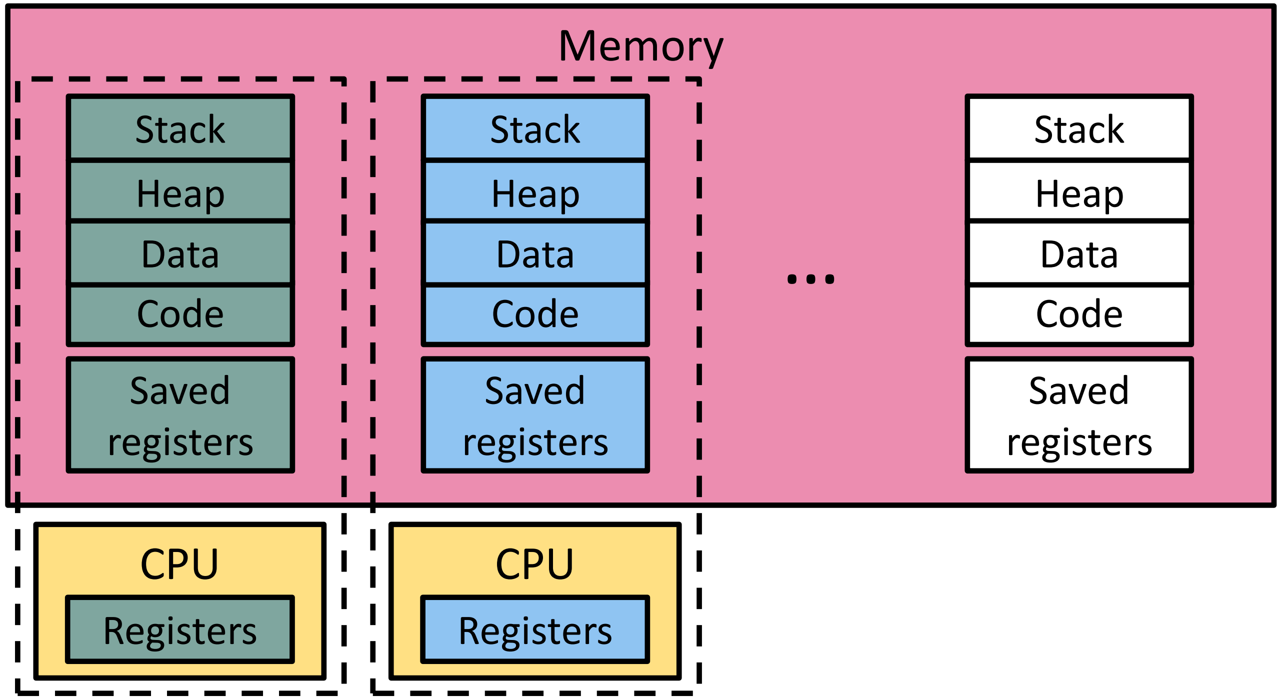

- Context switch
  1) Save current registers in memory
  2) **Schedule next process for execution**

# Multiprocessing: Context Switching (Review, 3/3)




- 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

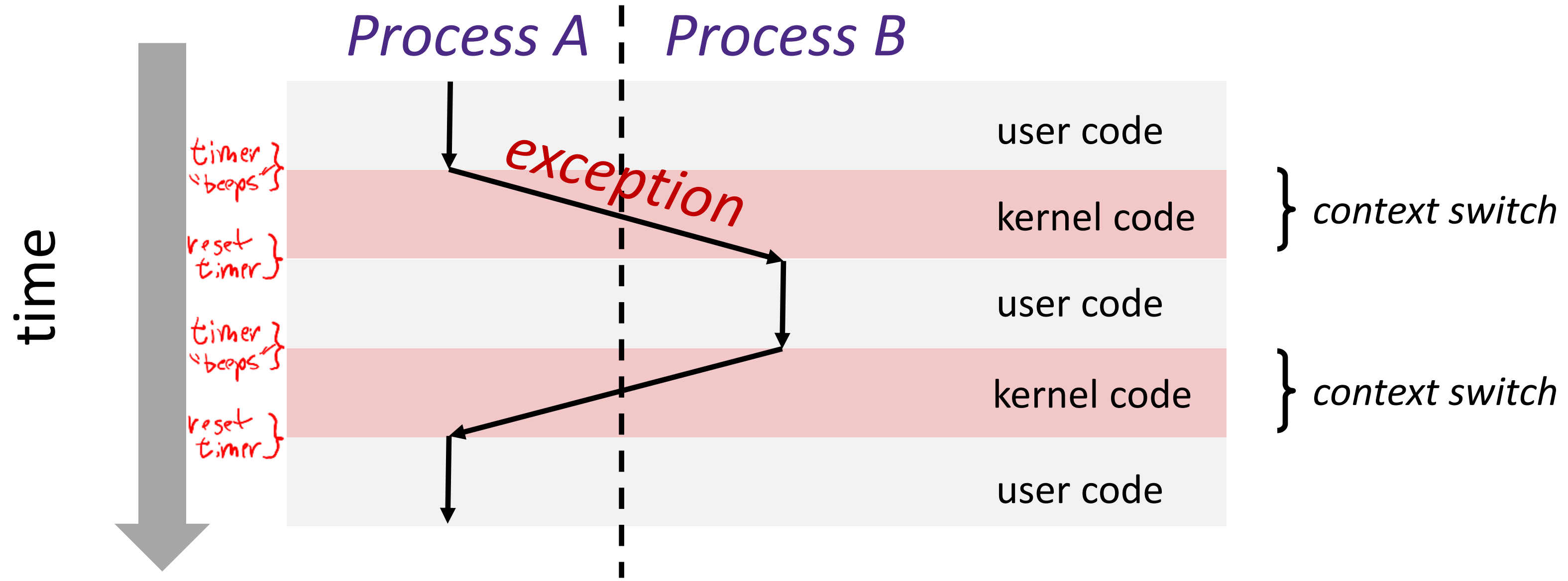



- Multicore processors have multiple CPUs ("cores") on a single chip
  - Each can execute a separate process, but ***still*** **constantly swapping processes**
    - Kernel schedules processes to cores
  - Share main memory (and some of the caches)

# Context Switching via Exceptions (Review)

Assume only one CPU

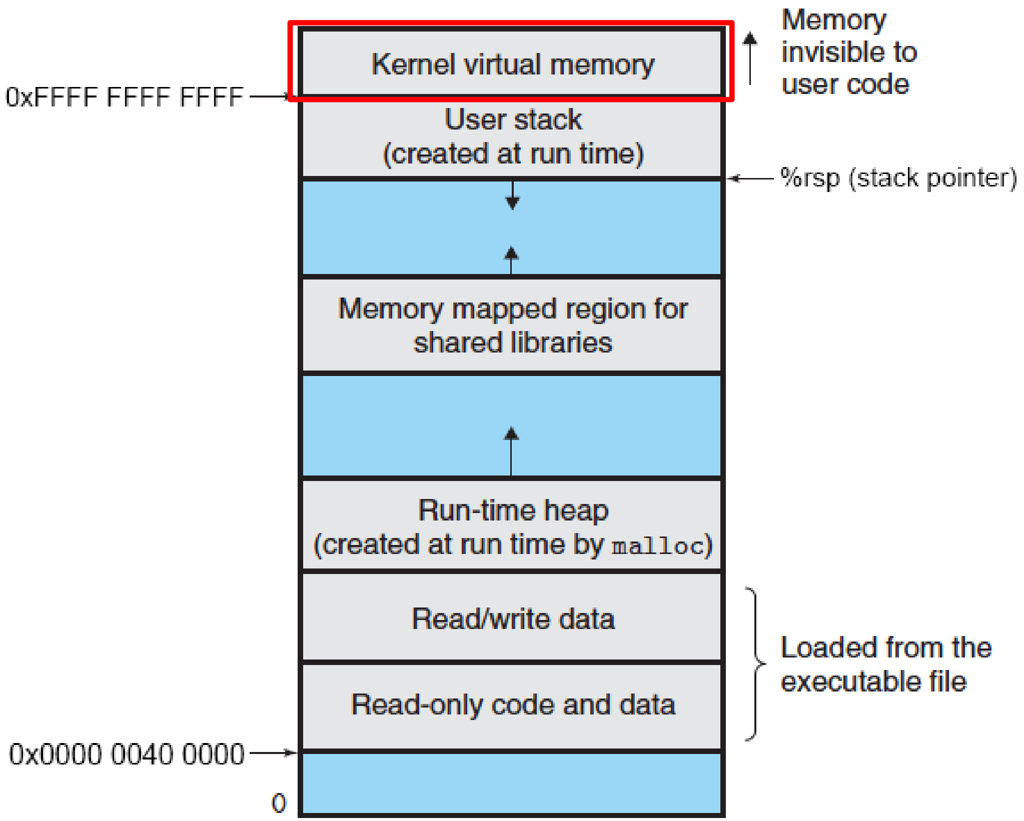
- Context switch passes control flow from one process to another and is performed using kernel code



# Context Switching: The Kernel

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*

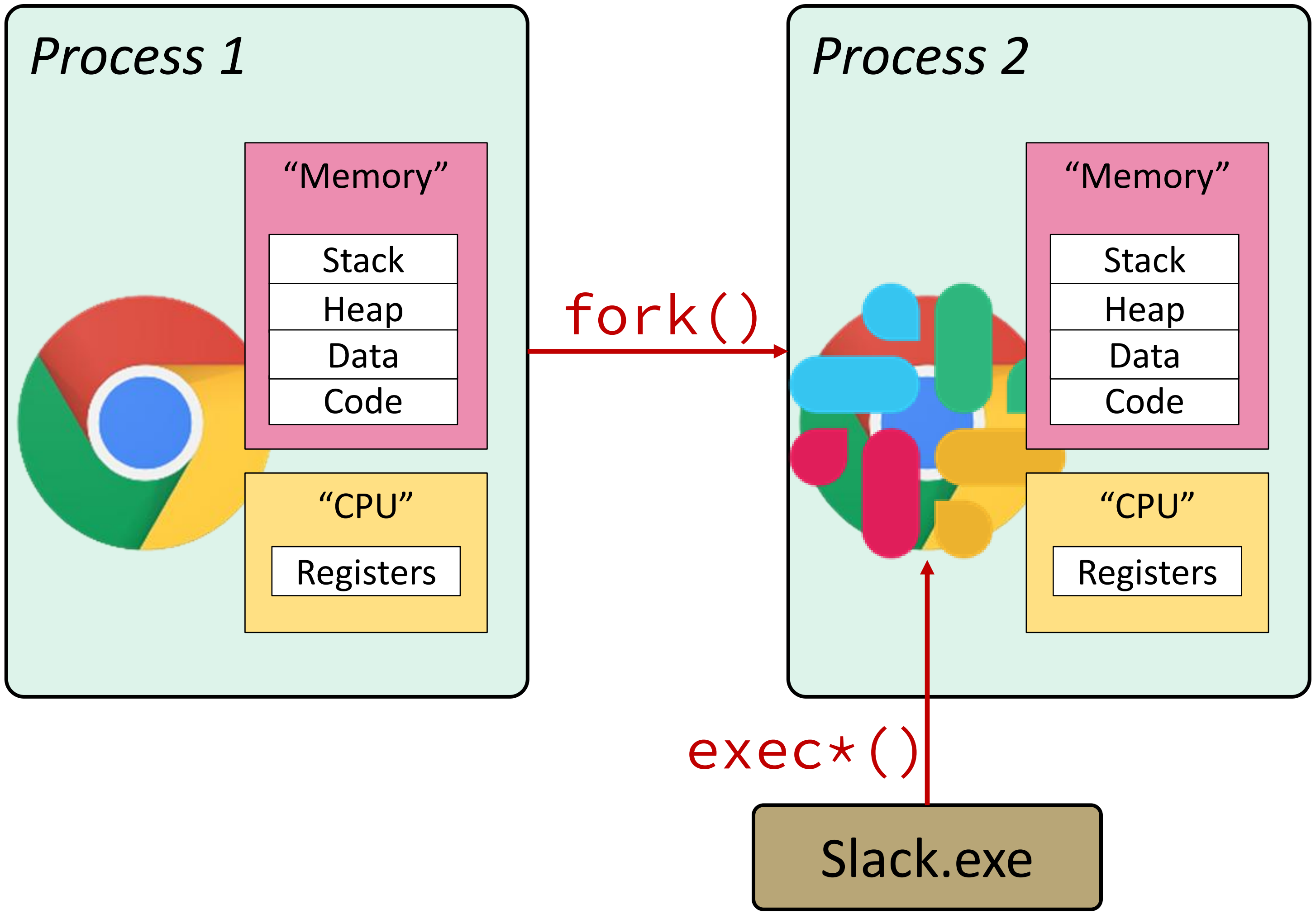



* sort of, the story became more complicated recently with Meltdown and Spectre (out of scope here)

# Lecture Outline (3/3)

- System Control Flow
- Processes
- **Process Management (x86-64 Linux)**

# Creating New Processes & Programs



# Process Management in Linux (Mostly Review)

- fork-exec model:
  - `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 "**child**" process from the calling "**parent**" process that is *almost* identical
    - Child has a newly assigned *process ID (PID)* that is different than the parent's PID
    - Child gets an identical, but separate, copy of the parent's **state** (*e.g.*, memory, registers)
  - Both start/resume execution at the return from `fork`
    - Returns `0` to the **child** process, and the *child's PID* to the **parent** process

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

- ⚠ Unique (and confusing) because it is called **once** but returns **"twice"**

# fork Illustration (1/3)

**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` Illustration (2/3)

**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");
}
```

**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");
}
```

# fork Illustration (3/3)

## 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

***We don't know which will appear first!***

# fork Example

```
void fork1() {
  int x = 1;
  pid_t fork_ret = fork();
  if (fork_ret == 0)
    printf("Child has x = %d\n", ++x);
  else
    printf("Parent has x = %d\n", --x);
  printf("Bye from process %d with x = %d\n", getpid(), x);
}
```

- Notes/Reminders:
  - Both processes continue/start execution after fork
    - Can't predict execution order between parent and child
  - Both processes start with x = 1
    - However, subsequent changes to x are independent
  - Shared open files: stdout is the same in both parent and child

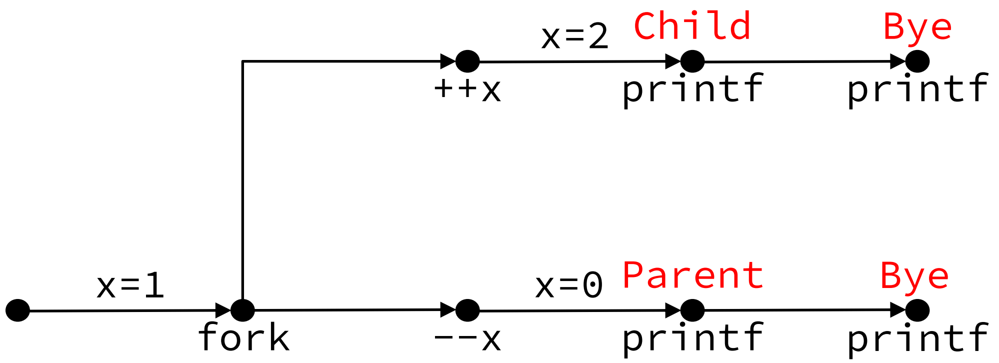
# Modeling Concurrency with Process Graphs

- A *process graph* is a useful tool for capturing the partial ordering of statements in a concurrent program
  - Each vertex indicates the execution of a notable statement
  - Edges (a → b) indicate sequential ordering of statements within a process
    - *i.e.*, a must happen before b
  - Vertices and edges can be labeled with important notes
    - *e.g.*, updated variable values on edges, program output on `printf` vertices
  - Each graph begins with a vertex with no in-edges

- Any *topological sort* of the graph corresponds to a feasible total ordering
  - An ordering of nodes that contains every node, and only follows edges (lines between nodes) in the direction of the arrows

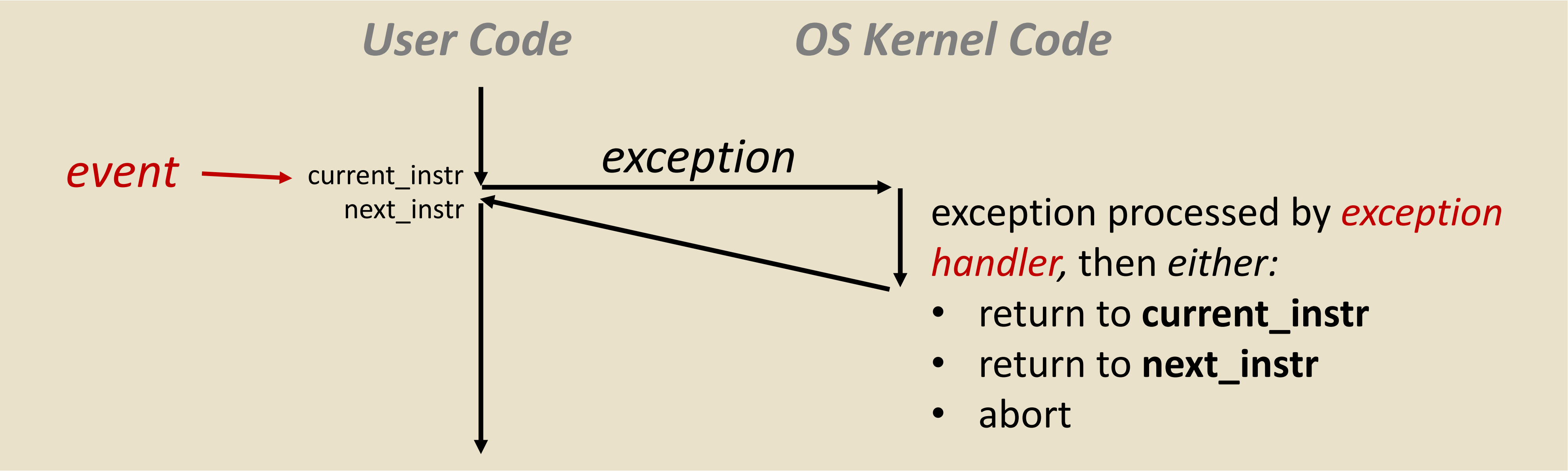
# fork Example: Process Graph

```
void fork1() {
  int x = 1;
  pid_t fork_ret = fork();
  if (fork_ret == 0)
    printf("Child has x = %d\n", ++x);
  else
    printf("Parent has x = %d\n", --x);
  printf("Bye from process %d with x = %d\n", getpid(), x);
}
```



# Summary (1/3)

- ***Exceptional control flow*** enables a computer to respond/react to system *events* that can be external to the running process
  - The event generates an ***exception*** that transfers control to ***exception handler*** in operating system kernel, which will have 1 of 3 possible outcomes:



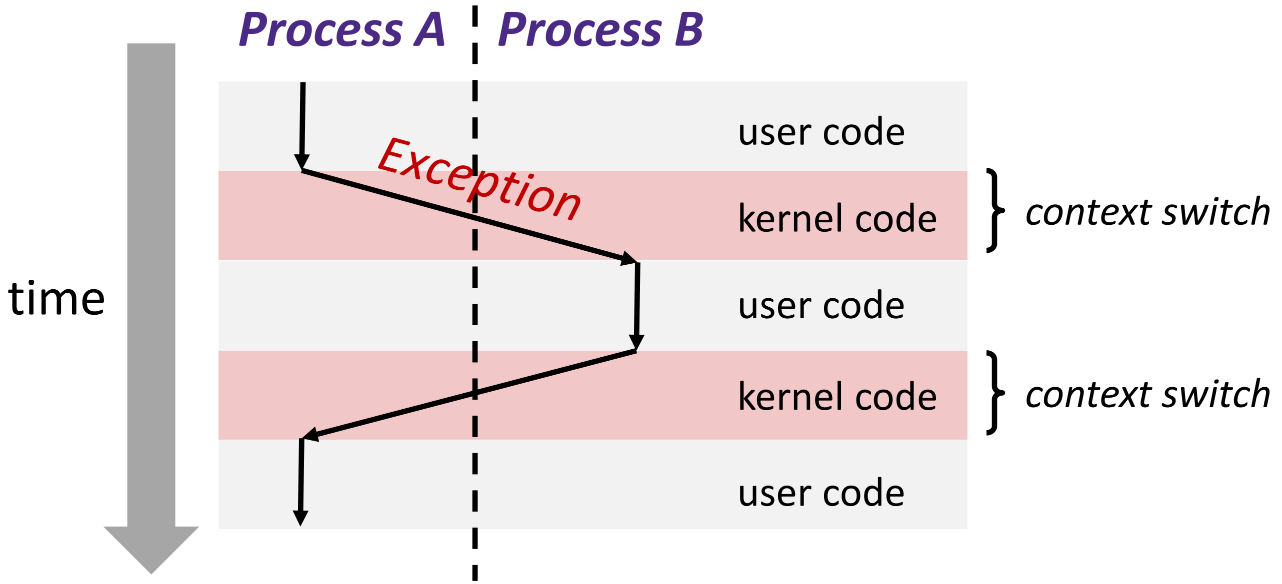
# Summary (2/3)

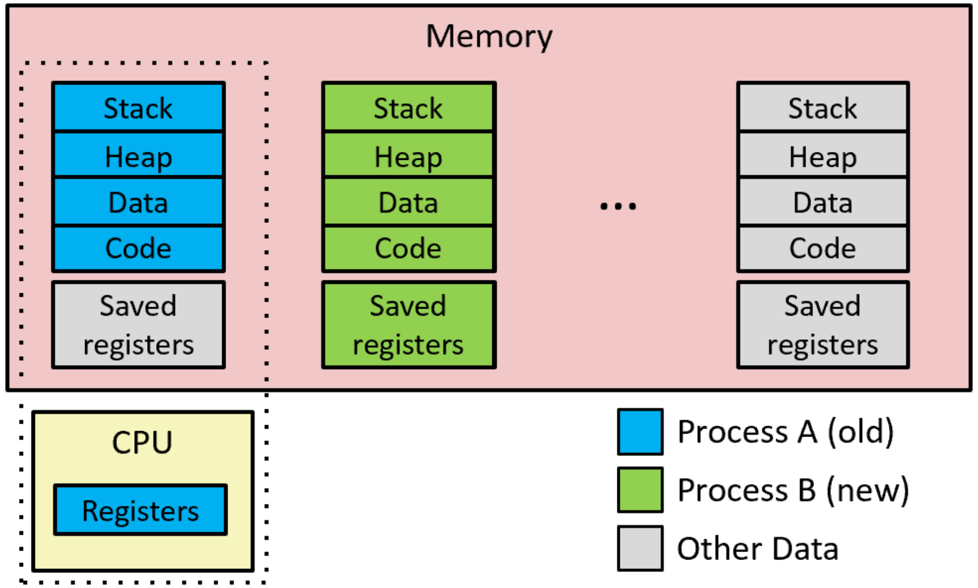
- *Asynchronous exceptions* (external to running process)
  - ***Interrupts*** don't affect the currently running process
- *Synchronous exceptions* (internal to running process)
  - ***Traps*** are intentional – asking the operating system to do something for you
  - ***Faults*** are unintentional but possibly recoverable
  - ***Aborts*** are unintentional and unrecoverable

- A ***process*** is an instance of an running program and provides two key abstractions: logical control flow and private address space
  - Concurrently executing processes are scheduled non-deterministically by the operating system

# Summary (3/3)

- Multiple running processes can be run *concurrently* via ***context switching***




- The ***fork-exec model***
  - Every process is assigned a unique ***process ID*** (pid)
  - `fork()` returns 0 to child, child's PID to parent