

Introduction to Operating Systems: Exceptional Control Flow

Computer Systems

Oct. 19, 2020

Troels Henriksen

Based on slides by:

Randal E. Bryant and David R. O'Hallaron

Why study operating systems?

- They are where the magic happens
- For inspiration
 - One of the most potent *engineering abstractions* in computing
 - Each program thinks it has an entire machine to itself
 - Controlled communication between programs.
 - Abstracts over hardware differences
- Practical skills
 - Performance characteristics of the abstraction
 - What is fundamentally possible?

Unix

■ What is Unix?

- Unix is an operating system developed in the 1970s by Ken Thompson and Dennis Ritchie
- Most modern operating systems heavily influenced by Unix (even Windows)
- Many operating systems are *direct descendants*: Linux, iOS, macOS, the *BSDs, etc

■ Why Unix?

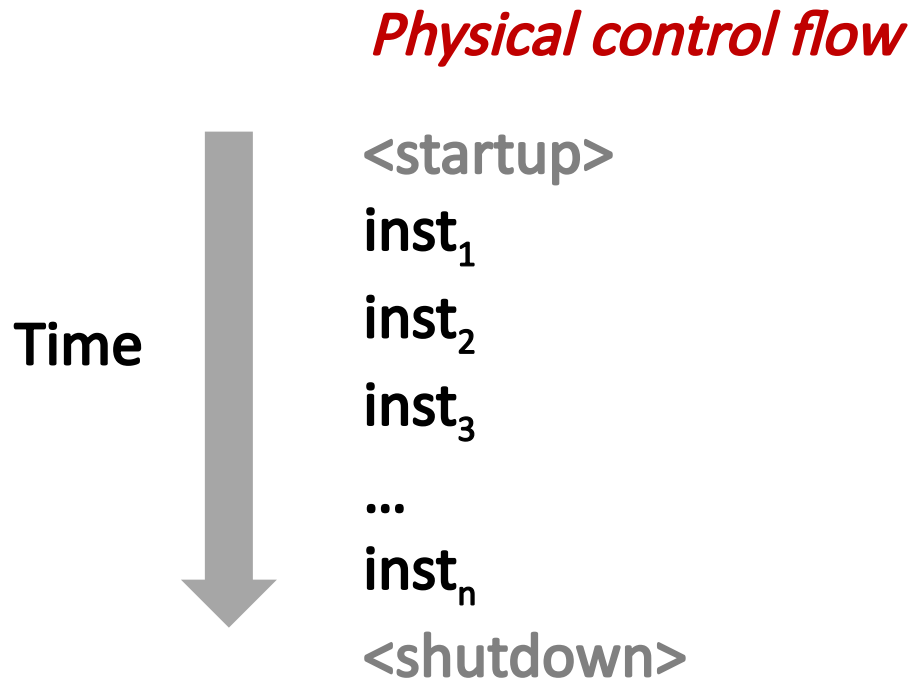
- Unix is *simple* and *representative* of modern systems
- We will use Unix designs for all examples

Today

- **Exceptional Control Flow**
- Exceptions
- Processes
- Process Control

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*)



Altering the Control Flow

■ Up to now: two mechanisms for changing control flow:

- Jumps and branches
- Call and return

React to changes in *program state*

■ Insufficient for a useful system:

Difficult to react to changes in *system state*

- Data arrives from a disk or a network adapter
- Instruction divides by zero
- User hits Ctrl-C at the keyboard
- System timer expires

■ System needs mechanisms for “exceptional control flow”

Exceptional Control Flow

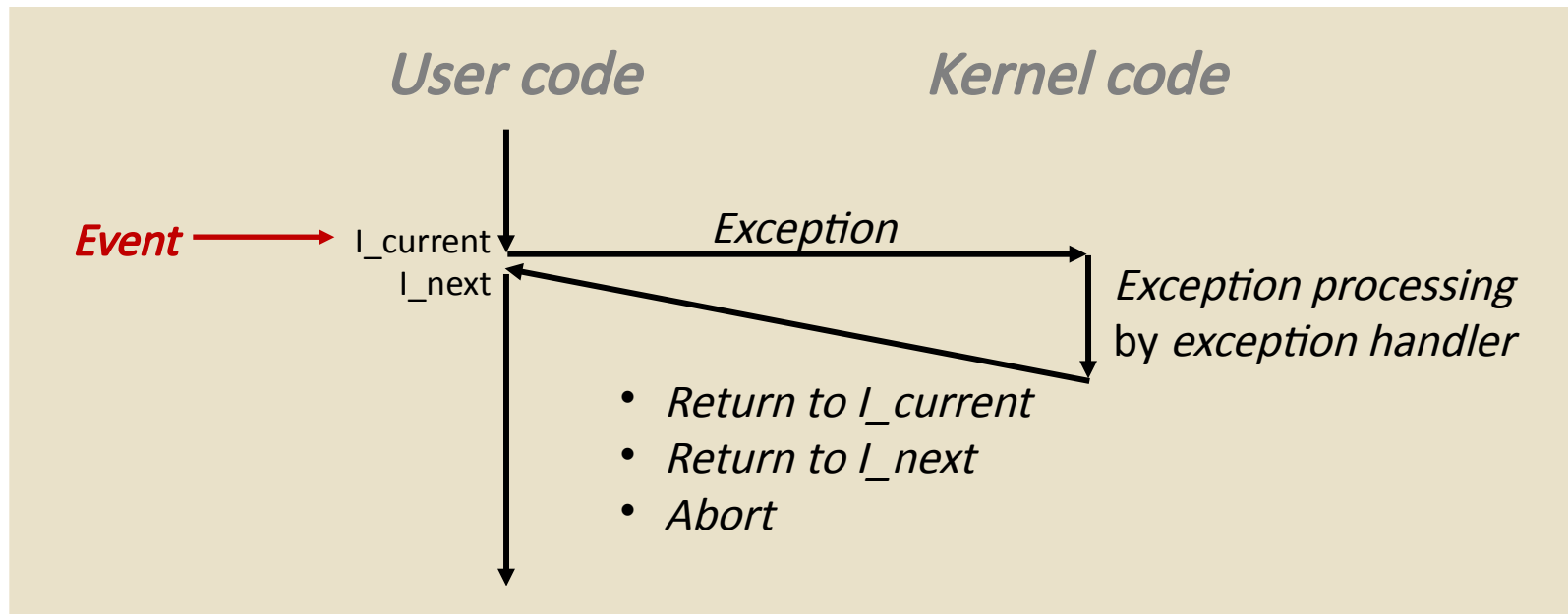
- Exists at all levels of a computer system
- Low level mechanisms
 - 1. **Exceptions**
 - Change in control flow in response to a system event (i.e., change in system state)
 - Implemented using combination of hardware and OS software
- Higher level mechanisms
 - 2. **Process context switch**
 - Implemented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

Today

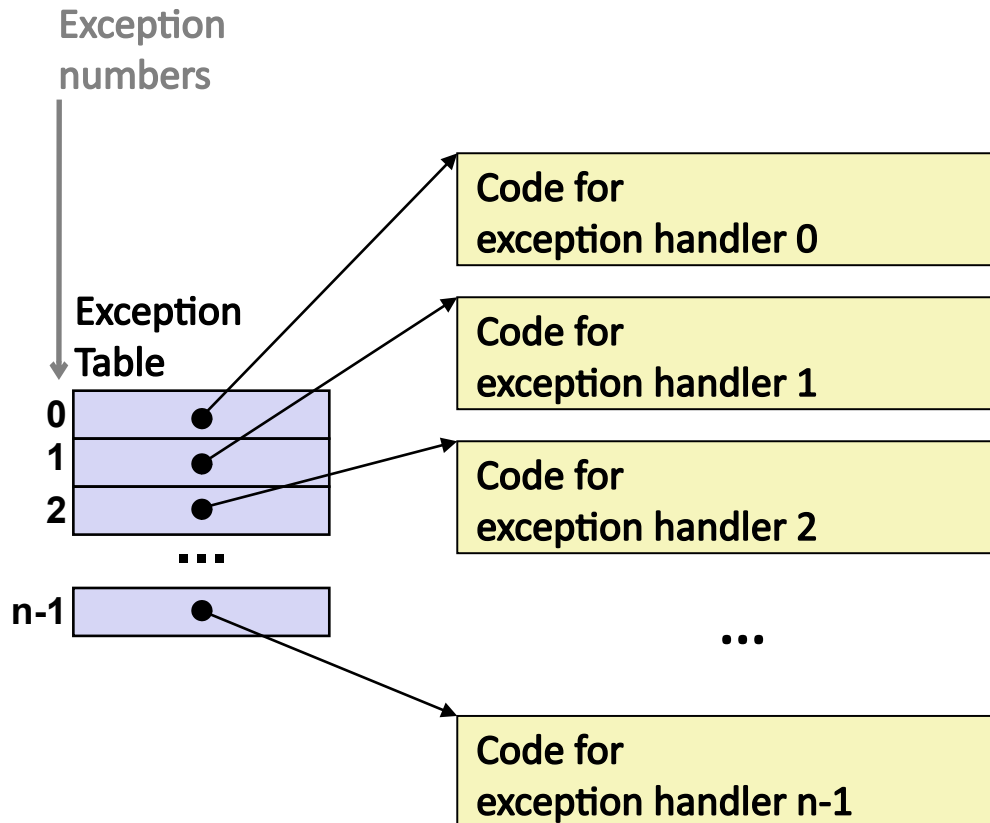
- Exceptional Control Flow
- **Exceptions**
- Processes
- Process Control

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



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 (note I diverge a bit from the book here):
 - *Traps*
 - Intentional
 - Examples: *system calls*, breakpoint traps, special instructions
 - Returns control to “next” instruction, like a function call
 - *Faults*
 - Unintentional but possibly recoverable
 - Examples: page faults (recoverable), protection faults (unrecoverable), floating point exceptions, illegal instruction
 - Either re-executes faulting (“current”) instruction or aborts
 - *Aborts*
 - Unintentional and unrecoverable (often no location info)
 - Examples: parity error, machine check
 - Aborts current program

System Calls

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

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

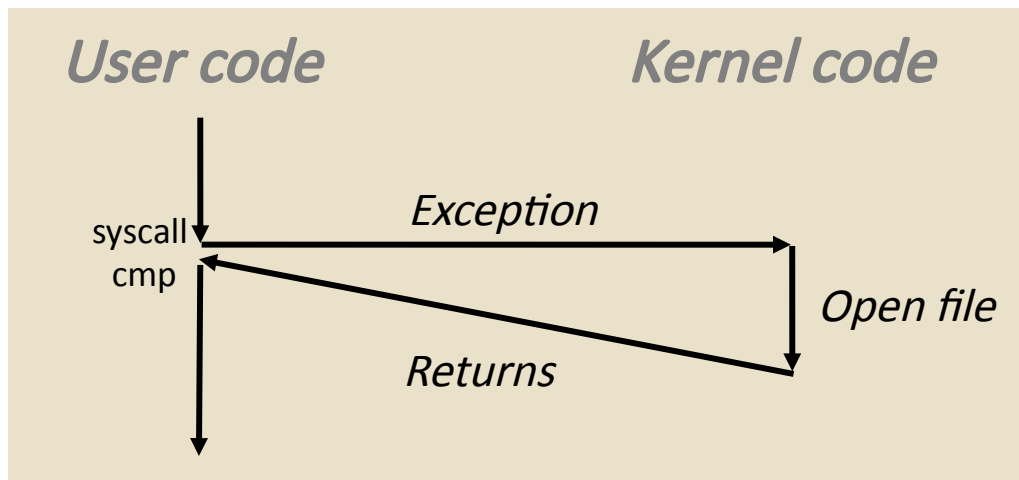
System Call Example: Opening File

- User calls: `open(filename, options)`
- Calls `__open` function, which invokes system call instruction `syscall`

```
00000000000e5d70 <__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  $0xffffffffffffffff001,%rax
...
e5dfa:  c3                  retq
```



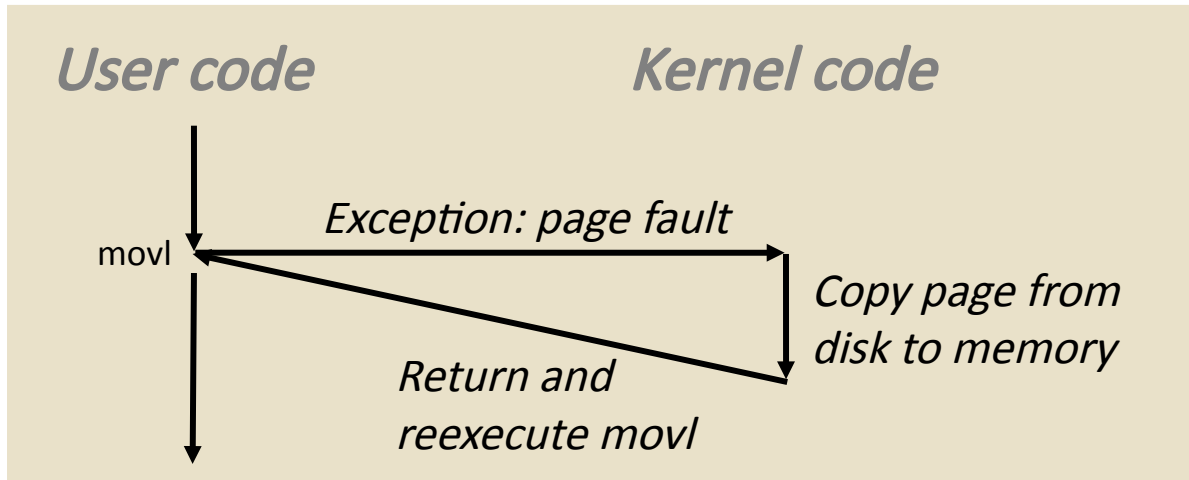
- `%rax` contains syscall number
- Other arguments in `%rdi`, `%rsi`, `%rdx`, `%r10`, `%r8`, `%r9`
- Return value in `%rax`
- Negative value is an error corresponding to negative `errno`

Fault Example: Page Fault

- User writes to memory location
- That portion (page) of user's memory is currently on disk

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

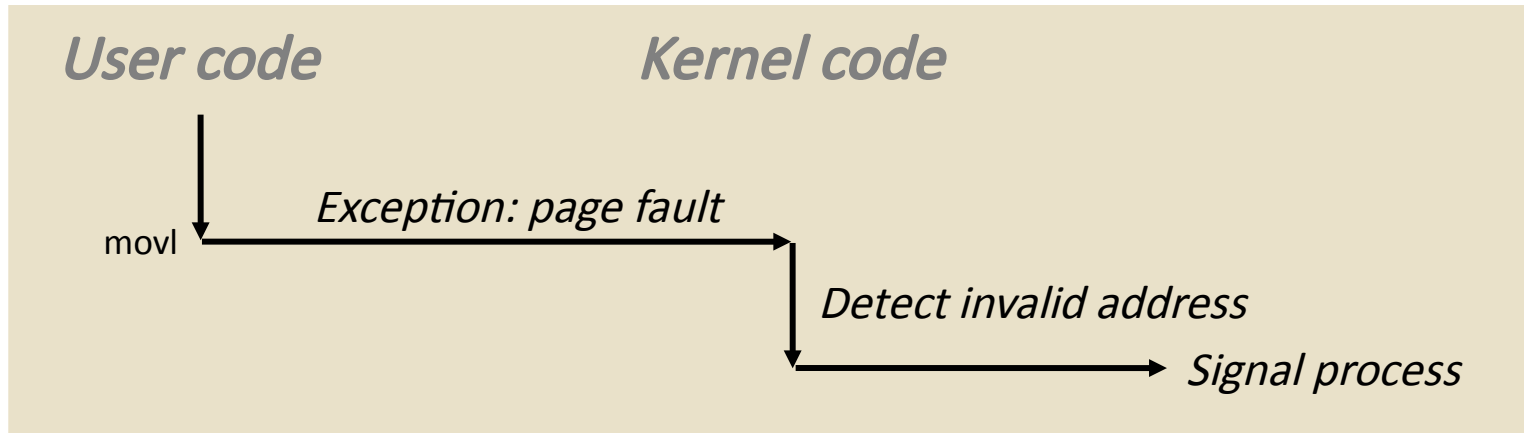
```
80483b7:  c7 05 10 9d 04 08 0d  movl    $0xd,0x8049d10
```



Fault Example: Invalid Memory Reference

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

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



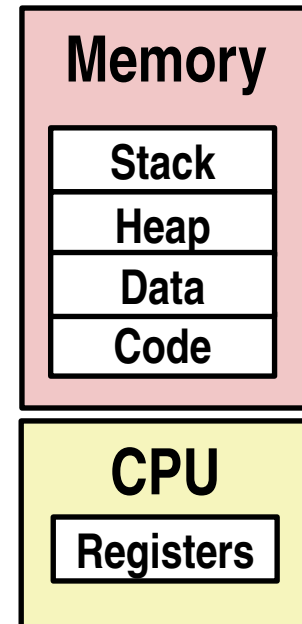
- Sends **SIGSEGV** signal to user process
- User process exits with “segmentation fault”

Today

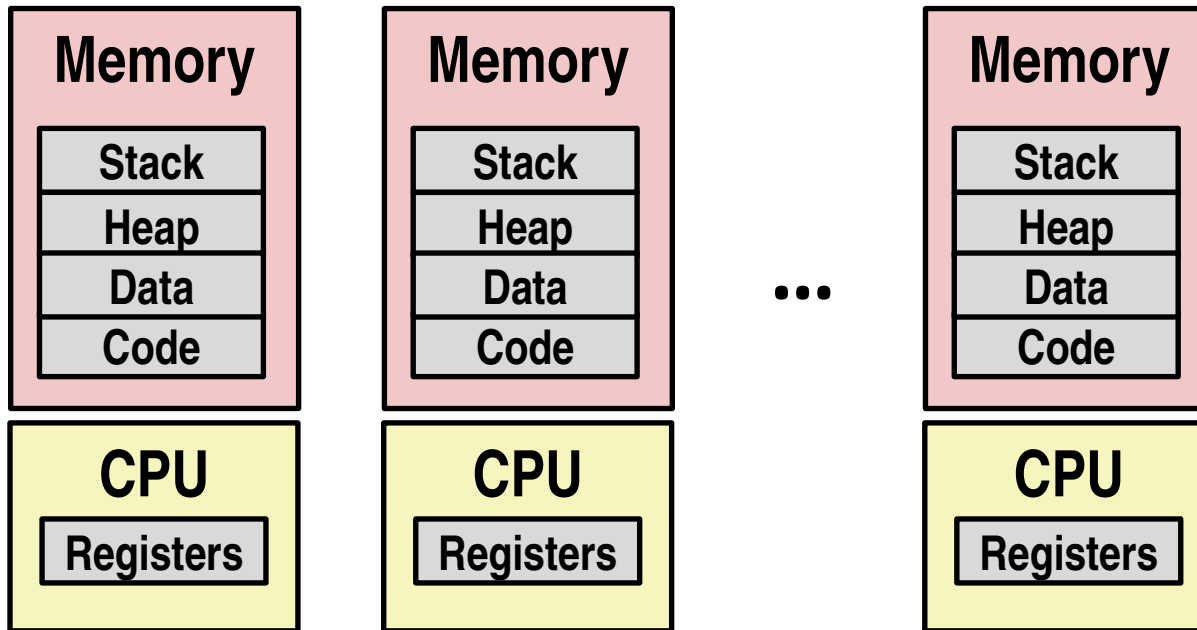
- Exceptional Control Flow
- Exceptions
- **Processes**
- Process Control

Processes

- 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:
 - *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*

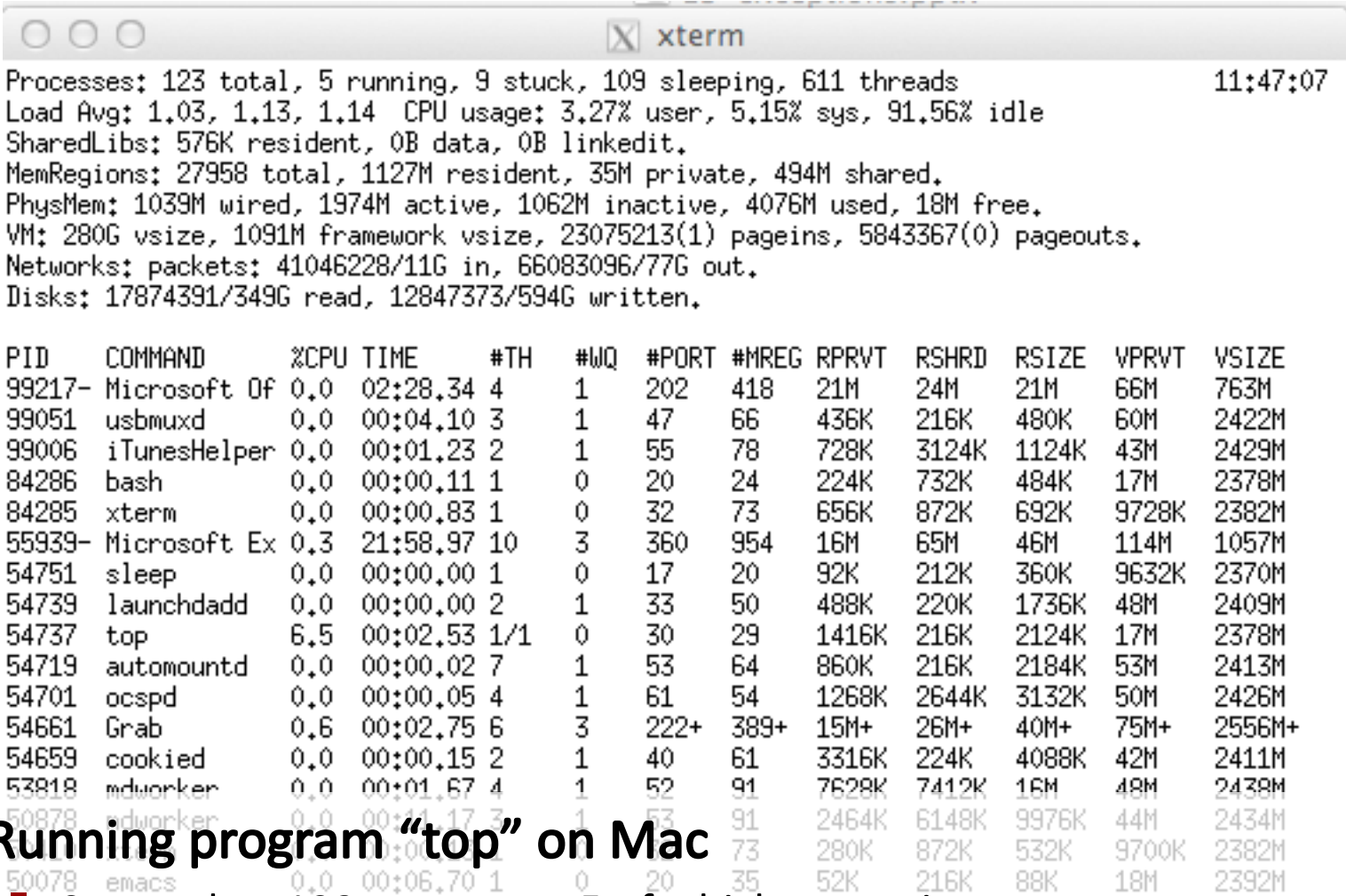


Multiprocessing: The Illusion



- **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



```

Processes: 123 total, 5 running, 9 stuck, 109 sleeping, 611 threads
Load Avg: 1.03, 1.13, 1.14  CPU usage: 3.27% user, 5.15% sys, 91.56% idle
SharedLibs: 576K resident, 0B data, 0B linkedit.
MemRegions: 27958 total, 1127M resident, 35M private, 494M shared.
PhysMem: 1039M wired, 1974M active, 1062M inactive, 4076M used, 18M free.
VM: 280G vsize, 1091M framework vsize, 23075213(1) pageins, 5843367(0) pageouts.
Networks: packets: 41046228/11G in, 66083096/77G out.
Disks: 17874391/349G read, 12847373/594G written.

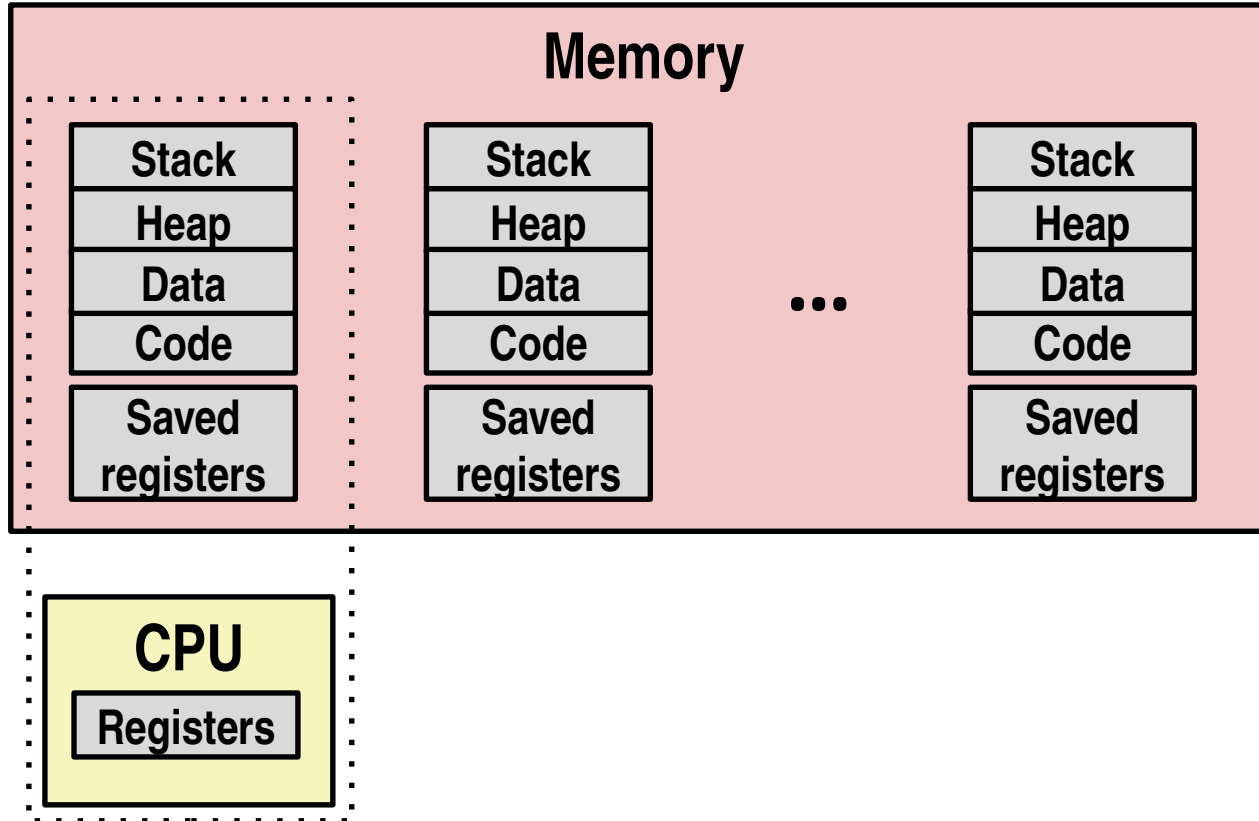
PID    COMMAND      %CPU  TIME    #TH   #WQ    #PORT  #MREG  RPRVT  RSHRD  RSIZE  VPRVT  VSIZE
99217-  Microsoft Of 0.0   02:28.34 4     1     202    418    21M    24M    21M    66M    763M
99051   usbmuxd      0.0   00:04.10 3     1     47     66     436K   216K   480K   60M    2422M
99006   iTunesHelper 0.0   00:01.23 2     1     55     78     728K   3124K  1124K  43M    2429M
84286   bash         0.0   00:00.11 1     0     20     24     224K   732K   484K   17M    2378M
84285   xterm        0.0   00:00.83 1     0     32     73     656K   872K   692K   9728K  2382M
55939-  Microsoft Ex 0.3   21:58.97 10    3     360    954    16M    65M    46M    114M   1057M
54751   sleep        0.0   00:00.00 1     0     17     20     92K    212K   360K   9632K  2370M
54739   launchdadd   0.0   00:00.00 2     1     33     50     488K   220K   1736K  48M    2409M
54737   top          6.5   00:02.53 1/1   0     30     29     1416K  216K   2124K  17M    2378M
54719   automountd   0.0   00:00.02 7     1     53     64     860K   216K   2184K  53M    2413M
54701   ocsdpd       0.0   00:00.05 4     1     61     54     1268K  2644K  3132K  50M    2426M
54661   Grab         0.6   00:02.75 6     3     222+   389+   15M+   26M+   40M+   75M+   2556M+
54659   cookied      0.0   00:00.15 2     1     40     61     3316K  224K   4088K  42M    2411M
53818   mdworker     0.0   00:01.67 4     1     52     91     7628K  7412K  16M    48M    2438M
50878   mdworker     0.0   00:01.17 3     1     53     91     2464K  6148K  9976K  44M    2434M
50078   emacs        0.0   00:06.70 1     0     20     35     52K    216K   88K    18M    2392M

```

Running program "top" on Mac

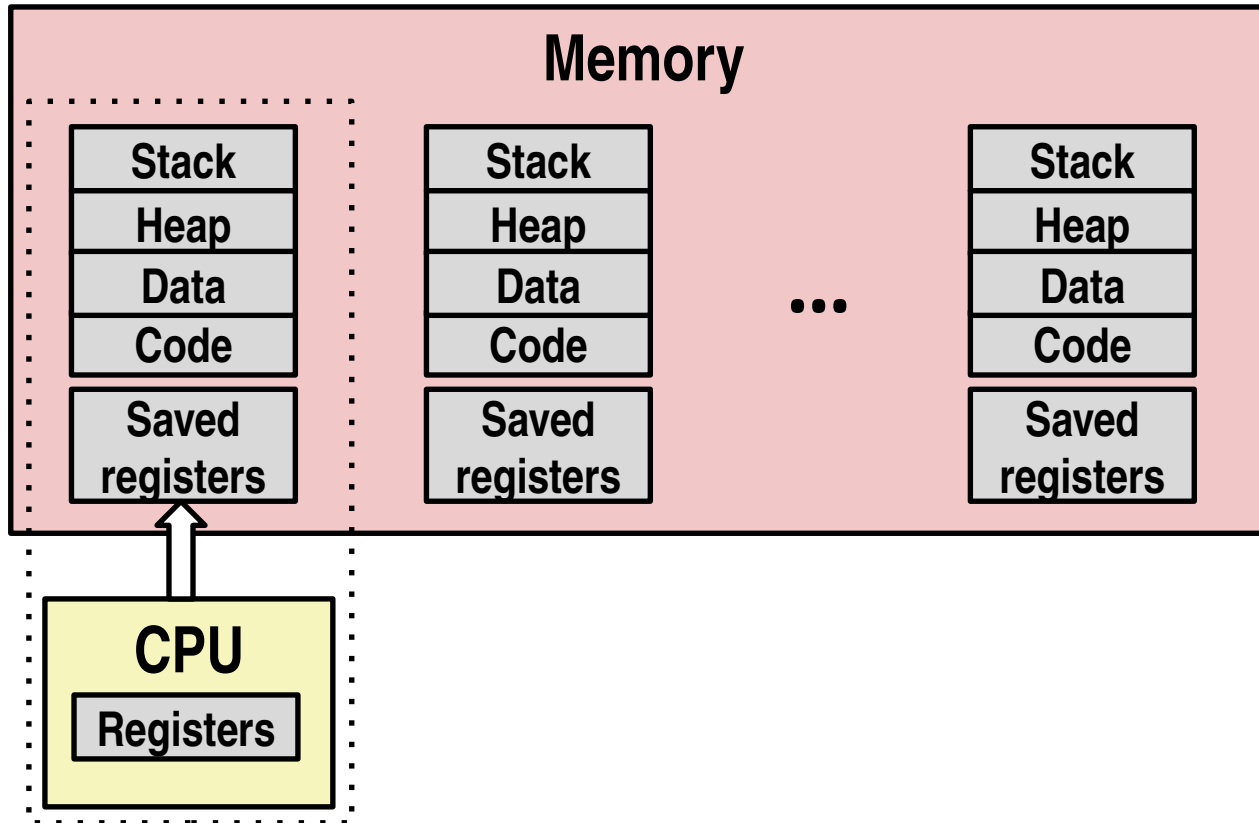
- System has 123 processes, 5 of which are active
- Identified by Process ID (PID)

Multiprocessing: The (Traditional) Reality



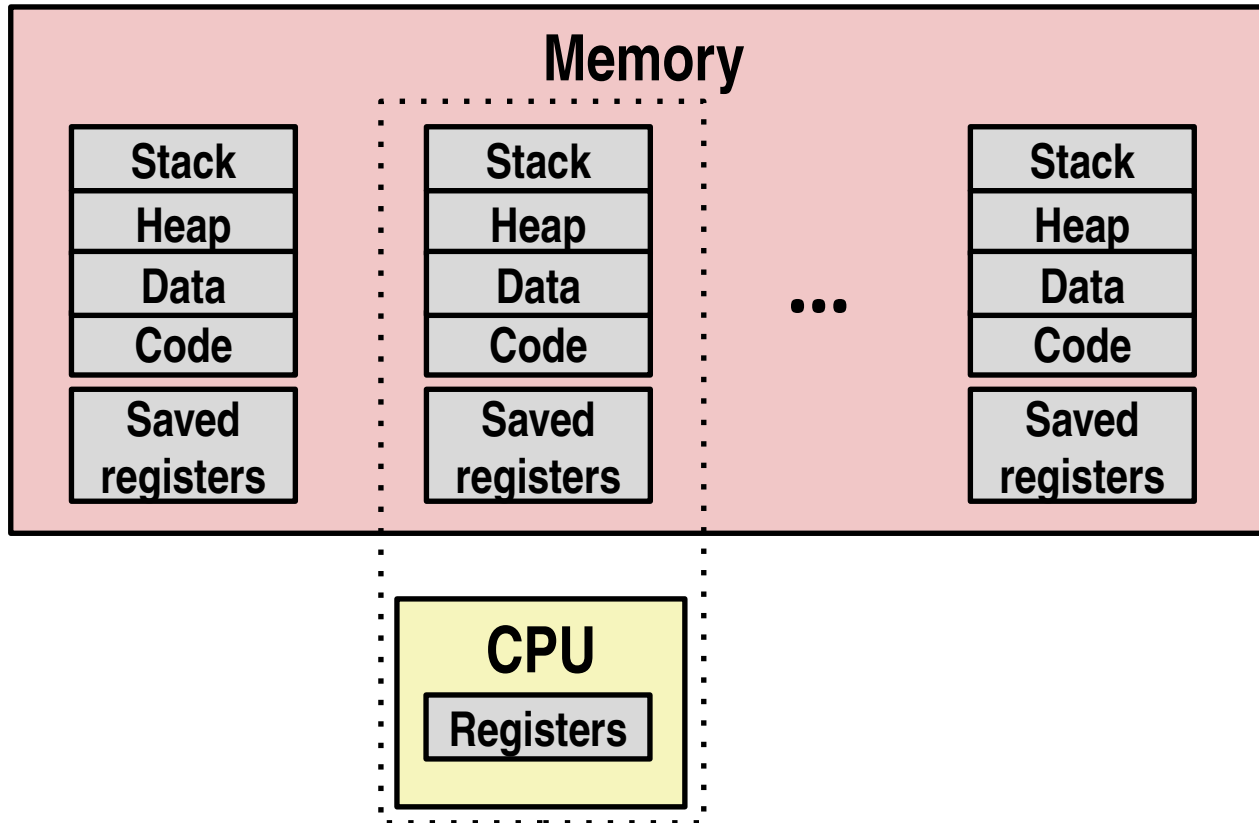
- **Single processor executes multiple processes concurrently**
 - Process executions interleaved (multitasking)
 - Address spaces managed by virtual memory system (later in course)
 - Register values for non-executing (suspended) processes saved in memory

Multiprocessing: The (Traditional) Reality



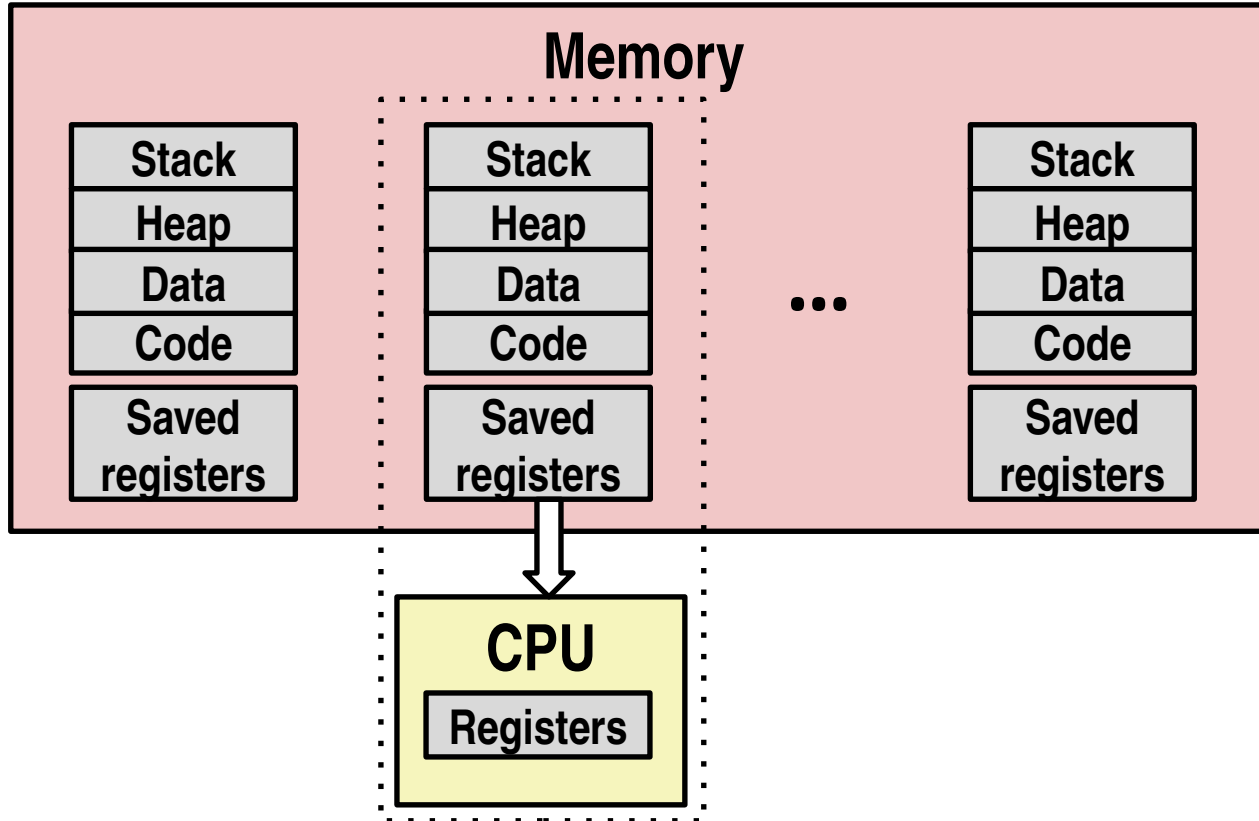
- Save current registers in memory

Multiprocessing: The (Traditional) Reality



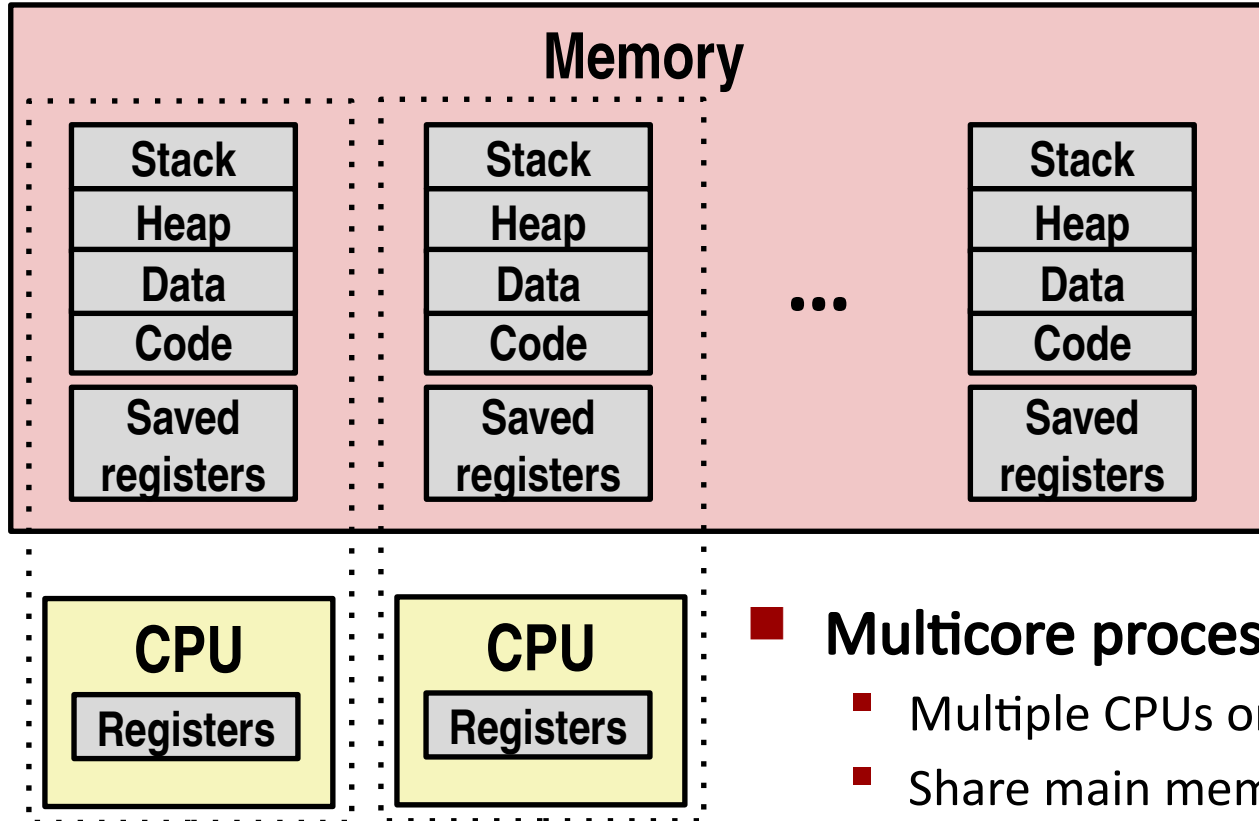
- Schedule next process for execution

Multiprocessing: The (Traditional) Reality



- Load saved registers and switch address space (context switch)

Multiprocessing: The (Modern) Reality

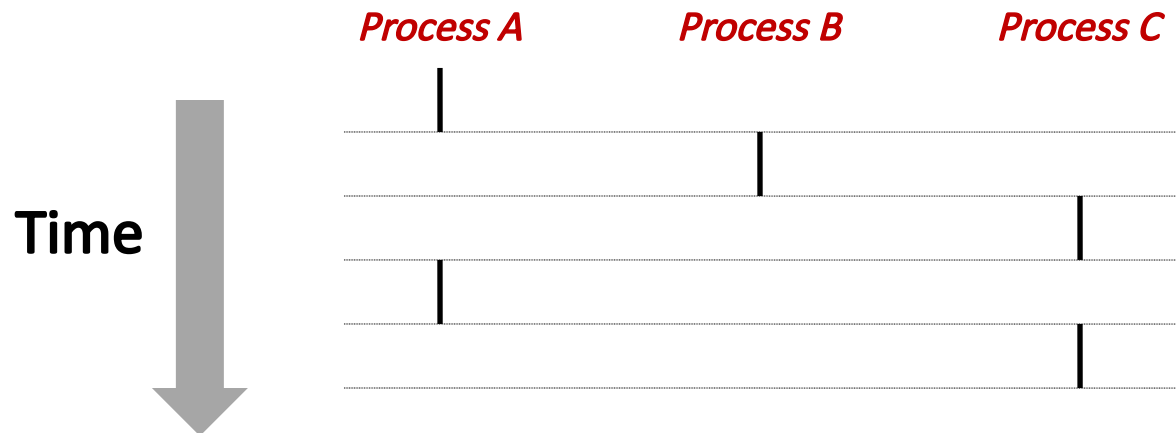


■ Multicore processors

- 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

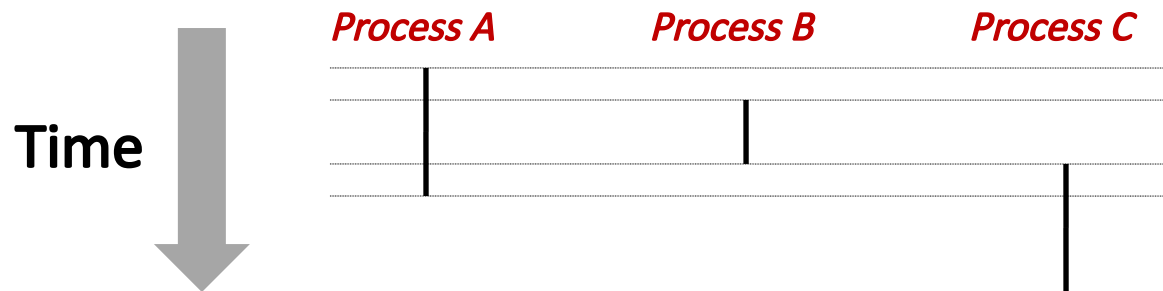
Concurrent Processes

- 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



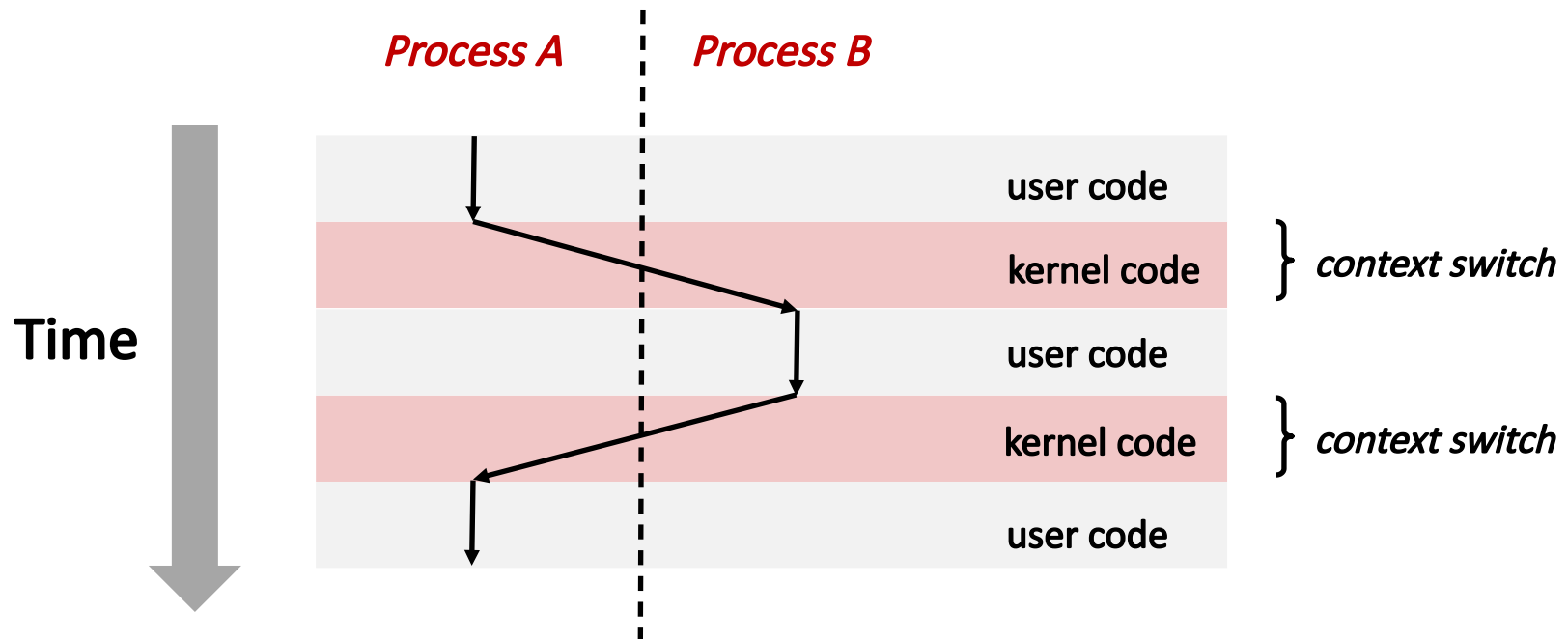
User View of Concurrent Processes

- Control flows for concurrent processes are physically disjoint in time
- However, we can think of concurrent processes as running in parallel with each other



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*



Today

- Exceptional Control Flow
- Exceptions
- Processes
- **Process Control**

System Call Error Handling

- On error, Linux system-level functions typically return -1 and set global variable `errno` to indicate cause.
- Hard and fast rule:
 - You must check the return status of every system-level function
 - Only exception is the handful of functions that return `void`
- Example:

```
if ((pid = fork()) < 0) {  
    fprintf(stderr, "fork error: %s\n", strerror(errno));  
    exit(0);  
}
```

Error-reporting functions

- Can simplify somewhat using an *error-reporting function*:

```
void unix_error(char *msg) /* Unix-style error */  
{  
    fprintf(stderr, "%s: %s\n", msg, strerror(errno));  
    exit(1);  
}
```

```
if ((pid = fork()) < 0)  
    unix_error("fork error");
```

Error-handling Wrappers

- We may simplify the code we present to you even further by using Stevens-style error-handling wrappers:

```
pid_t Fork(void)
{
    pid_t pid;

    if ((pid = fork()) < 0)
        unix_error("Fork error");
    return pid;
}
```

```
pid = Fork();
```


Obtaining Process IDs

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

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

Creating and Terminating Processes

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 (next lecture when we study signals)

■ Terminated

- Process is stopped permanently

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.

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

```
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

```
linux> ./fork
parent: x=0
child : x=2
```

- 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
 - $a \rightarrow b$ 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

Process Graph Example

```

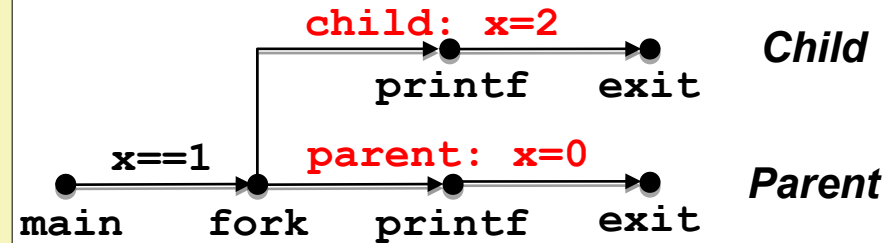
int main()
{
    pid_t pid;
    int x = 1;

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

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

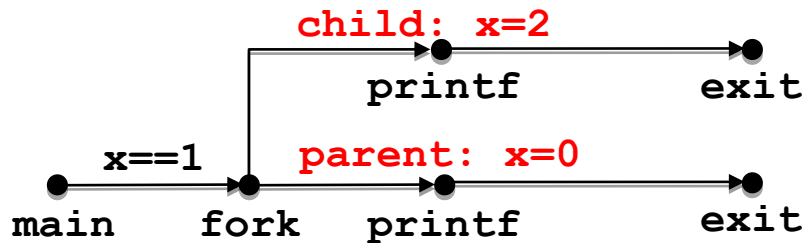
```

fork.c

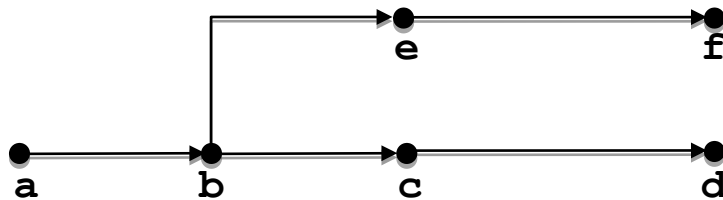


Interpreting Process Graphs

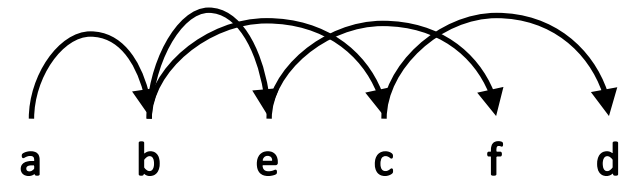
Original graph:



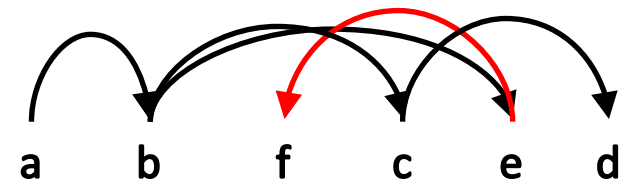
Relabeled graph:



Feasible total ordering:



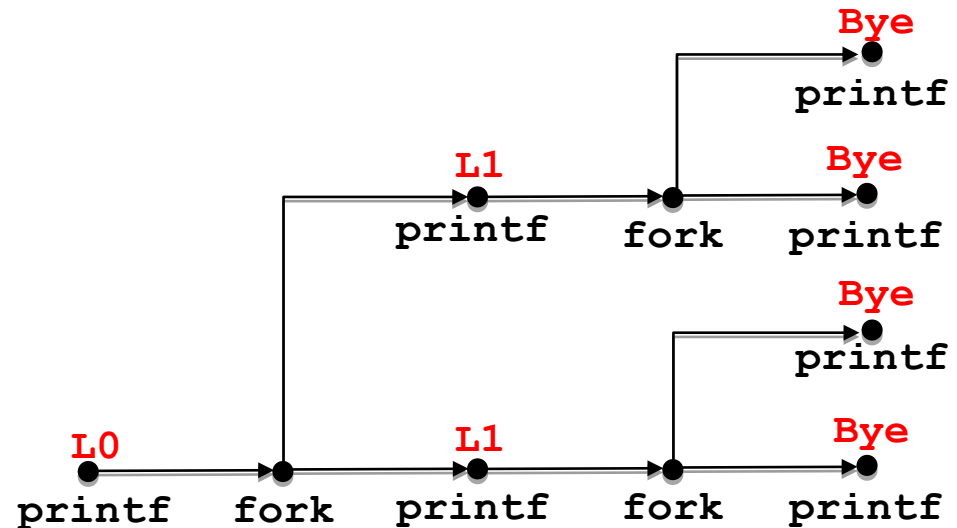
Infeasible total ordering:



fork Example: Two consecutive forks

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

forks.c



Feasible output:

L0
L1
Bye
Bye
L1
Bye
Bye

Infeasible output:

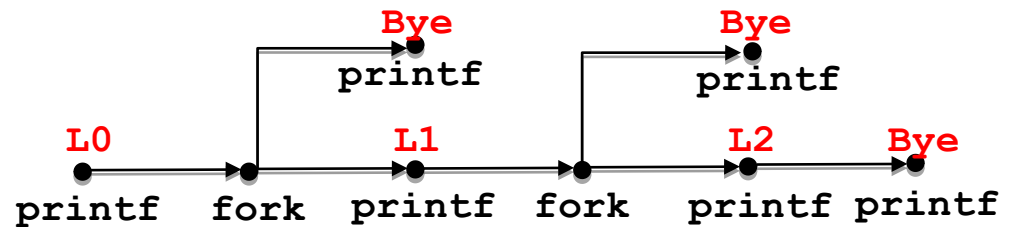
L0
Bye
L1
Bye
L1
Bye
Bye

fork Example: Nested forks in parent

```

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

```



Feasible output:

L0
L1
Bye
Bye
L2
Bye

Infeasible output:

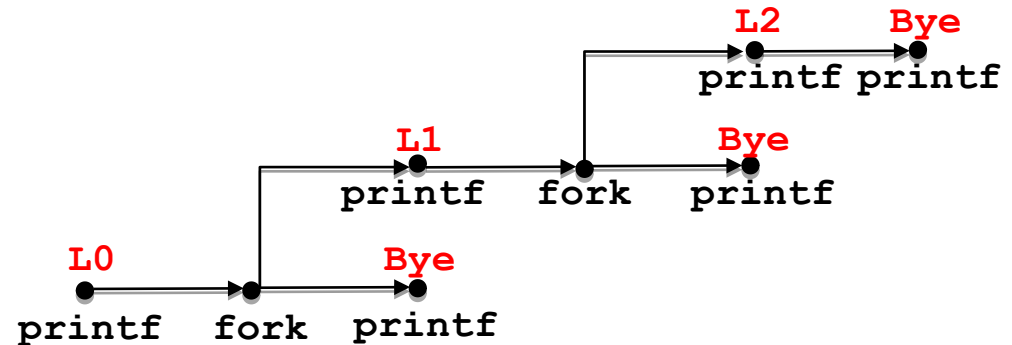
L0
Bye
L1
Bye
Bye
L2

fork Example: Nested forks in children

```

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

```



Feasible output:

L0
Bye
L1
L2
Bye
Bye

Infeasible output:

L0
Bye
L1
Bye
Bye
L2

Reaping Child Processes

■ 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

Zombie Example

```
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**

Non-terminating Child Example

```
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 tttyp9      00:00:00 tcsh
 6676 tttyp9      00:00:06 forks
 6677 tttyp9      00:00:00 ps
linux> kill 6676
linux> ps
  PID TTY          TIME CMD
 6585 tttyp9      00:00:00 tcsh
 6678 tttyp9      00:00:00 ps
```

Child process still active even though parent has terminated

Must kill child explicitly, or else will keep running indefinitely

`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`, `WEXITSTATUS`, `WIFSIGNALED`, `WTERMSIG`, `WIFSTOPPED`, `WSTOPSIG`, `WIFCONTINUED`
 - See textbook for details

wait: Synchronizing with Children

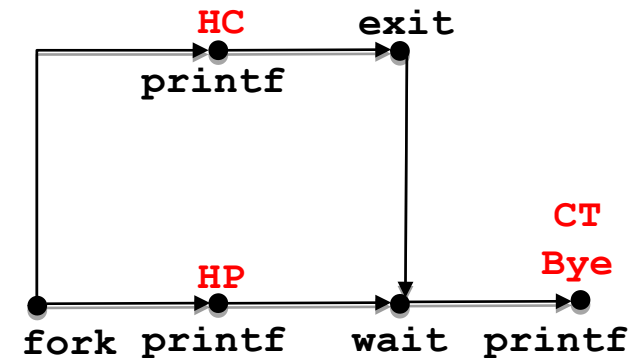
```

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

Another wait Example

- If multiple children completed, will take in arbitrary order
- Can use macros WIFEXITED and WEXITSTATUS to get information about exit status

```
void fork10() {
    pid_t pid[N];
    int i, child_status;

    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0) {
            exit(100+i); /* Child */
        }
    for (i = 0; i < N; i++) { /* Parent */
        pid_t wpid = wait(&child_status);
        if (WIFEXITED(child_status))
            printf("Child %d terminated with exit status %d\n",
                wpid, WEXITSTATUS(child_status));
        else
            printf("Child %d terminate abnormally\n", wpid);
    }
}
```

forks.c

waitpid: Waiting for a Specific Process

- `pid_t waitpid(pid_t pid, int &status, int options)`
 - Suspends current process until specific process terminates
 - Various options (see textbook)

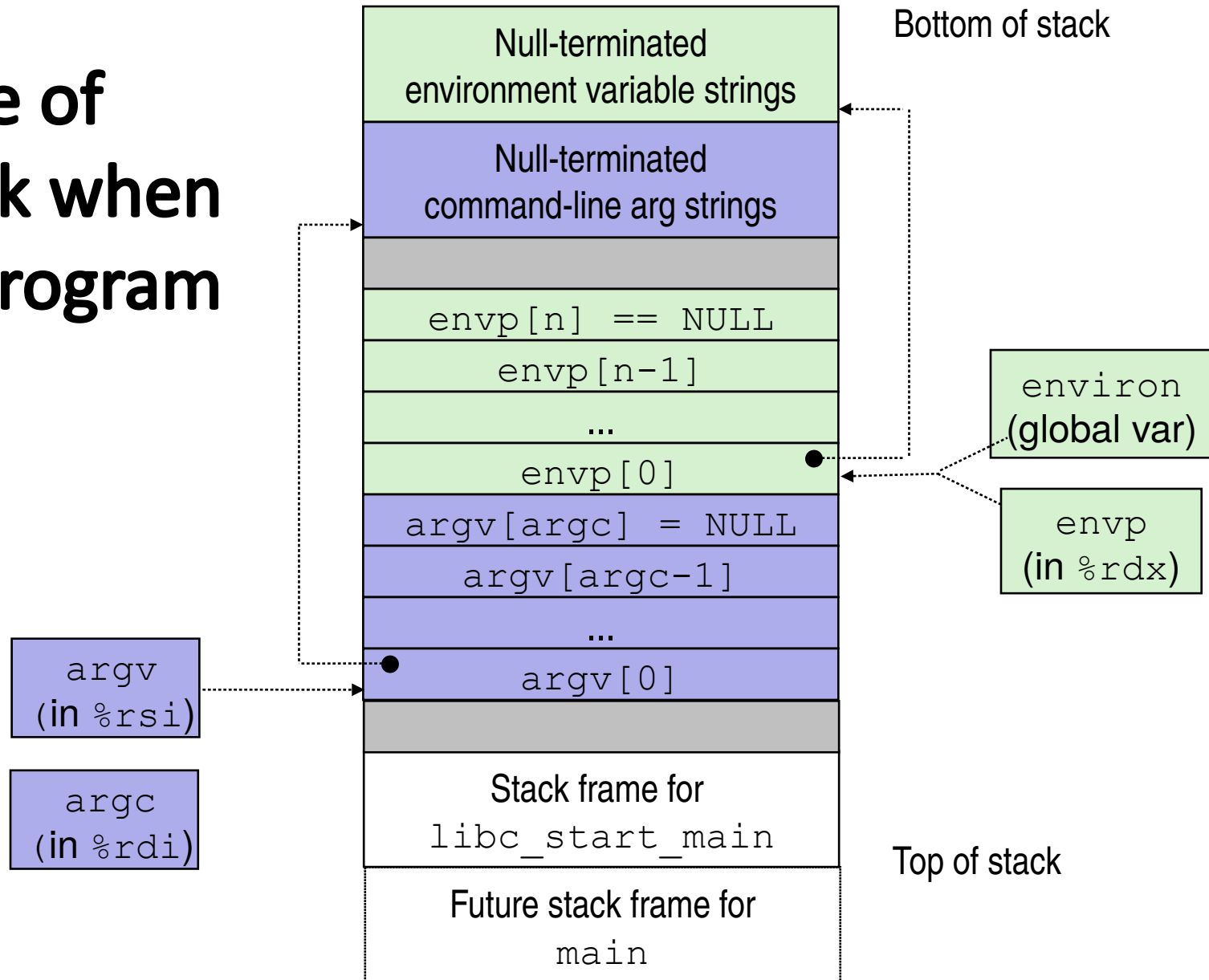
```
void fork11() {  
    pid_t pid[N];  
    int i;  
    int child_status;  
  
    for (i = 0; i < N; i++)  
        if ((pid[i] = fork()) == 0)  
            exit(100+i); /* Child */  
    for (i = N-1; i >= 0; i--) {  
        pid_t wpid = waitpid(pid[i], &child_status, 0);  
        if (WIFEXITED(child_status))  
            printf("Child %d terminated with exit status %d\n",  
                wpid, WEXITSTATUS(child_status));  
        else  
            printf("Child %d terminate abnormally\n", wpid);  
    }  
}
```

forks.c

execve : Loading and Running Programs

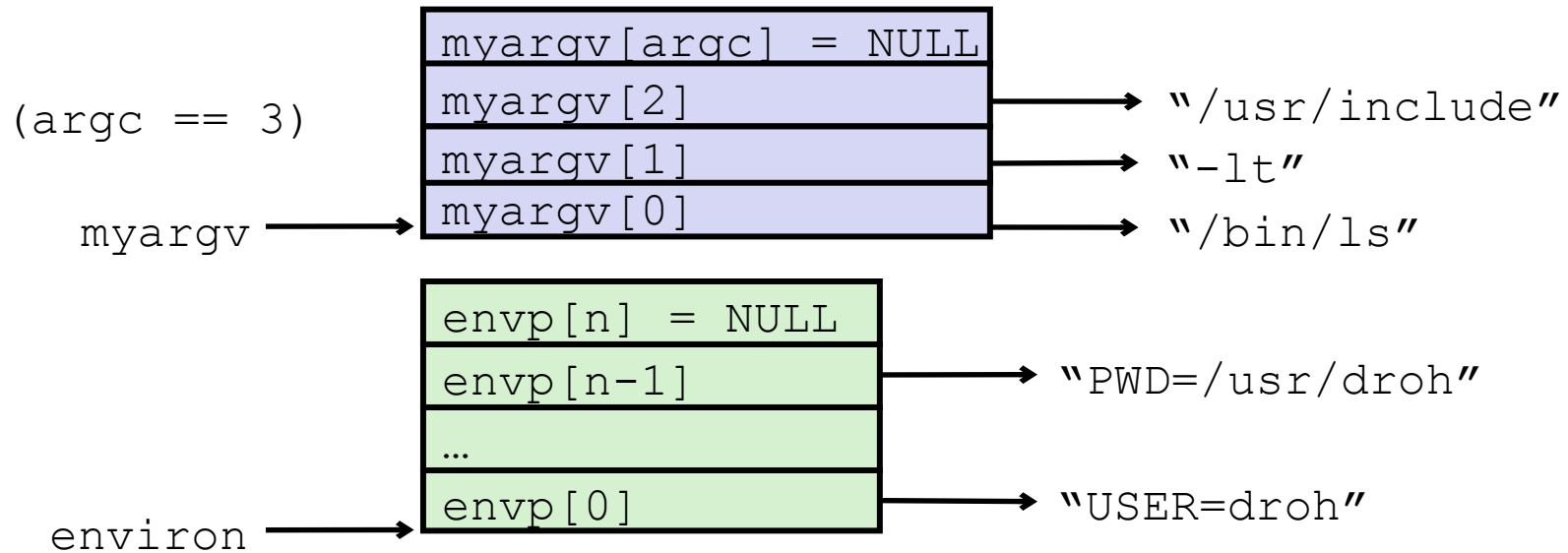
- `int execve(char *filename, char *argv[], char *envp[])`
- **Loads and runs in the current process:**
 - Executable file **filename**
 - Can be object file or script file beginning with `#!interpreter` (e.g., `#!/bin/bash`)
 - ...with argument list **argv**
 - By convention `argv[0]==filename`
 - ...and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

Structure of the stack when a new program starts



execve Example

- Executes `"/bin/ls -lt /usr/include"` 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);
    }
}
```

Summary

■ Exceptions

- Events that require nonstandard control flow
- Generated externally (interrupts) or internally (traps and faults)

■ Processes

- At any given time, system has multiple active processes
- Only one can execute at a time on a single core, though
- Each process appears to have total control of processor + private memory space

Summary (cont.)

■ Spawning processes

- Call `fork`
- One call, two returns

■ Process completion

- Call `exit`
- One call, no return

■ Reaping and waiting for processes

- Call `wait` or `waitpid`

■ Loading and running programs

- Call `execve` (or variant)
- One call, (normally) no return