



Exceptional Control Flow: Exceptions and Processes

Process Control

These slides adapted from materials provided by the textbook authors.

Exceptional Control Flow

- Exceptional Control Flow
- Exceptions
- Processes
- **Process Control**
 - Identify (getpid, getppid)
 - Create (fork)
 - Coordinate (wait, waitpid)
 - Execute other program (exec, execve, *etc*)
 - Quit (exit)

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(0);
}
```

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

Error-handling Wrappers

- We simplify the code we present to you even further by using Stevens-style¹ error-handling wrappers:

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

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

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

1 – Used in *Unix Network Programming*, by W. Richard Stevens

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 (learn more 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 (*coming soon!*)
 - 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 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

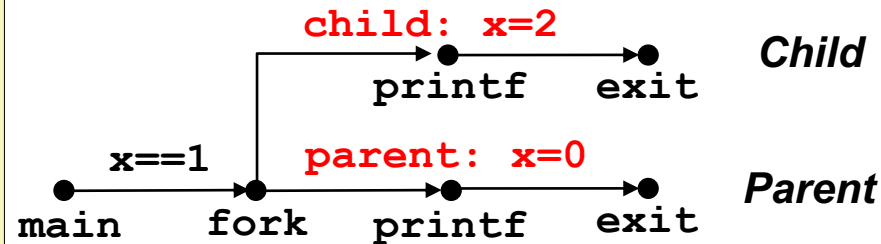
Process Graph Example

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

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

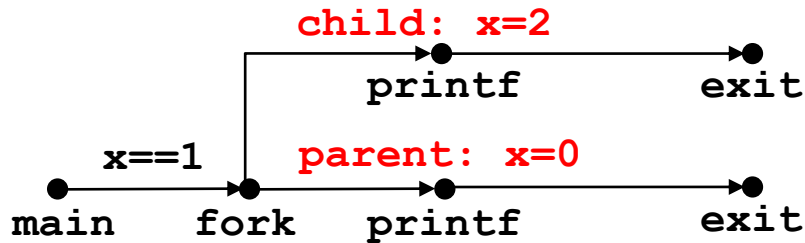
    /* Parent */
    printf("parent: x=%d\n", --x);
    exit(0);
}
```

fork.c

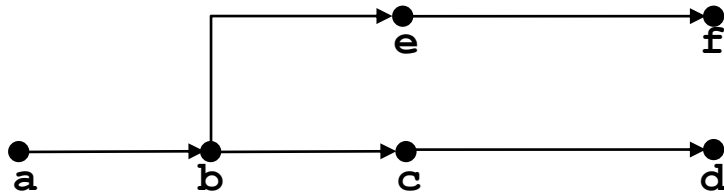


Interpreting Process Graphs

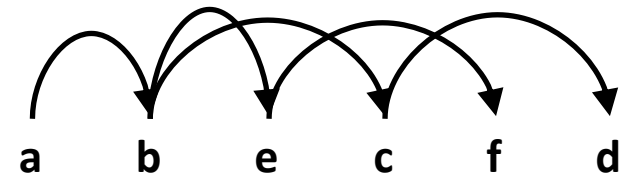
■ Original graph:



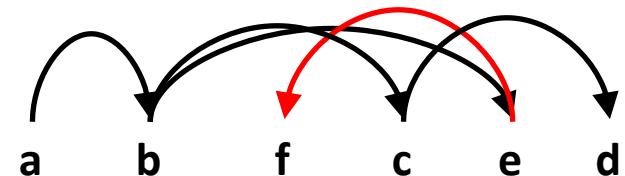
■ Relabelled graph:



Feasible total ordering:



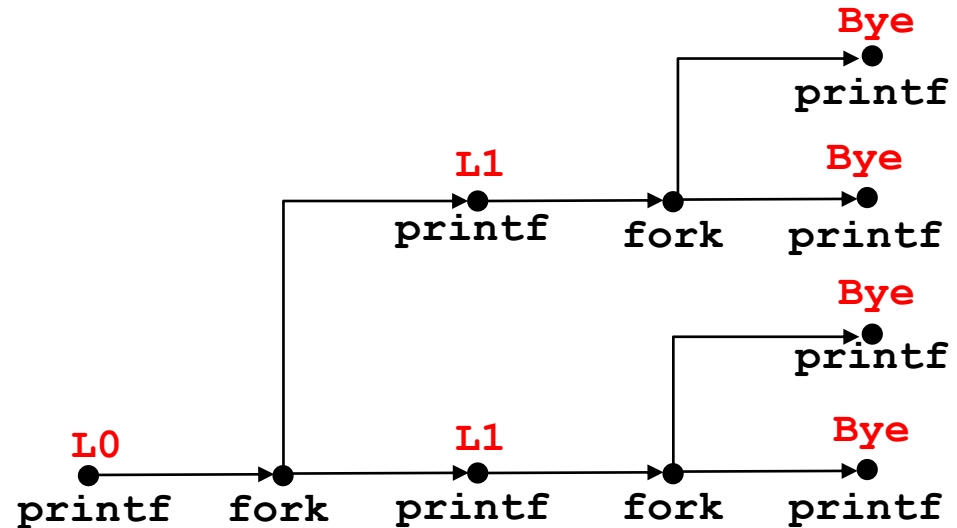
Infeasible total ordering:



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

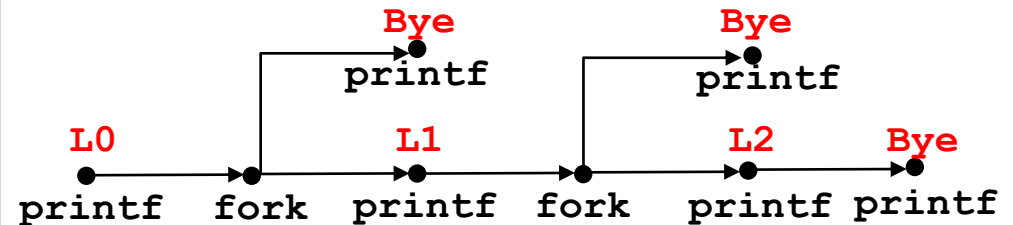
Infeasible output:

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

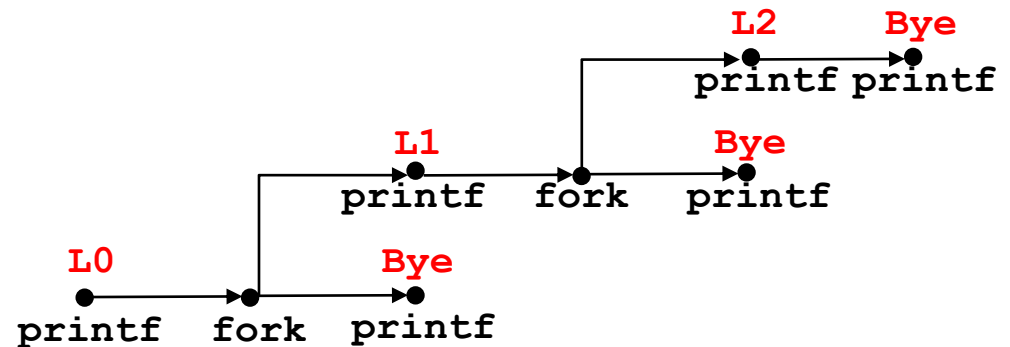
Infeasible output:

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

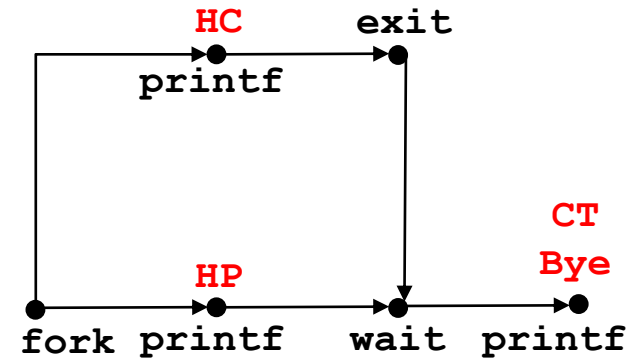
`wait`: Synchronizing with Children

- 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;

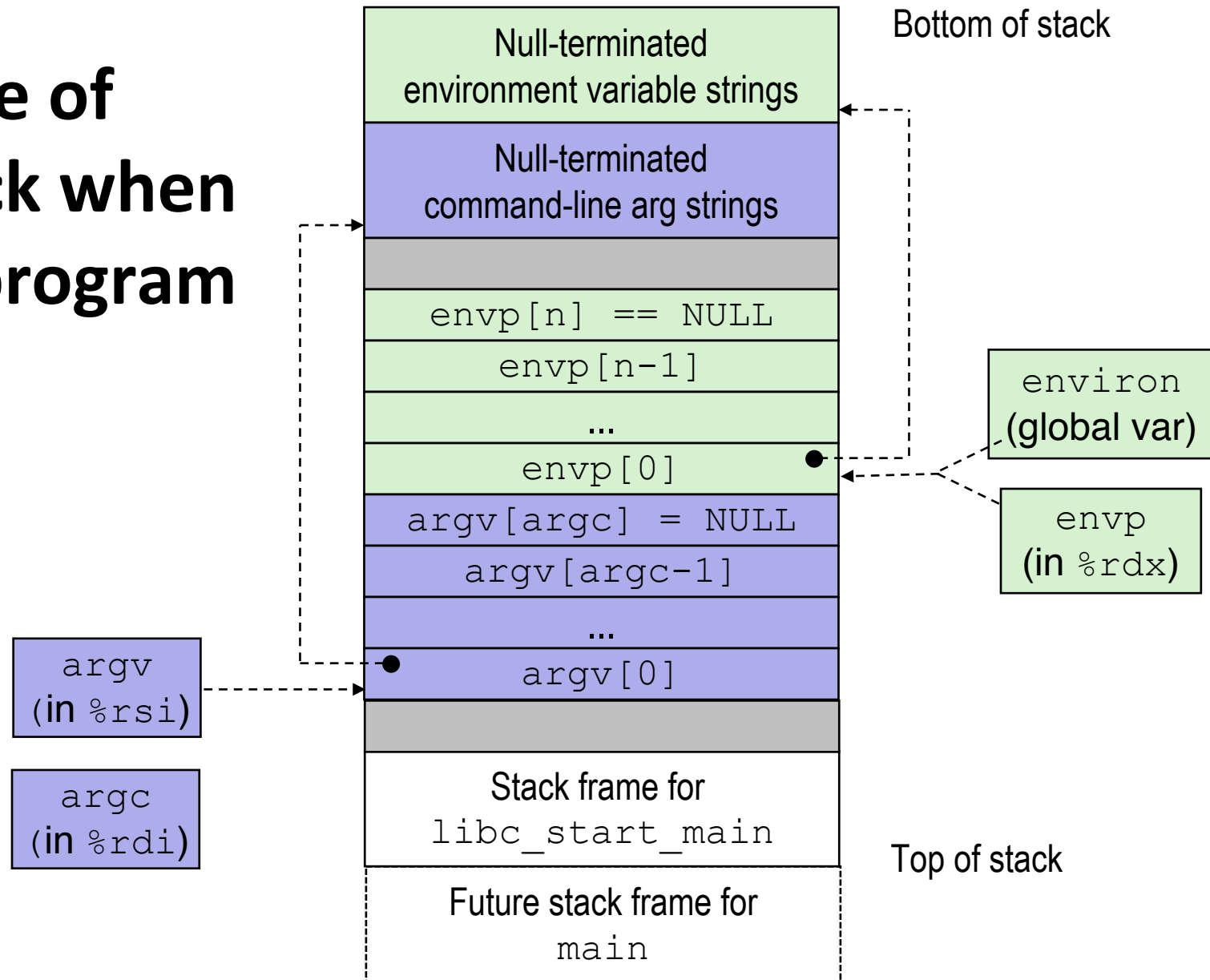
    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0)
            exit(100+i); /* Child */
    for (i = N-1; i >= 0; i--) {
        pid_t wpid = waitpid(pid[i], &child_status, 0);
        if (WIFEXITED(child_status))
            printf("Child %d terminated with exit status %d\n",
             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

forks.c

execve: Loading and Running Programs

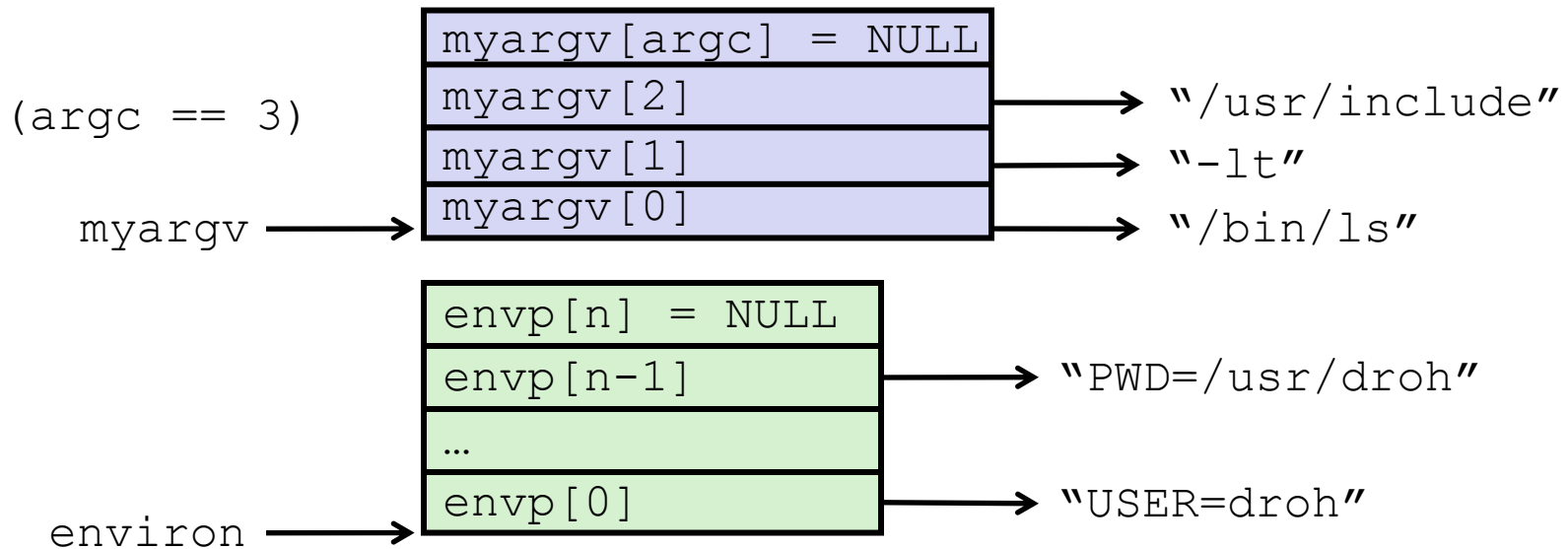
- `int execve(char *filename, char *argv[], char *envp[])`
- **Loads and runs in the current process:**
 - Executable file **filename**
 - Can be object file or script file beginning with `#!interpreter` (e.g., `#!/bin/bash`)
 - ...with argument list **argv**
 - By convention `argv[0]==filename`
 - ...and environment variable list **envp**
 - “name=value” strings (e.g., `USER=droh`)
 - `getenv`, `putenv`, `printenv`
- **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