

# Processes II, Virtual Memory I

CSE 351 Autumn 2021

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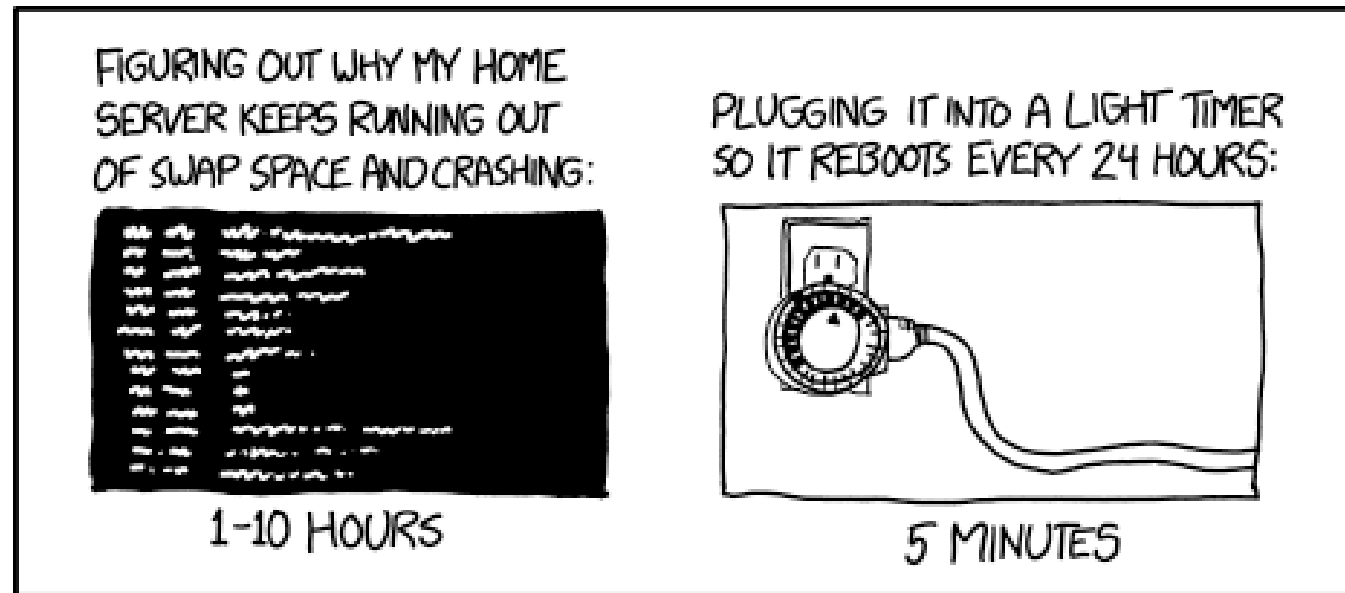
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WHY EVERYTHING I HAVE IS BROKEN

<https://xkcd.com/1495/>

# Relevant Course Information

- ❖ hw21 due Monday (11/22)
- ❖ hw22 due Friday (11/26)
  - Extra days to work, but probably want to finish by 11/24
- ❖ Lab 4 due Monday after Thanksgiving (11/29)

# 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);
}
```

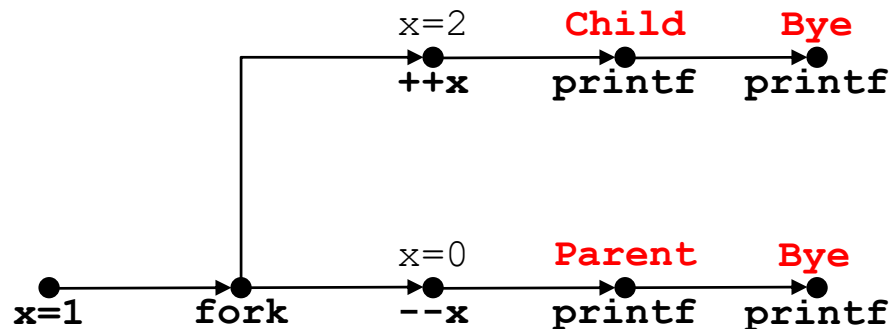
- ❖ Both processes continue/start execution after `fork`
  - Child starts at instruction after the call to `fork` (storing into `pid`)
- ❖ Can't predict execution order of parent and child
- ❖ Both processes start with `x = 1`
  - Subsequent changes to `x` are independent
- ❖ Shared open files: `stdout`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

# Fork Example: Possible Output

```
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);  
}
```



# Polling Question

❖ Are the following sequences of outputs possible?

■ Vote in Ed Lessons

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

Seq 1:      Seq 2:

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

- A. **No**      **No**
- B. **No**      **Yes**
- C. **Yes**      **No**
- D. **Yes**      **Yes**
- E. **We're lost...**

# Reading Review

- ❖ Terminology:
  - `exec*()`, `exit()`, `wait()`, `waitpid()`
  - `init/systemd`, reaping, zombie processes
  - Virtual memory: virtual vs. physical addresses and address space, swap space
  
- ❖ Questions from the Reading?

# Fork-Exec

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

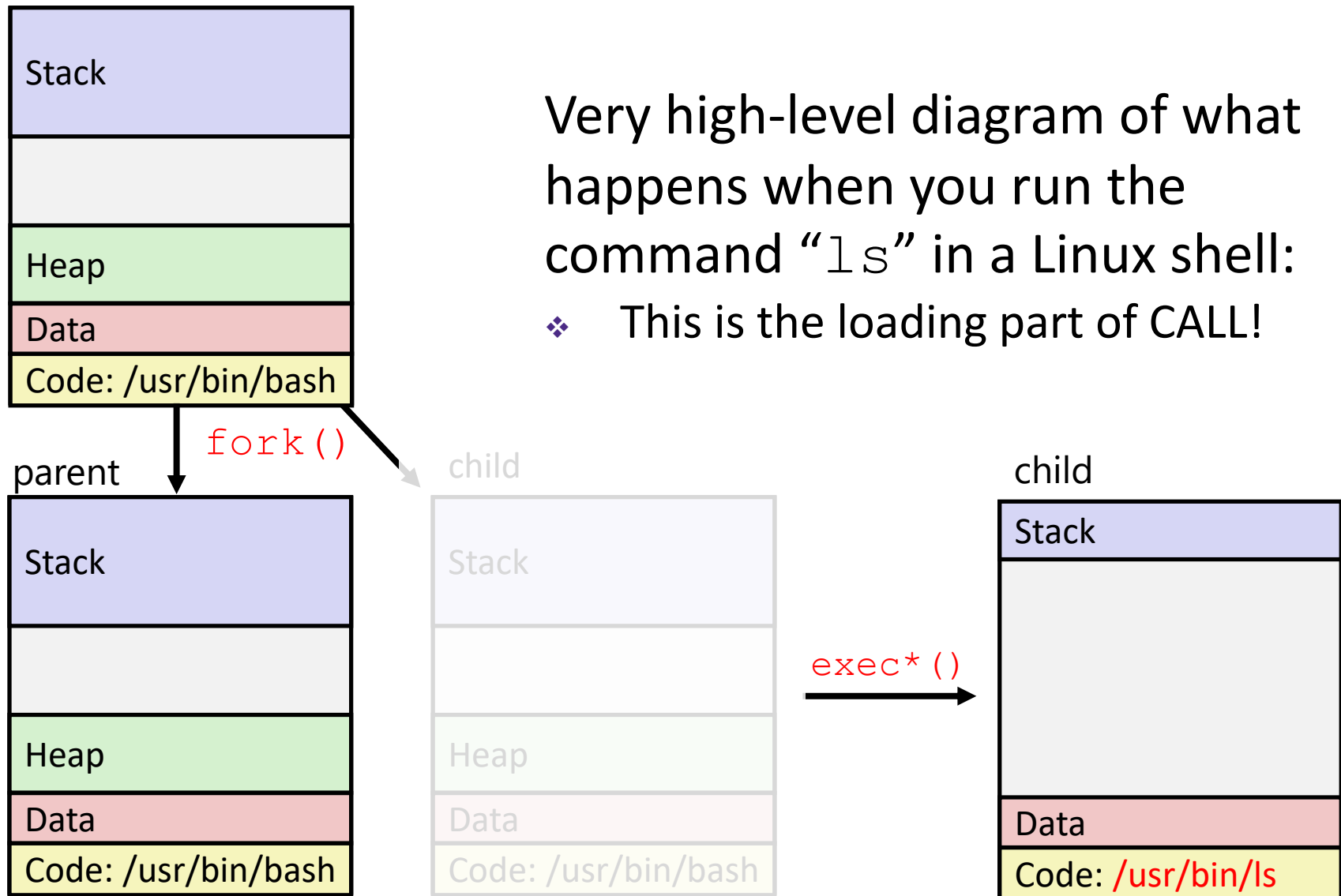
## ❖ fork-exec model:

- `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 fork_ret = fork();
    if (fork_ret != 0) {
        printf("Parent: created a child %d\n", fork_ret);
    } else {
        printf("Child: about to exec a new program\n");
        execv(path, argv);
    }
    printf("This line printed by parent only!\n");
}
```



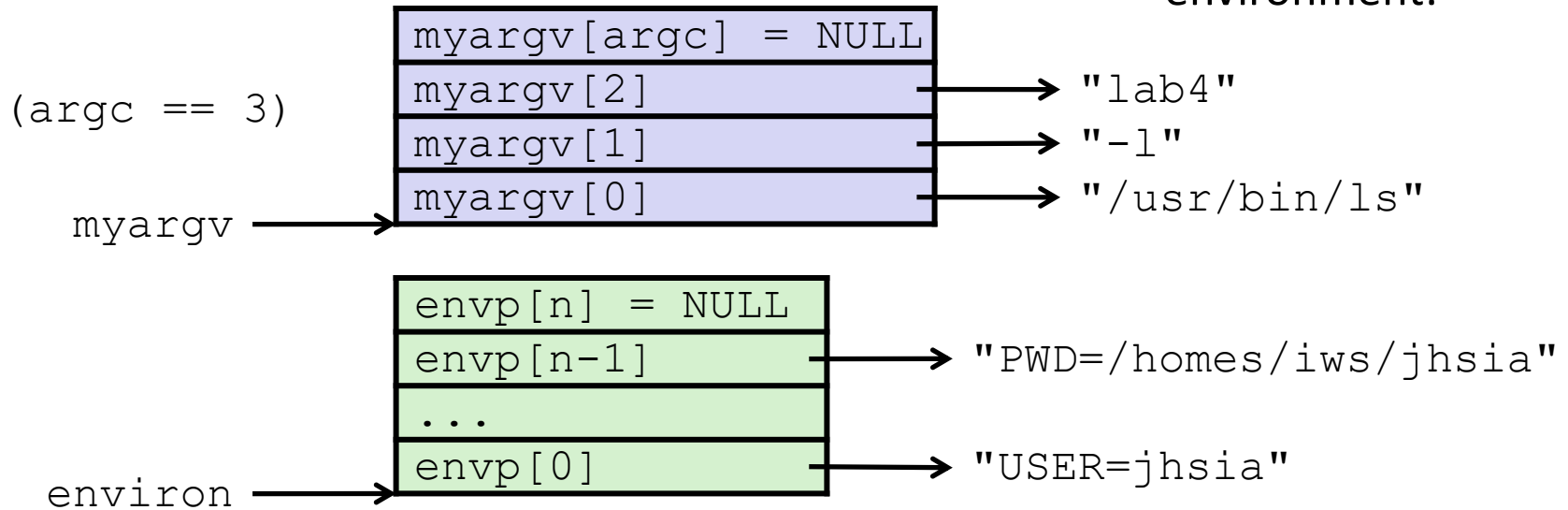
# Exec-ing a new program



# execve Example

This is extra  
(non-testable)  
material

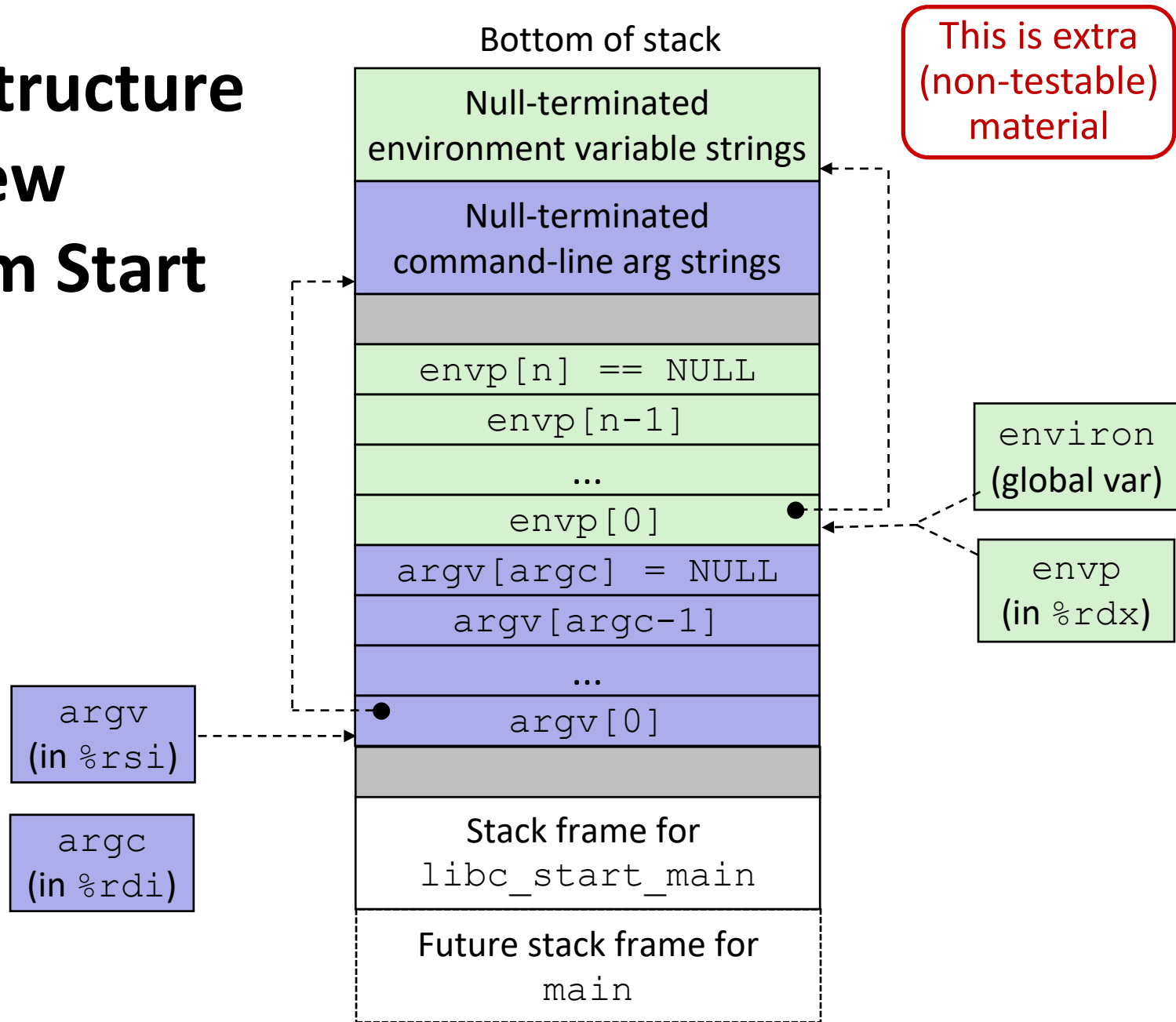
Execute `"/usr/bin/ls -l lab4"` in child process using current environment:



```
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 `printenv` command in a Linux shell to see your own environment variables

# Stack Structure on a New Program Start



# Processes

- ❖ Processes and context switching
- ❖ Creating new processes
  - `fork()` and `exec*()`
- ❖ **Ending a process**
  - `exit()`, `wait()`, `waitpid()`
  - **Zombies**

# exit: Ending a process

- ❖ **void** `exit(int status)`
  - Explicitly exits a process
    - Status code: 0 is used for a normal exit, nonzero for abnormal exit
- ❖ The `return` statement from `main()` also ends a process in C
  - The return value is the status code

# Zombies

- ❖ A terminated process 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
  - In long-running processes (*e.g.*, shells, servers) we need *explicit* reaping
- ❖ If parent terminates without reaping a child, then the orphaned child will be reaped by `init` process (pid 1)
  - **Note:** on recent Linux systems, `init` has been renamed `systemd`

# 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

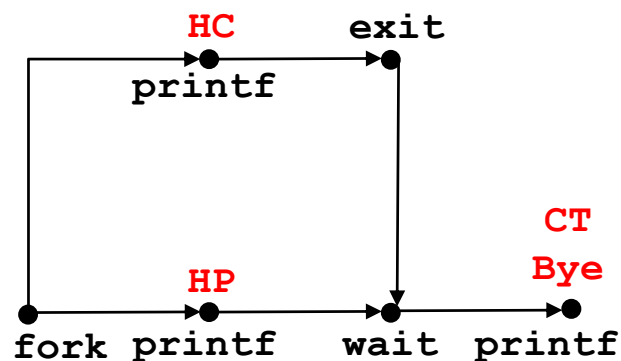
```

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");
}

```

*forks.c*



Feasible output:

HC  
HP  
CT  
Bye

Infeasible output:

HP  
CT  
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 */
    }
}
```

*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"

❖ 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);
    }
}
```

*forks.c*

```
linux> ./forks 8
Terminating Parent, PID = 6675
Running Child, PID = 6676
linux> ps
  PID TTY          TIME CMD
 6585 ttys9        00:00:00 tcsh
 6676 ttys9        00:00:06 forks
 6677 ttys9        00:00:00 ps
linux> kill 6676
linux> ps
  PID TTY          TIME CMD
 6585 ttys9        00:00:00 tcsh
 6678 ttys9        00:00:00 ps
```

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

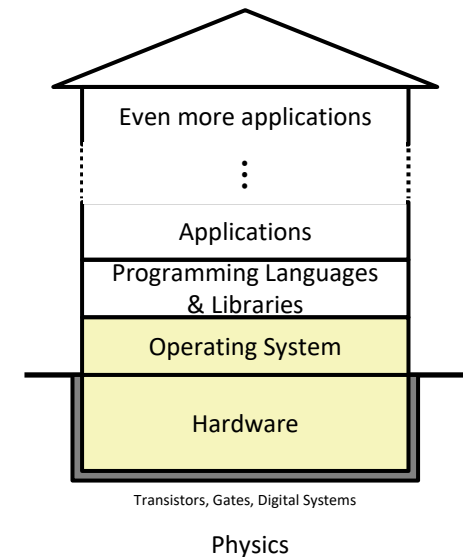
# Process Management Summary

- ❖ `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 */ }`
- ❖ `exit` or `return` from `main` to end a process
- ❖ `wait` or `waitpid` used to synchronize parent/child execution and to reap child process

# The Hardware/Software Interface

## ❖ Topic Group 3: **Scale & Coherence**

- Caches, Processes, **Virtual Memory**,  
Memory Allocation



- ❖ How do we maintain logical consistency in the face of more data and more processes?
  - How do we support control flow both within many processes and things external to the computer?
  - How do we support data access, including dynamic requests, across multiple processes?

# Virtual Memory (VM\*)

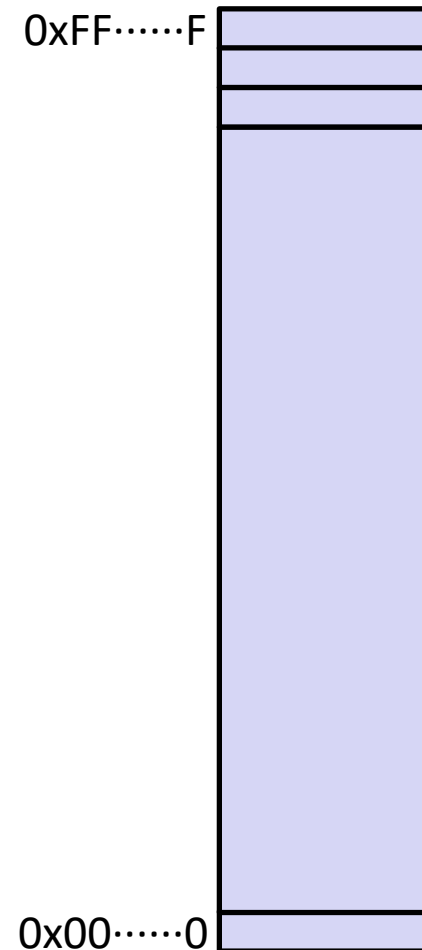
- ❖ Overview and motivation
- ❖ VM as a tool for caching
- ❖ Address translation
- ❖ VM as a tool for memory management
- ❖ VM as a tool for memory protection

**Warning:** Virtual memory is pretty complex, but crucial for understanding how processes work and for debugging performance

*\*Not to be confused with “Virtual Machine” which is a whole other thing.*

# Memory as we know it so far... is *virtual*!

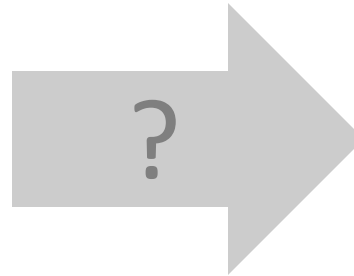
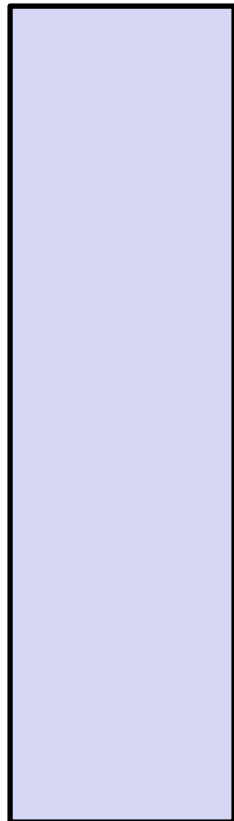
- ❖ Programs refer to virtual memory addresses
  - `movq (%rdi), %rax`
  - Conceptually memory is just a very large array of bytes
  - System provides private address space to each process
- ❖ Allocation: Compiler and run-time system
  - Where different program objects should be stored
  - All allocation within single virtual address space
- ❖ But...
  - We *probably* don't have  $2^w$  bytes of physical memory
  - We *certainly* don't have  $2^w$  bytes of physical memory for every process
  - Processes should not interfere with one another
    - Except in certain cases where they want to share code or data



# Problem 1: How Does Everything Fit?

64-bit virtual addresses can address  
several exabytes  
(18,446,744,073,709,551,616 bytes)

Physical main memory offers  
a few gigabytes  
(e.g., 8,589,934,592 bytes)



*(Not to scale; physical memory would be smaller than the period at the end of this sentence compared to the virtual address space.)*

1 virtual address space per process,  
with many processes...

# Problem 2: Memory Management

We have multiple processes:

Process 1  
Process 2  
Process 3  
...  
Process n

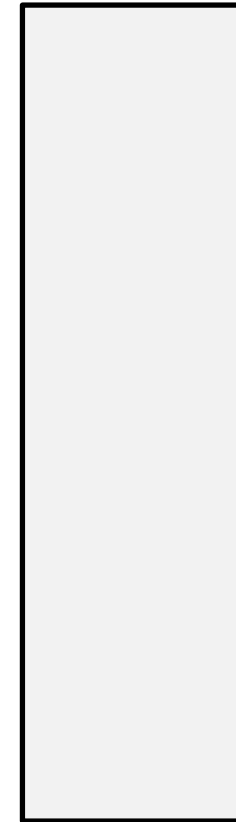
**X**

Each process has...

stack  
heap  
.text  
.data  
...

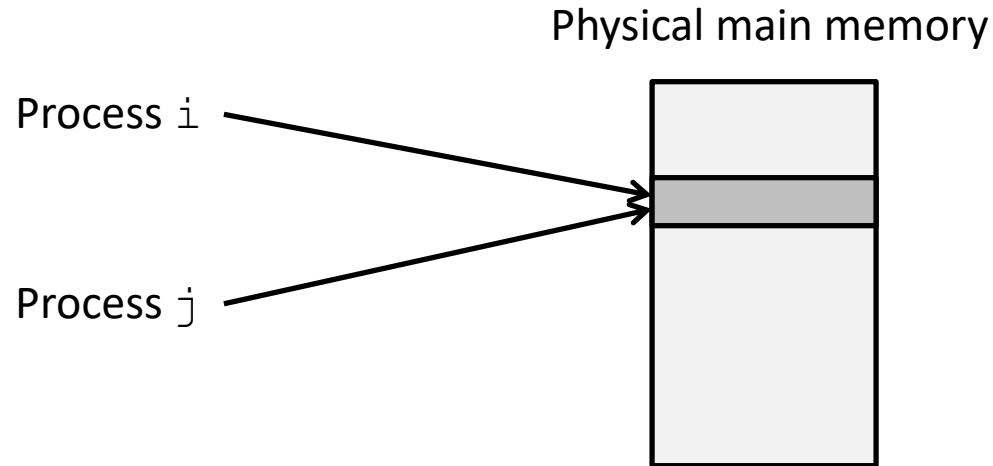
*What goes  
where?*

Physical main memory

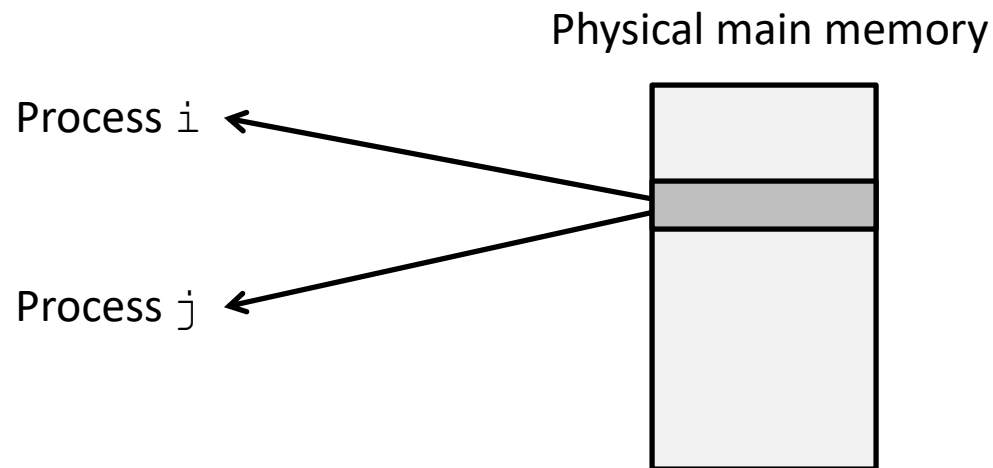




## Problem 3: How To Protect



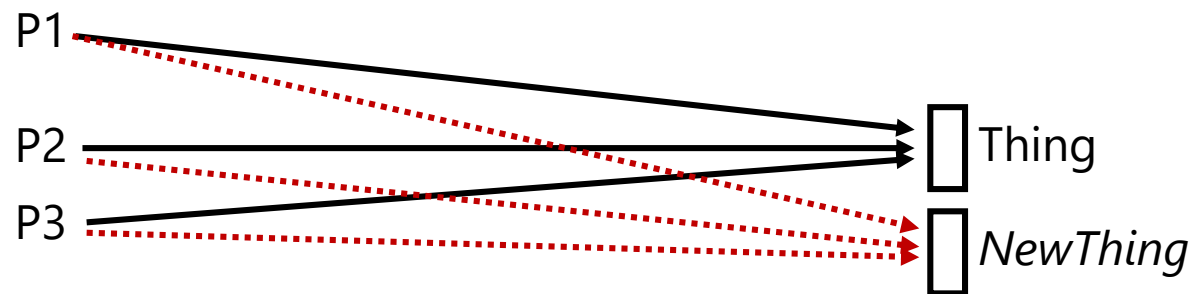
## Problem 4: How To Share?



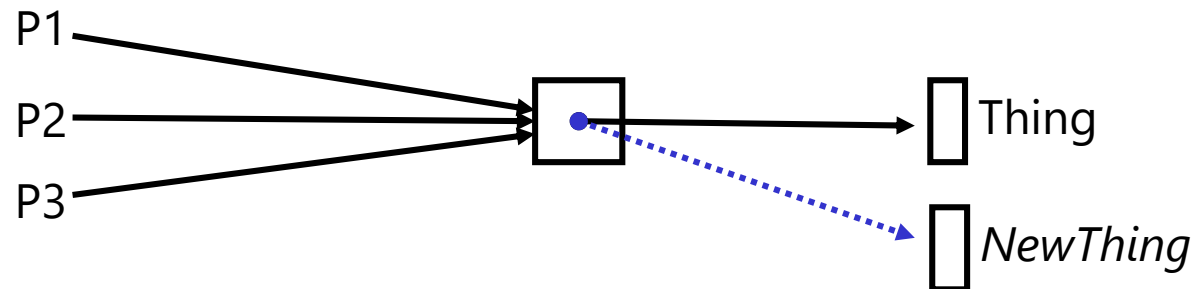
# How can we solve these problems?

- ❖ “Any problem in computer science can be solved by adding another level of **indirection**.” – *David Wheeler, inventor of the subroutine*

- ❖ Without Indirection



- ❖ With Indirection

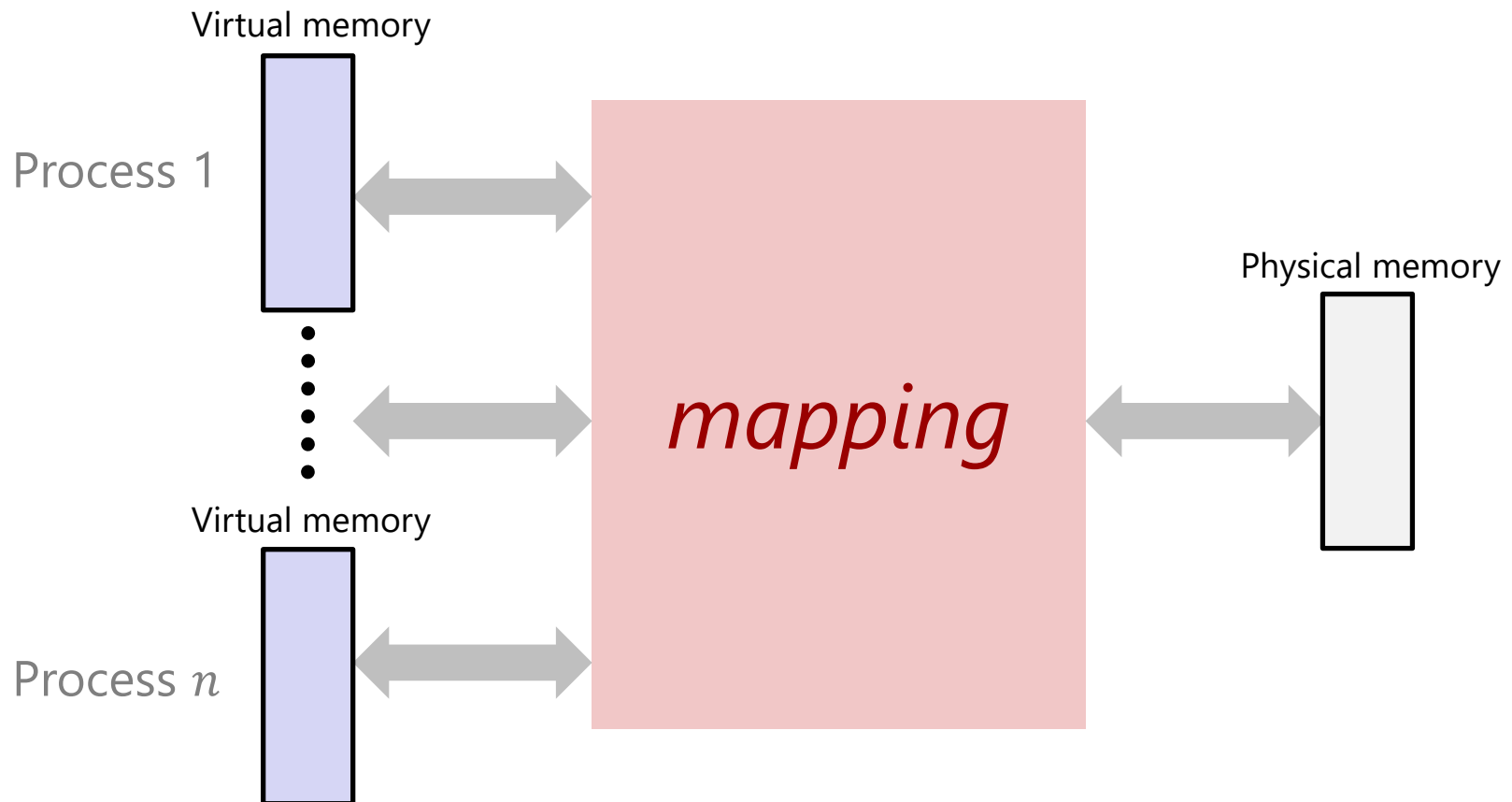


*What if I want to move Thing?*

# Indirection

- ❖ *Indirection*: The ability to reference something using a name, reference, or container instead of the value itself. A flexible mapping between a name and a thing allows changing the thing without notifying holders of the name.
  - Adds some work (now have to look up 2 things instead of 1)
  - But don't have to track all uses of name/address (single source!)
- ❖ Examples:
  - **Phone system**: cell phone number portability
  - **Domain Name Service (DNS)**: translation from name to IP address
  - **Call centers**: route calls to available operators, etc.
  - **Dynamic Host Configuration Protocol (DHCP)**: local network address assignment

# Indirection in Virtual Memory



- ❖ Each process gets its own private virtual address space
- ❖ Solves the previous problems!

# Address Spaces

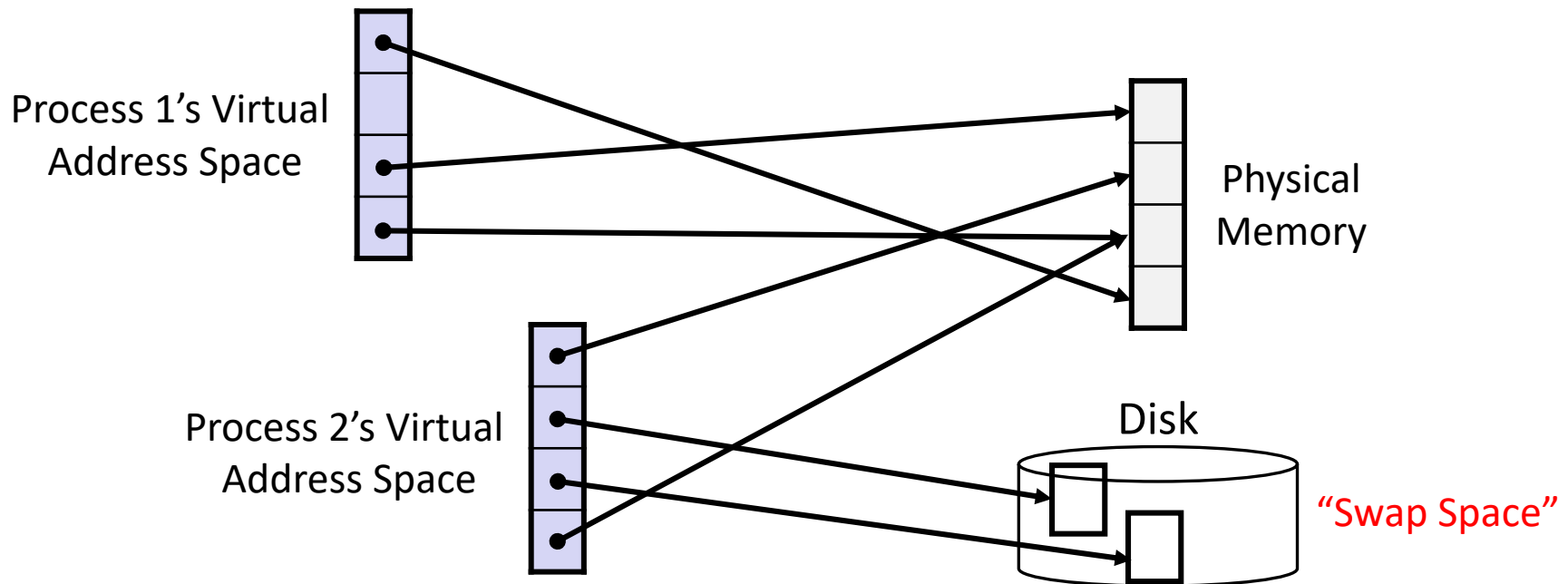
- ❖ **Virtual address space:** Set of  $N = 2^n$  virtual addr
  - $\{0, 1, 2, 3, \dots, N-1\}$
- ❖ **Physical address space:** Set of  $M = 2^m$  physical addr
  - $\{0, 1, 2, 3, \dots, M-1\}$
  
- ❖ Every byte in main memory has:
  - one physical address (PA)
  - zero, one, *or more* virtual addresses (VAs)

# Polling Questions

- ❖ On a 64-bit machine currently running 8 processes, how much virtual memory is there?
- ❖ True or False: A 32-bit machine with 8 GiB of RAM installed would never use all of it (in theory).

# Mapping

- ❖ A virtual address (VA) can be mapped to either **physical memory** or **disk**
  - Unused VAs may not have a mapping
  - VAs from *different* processes may map to same location in memory/disk



# Summary

- ❖ Virtual memory provides:
  - Ability to use limited memory (RAM) across multiple processes
  - Illusion of contiguous virtual address space for each process
  - Protection and sharing amongst processes



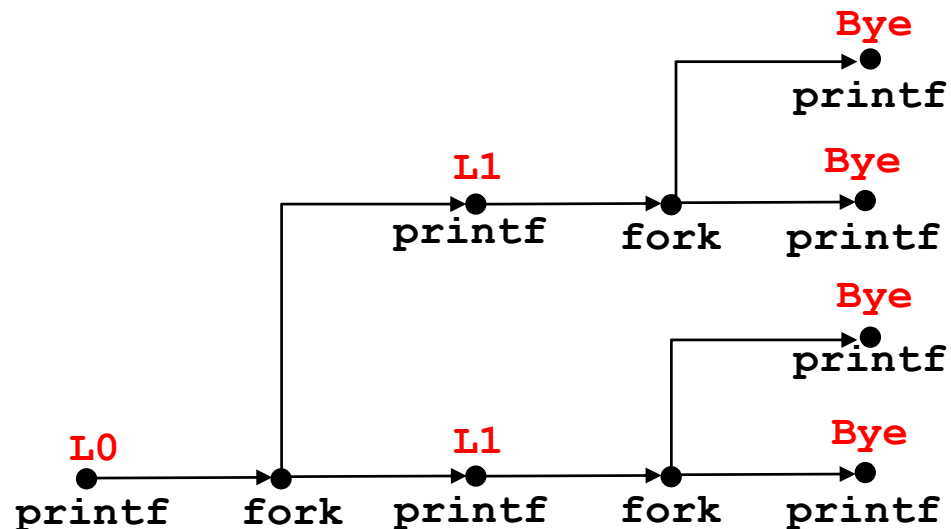
# BONUS SLIDES

## Detailed examples:

- ❖ Consecutive forks
- ❖ `wait()` example
- ❖ `waitpid()` example

# Example: Two consecutive forks

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



Feasible output:

- L0
- L1
- Bye
- Bye
- L1
- Bye
- Bye

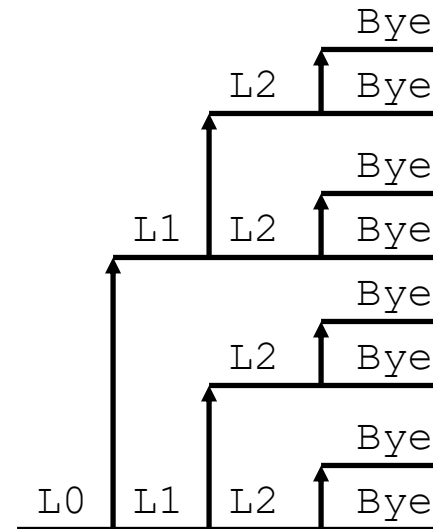
Infeasible output:

- L0
- Bye
- L1
- Bye
- L1
- Bye
- Bye

# Example: Three consecutive forks

- ❖ Both parent and child can continue forking

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



# 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;
    int child_status;
    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0)
            exit(100+i); /* Child */
    for (i = 0; i < N; i++) {
        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 terminated abnormally\n", wpid);
    }
}
```

# 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 (that we won't talk about)

```
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 = 0; i < N; 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 terminated abnormally\n", wpid);
    }
}
```