Fork & zombies

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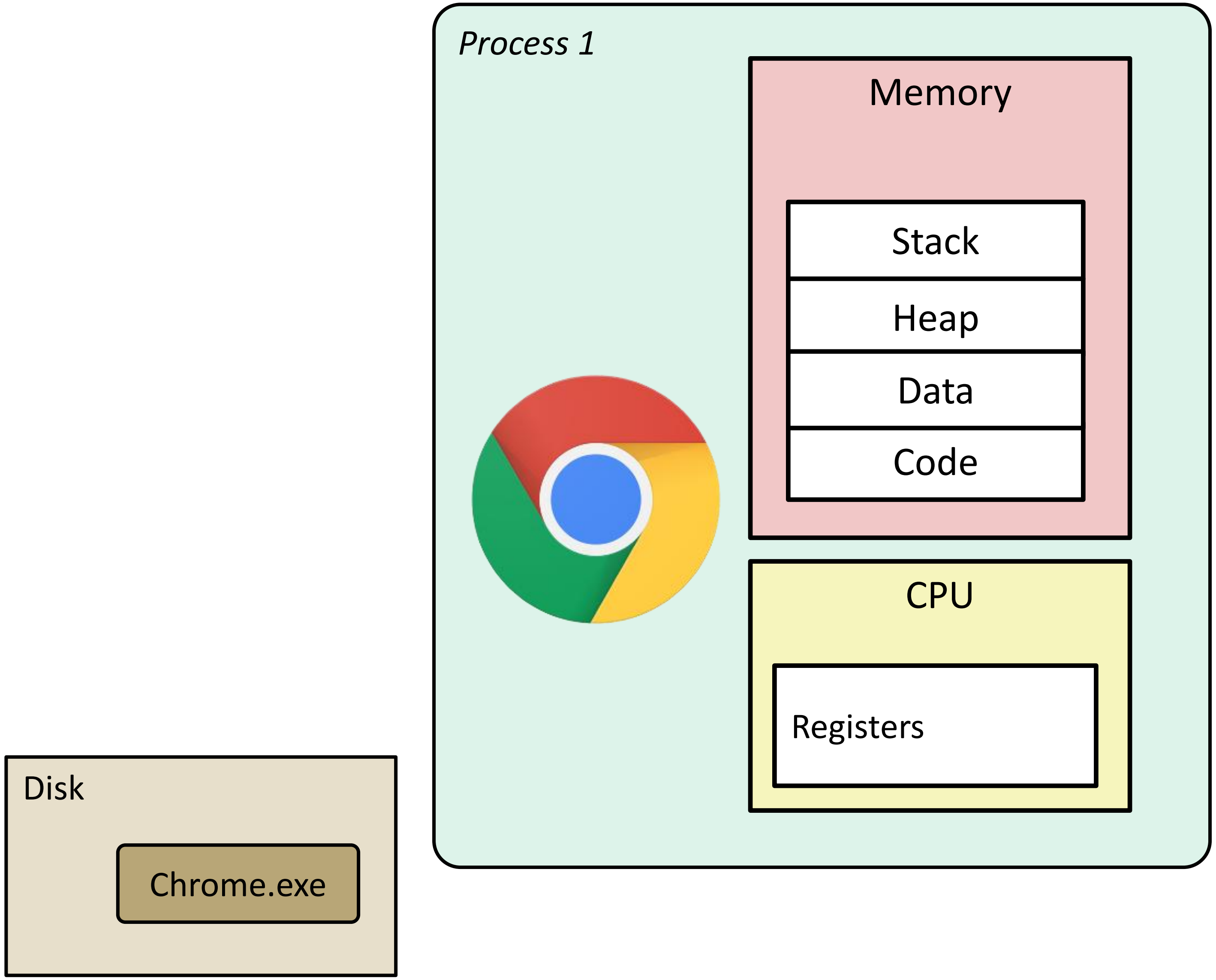
Processes

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

What is a process?

It's an *illusion*!



What is a process?

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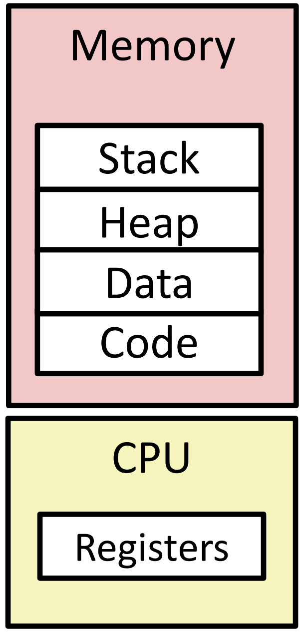
- Another *abstraction* in our computer system
  - Provided by the OS
  - OS uses a data structure to represent each process
  - Maintains the ***interface*** between the program and the underlying hardware (CPU + memory)
- What do *processes* have to do with *exceptional control flow*?
  - Exceptional 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?

hardware the "blueprint" an instance

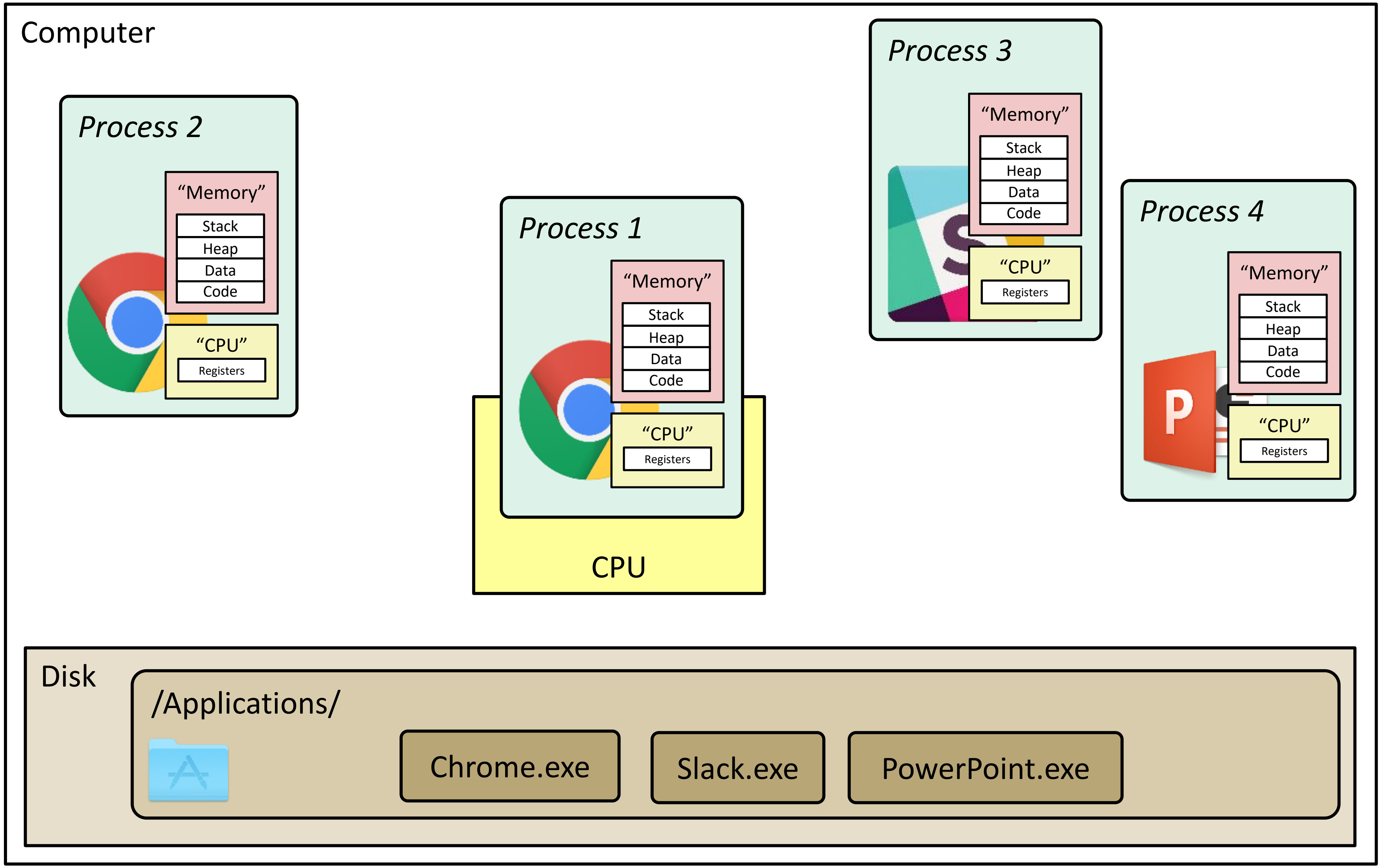
Processes

- A ***process*** is an instance of a running program
  - One of the most profound ideas in computer science
  - Not the same as “program” or “processor”
- 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***



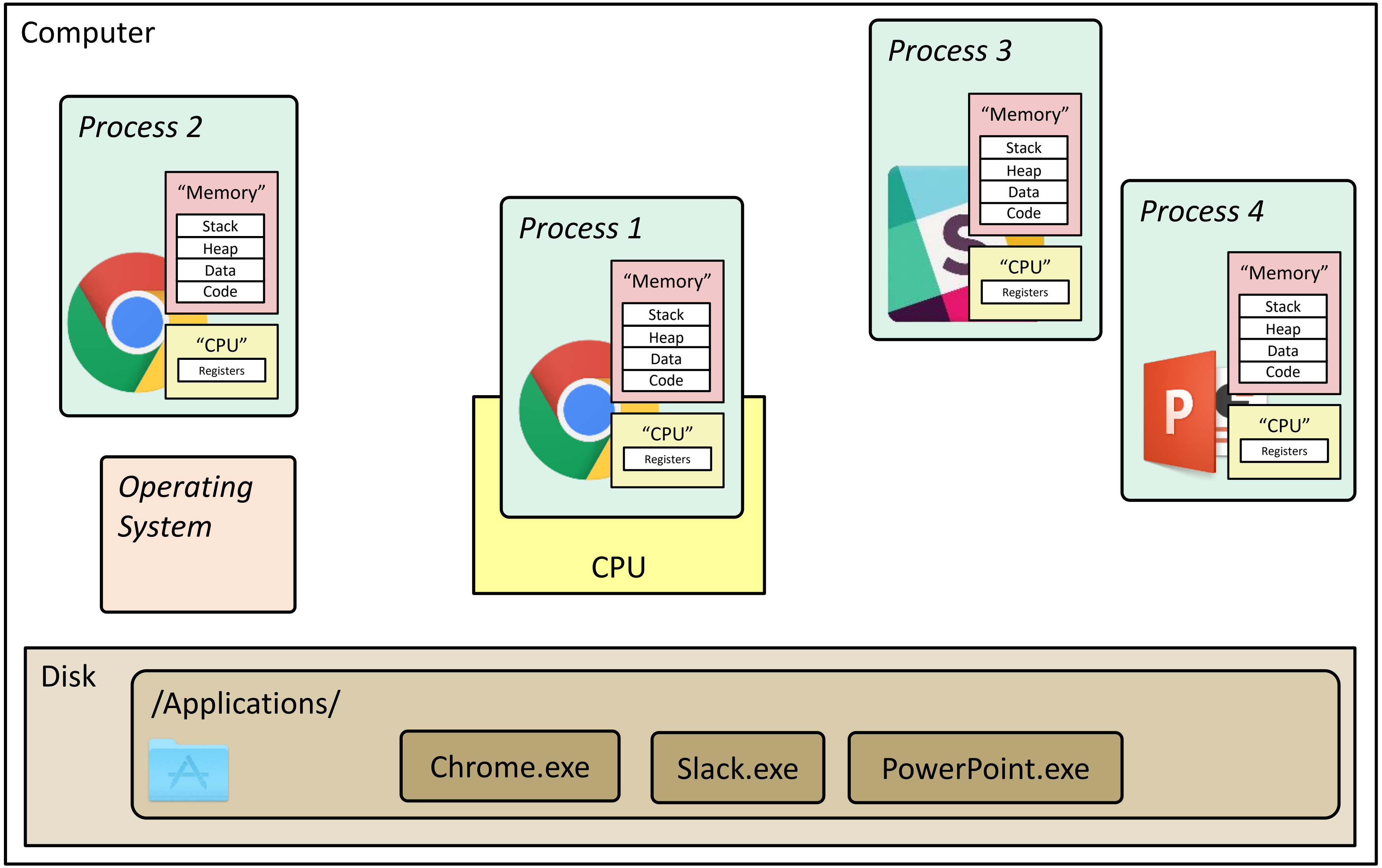
What is a process?

It's an *illusion*!



What is a process?

It's an *illusion*!



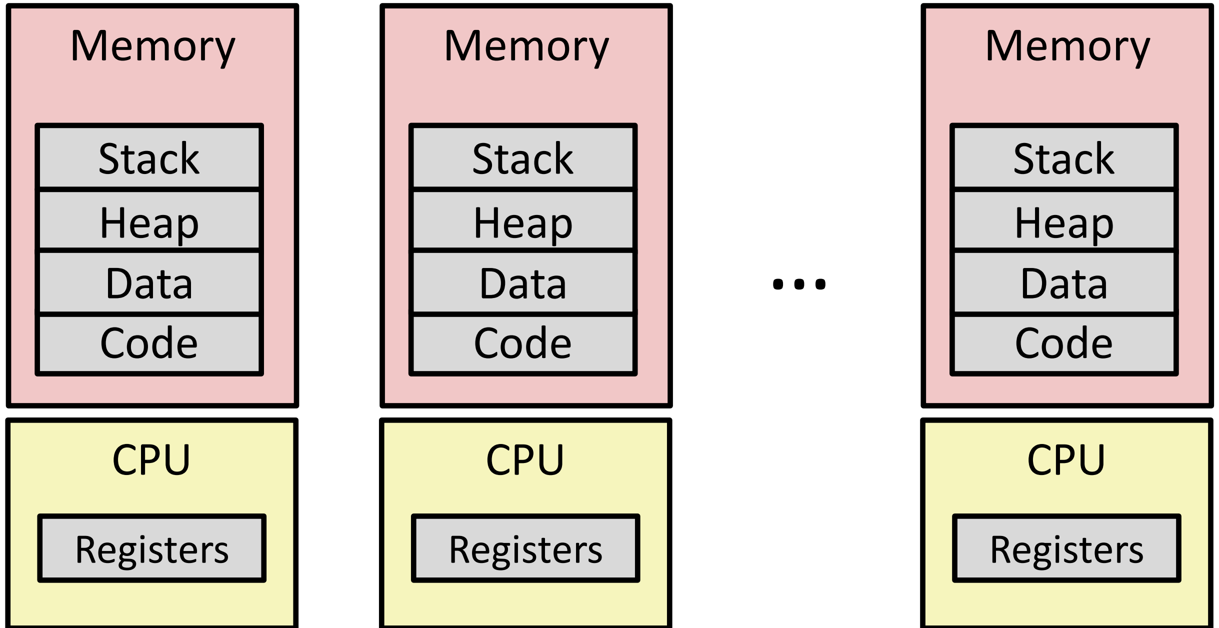
Multiprocessing on Uniprocessor: The Illusion

- While true multiprocessing is not possible on a uniprocessor, there are techniques that can simulate the multiprocessing:
  - ✓ **Process Scheduling:** The OS can rapidly switch between processes, giving the illusion of simultaneous execution. This is known as **context switching**.
  - ✓ **Asynchronous I/O:** When a process waits for I/O (reading from a disk), the operating system can switch to another process, making better use of CPU time.
  - ✓ **Multithreading:** Within a single process, multiple threads can be created to execute different tasks concurrently. This can improve responsiveness and resource utilization, even on a uniprocessor.
  - ✓ **Distributed Computing:** While not strictly multiprocessing, distributed computing involves using multiple computers connected by a network to work on a single task. This can simulate the behavior of a multiprocessor system.

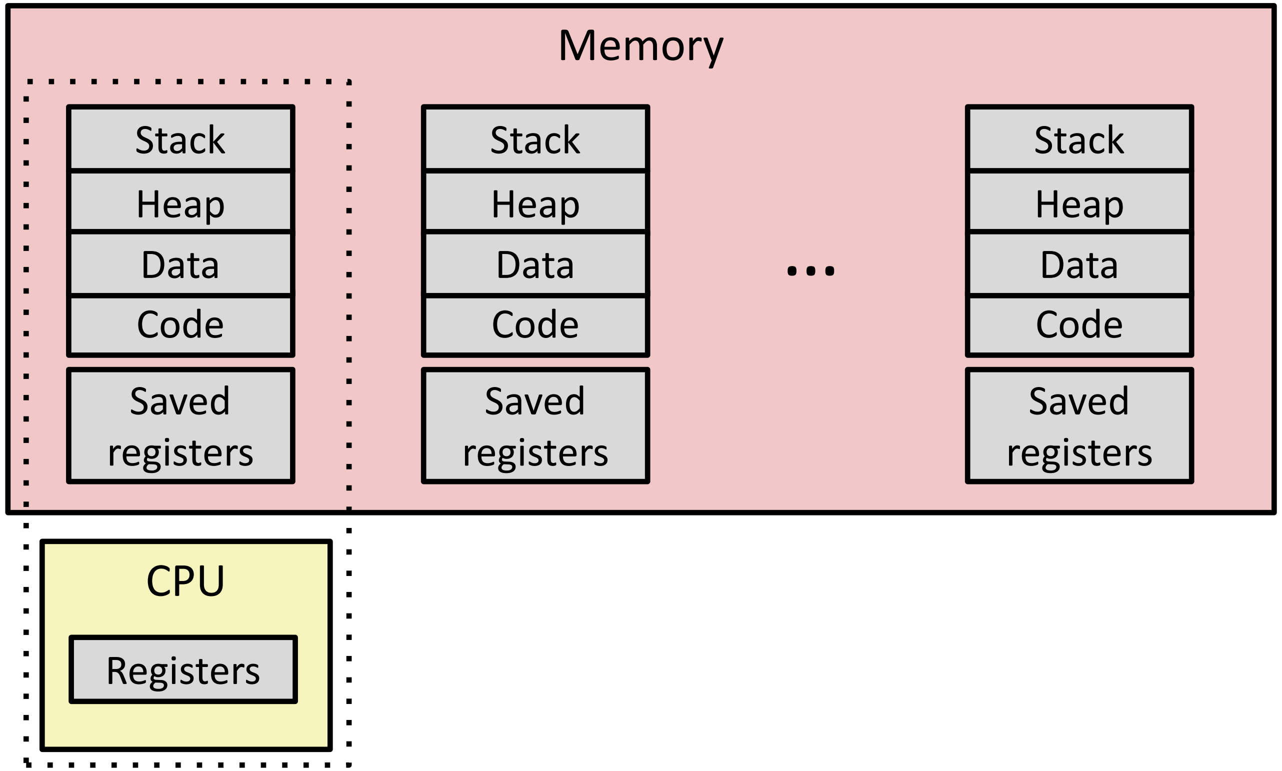
- Computer runs many processes simultaneously
  - Applications for one or more users
    - Web browsers, email clients, editors, …
  - Background tasks
    - Monitoring network & I/O devices

user-level

mostly kernel/OS-level

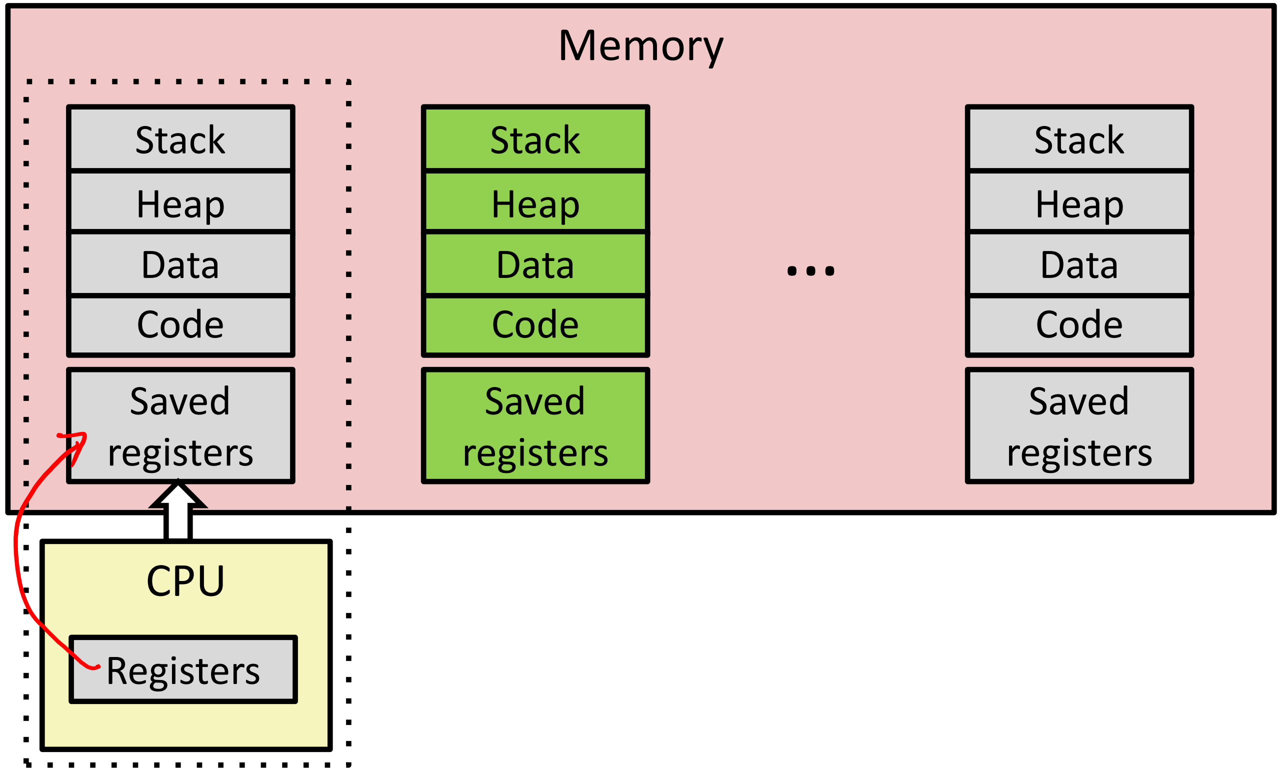


Multiprocessing: The Reality



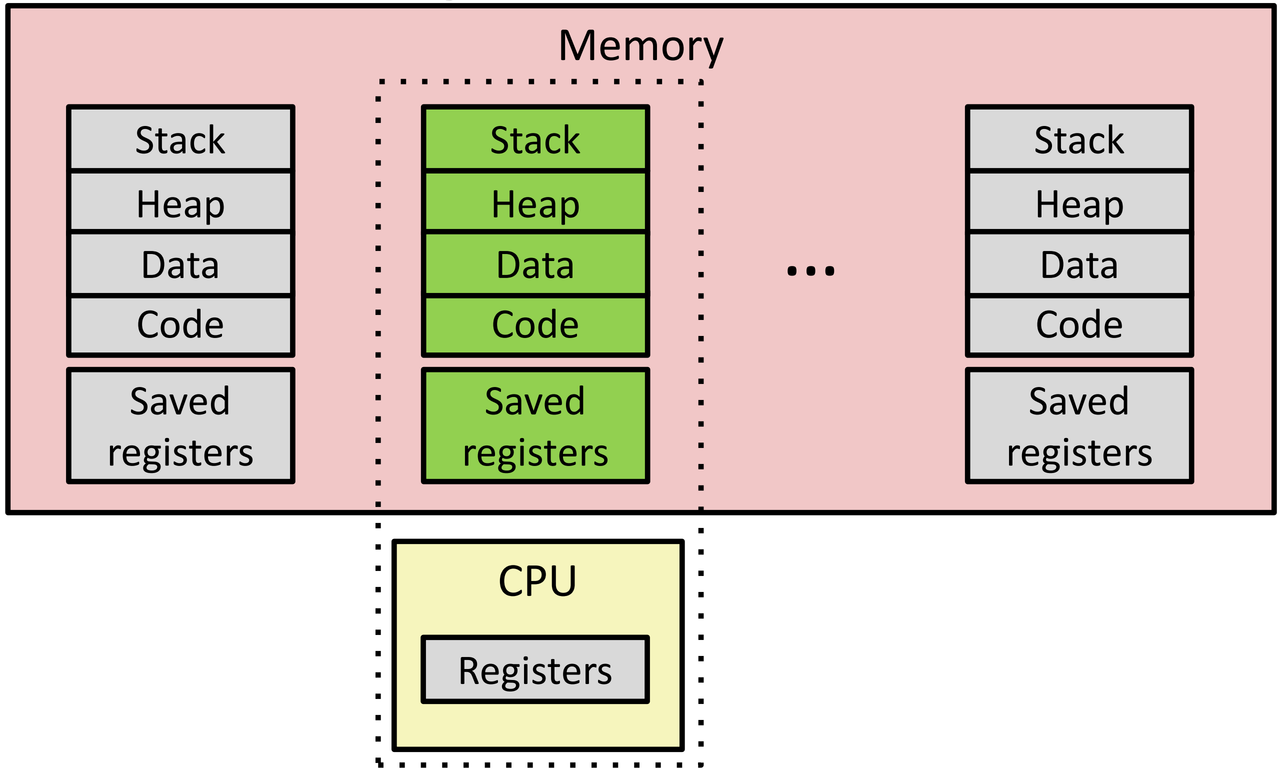
- Single processor executes multiple processes *concurrently*
  - Process executions interleaved, CPU runs *one at a time*
  - Address spaces managed by virtual memory system (later in course)
  - *Execution context* (register values, stack, …) for other processes saved in memory

Multiprocessing



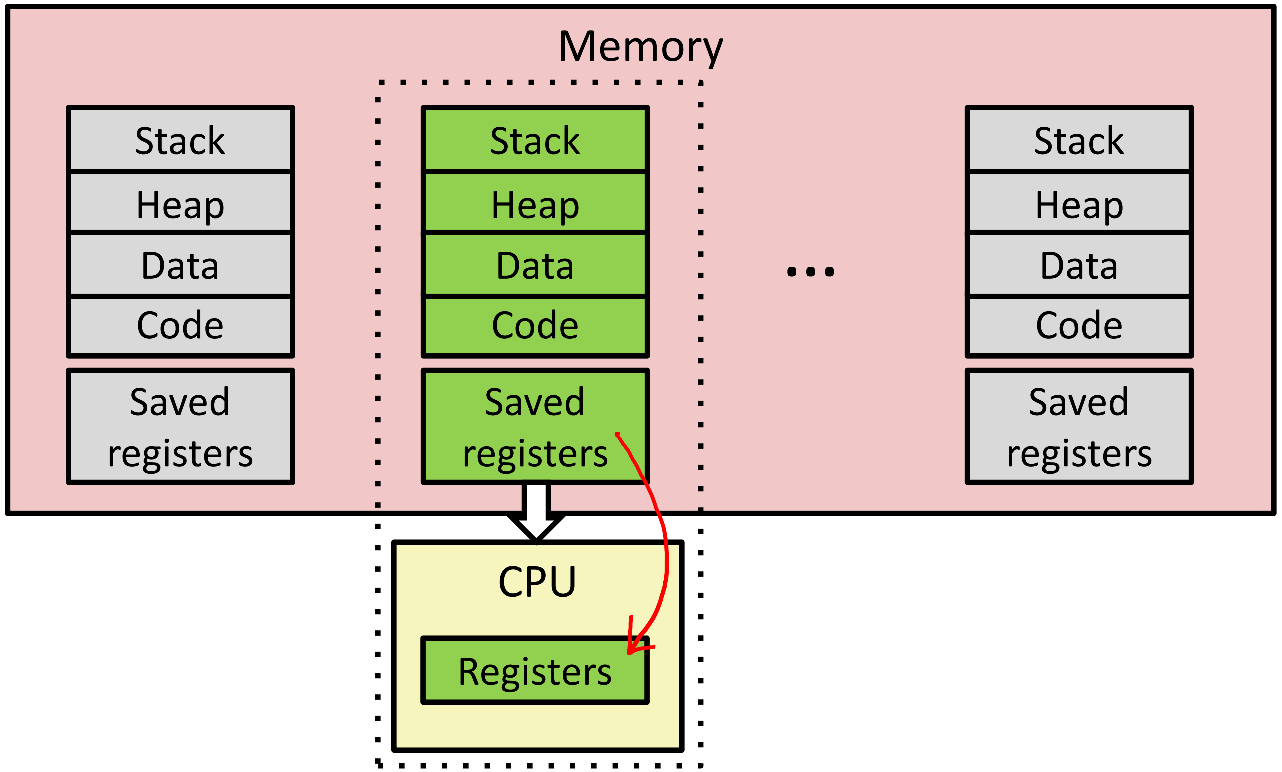
- Context switch
  1) **Save current registers in memory**

Multiprocessing



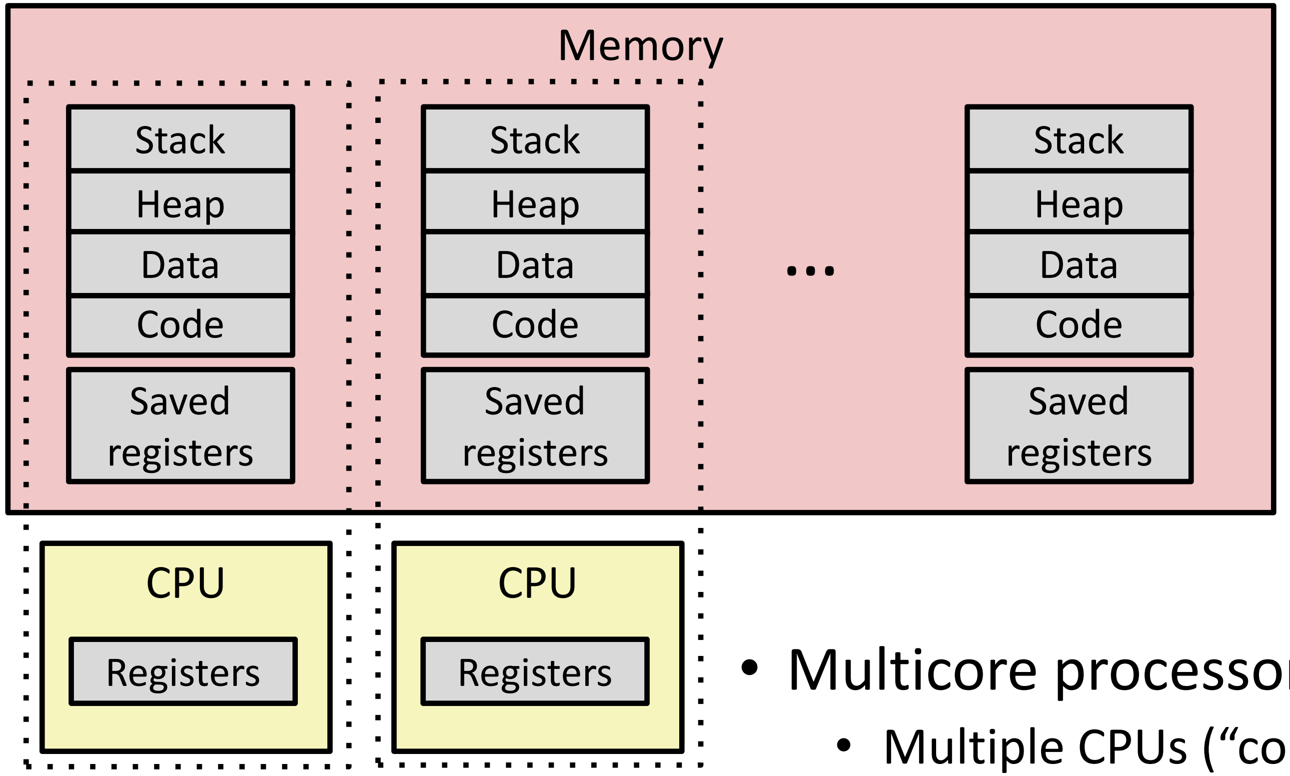
- Context switch
  1) Save current registers in memory
  2) **Schedule next process for execution** (OS decides)

Multiprocessing



- 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

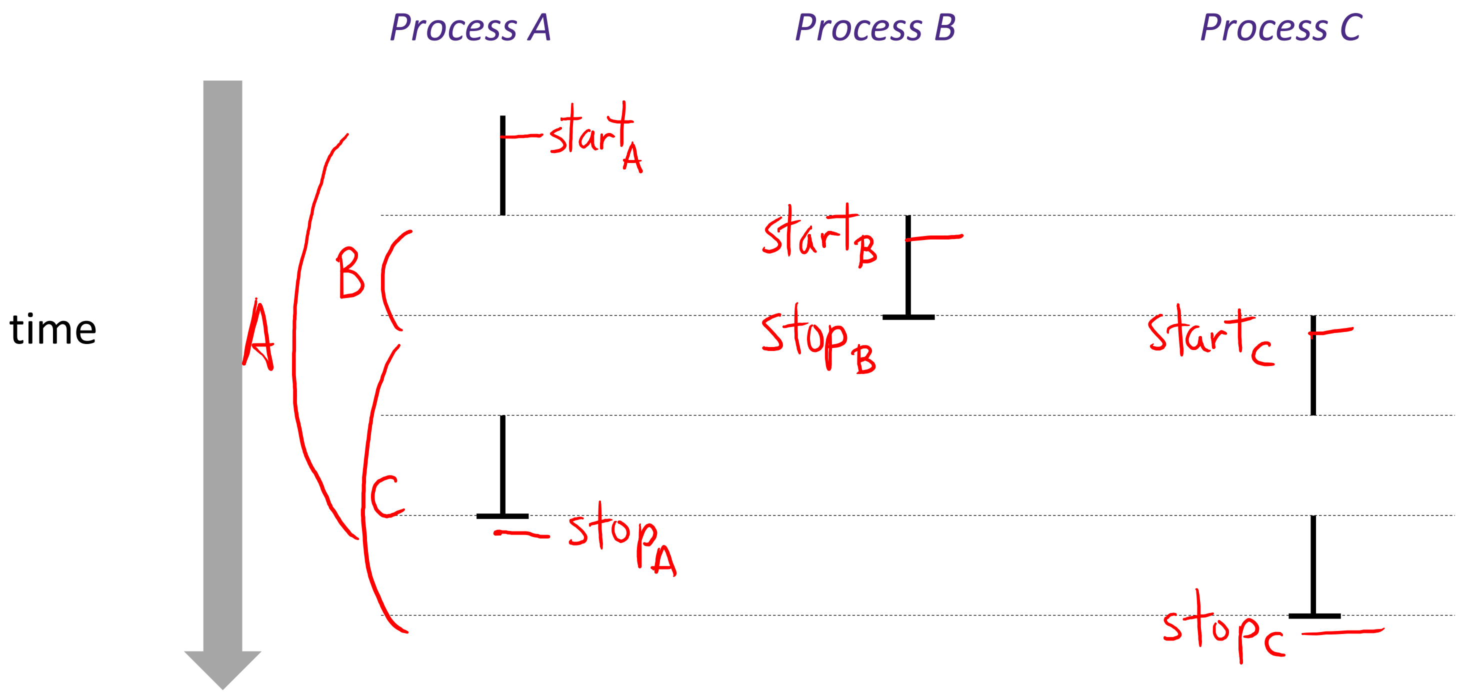


- Multicore processors
  - Multiple CPUs ("cores") on single chip
  - Share main memory (and some of the caches)
  - Each can execute a separate process
    - Kernel schedules processes to cores
    - ***Still* constantly swapping processes**

Concurrent Processes

Assume only <u>one</u> CPU

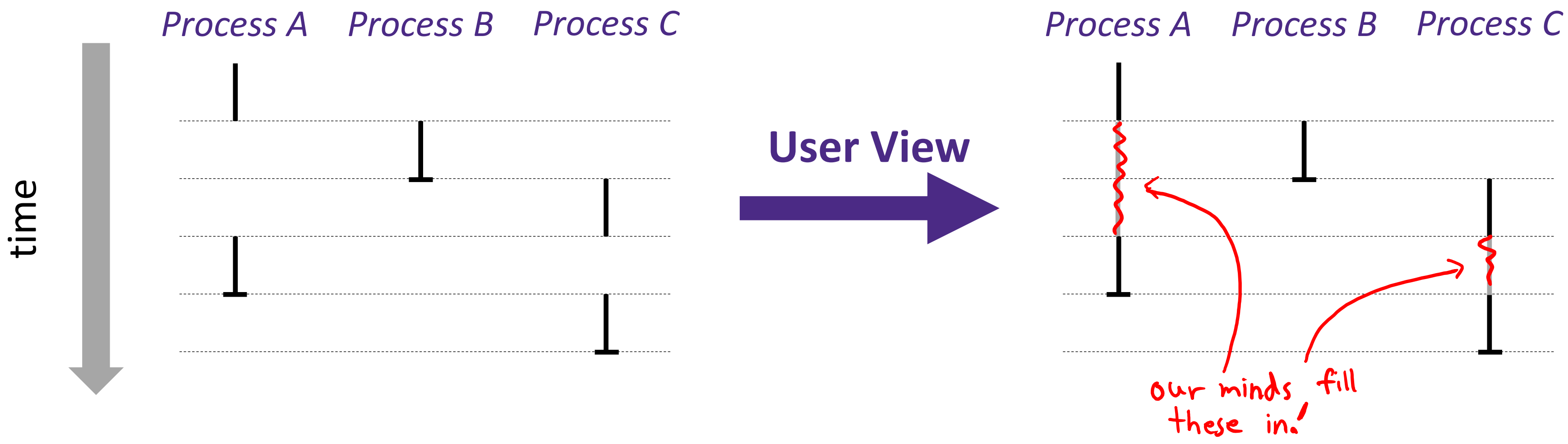
- Each process is a logical control flow
- Two processes *run concurrently* if their instruction executions overlap in time
  - Otherwise, they are *sequential*
- <u>Example</u>: (running on single core)
  - Concurrent: A & B, A & C
  - Sequential: B & C



User’s View of Concurrency

Assume only <u>one</u> CPU

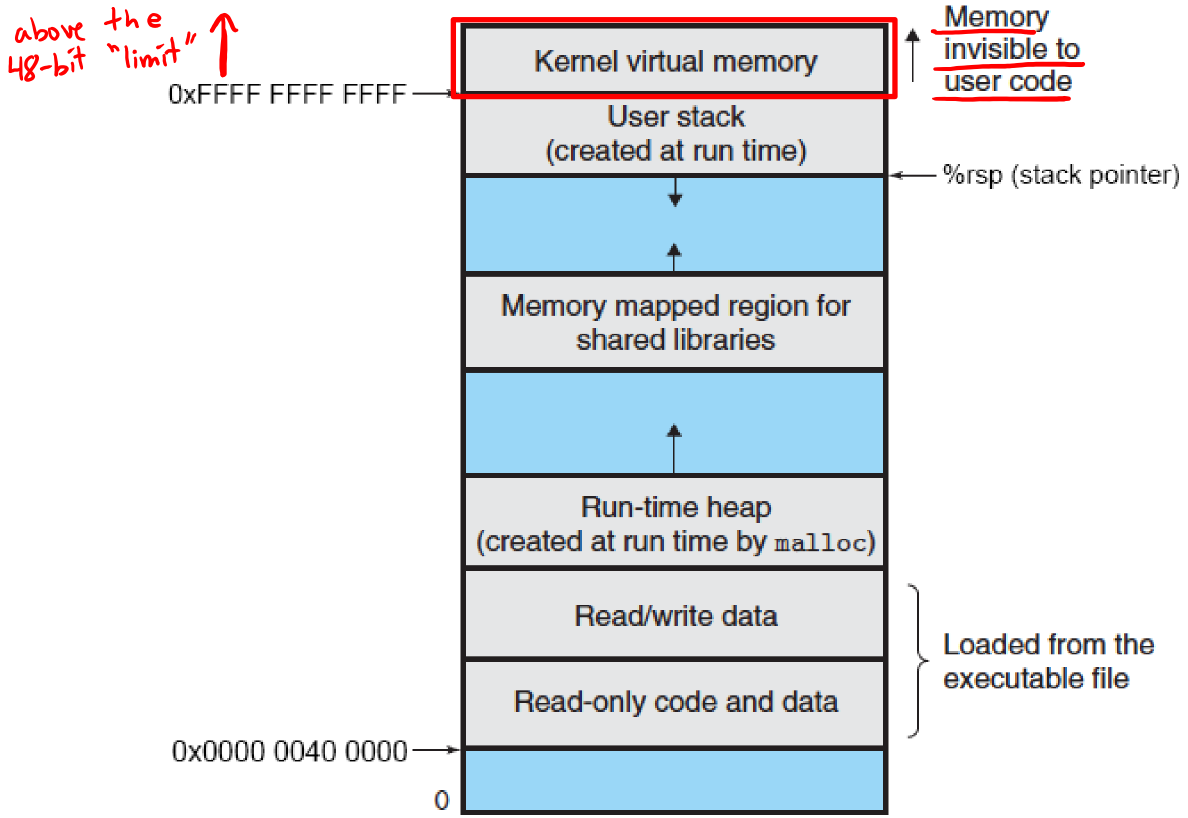
- Control flows for concurrent processes are physically disjoint in time
  - CPU only executes instructions for one process at a time
- However, the user can *think of* concurrent processes as executing at the same time, in *parallel*



Context Switching

Assume only one CPU

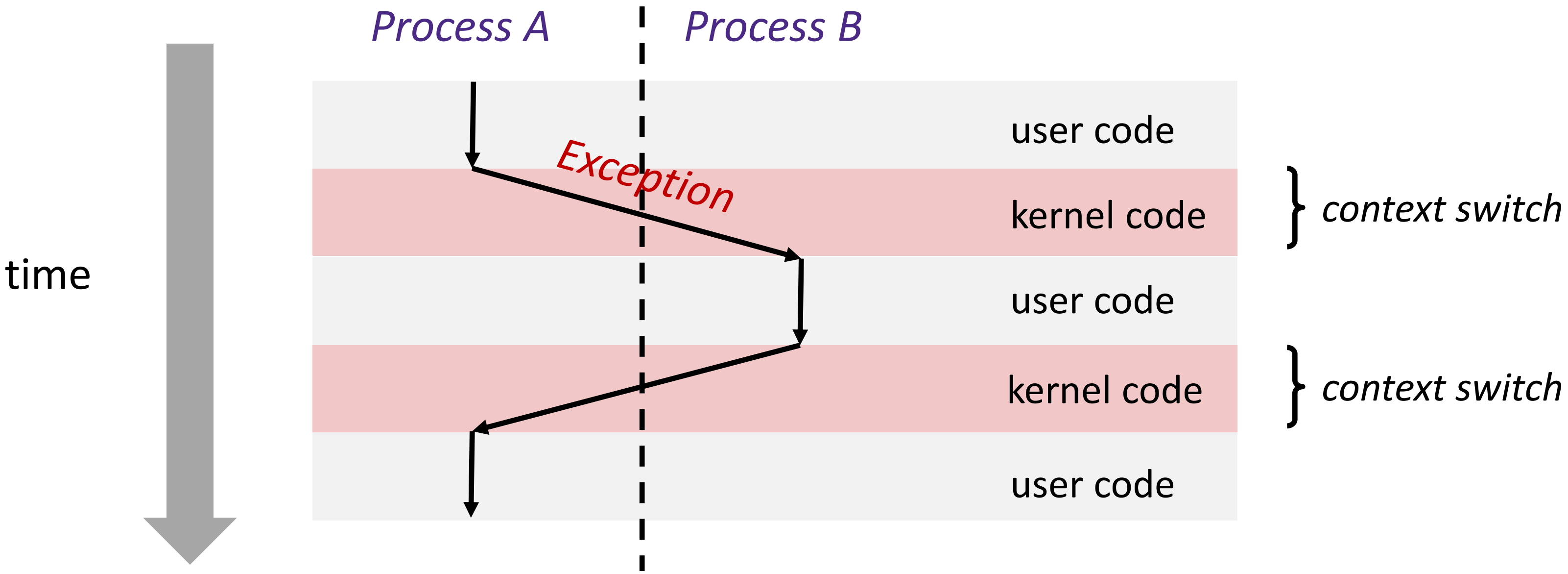
- Processes are managed by a *shared* chunk of OS code called the kernel
  - The kernel is not a separate process, but rather runs as part of a user process
- In x86-64 Linux:
  - Same address in each process refers to same shared memory location



Context Switching

Assume only one CPU

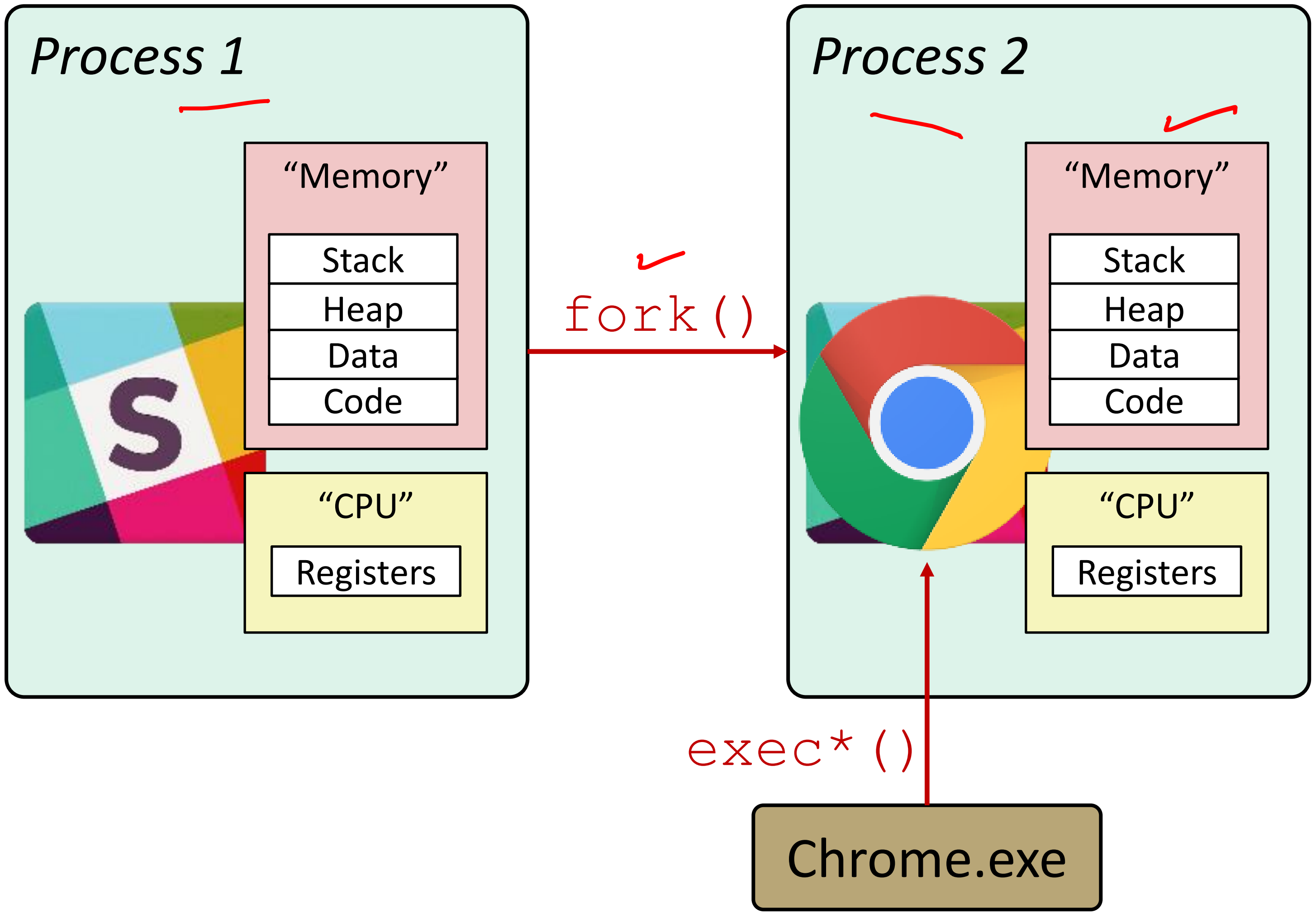
- Processes are managed by a *shared* chunk of OS code called the kernel
  - The kernel is not a separate process, but rather runs as part of a user process
- Context switch passes control flow from one process to another and is performed using kernel code



Processes

- Processes and context switching
- **Creating new processes**
  - **`fork()`, `exec*()`, and `wait()`**
- 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 pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

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

Understanding fork

Process X (parent)

PID X

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

fork

Process Y (child)

PID Y

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

Understanding fork

Process X (parent)

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

Process Y (child)

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

PID X

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

pid = Y

PID Y

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

pid = 0

Understanding fork

Process X (parent)

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

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

pid = Y

`hello from parent`

Process Y (child)

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

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

pid = 0

`hello from child`

Which one appears first?

non-deterministic!

Fork Example

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

- Both processes continue/start execution after `fork`
  - Child starts at instruction after the call to `fork` (storing into `pid`)
- Can’t predict execution order of parent and child
- Both processes start with `x=1`
  - Subsequent changes to `x` are independent
- Shared open files: stdout is the same in both parent and child

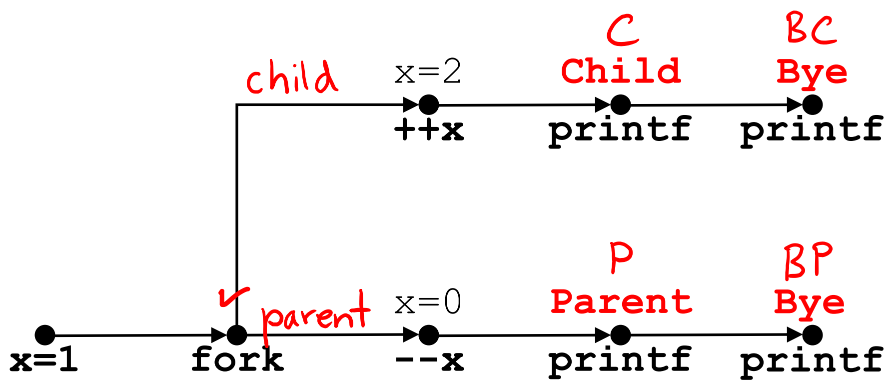
Modeling `fork` with Process Graphs

- A *process graph* is a useful tool for capturing the partial ordering of statements in a concurrent program
  - Each vertex is the execution of a statement
  - a $\rightarrow$ b means a happens before b
  - Edges can be labeled with current value of variables
  - **printf** vertices can be labeled with output
  - Each graph begins with a vertex with no in-edges

- Any *topological sort* of the graph corresponds to a feasible total ordering
  - Total ordering of vertices where all edges point from left to right

Fork Example: Possible Output

```
void fork1() {
    int x = 1;
    pid_t pid = fork();
    if (pid == 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);
}
```



Possible

C	P	C	C	
BC	BP	P	P	etc...
P	C	BC	BP	
BP	BP	BP	BC	

Not Possible

C	P	
BC	BC	etc...
BP	C	
P	BP	

as long as C comes before BC
and P comes before BP

Fork-Exec

Note: the return values of `fork` and `exec*` should be checked for errors

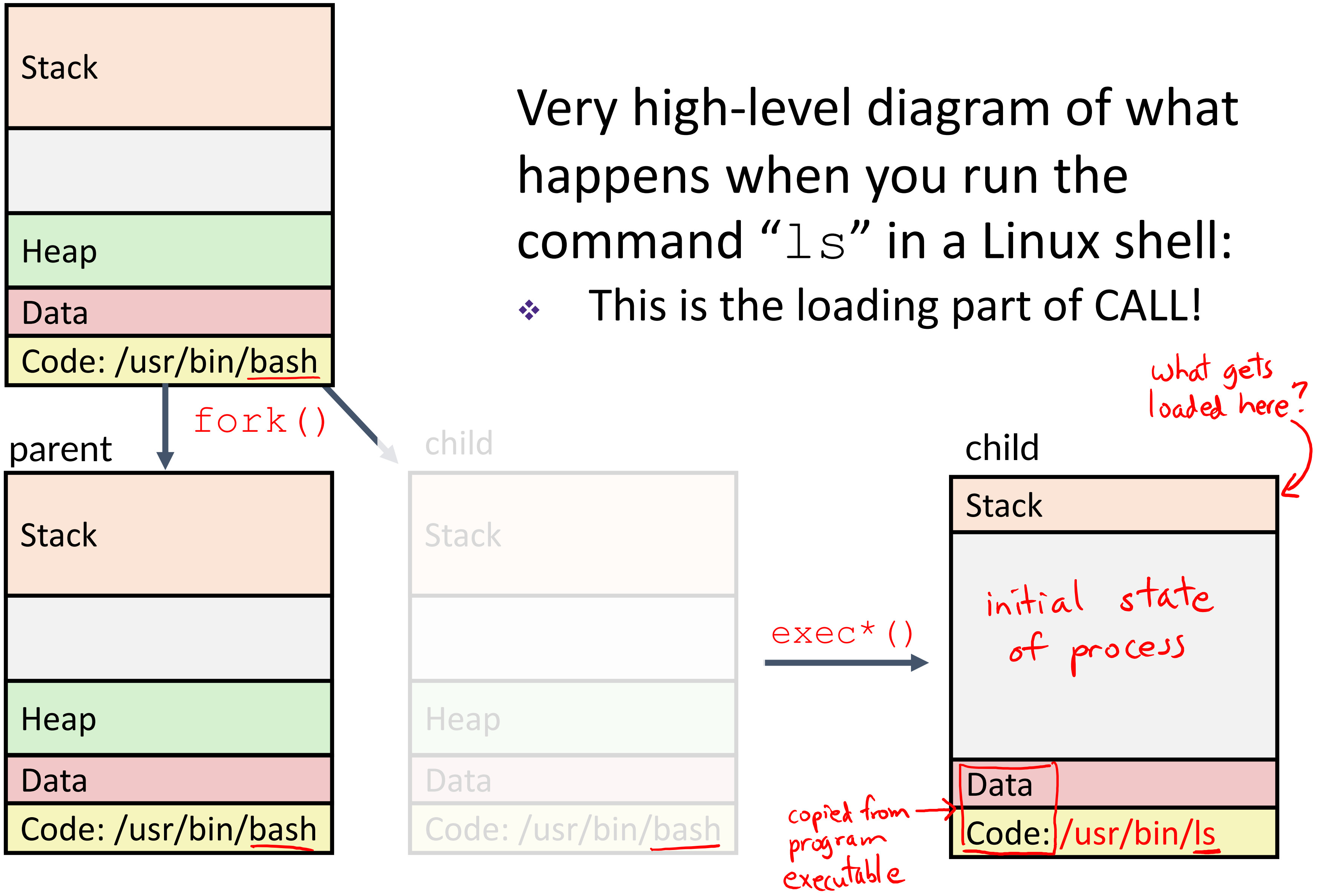
- fork-exec model:
  - `fork()` creates a copy of the current process
  - `exec*()` replaces the current process' code and address space with the code for a different program
    - Whole family of `exec` calls – see **`exec(3)`** and **`execve(2)`**

```
// Example arguments: path="/usr/bin/ls",
//      argv[0]="/usr/bin/ls", argv[1]="-ahl", argv[2]=NULL
void fork_exec(char *path, char *argv[]) {
   pid_t pid = fork();
   if (pid != 0) {
      printf("Parent: created a child %d\n", pid);
   } else {
      printf("Child: about to exec a new program\n");
      execv(path, argv);
   }
   printf("This line printed by parent only!\n");
}
```

Exec-ing a new program

Very high-level diagram of what happens when you run the command "`ls`" in a Linux shell:

- This is the loading part of CALL!



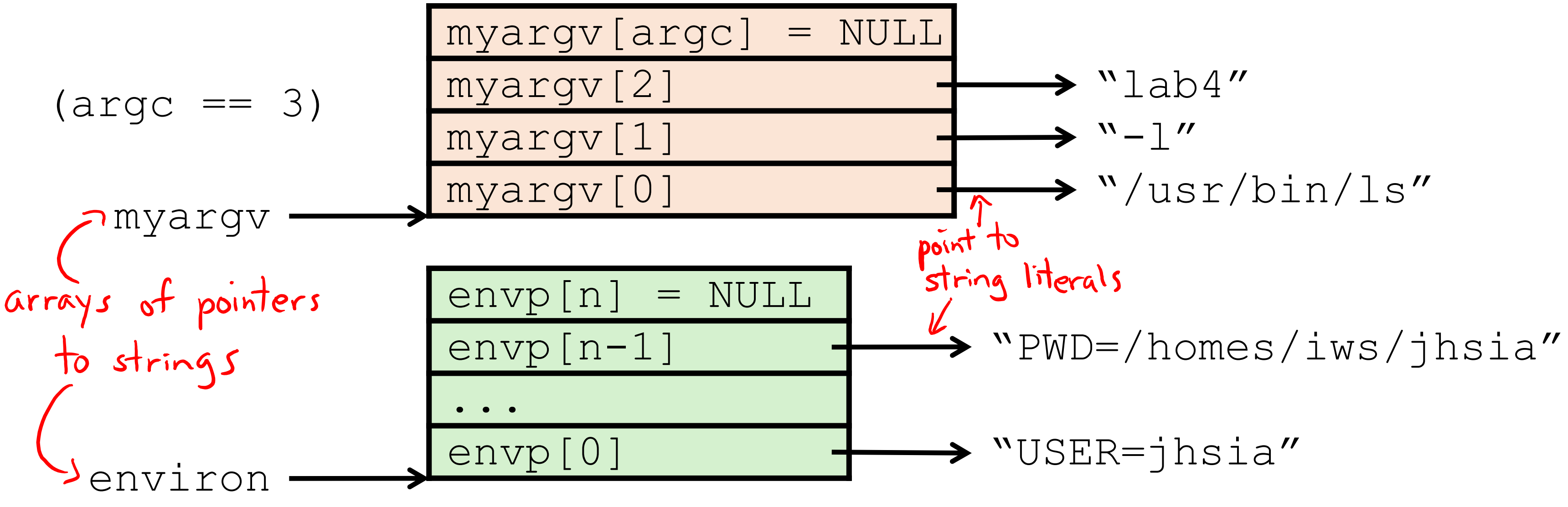
execve Example

int main(int argc, char* argv[])

$\underbrace{\text{int argc, char* argv[]}}_{\text{get command-line arguments into program}}$

arguments

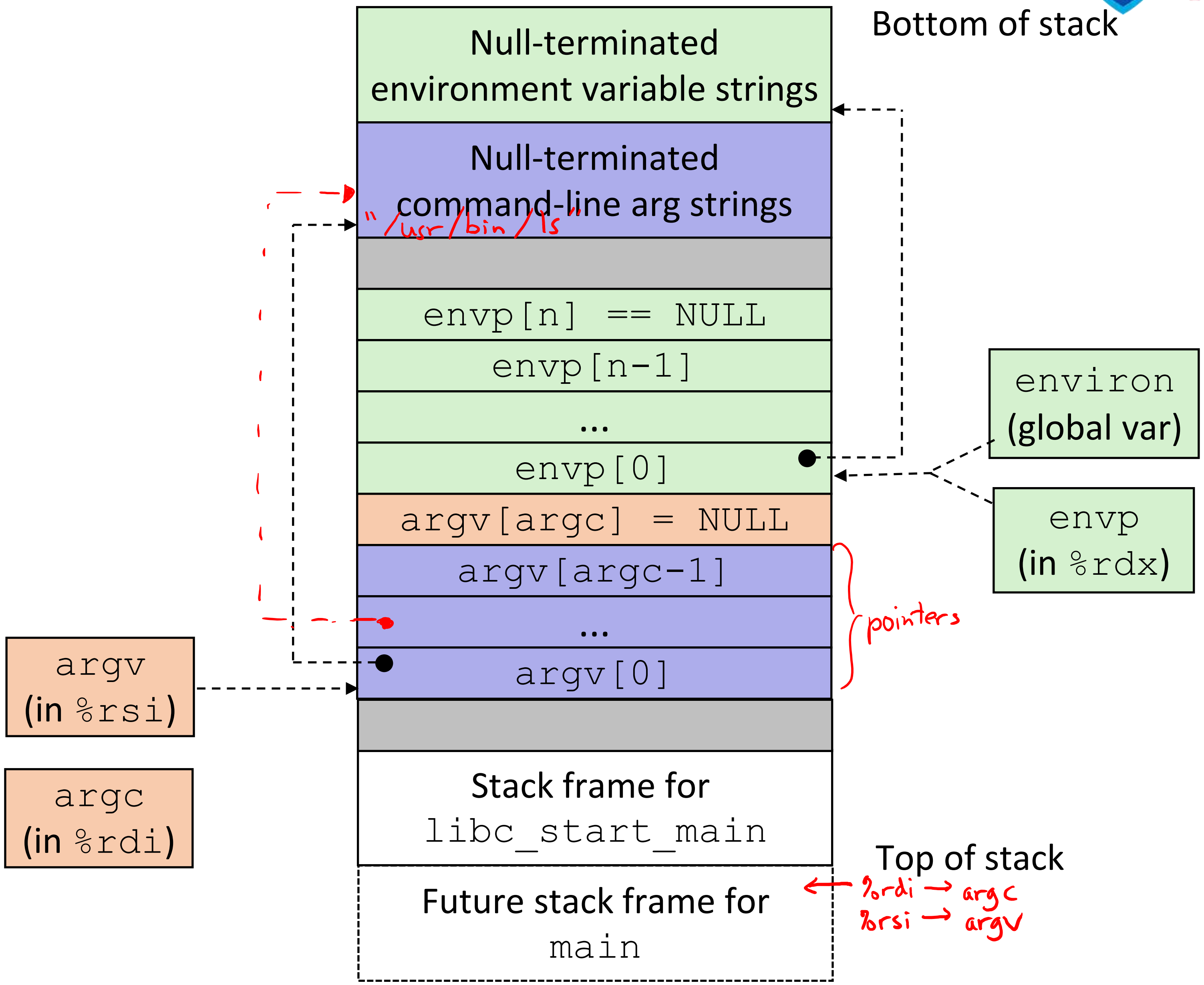
Execute "/usr/bin/ls -l lab4" in child process using current environment:




```
if ((pid = fork()) == 0) {    /* Child runs program */
    if (execve(myargv[0], myargv, environ) < 0) {
        printf("%s: Command not found.\n", myargv[0]);
        exit(1);
    }
}
```

Run the $\boxed{\texttt{printenv}}$ command in a Linux shell to see your own environment variables

Structure of the Stack when a new program starts



`exit`: Ending a process

- **`void`** `exit(`**`int`** `status)`
  - Exits a process
    - Status code: 0 is used for a normal exit, nonzero for abnormal exit

Processes

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

Zombies

- When a process terminates, it still consumes system resources
  - Various tables maintained by OS
  - Called a "zombie" (a living corpse, half alive and half dead)
- *Reaping* is performed by parent on terminated child
  - Parent is given exit status information and kernel then deletes zombie child process
- What if parent doesn't reap?
  - If any parent terminates without reaping a child, then the orphaned child will be reaped by `init` process (pid == 1)
    - **Note:** on more recent Linux systems, **`init`** has been renamed **`systemd`**
  - In long-running processes (e.g. shells, servers) we need *explicit* reaping

`wait`: Synchronizing with Children

- **`int`** `wait(`**`int *`**`child_status)`
  - Suspends current process (*i.e.* the parent) until one of its children terminates
  - Return value is the PID of the child process that terminated
    - *On successful return, the child process is reaped*
  - If `child_status != NULL`, then the `*child_status` value indicates why the child process terminated
    - Special macros for interpreting this status – see **`man wait(2)`**
- **Note:** If parent process has multiple children, `wait` will return when *any* of the children terminates
  - `waitpid` can be used to wait on a specific child process

wait: Synchronizing with Children

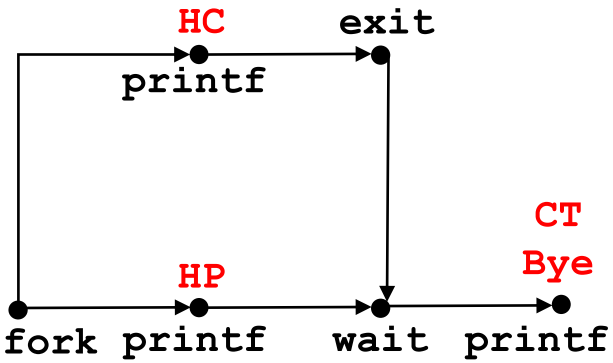
```
void fork_wait() {
    int child_status;

    if (fork() == 0) {
        printf("HC: hello from child\n");
        exit(0);
    } else {
        printf("HP: hello from parent\n");
        wait(&child_status);
        printf("CT: child has terminated\n");
    }
    printf("Bye\n");
}
```

child

parent

forks.c



Feasible output:		Infeasible output:
HC	HP	HP
HP	HC	CT
CT	CT	Bye
Bye	Bye	HC

Example: Zombie

```
void fork7() {
    if (fork() == 0) {
        /* Child */
        printf("Terminating Child, PID = %d\n",
               getpid());
        exit(0);
    } else {
        printf("Running Parent, PID = %d\n",
               getpid());
        while (1); /* Infinite loop */
    }
}
```

parent persists

forks.c

```
linux> ./forks 7 &
[1] 6639
Running Parent, PID = 6639
Terminating Child, PID = 6640
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6639 ttyp9    00:00:03 forks
 6640 ttyp9    00:00:00 forks <defunct>
 6641 ttyp9    00:00:00 ps
linux> kill 6639
[1]    Terminated
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6642 ttyp9    00:00:00 ps
```

parent

child

- `ps` shows child process as "defunct"
- Killing parent allows child to be reaped by `init`

Example:

Non-terminating Child

```
void fork8() {
    if (fork() == 0) {
        /* Child */
        printf("Running Child, PID = %d\n",
               getpid());
        while (1); /* Infinite loop */
    } else {
        printf("Terminating Parent, PID = %d\n",
               getpid());
        exit(0);
    }
}
```

child persists

forks.c

```
linux> ./forks 8
Terminating Parent, PID = 6675
Running Child, PID = 6676
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6676 ttyp9    00:00:06 forks
 6677 ttyp9    00:00:00 ps
linux> kill 6676
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6678 ttyp9    00:00:00 ps
```

- Child process still active even though parent has terminated
- Must kill explicitly, or else will keep running indefinitely

Process Management Summary

- `fork` makes two copies of the same process (parent & child)
  - Returns different values to the two processes
- `exec*` replaces current process from file (new program)
  - Two-process program:
    - First `fork()`
    - **if** (pid == 0) { */* child code */* } **else** { */* parent code */* }
  - Two different programs:
    - First `fork()`
    - **if** (pid == 0) { execv(…) } **else** { */* parent code */* }

- `wait` or `waitpid` used to synchronize parent/child execution and to reap child process

Summary

- Processes
  - At any given time, system has multiple active processes
  - On a one-CPU system, only one can execute at a time, but each process appears to have total control of the processor
  - OS periodically "context switches" between active processes
    - Implemented using *exceptional control flow*
- Process management
  - `fork`: one call, two returns
  - `execve`: one call, usually no return
  - `wait` or `waitpid`: synchronization
  - `exit`: one call, no return

Thanks

Q & A