Lecture 15: OS and Processes

CS 105

Fall 2024

Intro to Operating Systems

- the **operating system** is a piece of software that manages a computer's resources for its users and their applications
  - Examples: OSX, Windows, Ubuntu, iOS, Android, Chrome OS

- resource allocation
- isolation
- communication
- access control

- multiprocessing
- virtual memory
- reliable networking
- virtual machines

- user interface
- file I/O
- device management
- process control

- OS is divided into two pieces: user-mode and kernel-mode
  - core OS functionality is implemented by the OS **kernel**

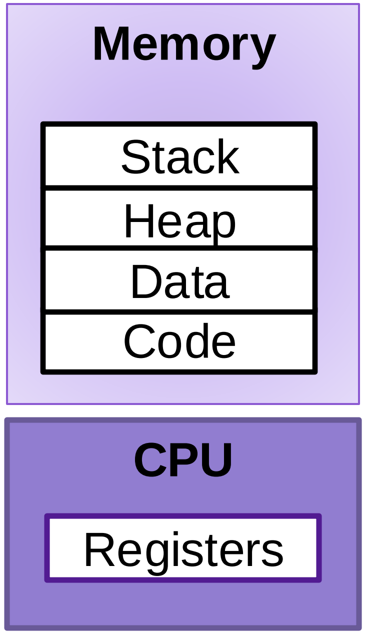
Operating System Modes

Kernel Mode	User Mode
• unrestricted access to hardware	• must ask kernel to access hw (system call)
• mediates all hardware access (access control)	
• can execute privileged instructions	• attempts to execute privileged instructions cause exceptions

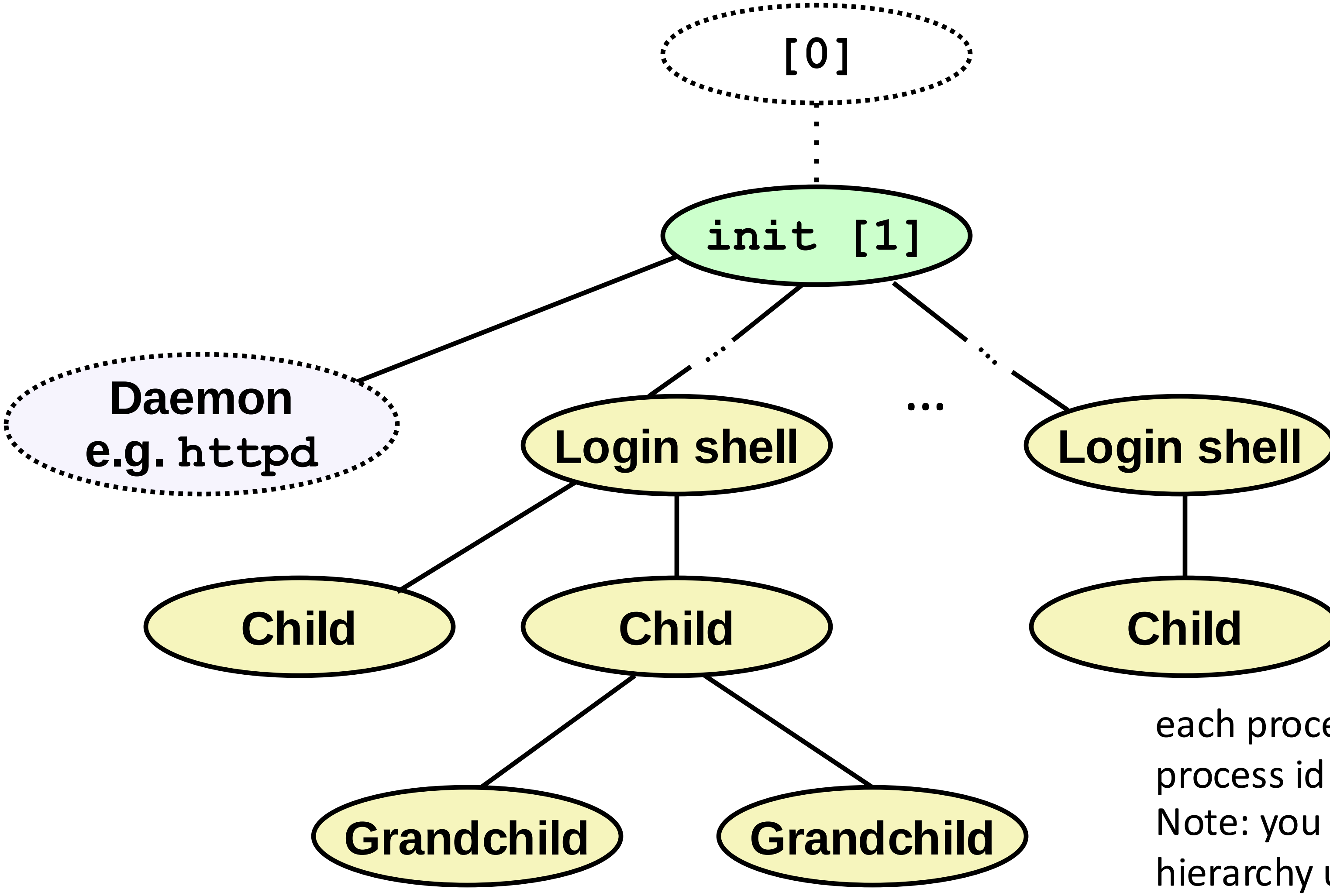
- Operating system mode is set in hardware, can't be changed by user-level code

Processes

- A ***program*** is a file containing code + data that describes a computation
- 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"



Linux Process Hierarchy



each process has a unique process id (**pid**)
Note: you can view the hierarchy using the Linux `pstree` command

Creating Processes

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

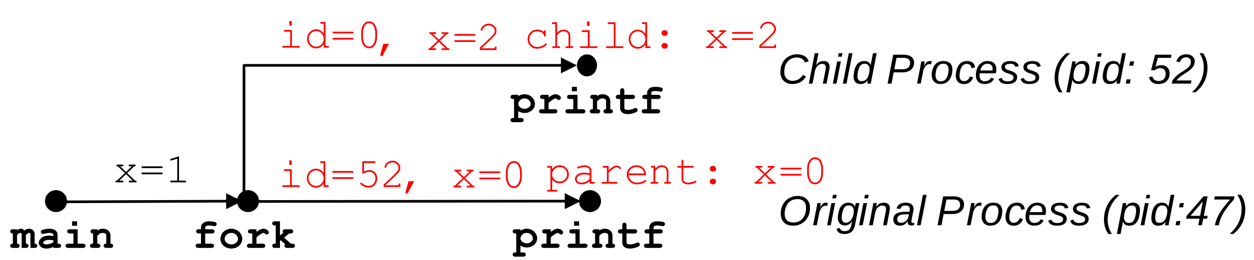
- **`int fork(void)`**
  - Returns 0 to the child process, child's PID to parent process
  - Child is *almost* identical to parent:
    - Child get an identical (but separate) copy of the parent's virtual address space.
    - Child gets identical copies of the parent's open file descriptors
    - Child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

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

`fork` Example

```c
int main(){

  pid_t id;
  int x = 1;

  id = fork();
  if (id == 0) {  /* Child */
    printf("child : x=%d\n", ++x);
            return 0;
  }

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

- **Call once, return twice**
- **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



`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

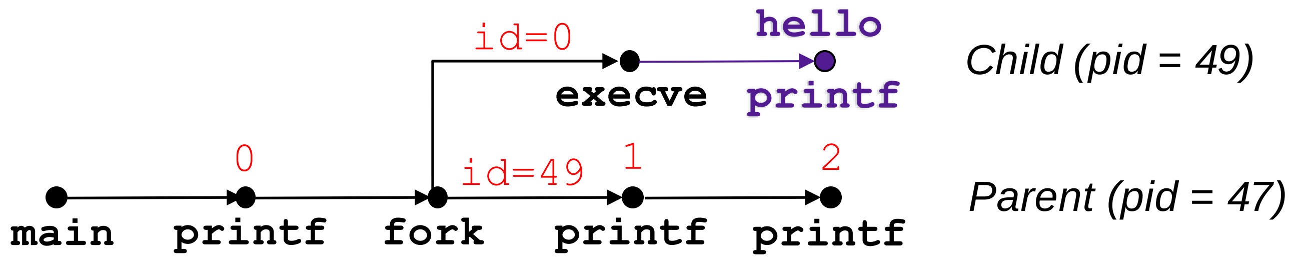
execve Example

```c
int main(int argc, char** argv){

  printf("0\n");
  pid_t id = fork();

  if(id == 0){ // if child
    execve("hello", NULL, NULL);
  } else { // if parent
    printf("1\n");
  }

  printf("2\n");
  return 0;
}
```

exec.c

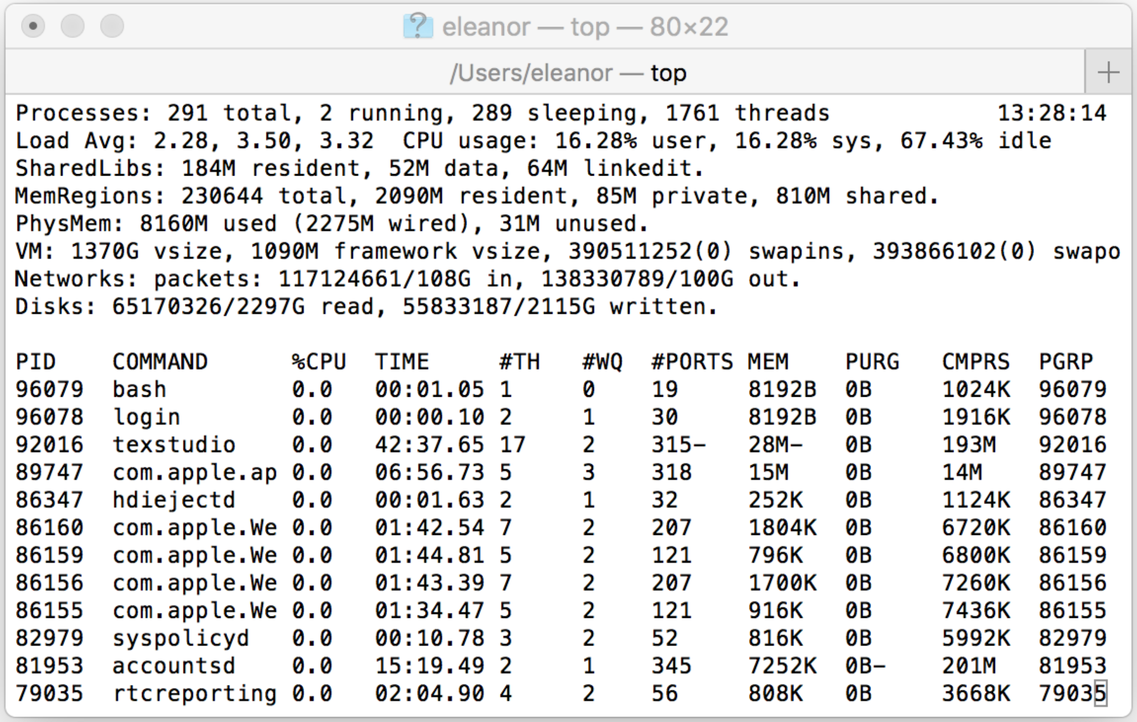
```c
int main(int argc, char** argv){
  printf("Hello!\n");

  return 0;
}
```

hello.c



Multiprocessing

- Computer runs many processes simultaneously
- Running program “top” on Mac
  - Identified by Process ID (PID)

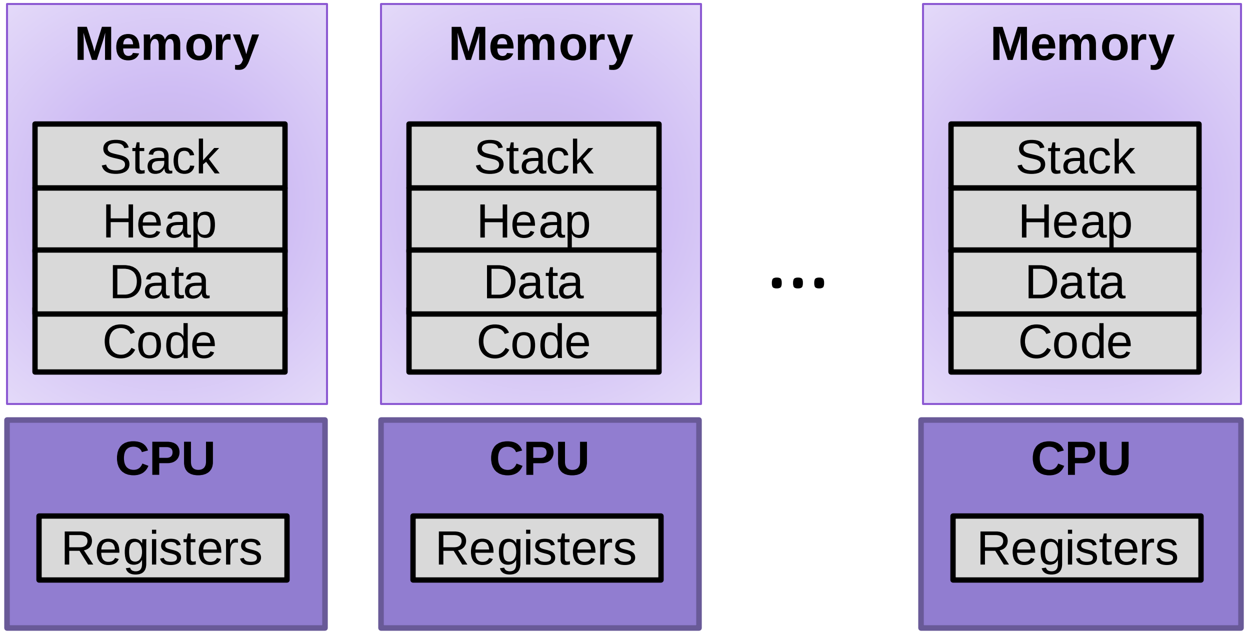


eleanor — top — 80×22

/Users/eleanor — top

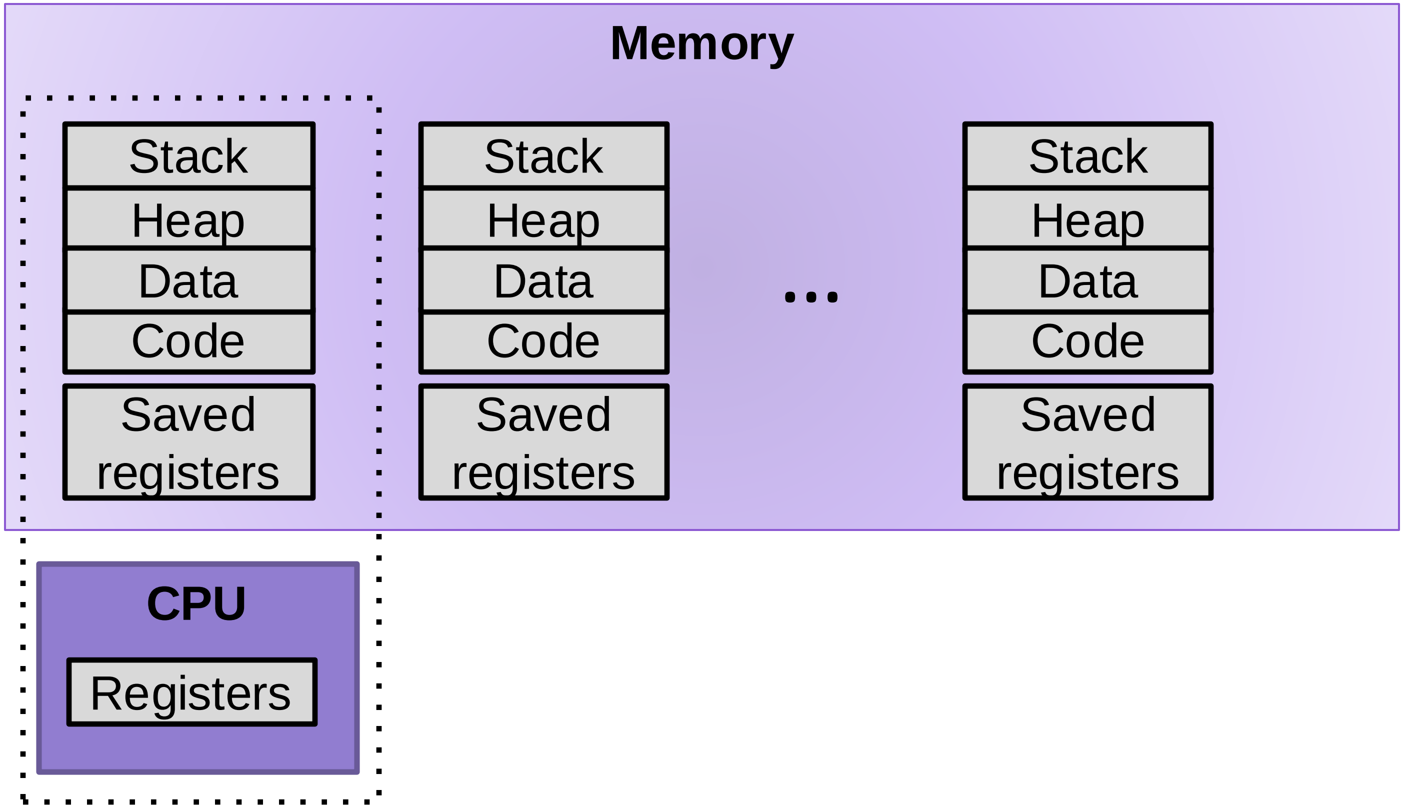
```
Processes: 291 total, 2 running, 289 sleeping, 1761 threads            13:28:14
Load Avg: 2.28, 3.50, 3.32  CPU usage: 16.28% user, 16.28% sys, 67.43% idle
SharedLibs: 184M resident, 52M data, 64M linkedit.
MemRegions: 230644 total, 2090M resident, 85M private, 810M shared.
PhysMem: 8160M used (2275M 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 Illusion



- 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***

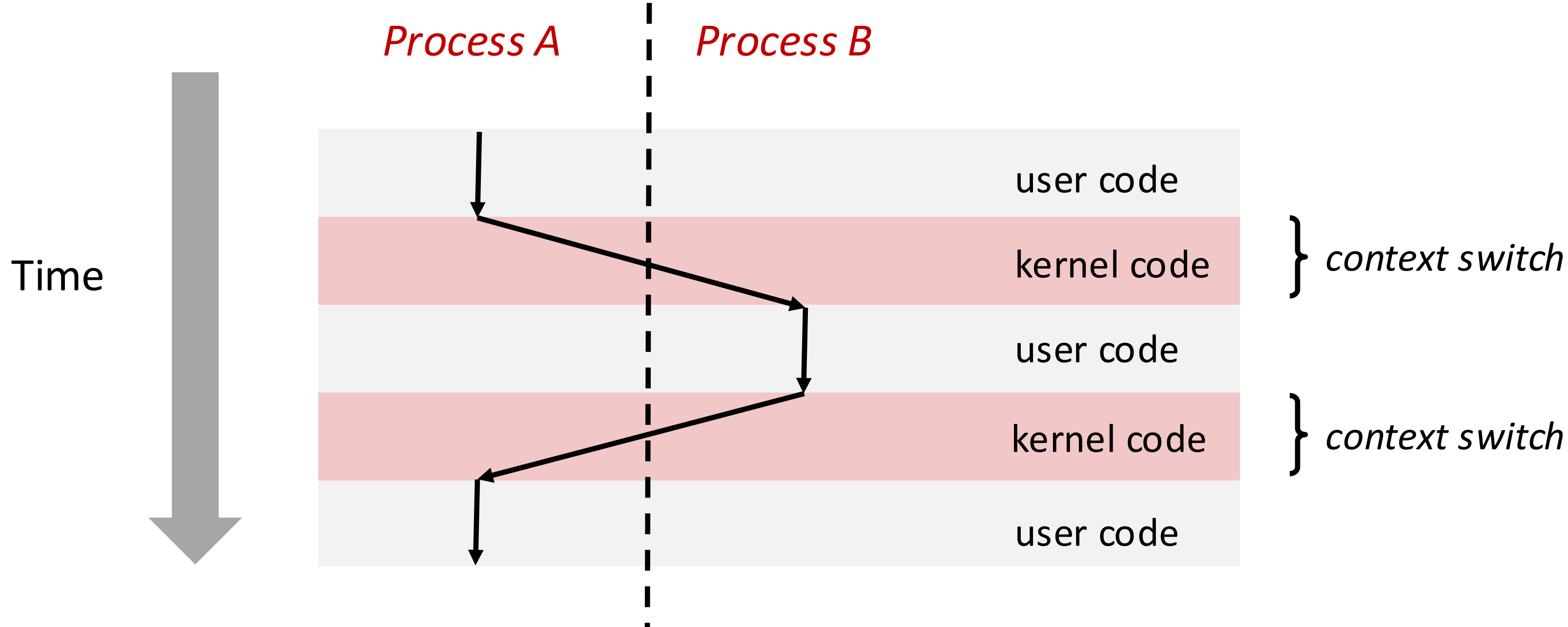
Multiprocessing: The (Traditional) Reality



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

Context Switching

- Processes are managed by a shared chunk of memory-resident kernel code
  - Important: the kernel code is not a separate process, but rather code and data structures that the OS uses to manage all processes
- Control flow passes from one process to another via a ***context switch***

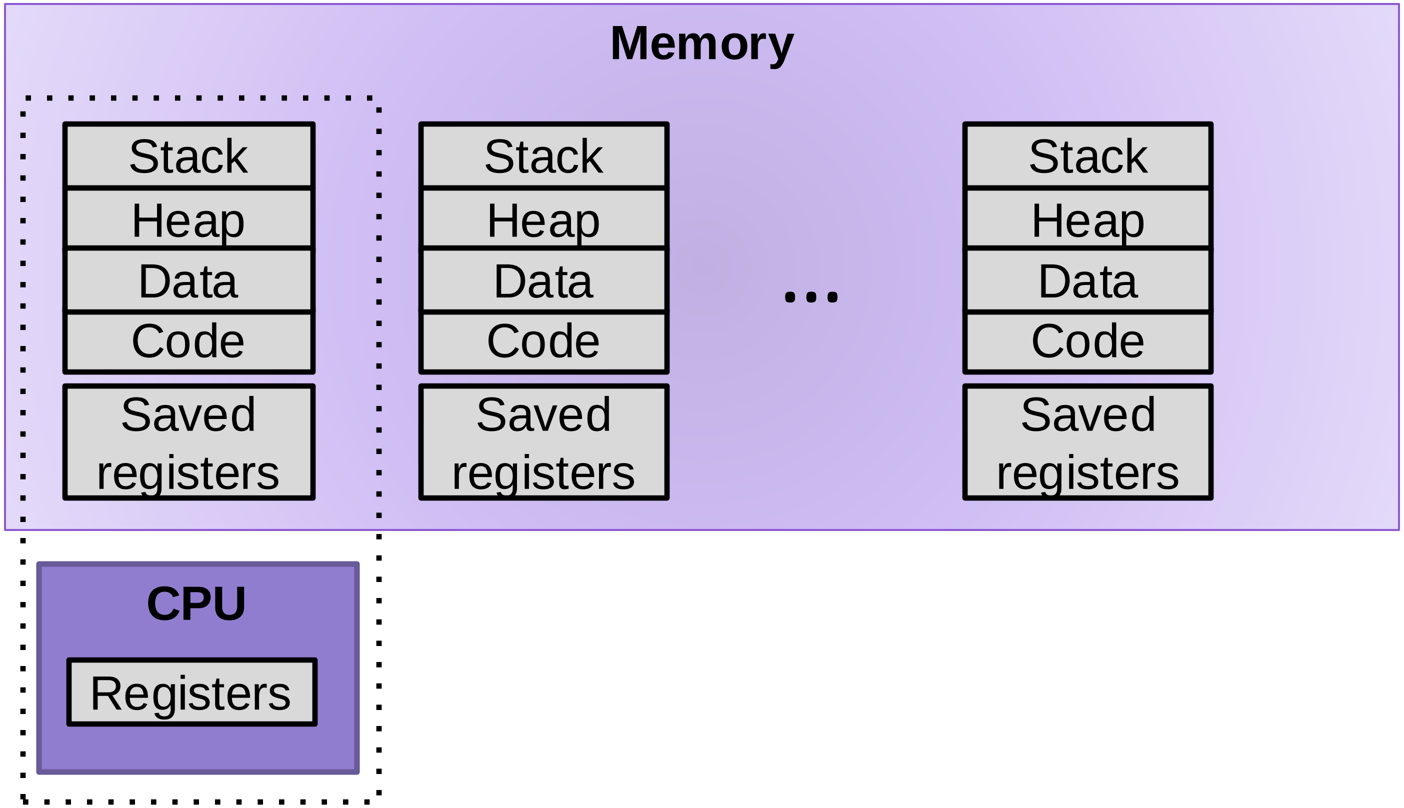


Process Control Block (PCB)

- To implement a context switch, OS maintains a PCB for each process containing:
  - process table, which contains information about the process (id, user, privilege level, arguments, status)
  - location of executable on disk
  - file table
  - register values (general-purpose registers, float registers, pc, eflags…)
  - memory state
  - scheduling information

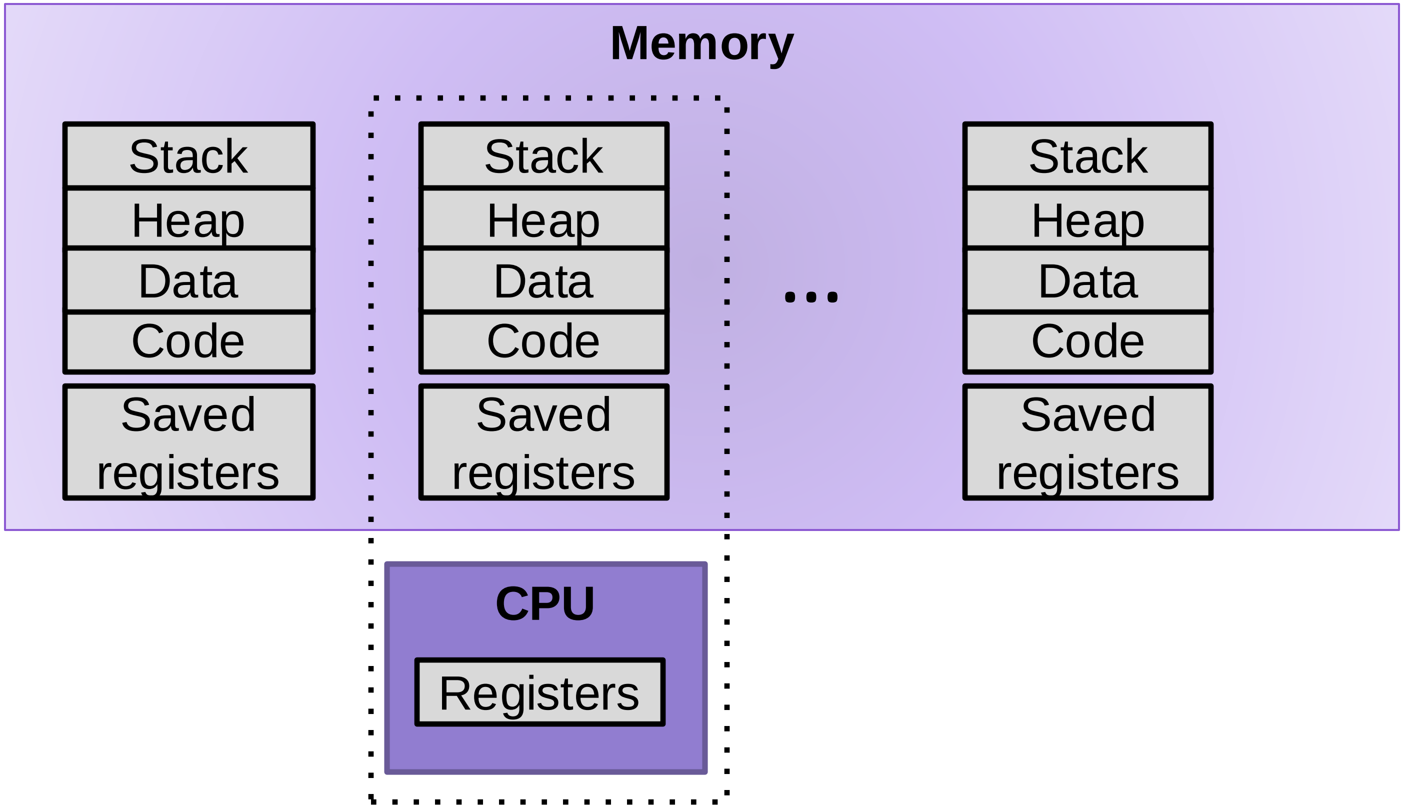
... and more!

Multiprocessing: The (Traditional) Reality



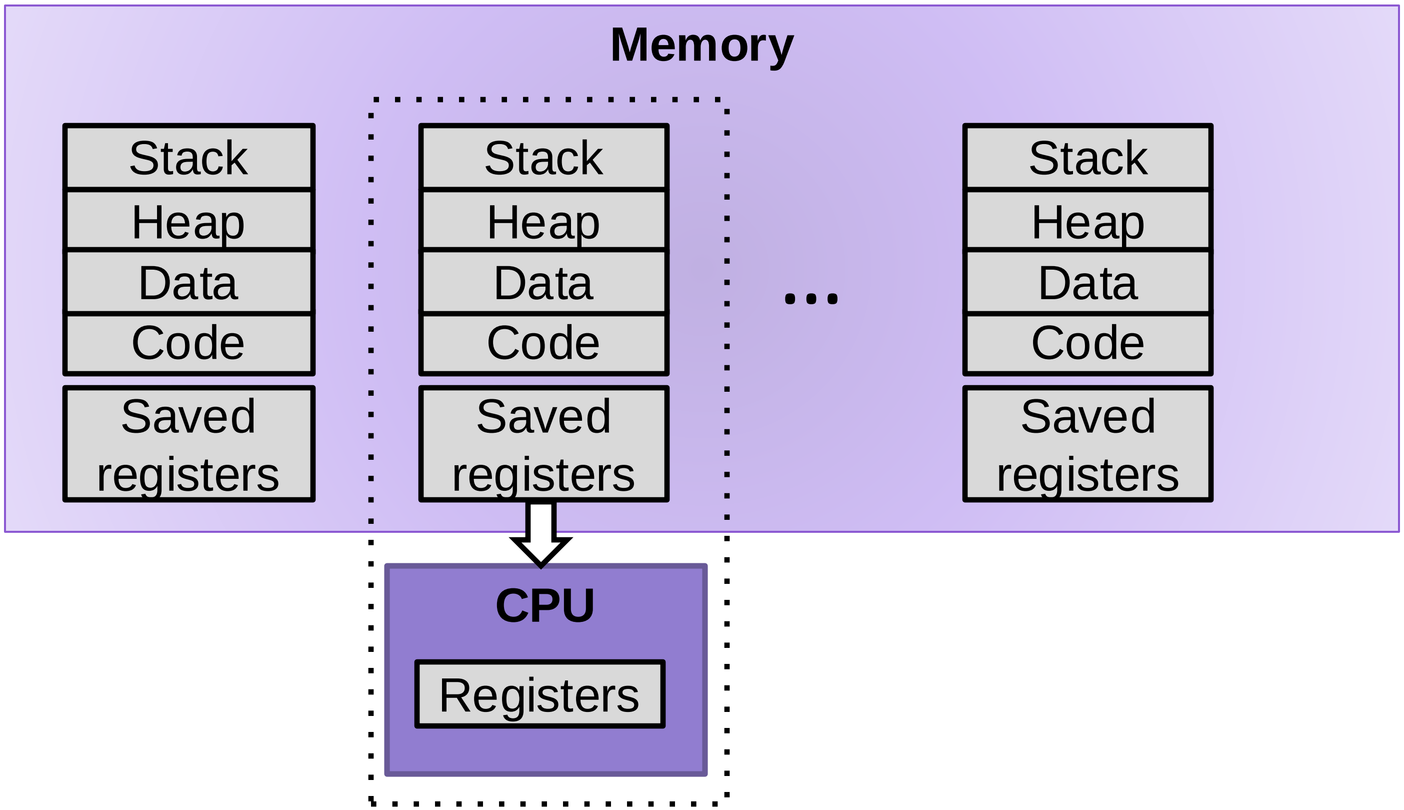
1. Save current registers to memory (in PCB)

Multiprocessing: The (Traditional) Reality



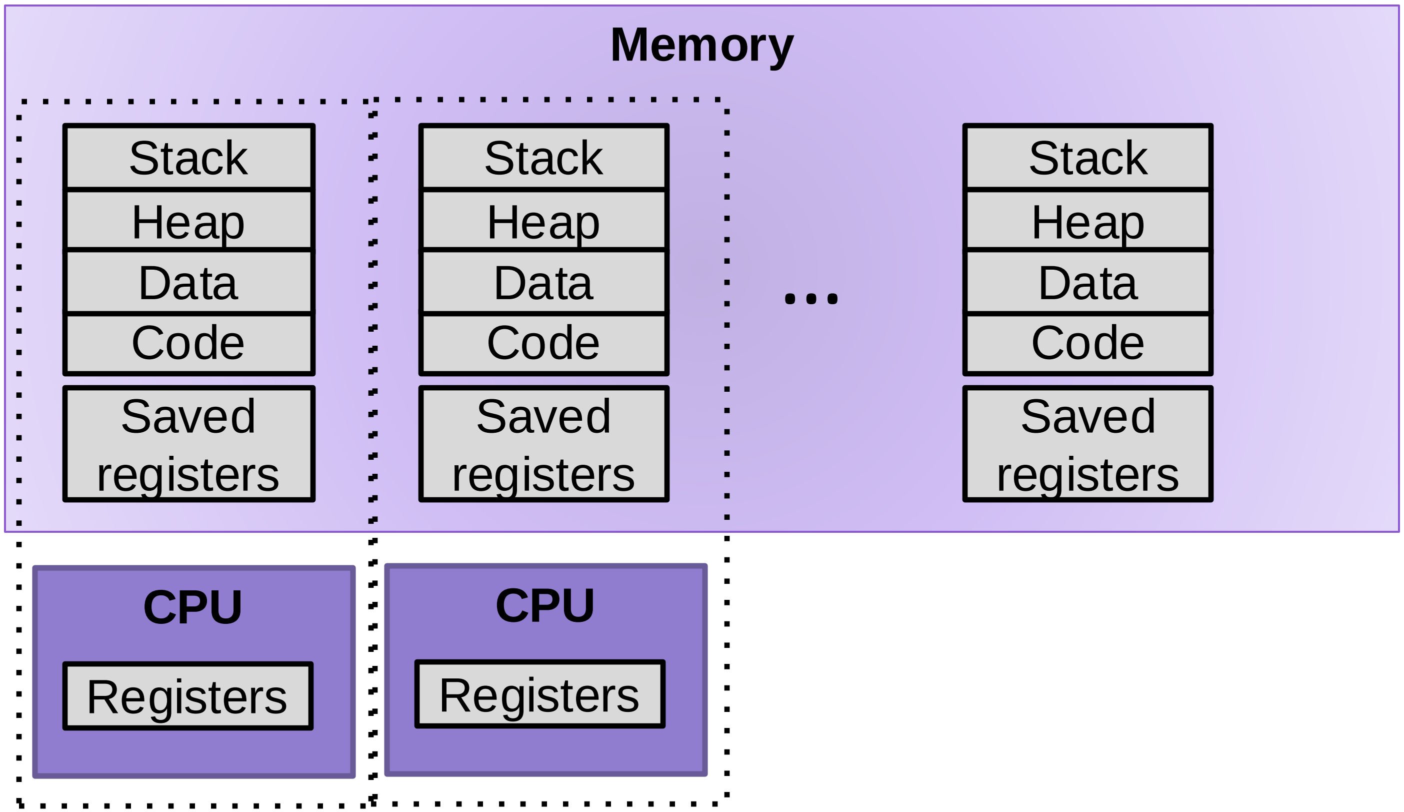
1. Save current registers to memory (in PCB)
2. Schedule next process for execution

Multiprocessing: The (Traditional) Reality



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

Multiprocessing: The (Modern) Reality

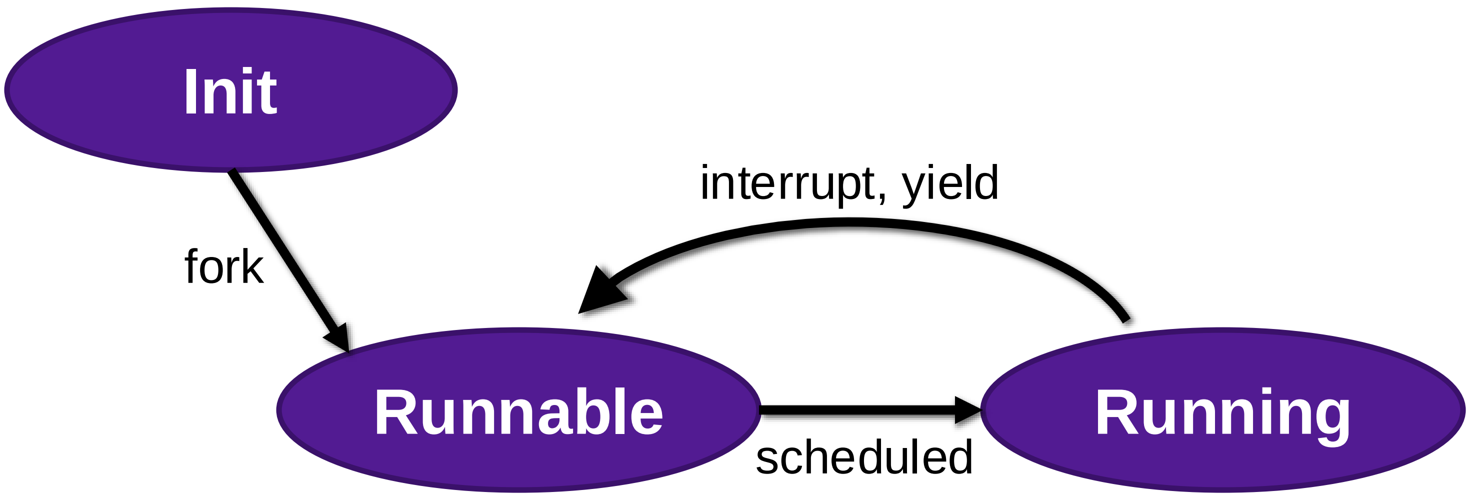


- Multicore processors
  - Multiple CPUs on single chip
  - Share main memory (and some of the caches)
  - Each can execute a separate process
    - Scheduling of processors onto cores done by kernel

Exercise: Context Switching

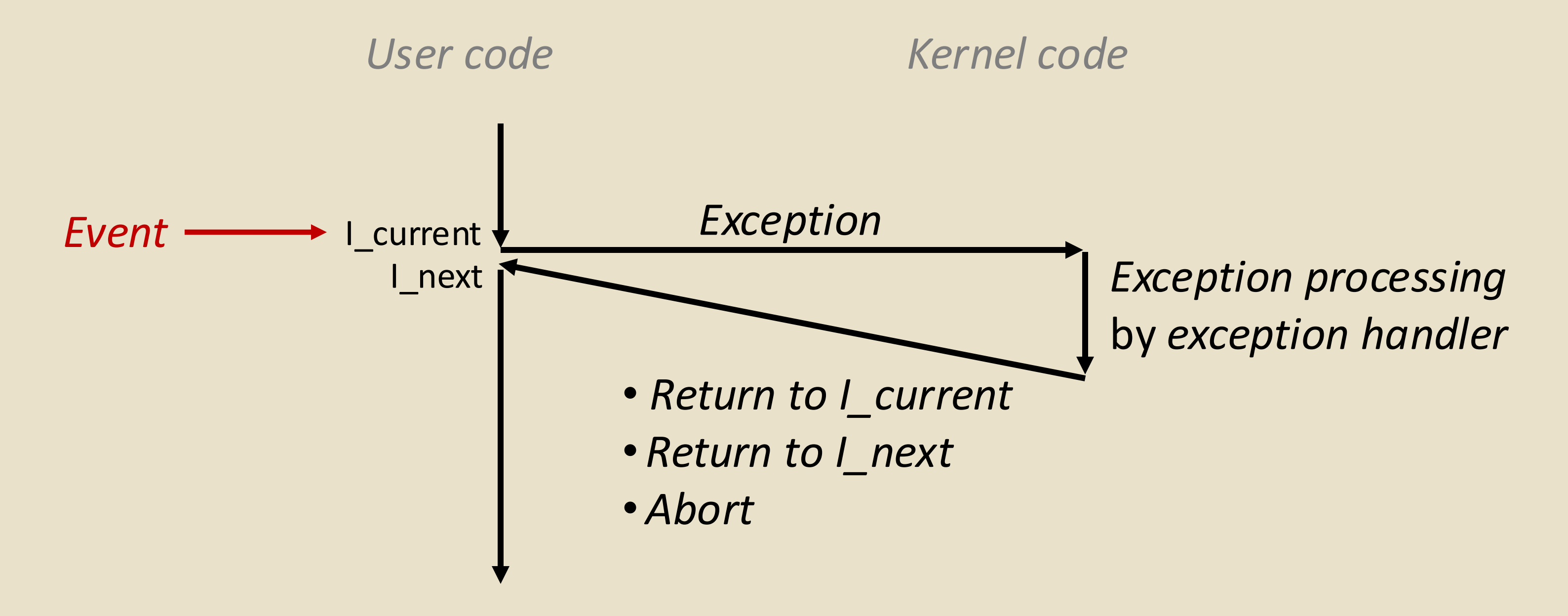
A hardware designer argues that there are now enough on-chip transistors to build a CPU with 1024 integer registers and 512 floating point registers. As a result, the compiler should almost never need to store anything on the stack. As a new operating systems expert, would you recommend building this new design.

Process Life Cycle

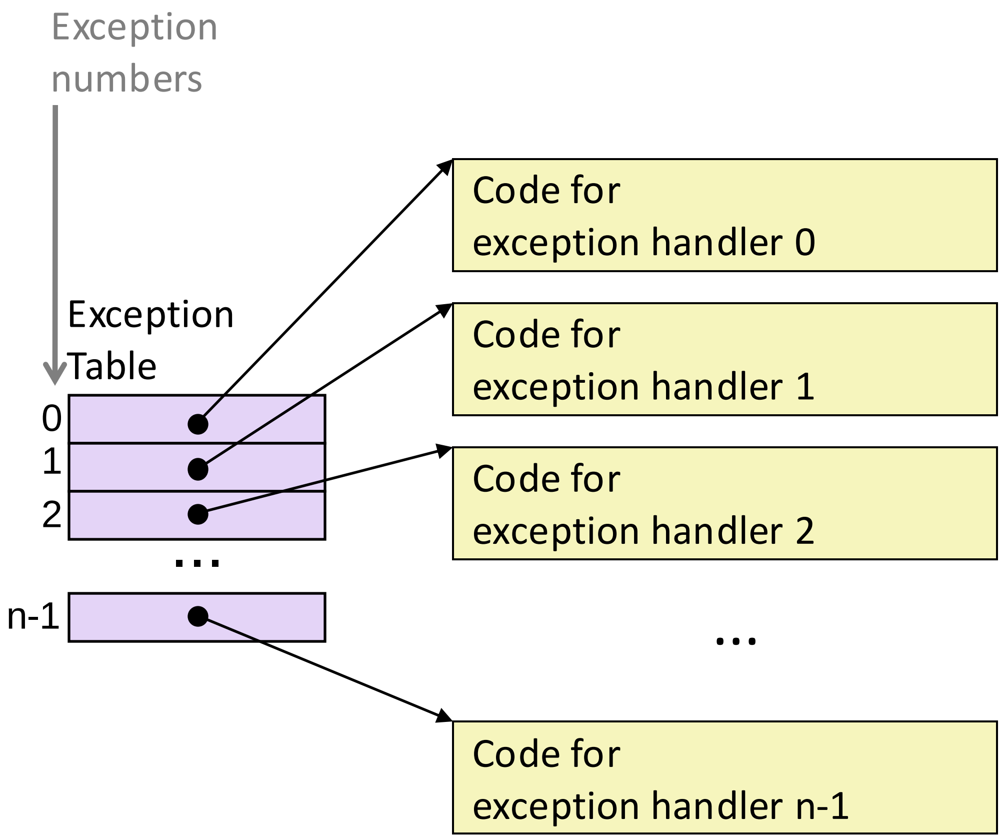


Exceptions

- An **exception** is a transfer of control to the OS *kernel* in response to some *event* (i.e., change in processor state)



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

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, divide-by-zero, parity error, machine check
  - Aborts current program

Interrupts (Asynchronous Exceptions)

Caused by events external to the process

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

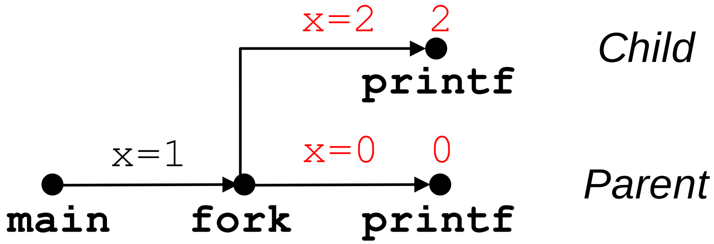
Examples:

- 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

`fork` Example

```
int main(){

  pid_t pid;
  int x = 1;

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

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

- **Call once, return twice**
- **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
- **Concurrent execution**
  - Can't predict execution order of parent and child



Exercise: What are all the possible outputs of this program?

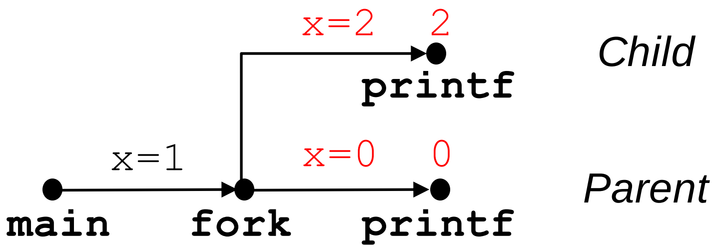
Modeling `fork` with Process Graphs

- 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

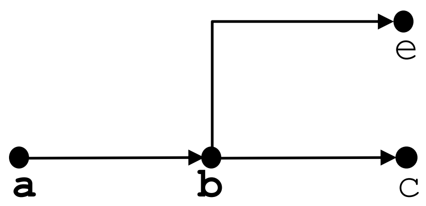
- Any topological sort of the graph corresponds to a feasible total ordering.
  - Total ordering of vertices where all edges point from left to right

Interpreting Process Graphs

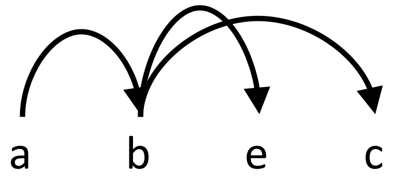
- Original graph:



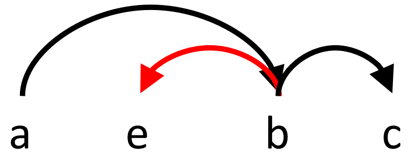
- Relabeled graph:



Feasible total ordering:

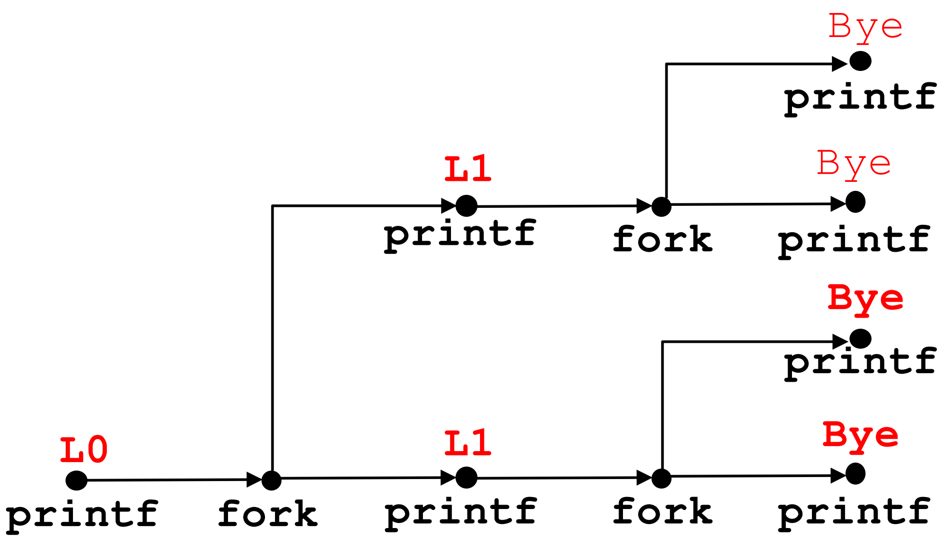


Infeasible total ordering:



`fork` Example: Two consecutive `fork`s

```
void fork1()
{
    printf("L0\n");
    fork();
    printf("L1\n");
    fork();
    printf("Bye\n");
}
```



Which of these outputs are feasible?

L0	L0
L1	Bye
Bye	L1
Bye	Bye
L1	L1
Bye	Bye
Bye	Bye

Exercise: Forks and Feasible Schedules

- For each of the following programs, draw the process graph and then determine which of the possible outputs are feasible

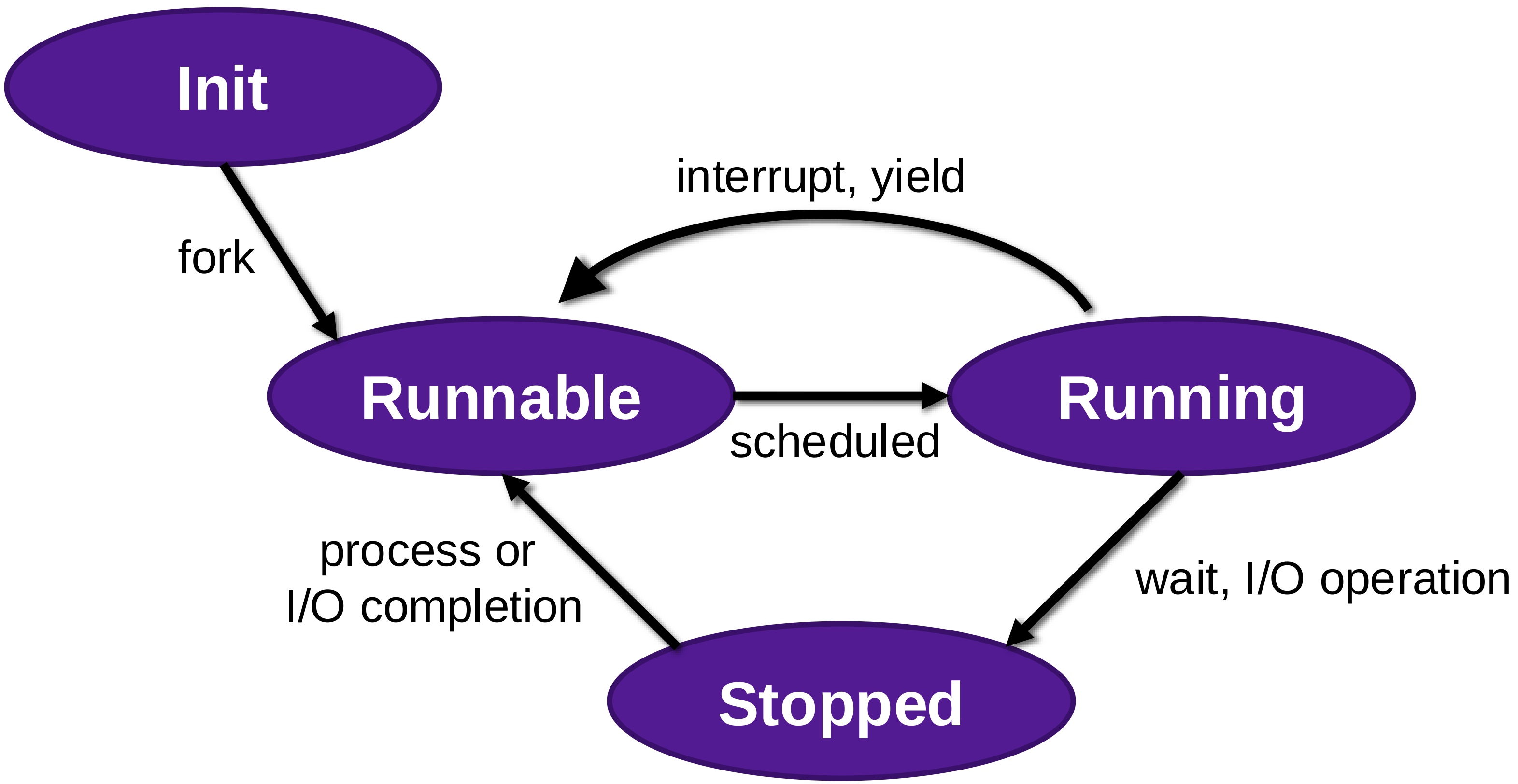
```
void fork2(){
   printf("L0\n");
   if (fork() != 0) {
      printf("L1\n");
      if (fork() != 0) {
         printf("L2\n");
            }
   }
   printf("Bye\n");
}
```

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

```
void fork3(){
   printf("L0\n");
   if (fork() == 0) {
      printf("L1\n");
      if (fork() == 0) {
         printf("L2\n");
      }
   }
   printf("Bye\n");
}
```

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

Process Life Cycle



Reaping Children

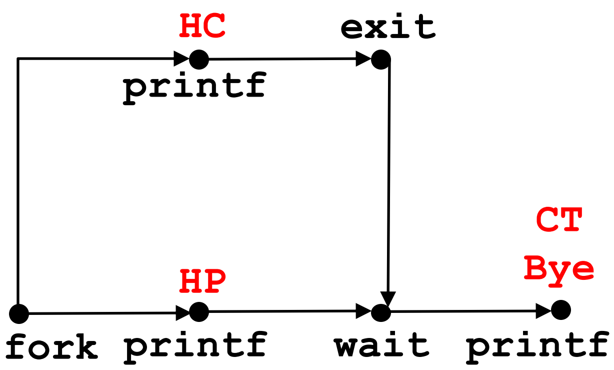
- Reaping
  - Performed by parent on terminated child (using `wait` or `waitpid`)
  - Parent is given exit status information
  - Kernel then deletes zombie child process

- **`int wait(int* child_status)`**
  - Suspends current process until any 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

- **`int waitpid(pid_t pid, int* child_status, int opt)`**
  - Suspends current process child with pid terminates

wait Example

```
void fork6() {
   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");
}
```



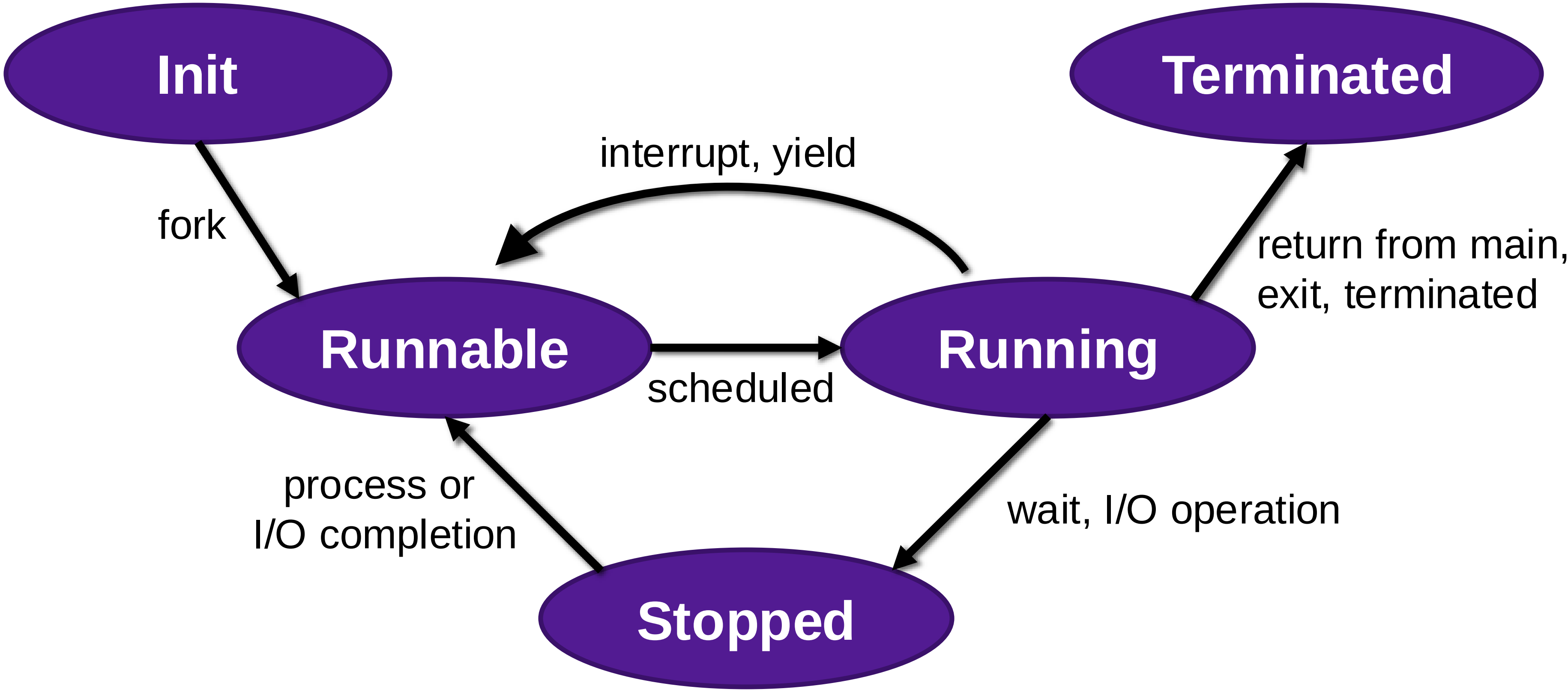
Feasible output:
HC
HP
CT
Bye

Infeasible output:
HP
CT
Bye
HC

Reaping Children

- 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

Process Life Cycle



Terminating Processes

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

- `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.