Process Control

HPPS

Troels Henriksen

Based on slides by:

Randal E. Bryant and David R. O'Hallaron

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(1);
}
```

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();
```

- Provided in `csapp.h/csapp.c` library provided by book authors (and included in today's lab directory).

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
- **Terminated**
  - Process is stopped permanently

Terminating Processes

- **Process becomes terminated for one of three reasons:**
  - Receiving a signal whose default action is to terminate
  - 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 */
        x = x + 1;
        printf("child : x=%d\n", x);
        exit(0);
    }

    /* Parent */
    x = x - 1;
    printf("parent: x=%d\n", x);
    exit(0);
}
```

```
$ ./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

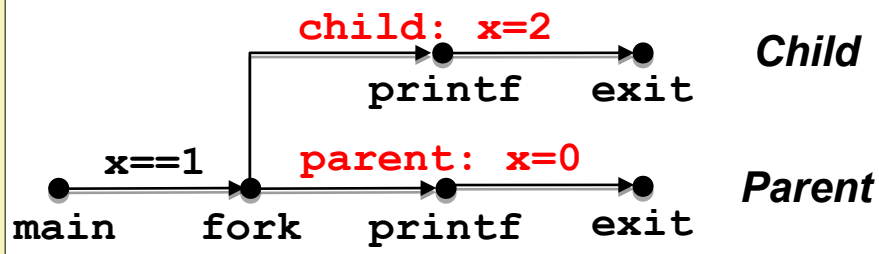
Modeling `fork` with Process Graphs

- **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 -> 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

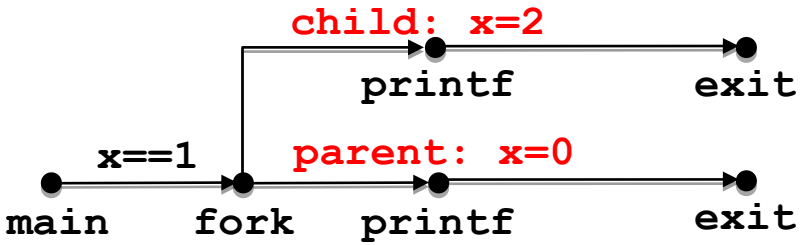
```c
int main()
{
    pid_t pid;
    int x = 1;

    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

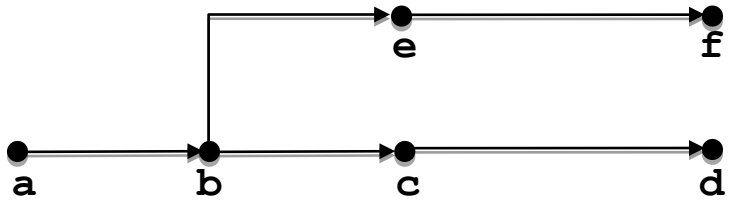


Interpreting Process Graphs

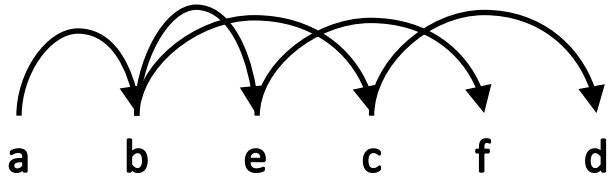
- Original graph:



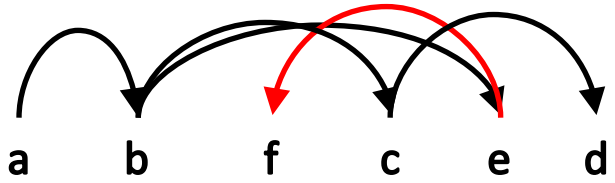
- Relabeled graph:



Feasible total ordering:

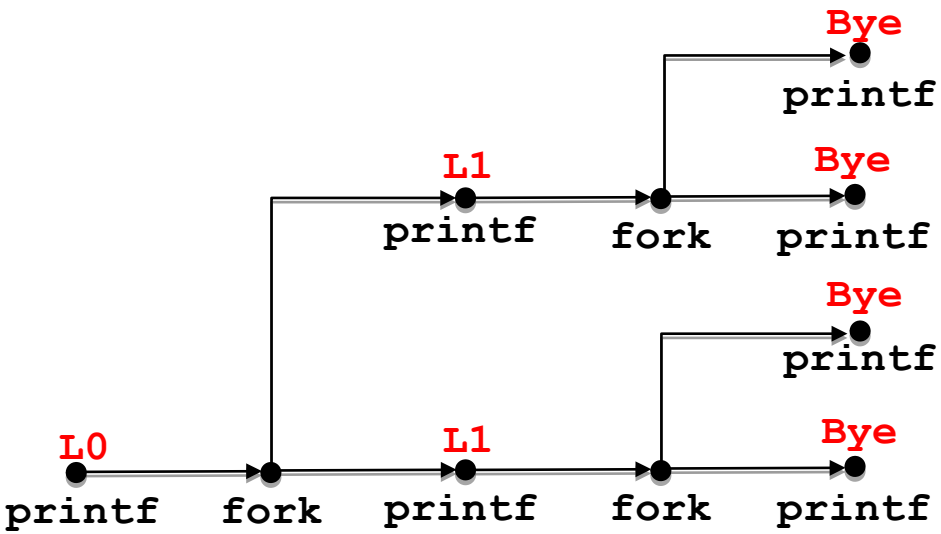


Infeasible total ordering:



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

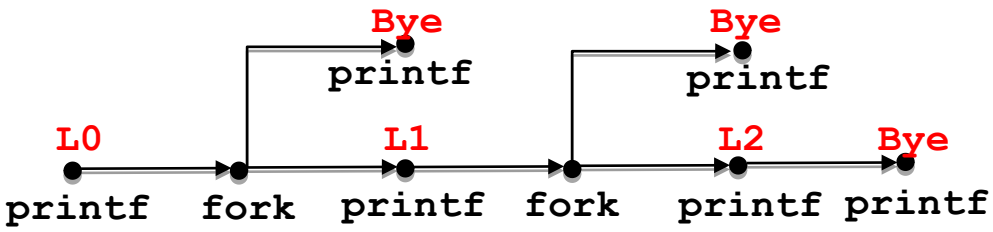
Infeasible output:

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

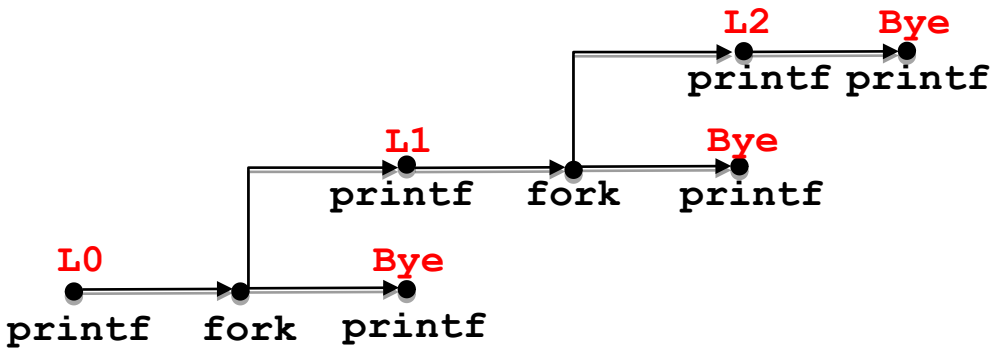
Infeasible output:

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

```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

```
$ ./forks 7 &
[1] 6639
Running Parent, PID = 6639
Terminating Child, PID = 6640
$ 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
$ kill 6639
[1]    Terminated
$ 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

```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

`wait`: Synchronizing with Children

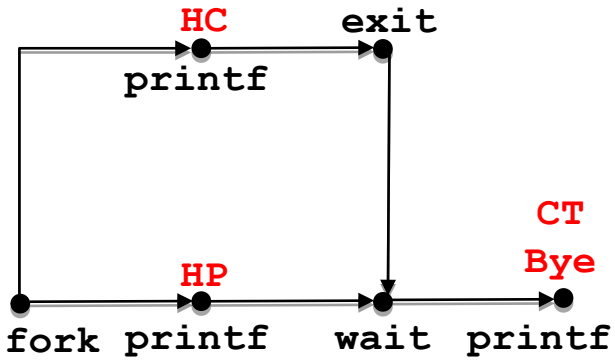
- **Parent reaps a child by calling the `wait` function**

- **`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);
    }
}
```

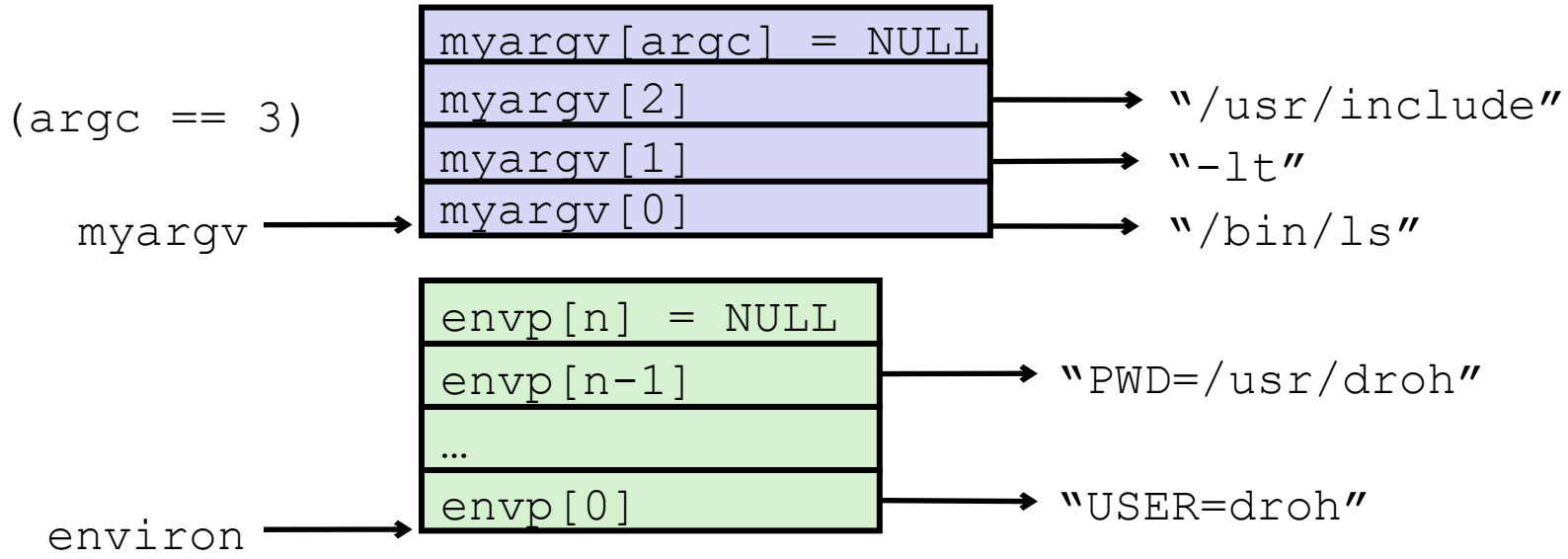
forks.c

`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

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

- **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