Lecture 18: Processes

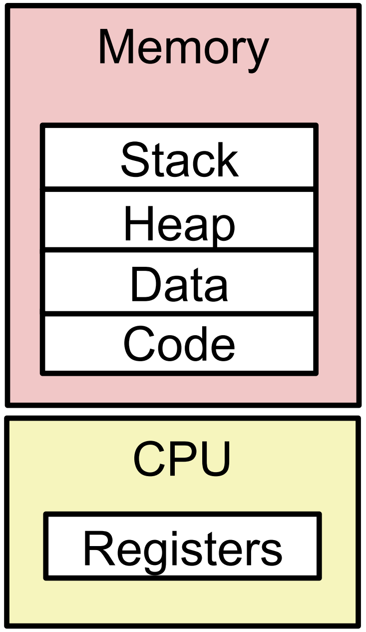
CS 105

April 1, 2019

Processes

- Definition: A ***program*** is a file containing code + data that describes a computation
- Definition: 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:
  - ***Private address space***
    - Each program seems to have exclusive use of main memory.
    - Provided by kernel mechanism called *virtual memory*
  - ***Logical control flow***
    - Each program seems to have exclusive use of the CPU
    - Provided by kernel mechanism called *context switching*



Memory

Stack

Heap

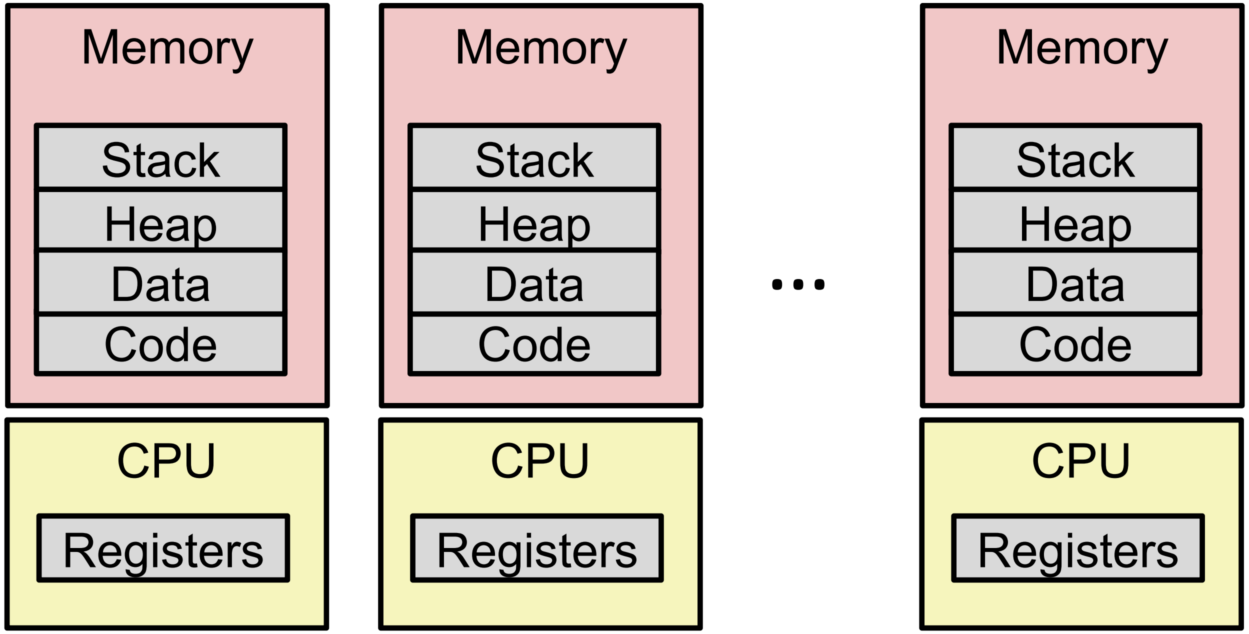
Data

Code

CPU

Registers

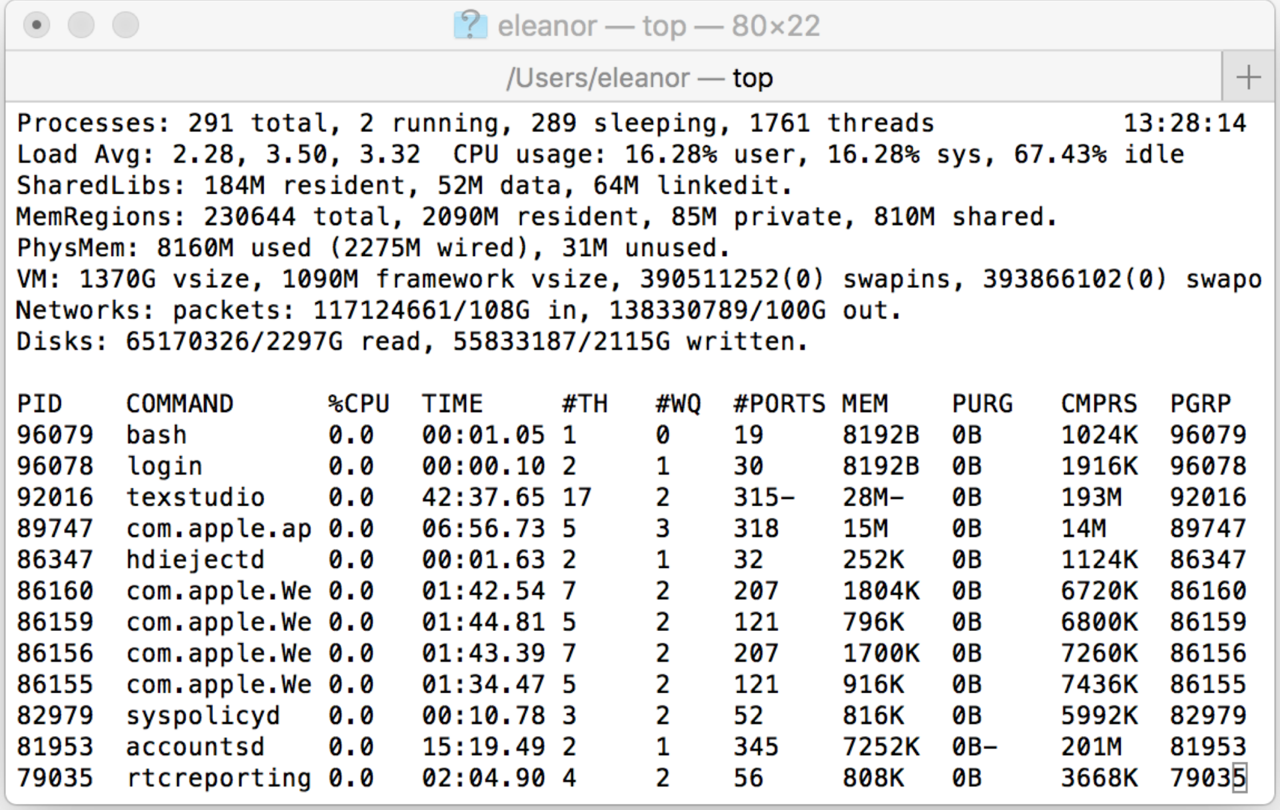
Multiprocessing: The Illusion



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

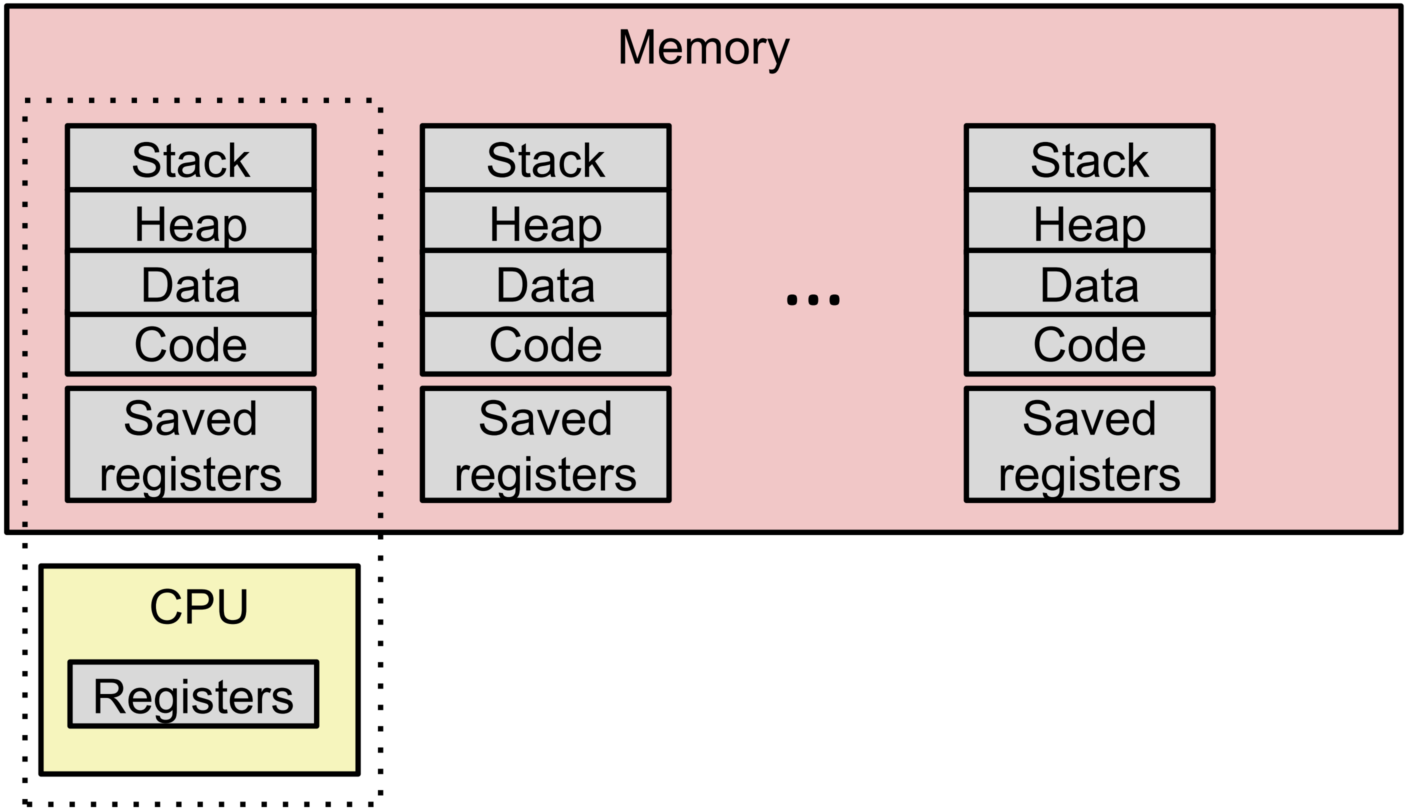
Multiprocessing Example

- Running program “top” on Mac
  - System has 123 processes, 5 of which are active
  - Identified by Process ID (PID)



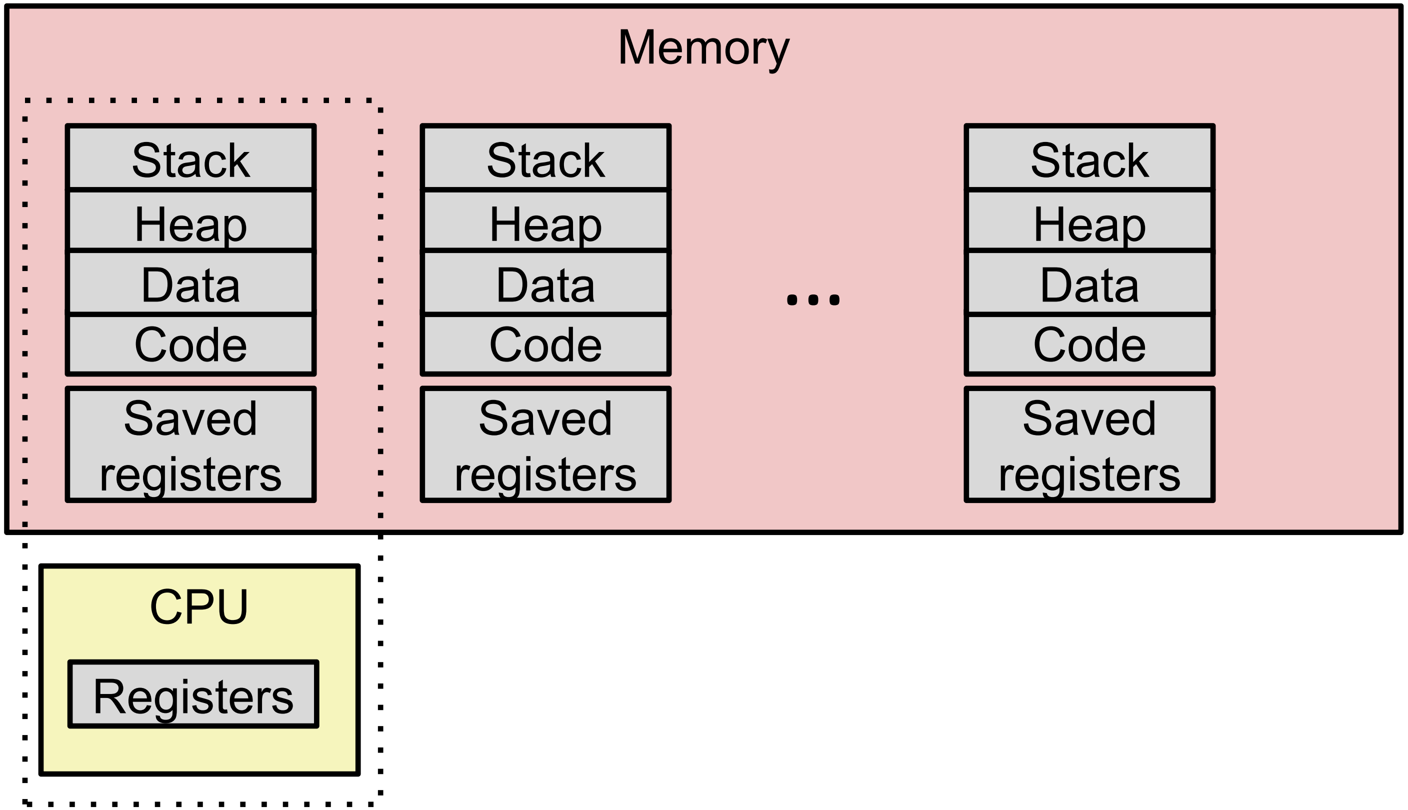
```
Processes: 291 total, 2 running, 289 sleeping, 1761 threads            13:28:14
Load Avg: 2.28, 3.50, 3.32  CPU usage: 16.28% user, 16.28% sys, 67.43% idle
SharedLibs: 184M resident, 52M data, 64M linkedit.
MemRegions: 230644 total, 2090M resident, 85M private, 810M shared.
PhysMem: 8160M used (2275M wired), 31M unused.
VM: 1370G vsize, 1090M framework vsize, 390511252(0) swapins, 393866102(0) swapo
Networks: packets: 117124661/108G in, 138330789/100G out.
Disks: 65170326/2297G read, 55833187/2115G written.

PID    COMMAND      %CPU TIME     #TH   #WQ  #PORTS MEM    PURG   CMPRS  PGRP
96079  bash         0.0  00:01.05 1     0    19     8192B  0B     1024K  96079
96078  login        0.0  00:00.10 2     1    30     8192B  0B     1916K  96078
92016  texstudio    0.0  42:37.65 17    2    315-   28M-   0B     193M   92016
89747  com.apple.ap 0.0  06:56.73 5     3    318    15M    0B     14M    89747
86347  hdiejectd    0.0  00:01.63 2     1    32     252K   0B     1124K  86347
86160  com.apple.We 0.0  01:42.54 7     2    207    1804K  0B     6720K  86160
86159  com.apple.We 0.0  01:44.81 5     2    121    796K   0B     6800K  86159
86156  com.apple.We 0.0  01:43.39 7     2    207    1700K  0B     7260K  86156
86155  com.apple.We 0.0  01:34.47 5     2    121    916K   0B     7436K  86155
82979  syspolicyd   0.0  00:10.78 3     2    52     816K   0B     5992K  82979
81953  accountsd    0.0  15:19.49 2     1    345    7252K  0B-    201M   81953
79035  rtcreporting 0.0  02:04.90 4     2    56     808K   0B     3668K  79035
```

Multiprocessing: The (Traditional) Reality



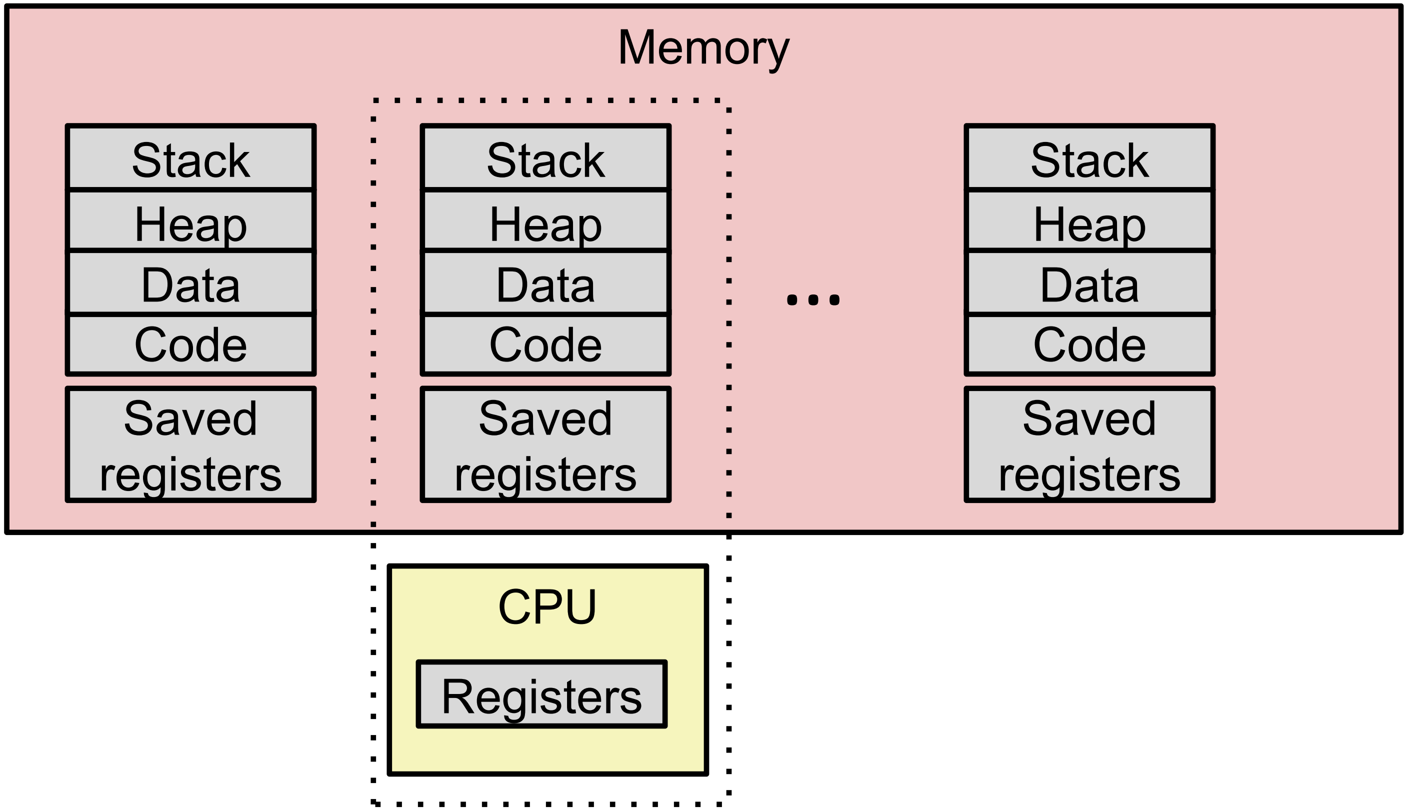
- Single processor executes multiple processes concurrently
  - Process executions interleaved (multitasking)
  - Address spaces managed by virtual memory system
  - Register values for nonexecuting processes saved in memory

Multiprocessing: The (Traditional) Reality



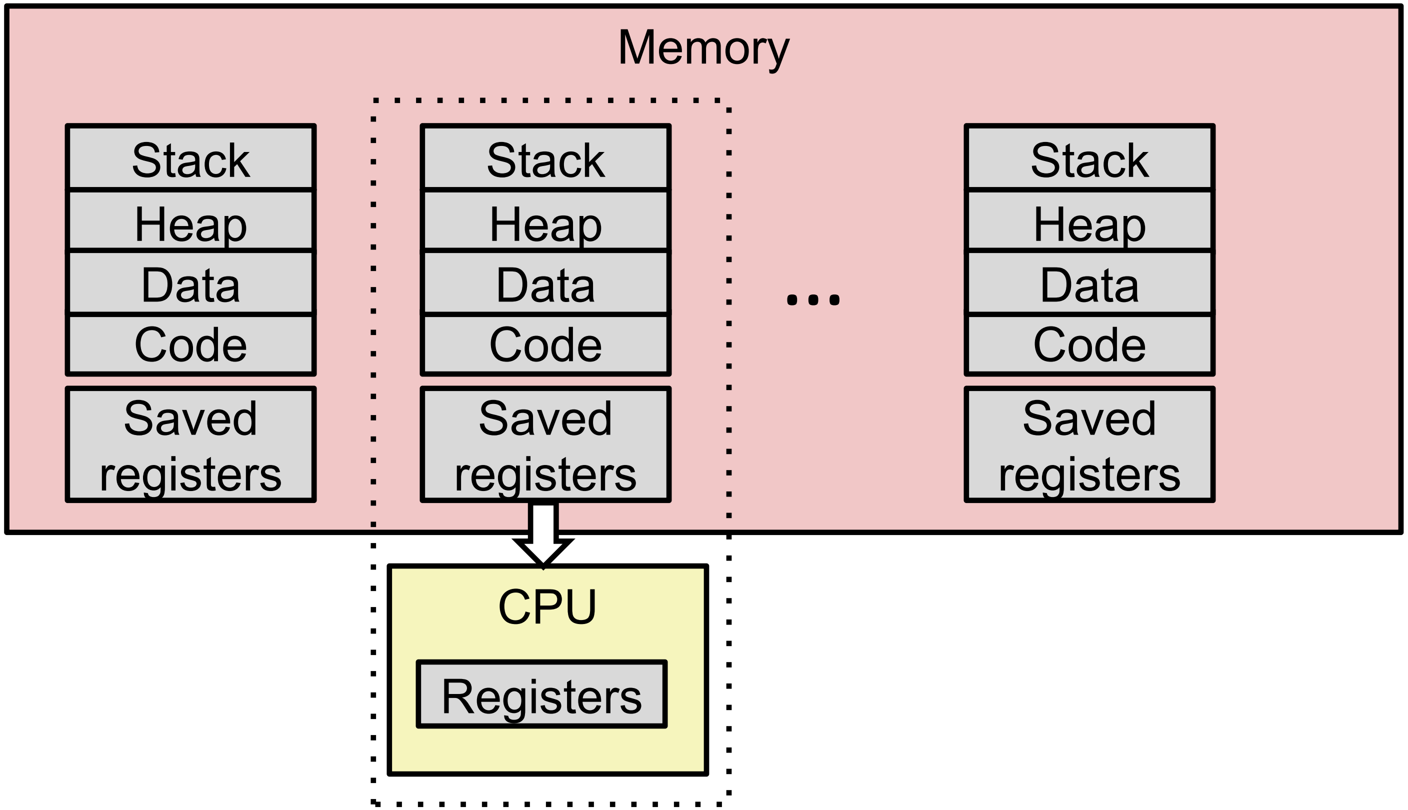
1. Save current registers in memory

Multiprocessing: The (Traditional) Reality



1. Save current registers in memory
2. Schedule next process for execution

Multiprocessing: The (Traditional) Reality

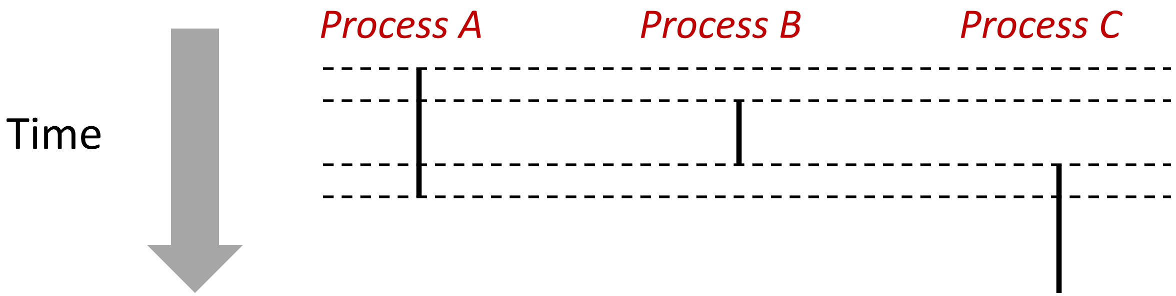


1. Save current registers in memory
2. Schedule next process for execution
3. Load saved registers and switch address space (context switch)

User View of Concurrent Processes

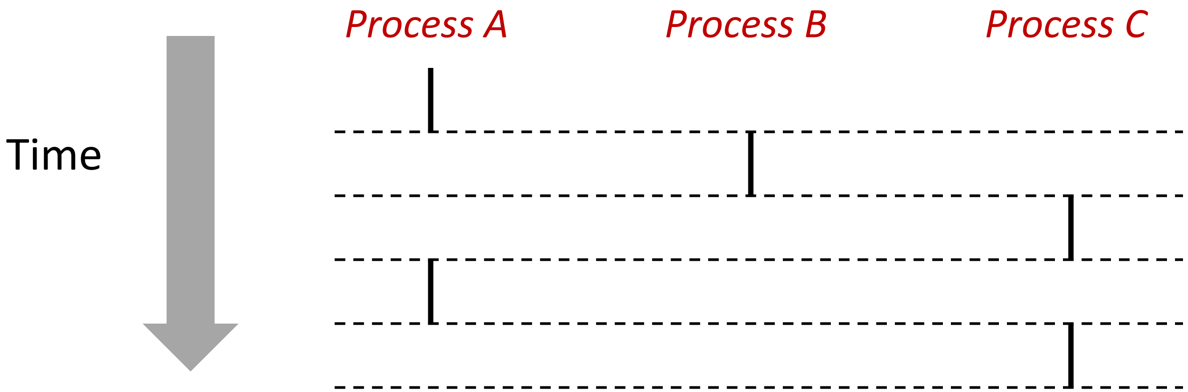
- Control flows for concurrent processes are physically disjoint in time

- However, we can think of concurrent processes as running in parallel with each other



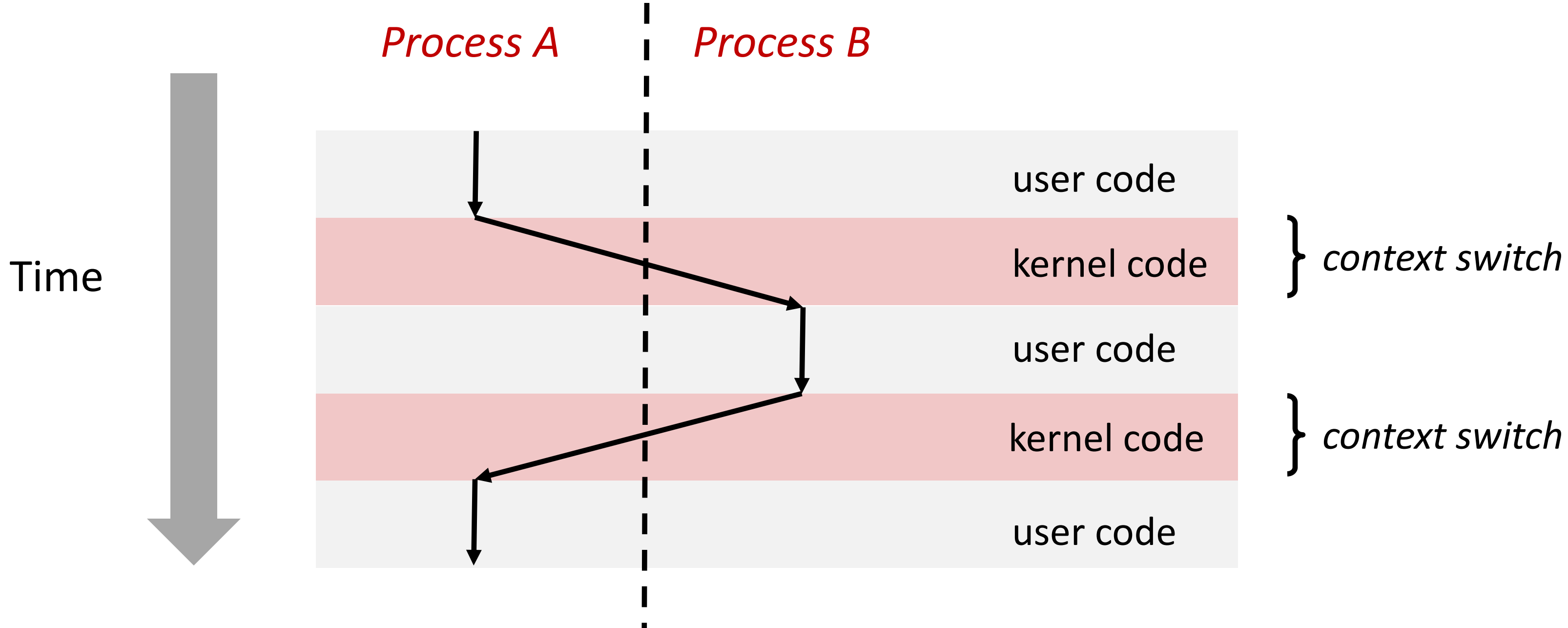
Concurrent Processes

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



Context Switching

- Processes are managed by a shared chunk of memory-resident OS code called the ***kernel***
  - Important: the kernel is not a separate process, but rather runs as part of some existing process.
- Control flow passes from one process to another via a ***context switch***

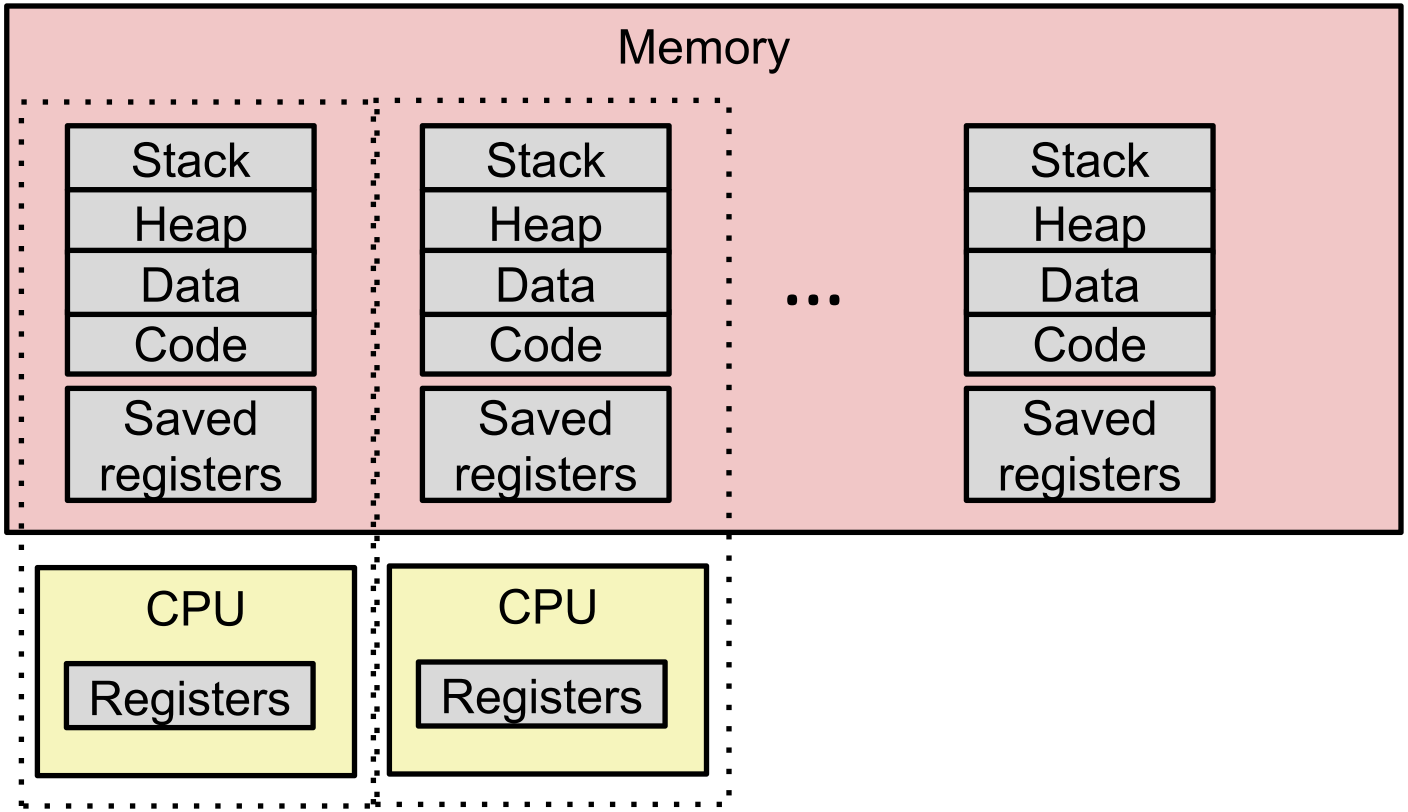


Process Control Block (PCB)

- To implement a context switch, OS maintains a PCB for each process containing:
  - location in memory
  - register values
  - PC, SP, eflags/status register
  - location of executable on disk
  - page tables
  - which user is executing this process
  - process identifier (pid)
  - process privilege level
  - process arguments (for identification with ps)
  - process status
  - scheduling information

... and more!

Multiprocessing: The (Modern) Reality



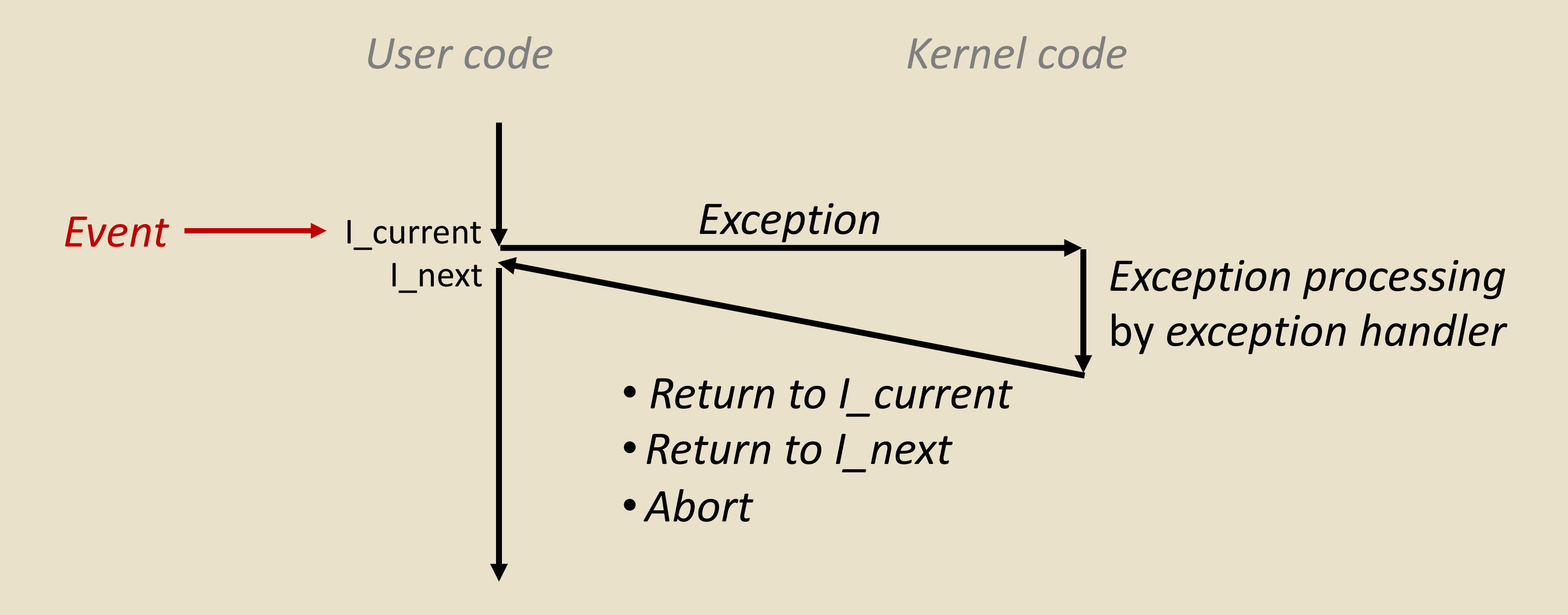
- Multicore processors
  - Multiple CPUs on single chip
  - Share main memory (and some of the caches)
  - Each can execute a separate process
    - Scheduling of processors onto cores done by kernel

Exceptional Control Flow

- Exists at all levels of a computer system
- Low level mechanisms
  - 1. **Exceptions**
    - Change in control flow in response to a system event (i.e., change in system state)
    - Implemented using combination of hardware and OS software
- Higher level mechanisms
  - 2. **Process context switch**
    - Implemented by OS software and hardware timer
  - 3. **Signals**
    - Implemented by OS software
  - 4. **Nonlocal jumps**: `setjmp()` and `longjmp()`
    - Implemented by C runtime library

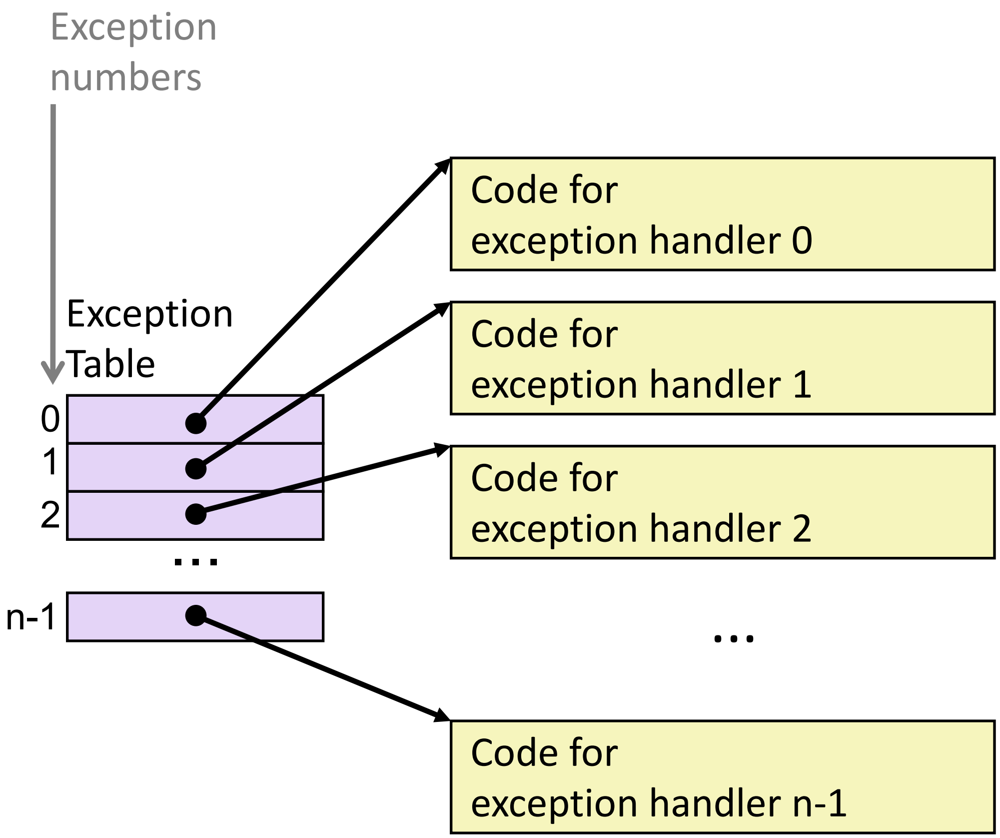
Exceptions

- An *exception* is a transfer of control to the OS *kernel* in response to some *event* (i.e., change in processor state)
  - Kernel is the memory-resident part of the OS
  - Examples of events: Divide by 0, arithmetic overflow, page fault, I/O request completes, typing Ctrl-C



- *Return to I_current*
- *Return to I_next*
- *Abort*

Exception Tables



- 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

Asynchronous Exceptions (Interrupts)

- Caused by events external to the processor
  - Indicated by setting the processor's *interrupt pin*
  - Handler returns to "next" instruction

- Examples:
  - Timer interrupt
    - Every few ms, an external timer chip triggers an interrupt
    - Used by the kernel to take back control from user programs
  - I/O interrupt from external device
    - Hitting Ctrl-C at the keyboard
    - Arrival of a packet from a network
    - Arrival of data from a disk

Synchronous Exceptions

- Caused by events that occur as a result of executing an instruction:
  - ***Traps***
    - Intentional
    - Examples: ***system calls***, breakpoint traps, special instructions
    - Returns control to "next" instruction
  - ***Faults***
    - Unintentional but possibly recoverable
    - Examples: page faults (recoverable), protection faults (unrecoverable), floating point exceptions
    - Either re-executes faulting ("current") instruction or aborts
  - ***Aborts***
    - Unintentional and unrecoverable
    - Examples: illegal instruction, parity error, machine check
    - Aborts current program

Process Status

From a programmer's perspective, we can think of a process as being in one of three states

- Running
  - Process is either executing, or waiting to be executed and will eventually be *scheduled* (i.e., chosen to execute) by the kernel
- Stopped
  - Process execution is *suspended* and will not be scheduled until further notice
- Terminated
  - Process is stopped permanently

So who should be allowed to create a process?

Creating Processes

- *Parent process* creates a new running *child process* by calling `fork`

- `int fork(void)`
  - Returns 0 to the child process, child's PID to parent process
  - Child is *almost* identical to parent:
    - Child get an identical (but separate) copy of the parent's virtual address space.
    - Child gets identical copies of the parent's open file descriptors
    - Child has a different PID than the parent

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

Obtaining Process IDs

- `pid_t getpid(void)`
  - Returns PID of current process

- `pid_t getppid(void)`
  - Returns PID of parent process

Terminating Processes

- Process becomes terminated for one of three reasons:
  - Receiving a signal whose default action is to terminate (next lecture)
  - Returning from the `main` routine
  - Calling the `exit` function

- `void exit(int status)`
  - Terminates with an *exit status* of `status`
  - Convention: normal return status is 0, nonzero on error
  - Another way to explicitly set the exit status is to return an integer value from the main routine

- `exit` is called once but never returns.

`fork` Example

```
int main()
{
    pid_t pid;
    int x = 1;

    pid = Fork();
    if (pid == 0) {  /* Child */
        printf("child : x=%d\n", ++x);
	exit(0);
    }

    /* Parent */
    printf("parent: x=%d\n", --x);
    exit(0);
}
```

fork.c

- **Call once, return twice**
- **Concurrent execution**
  - Can't predict execution order of parent and child
- **Duplicate but separate address space**
  - `x` has a value of 1 when fork returns in parent and child
  - Subsequent changes to `x` are independent
- **Shared open files**
  - `stdout` is the same in both parent and child

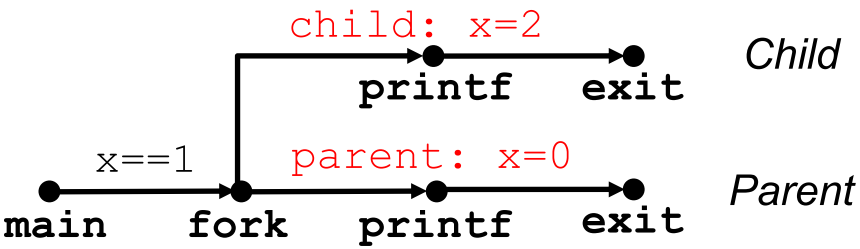
Modeling `fork` with Process Graphs

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

Process Graph Example

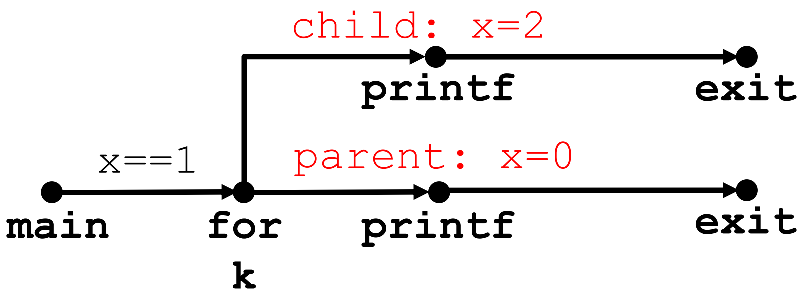
```c
int main()
{
    pid_t pid;
    int x = 1;

    pid = Fork();
    if (pid == 0) {  /* Child */
        printf("child : x=%d\n", ++x);
       exit(0);
    }

    /* Parent */
    printf("parent: x=%d\n", --x);
    exit(0);
}
```

fork.c

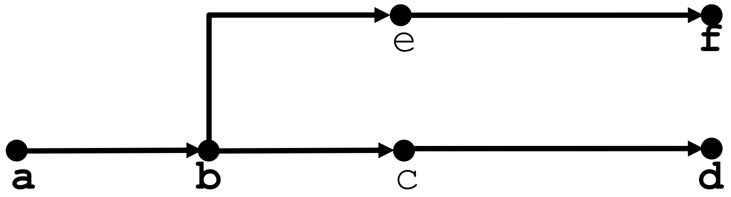


Interpreting Process Graphs

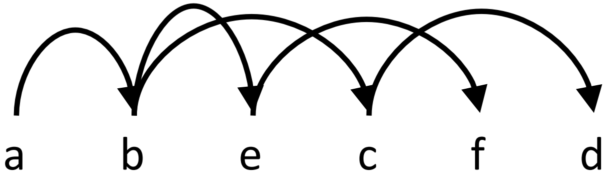
- Original graph:



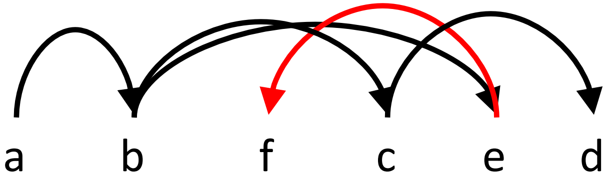
- Relabled graph:



Feasible total ordering:



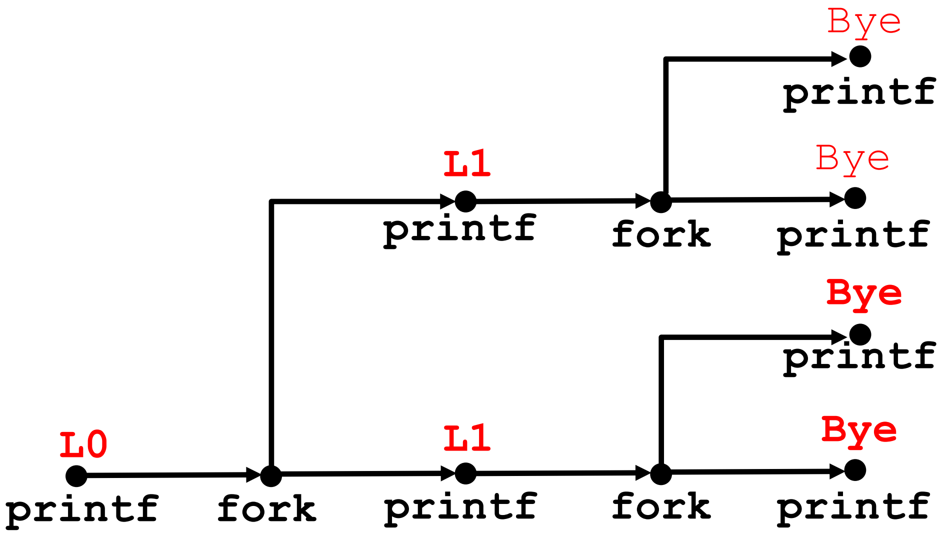
Infeasible total ordering:



`fork` Example: Two consecutive `fork`s

```
void fork2()
{
    printf("L0\n");
    fork();
    printf("L1\n");
    fork();
    printf("Bye\n");
}
```

forks.c



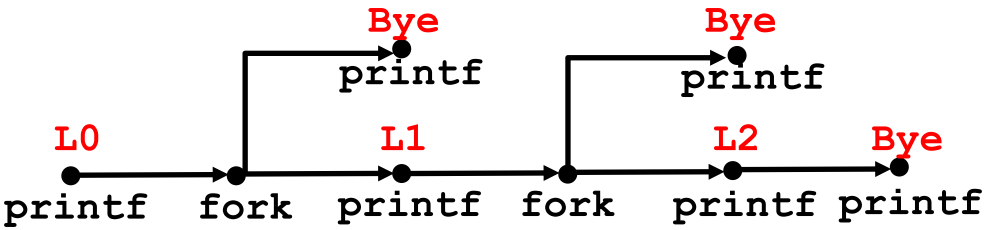
Which of these outputs are feasible?

```
L0
L1
Bye
Bye
L1
Bye
Bye
```

```
L0
Bye
L1
Bye
L1
Bye
Bye
```

`fork` Example: Nested `fork`s in parent

```c
void fork4()
{
    printf("L0\n");
    if (fork() != 0) {
        printf("L1\n");
        if (fork() != 0) {
            printf("L2\n");
        }
    }
    printf("Bye\n");
}                                 forks.c
```



Which of these outputs are feasible?

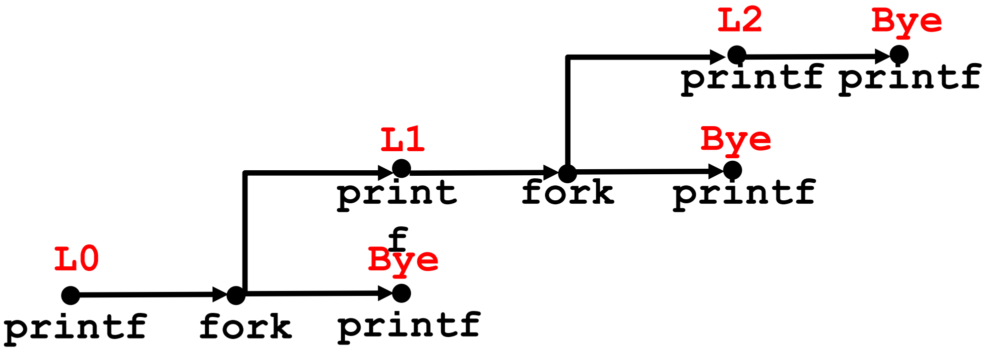
```
L0
L1
Bye
Bye
L2
Bye
```

```
L0
Bye
L1
Bye
Bye
L2
```

`fork` Example: Nested `fork`s in children

```
void fork5()
{
    printf("L0\n");
    if (fork() == 0) {
        printf("L1\n");
        if (fork() == 0) {
            printf("L2\n");
        }
    }
    printf("Bye\n");
}
```

forks.c



Which of these outputs are feasible?

L0	L0
Bye	Bye
L1	L1
L2	Bye
Bye	Bye
Bye	L2

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);
    }
}
```

```c
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);
    }
}
```

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 child explicitly, or else will keep running indefinitely

“Reaping” Children

- Idea
  - When process terminates, it still consumes system resources
    - Examples: Exit status, various OS tables
  - Called a “zombie”
    - Living corpse, half alive and half dead
- Reaping
  - Performed by parent on terminated child (using `wait` or `waitpid`)
  - Parent is given exit status information
  - 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)
  - So, only need explicit reaping in long-running processes
    - e.g., shells and servers

```c
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 */
    }
}
```

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
```

- `ps` shows child process as "defunct" (i.e., a zombie)
- Killing parent allows child to be reaped by `init`

`wait`: Synchronizing with Children

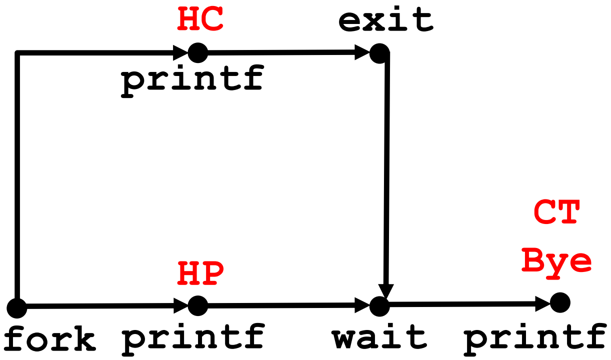
- Parent reaps a child by calling the **`wait`** function

- **`int wait(int *child_status)`**
  - Suspends current process until one of its children terminates
  - Return value is the **`pid`** of the child process that terminated
  - If **`child_status != NULL`**, then the integer it points to will be set to a value that indicates reason the child terminated and the exit status:
    - Checked using macros defined in `wait.h`
      - **`WIFEXITED, WEXITSTATIS, WIFSIGNALED, WTERMSIG, WIFSTOPPED, WSTOPSIG, WIFCONTINUED`**
      - See textbook for details

`wait` Example

```
void fork9() {
    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");
}
```

forks.c



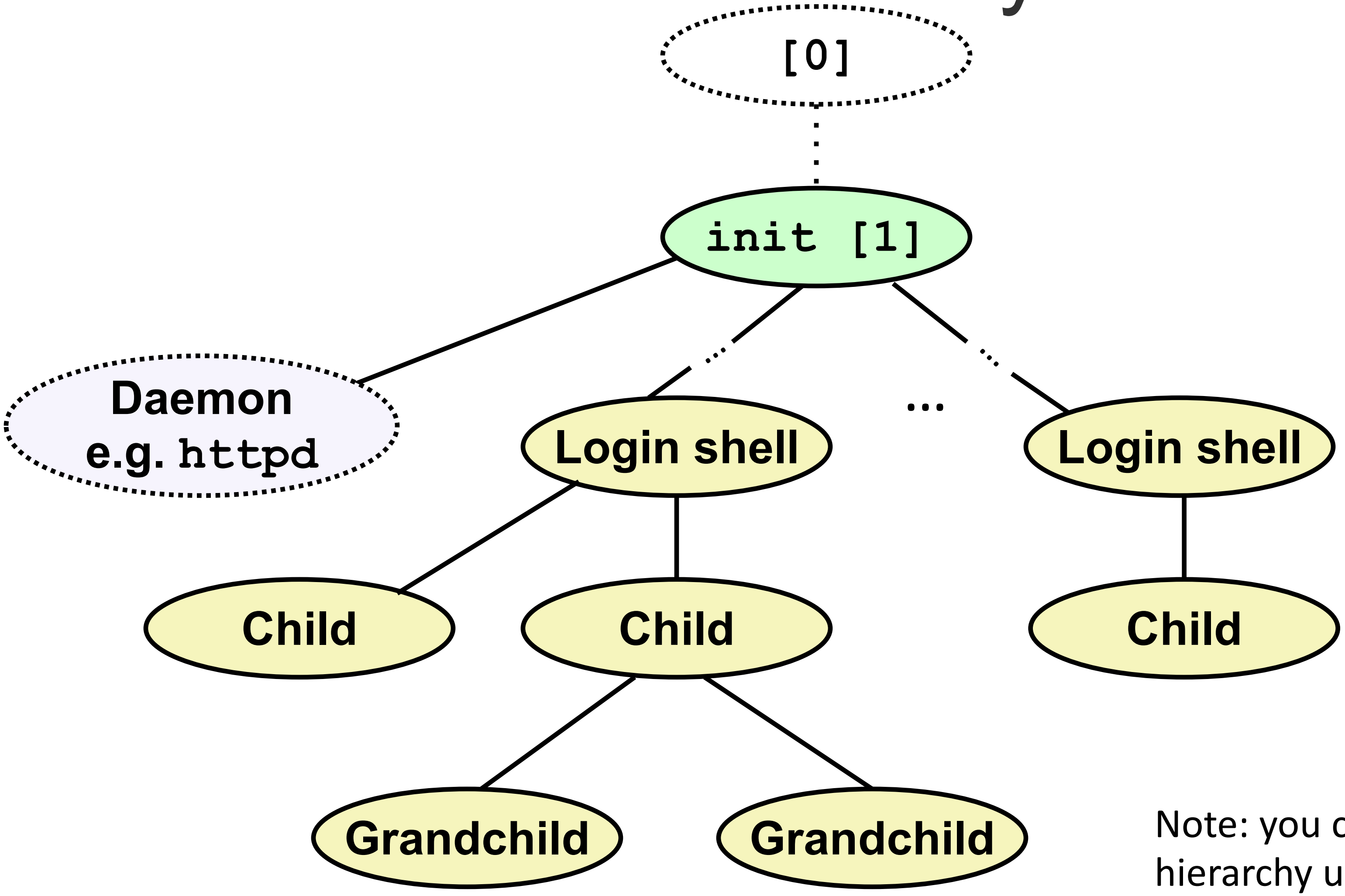
Feasible output:
HC
HP
CT
Bye

Infeasible output:
HP
CT
Bye
HC

`execve`: Loading and Running Programs

- `int execve(char *filename, char *argv[], char *envp[])`
- Loads and runs in the current process:
  - Executable file **`filename`**
    - Can be object file or script file beginning with `#!interpreter` (e.g., `#!/bin/bash`)
  - …with argument list **`argv`**
    - By convention **`argv[0]==filename`**
  - …and environment variable list **`envp`**
    - "name=value" strings (e.g., `USER=droh`)
    - `getenv, putenv, printenv`
- Overwrites code, data, and stack
  - Retains PID, open files and signal context
- Called once and never returns
  - …except if there is an error

Linux Process Heirarchy



Note: you can view the hierarchy using the Linux `pstree` command

`pstree` on `big`

```
big:~ 2$ pstree
systemd─┬─accounts-daemon─┬─{gdbus}
        │                 └─{gmain}
        ├─acpid
        ├─agetty
        ├─atd
        ├─cron
…
        ├─rpcbind
        ├─rsyslogd─┬─{in:imklog}
        │          ├─{in:imuxsock}
        │          └─{rs:main Q:Reg}
        ├─4*[sh───csim]
        ├─snapd───16*[{snapd}]
        ├─sshd─┬─sshd───sshd───bash───pstree
        │      └─sshd───sshd───bash
…
```

partial output