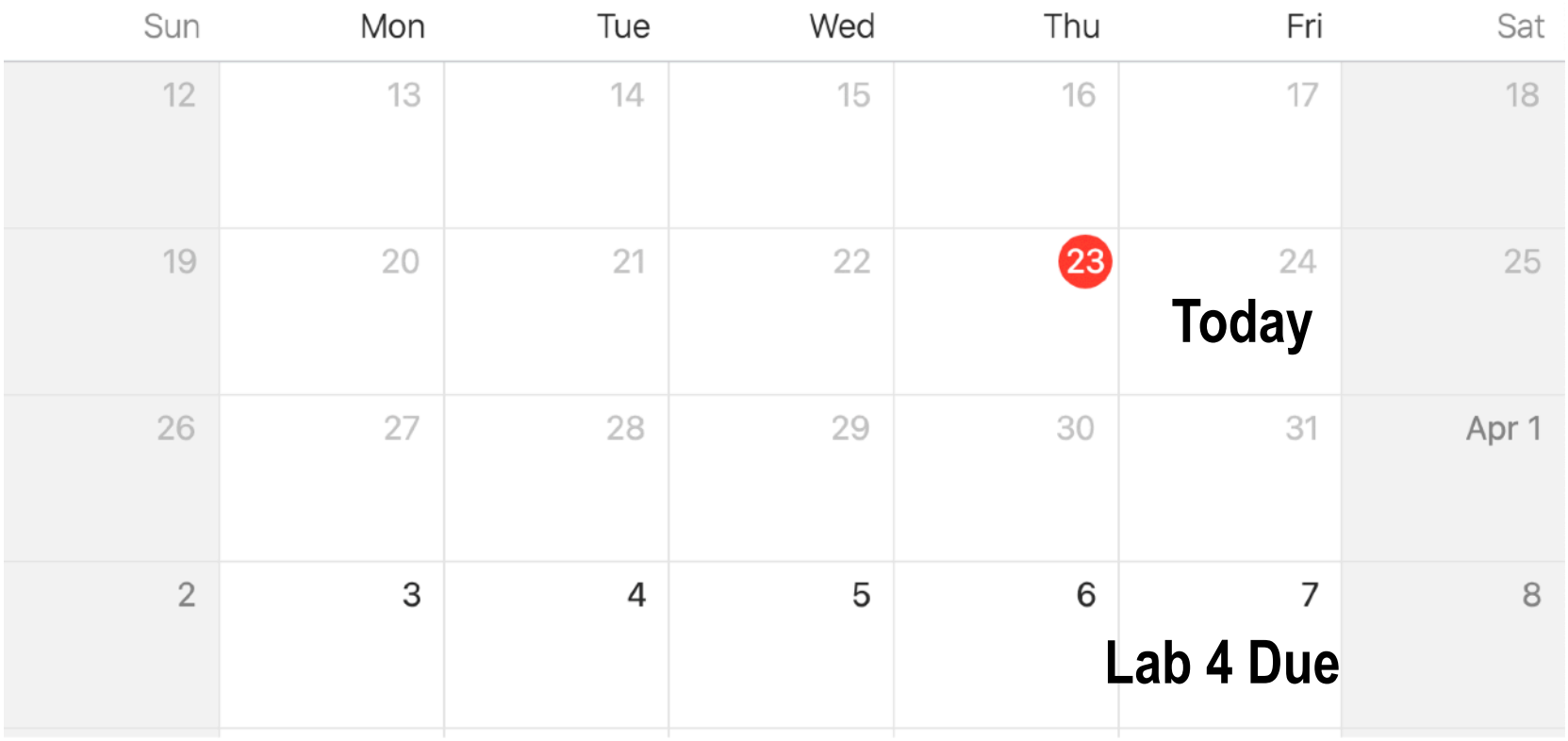
CSC 252: Computer Organization
Spring 2023: Lecture 19

Instructor: Yuhao Zhu

Department of Computer Science
University of Rochester

Announcements

- Cache problem set: https://www.cs.rochester.edu/courses/252/spring2023/handouts.html Won't be graded.
- Mid-term solution posted: https://www.cs.rochester.edu/courses/252/spring2023/handouts.html



Announcements

- Two videos from last year:
  - https://rochester.hosted.panopto.com/Panopto/Pages/Viewer.aspx?id=5cc587bf-960a-4346-8044-ae62012716a1
  - https://rochester.hosted.panopto.com/Panopto/Pages/Viewer.aspx?id=9539300d-cc1a-40a6-a772-ae6701269b76

Today

- Process Control
- Signals: The Way to Communicate with Processes

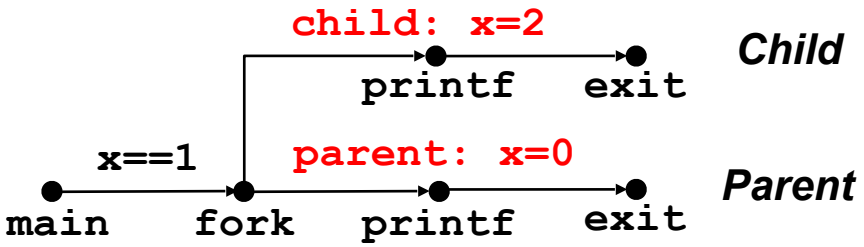
Creating Processes

- Parent process creates a new child process by calling `fork`
- Child get an identical (but separate) copy of the parent's (virtual) address space (i.e., same stack copies, code, etc.)
- `int fork(void)`
  - Returns **0** to the child process
  - Returns **child's PID** to the parent process

Process Graph Example

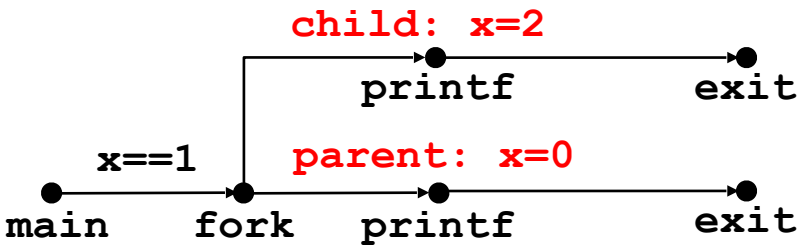
```c
int main()
{
    pid_t pid;
    int x = 1;

    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

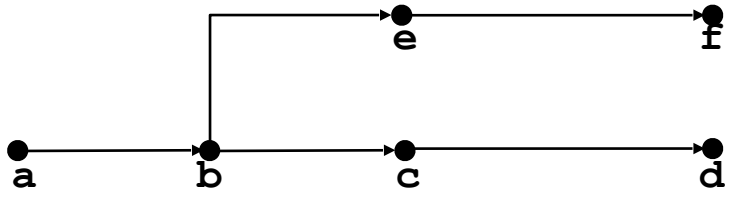


Interpreting Process Graphs

- Original graph:



- Abstracted graph:



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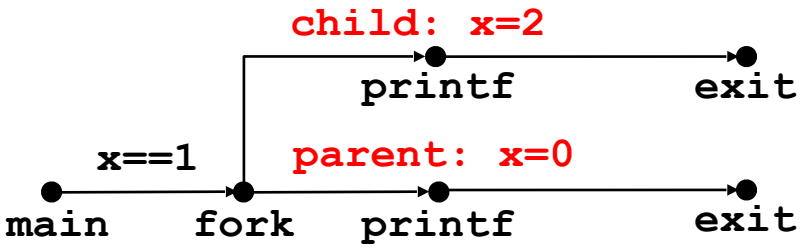

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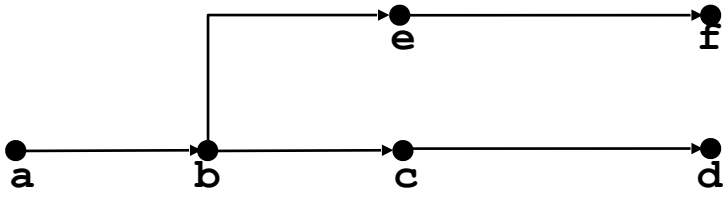

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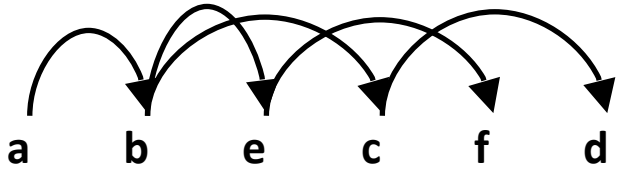

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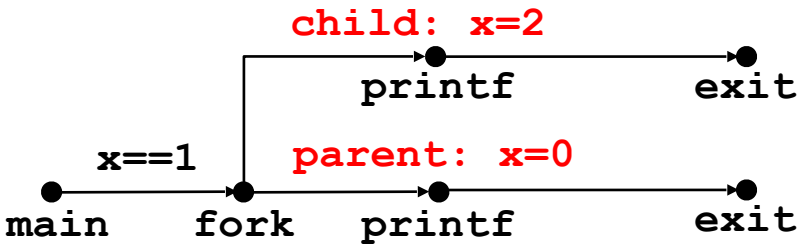

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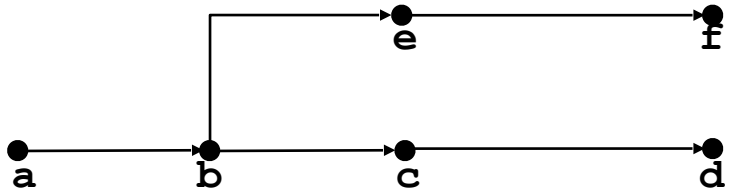

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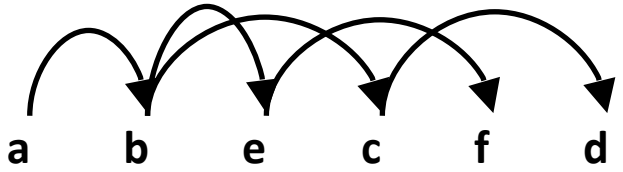

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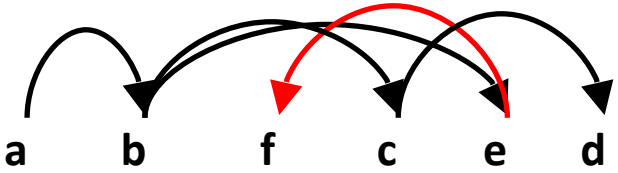

`fork` Example: Two consecutive `fork`s

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

forks.c

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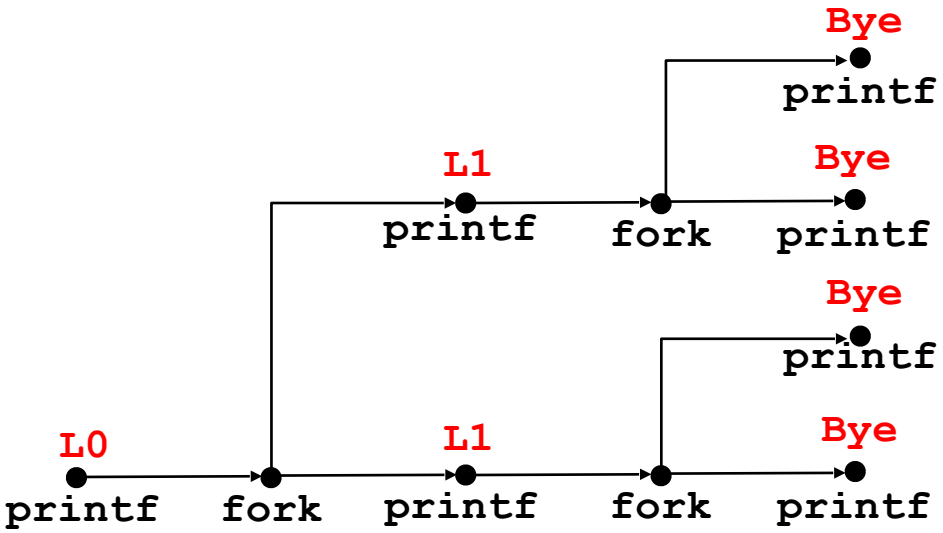

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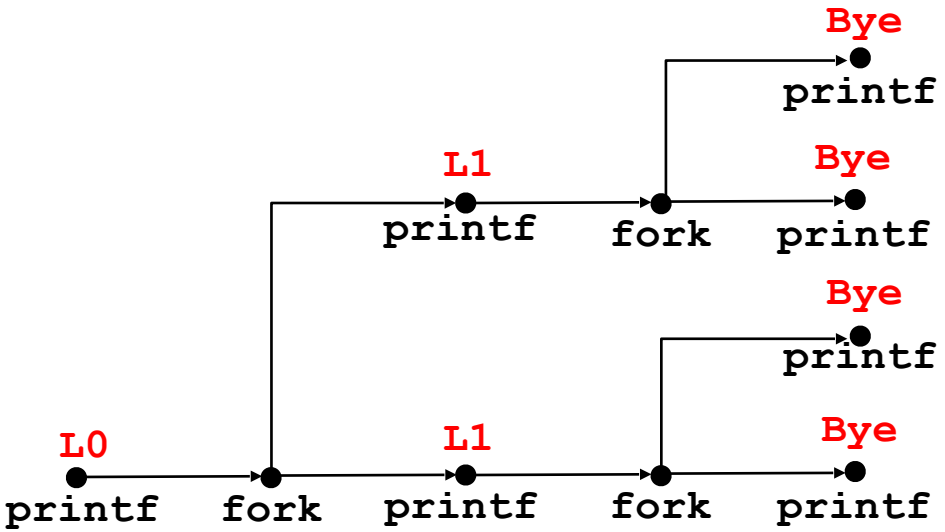

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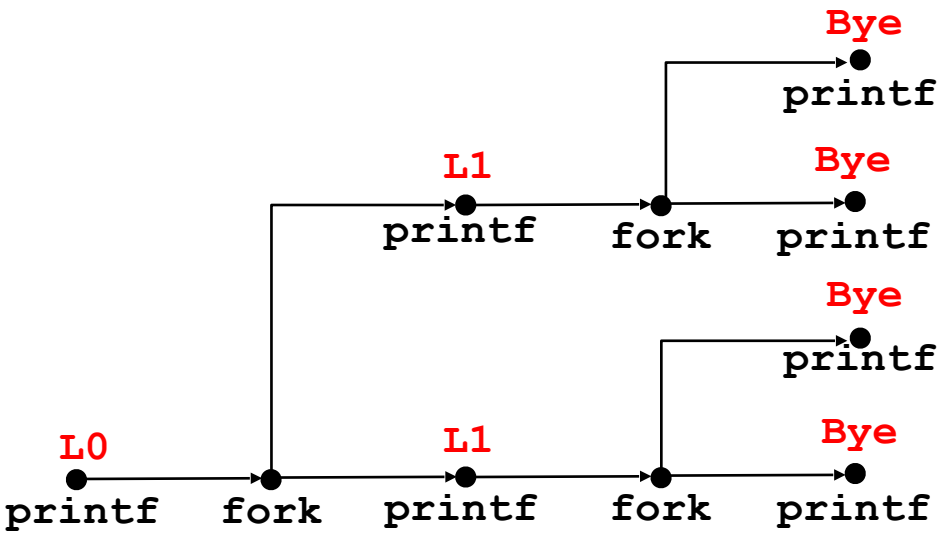

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Infeasible output:

L0
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L1
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`fork` Example: Nested `fork`s in parent

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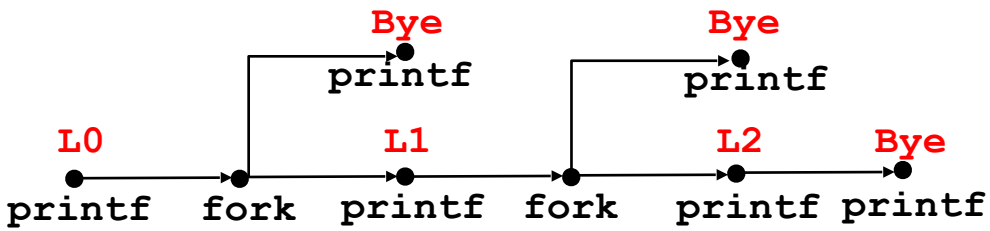

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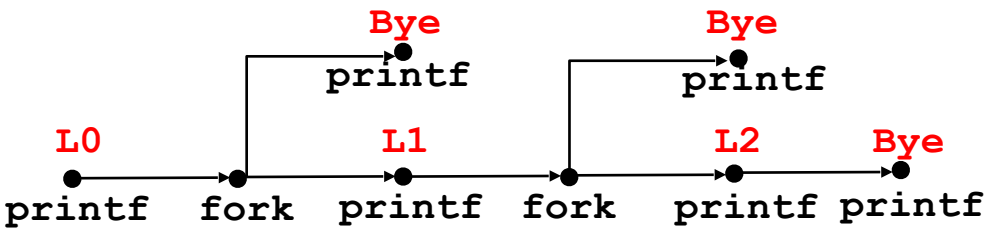

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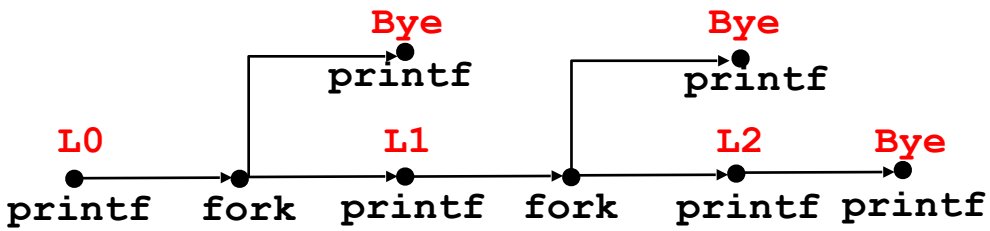

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Infeasible output:

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`fork` Example: Nested `fork`s in children

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

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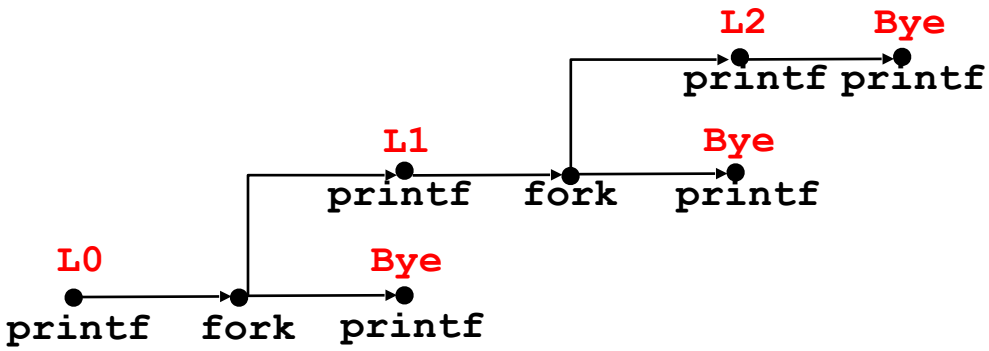

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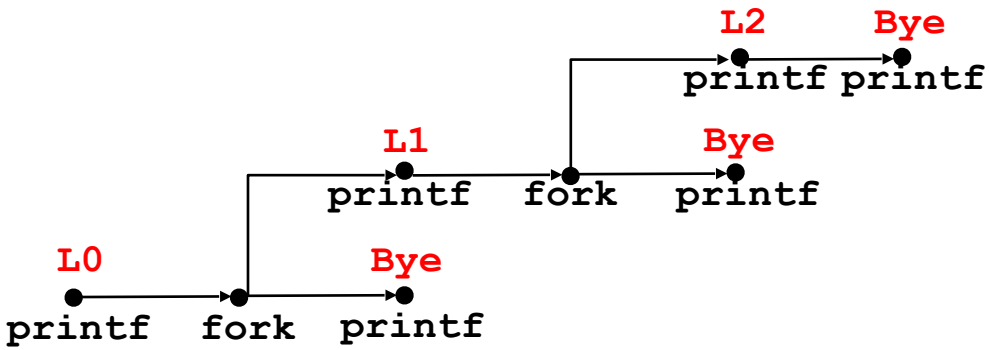

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L0
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L2
Bye
Bye

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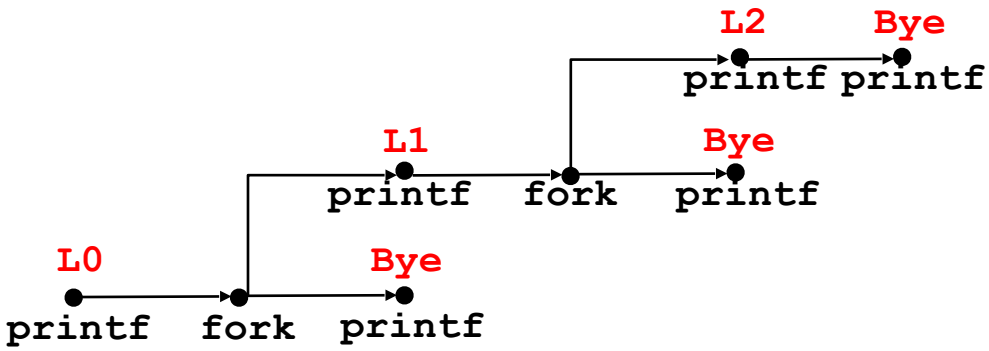

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L0
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L1
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Infeasible output:

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Reaping Child Processes

- 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
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  - Parent is given exit status information
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  - 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

`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

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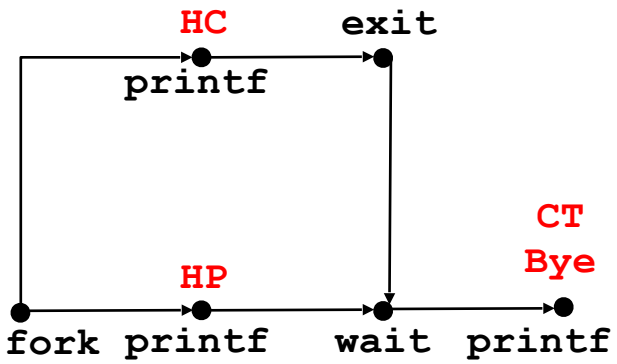

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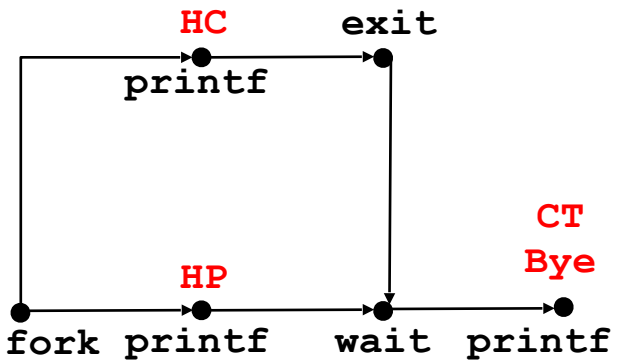

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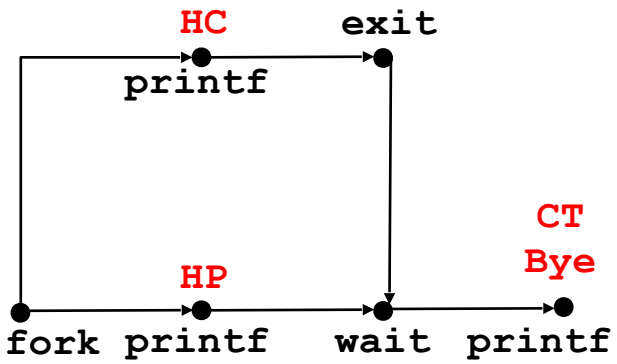

Feasible output:

HC
HP
CT
Bye

Infeasible output:

HP
CT
Bye
HC

`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

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() {
   int i, child_status;

    for (i = 0; i < N; i++)
        if (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)

```c
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);
    }
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```

forks.c

`execve`: Loading and Running Programs

Executes "`/bin/ls -lt /usr/include`" in child process using current environment:

```
char *myargv[] = {"/bin/ls", "-lt", "/usr/include"};
char *environ[] = {"USER=droh", "PWD="/usr/droh"};

if ((pid = Fork()) == 0) {   /* Child runs program */
    if (execve(myargv[0], myargv, environ) < 0) {
        printf("%s: Command not found.\n", myargv[0]);
        exit(1);
    }
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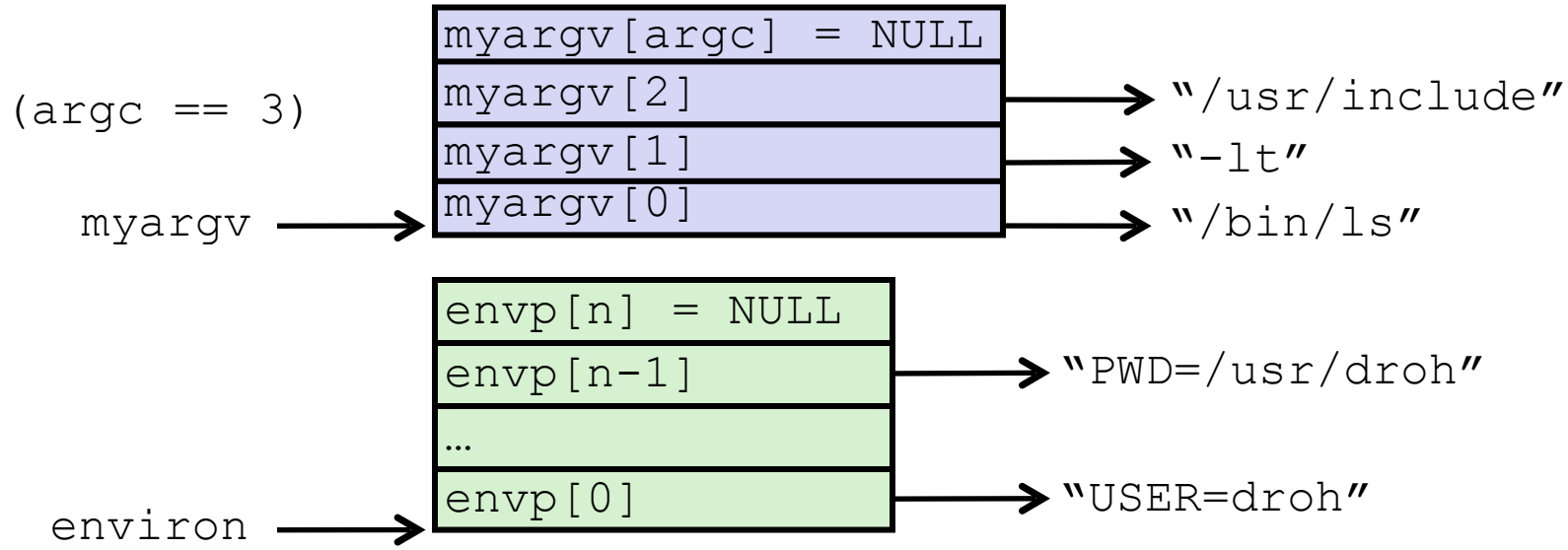
    - "name=value" strings (e.g., `USER=droh`)
- Overwrites code, data, and stack
  - Retains PID, open files and signal context
- Called once and never returns
  - …except if there is an error

`execve` Example

Executes "`/bin/ls -lt /usr/include`" in child process using current environment:

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        exit(1);
    }
}
```

Summary

- 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
- 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

Today

- Process Control
- Signals: The Way to Communicate with Processes

Signals

- A signal is a small message that notifies a process that an event of some type has occurred in the system
  - Sent from the **OS kernel**
  - Could be requested by another process, by user, or automatically by the kernel
  - Signal type is identified by small integer ID's (1-30)

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  - Signal type is identified by small integer ID's (1-30)

ID	Name	Default Action	Corresponding Event
2	SIGINT	Terminate	User typed ctrl-c
9	SIGKILL	Terminate	Kill program (cannot override or ignore)
11	SIGSEGV	Terminate	Segmentation violation
14	SIGALRM	Terminate	Timer signal
17	SIGCHLD	Ignore	Child stopped or terminated

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  - Another process has invoked the `kill` system call to explicitly request the kernel to send a signal to the destination process.
    - Note: `kill` doesn't mean you are going to kill the target process. It is just a system call that allows you to send signals. Of course the signal you send could be SIGKILL.

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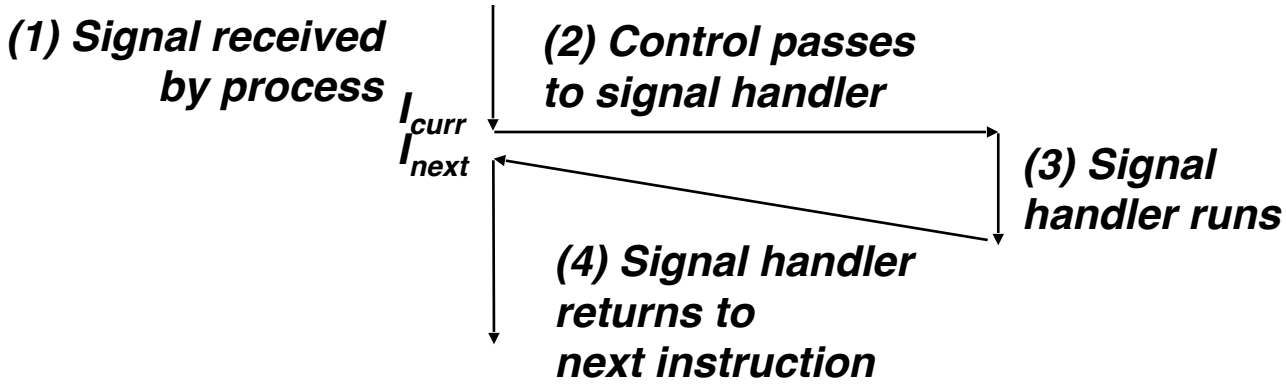

Sending Signals with `/bin/kill` Program

- `/bin/kill` program sends arbitrary signal to a process
- Examples
  - **`/bin/kill -9 24818`**
    Send SIGKILL to process 24818
  - `/bin/kill` itself doesn't kill the process. 9 is the ID for the SIGKILL signal, which terminates the process

```
linux> ./forks 16
Child1: pid=24818 pgrp=24817
Child2: pid=24819 pgrp=24817

linux> ps
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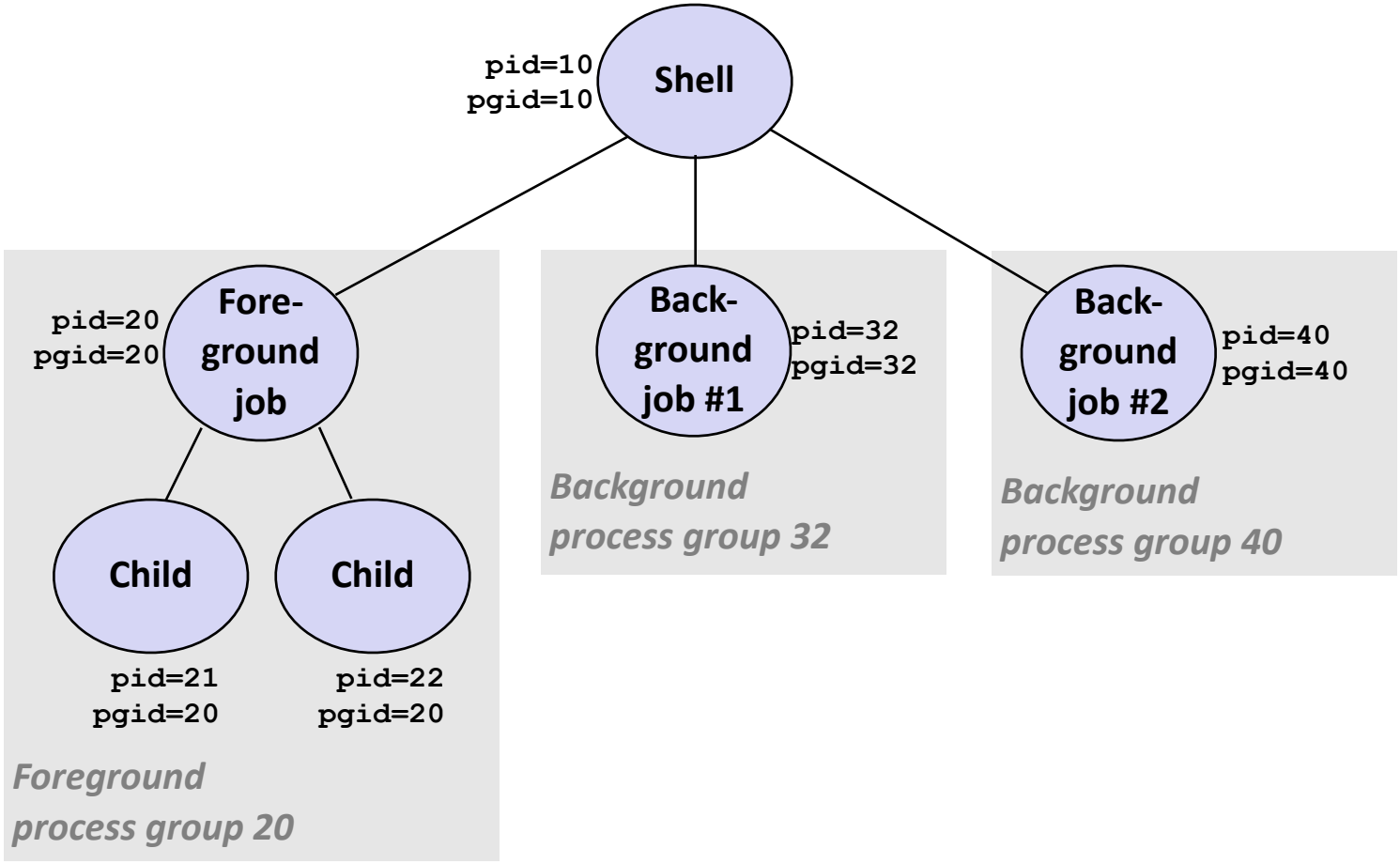
Process Groups

- Every process belongs to exactly one process group



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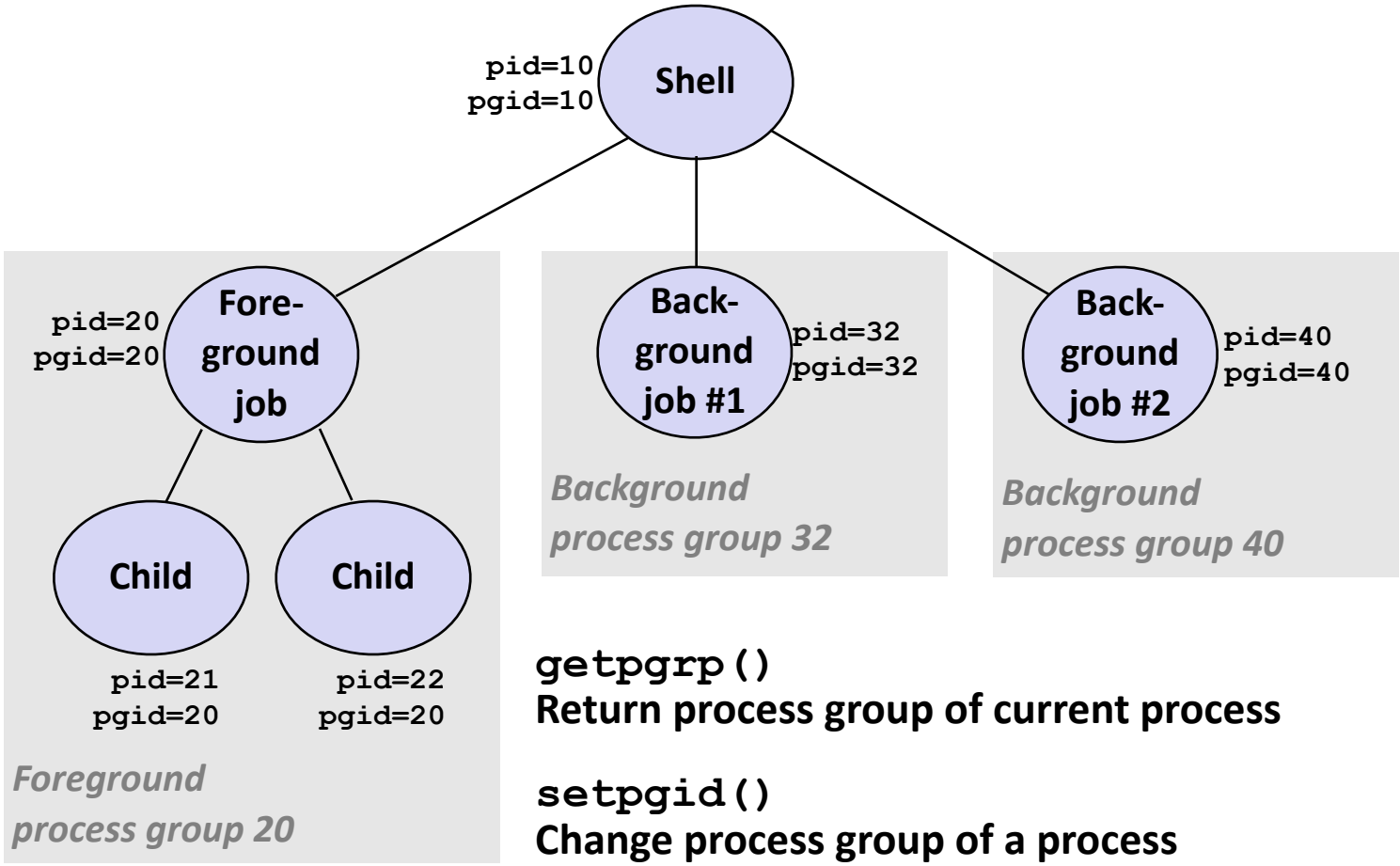

`getpgrp()`
Return process group of current process

`setpgid()`
Change process group of a process

Sending Signals with `/bin/kill` Program

- `/bin/kill` program sends arbitrary signal to a process or process group

- Examples
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Sending Signals from the Keyboard

- Typing ctrl-c causes the kernel to send a SIGINT to every process in the foreground process group.
  - SIGINT – default action is to terminate each process
- Typing ctrl-z causes the kernel to send a SIGTSTP to every job in the foreground process group.
  - SIGTSTP – default action is to stop (suspend) each process

Example of `ctrl-c` and `ctrl-z`

```
bluefish> ./forks 17
Child: pid=28108 pgrp=28107
Parent: pid=28107 pgrp=28107

<types ctrl-z>
Suspended
bluefish> ps w
  PID TTY      STAT   TIME COMMAND
27699 pts/8    Ss     0:00 -tcsh
28107 pts/8    T      0:01 ./forks 17
28108 pts/8    T      0:01 ./forks 17
28109 pts/8    R+     0:00 ps w

bluefish> fg
./forks 17
<types ctrl-c>
bluefish> ps w
  PID TTY      STAT   TIME COMMAND
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```

STAT (process state) Legend:

First letter:

S: sleeping

T: stopped

R: running

Second letter:

s: session leader

+: foreground proc group

See “man ps” for more details

Sending Signals with `kill` Function

```c
void fork12()
{
    pid_t pid[N];
    int i;
    int child_status;

    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0) {
            /* Child: Infinite Loop */
            while(1)
                ;
        }

    for (i = 0; i < N; i++) {
        printf("Killing process %d\n", pid[i]);
        kill(pid[i], SIGINT);
    }

    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);
    }
}
```

forks.c

Default Actions to Signals

- Each signal type has a predefined default action, which is one of:
  - The process terminates
  - The process stops until restarted by a SIGCONT signal
  - The process ignores the signal

Installing Signal Handlers

- The signal function modifies the default action associated with the receipt of signal signum:
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    - When the handler executes its return statement, control passes back to instruction in the control flow of the process that was interrupted by receipt of the signal

Signal Handling Example

```c
void sigint_handler(int sig) /* SIGINT handler */
{
    printf("So you think you can stop the bomb with ctrl-c, do you?\n");
    sleep(2);
    printf("Well...");
    fflush(stdout);
    sleep(1);
    printf("OK. :-)\n");
    exit(0);
}

int main()
{
    /* Install the SIGINT handler */
    if (signal(SIGINT, sigint_handler) == SIG_ERR)
        unix_error("signal error");

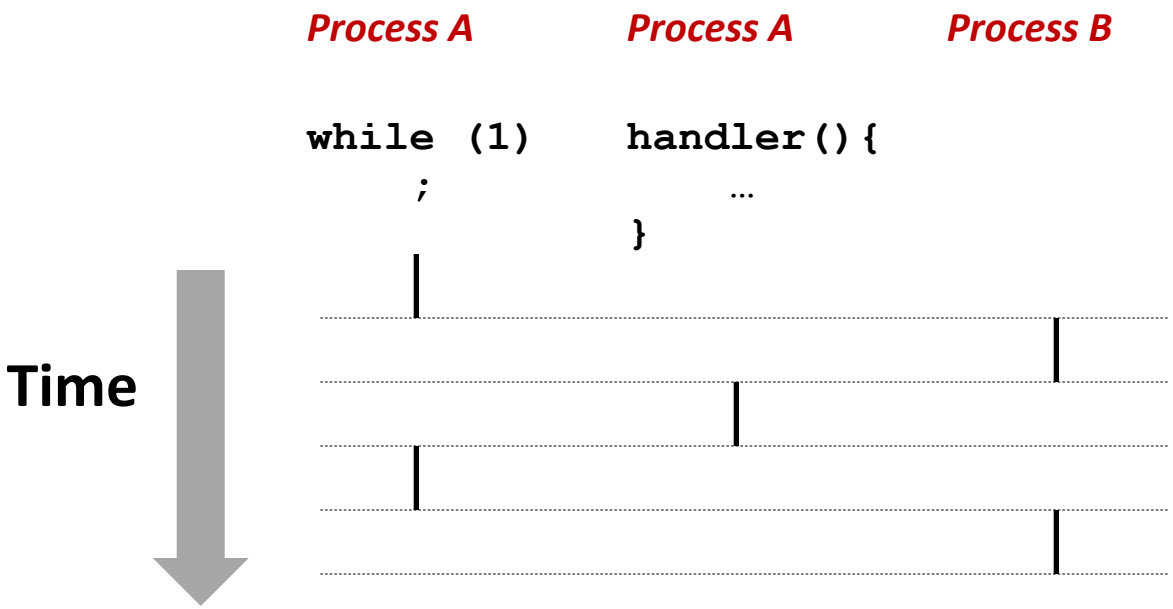
    /* Wait for the receipt of a signal */
    pause();

    return 0;
}
```

sigint.c

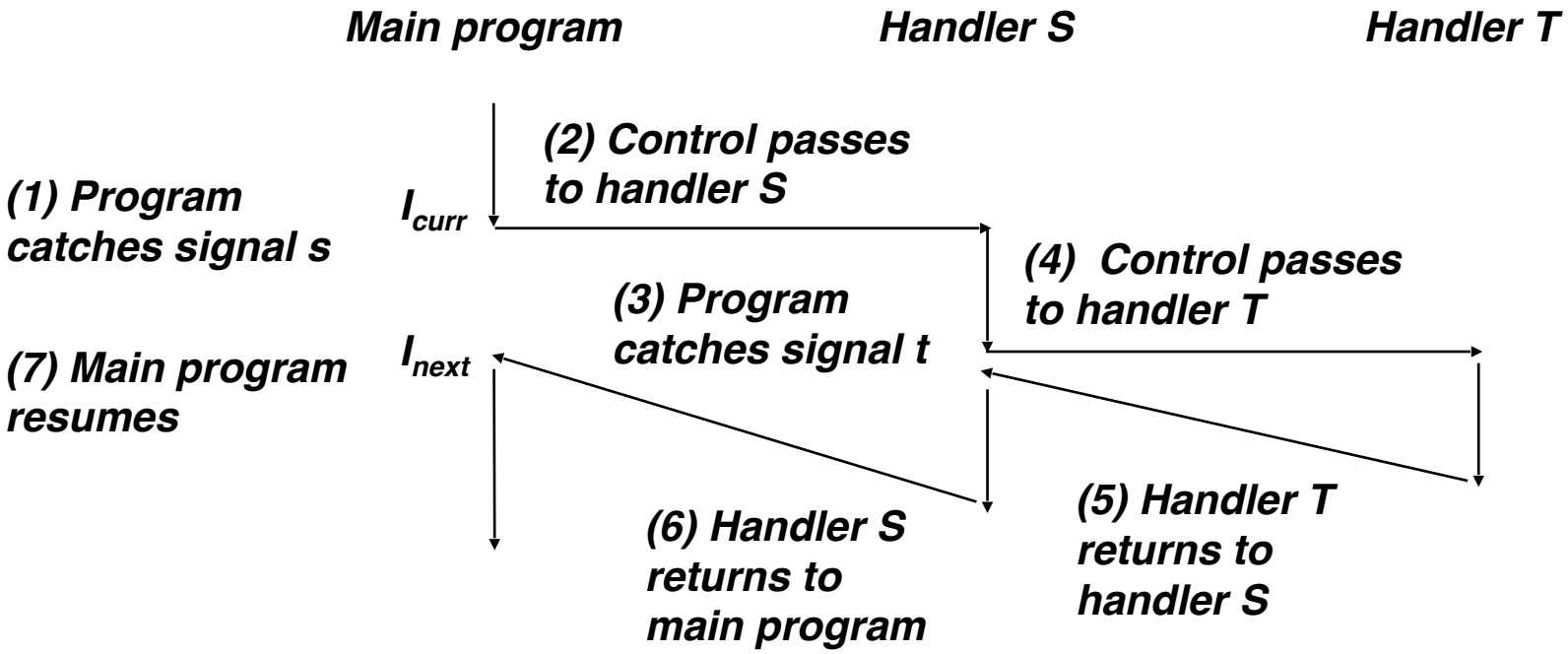
Signals Handlers as Concurrent Flows

- A signal handler is a separate logical flow (not process) that runs concurrently with the main program



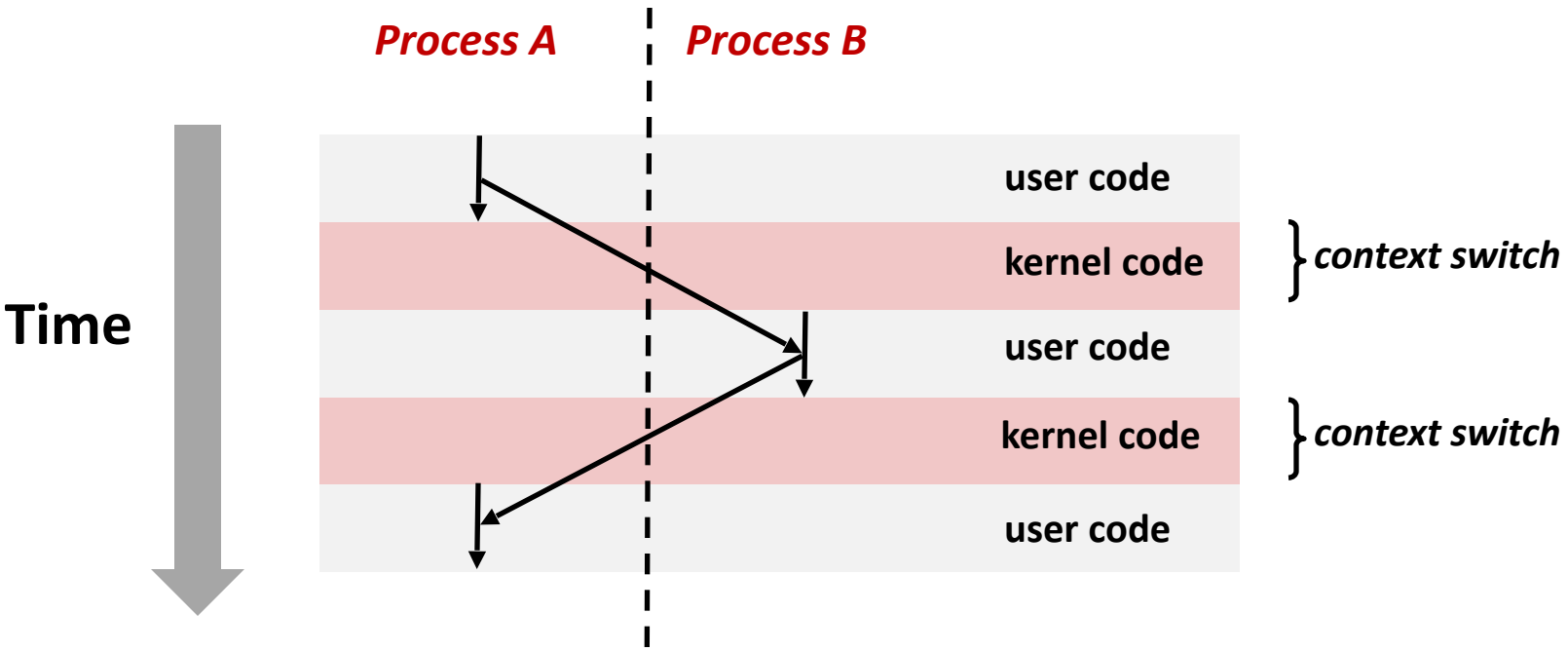
Nested Signal Handlers

- Handlers can be interrupted by other handlers



Receiving/Responding to Signals

- Kernel handles signals delivered to a process *p* **when it switches to *p* from kernel mode to user mode** (e.g., after a context switch)



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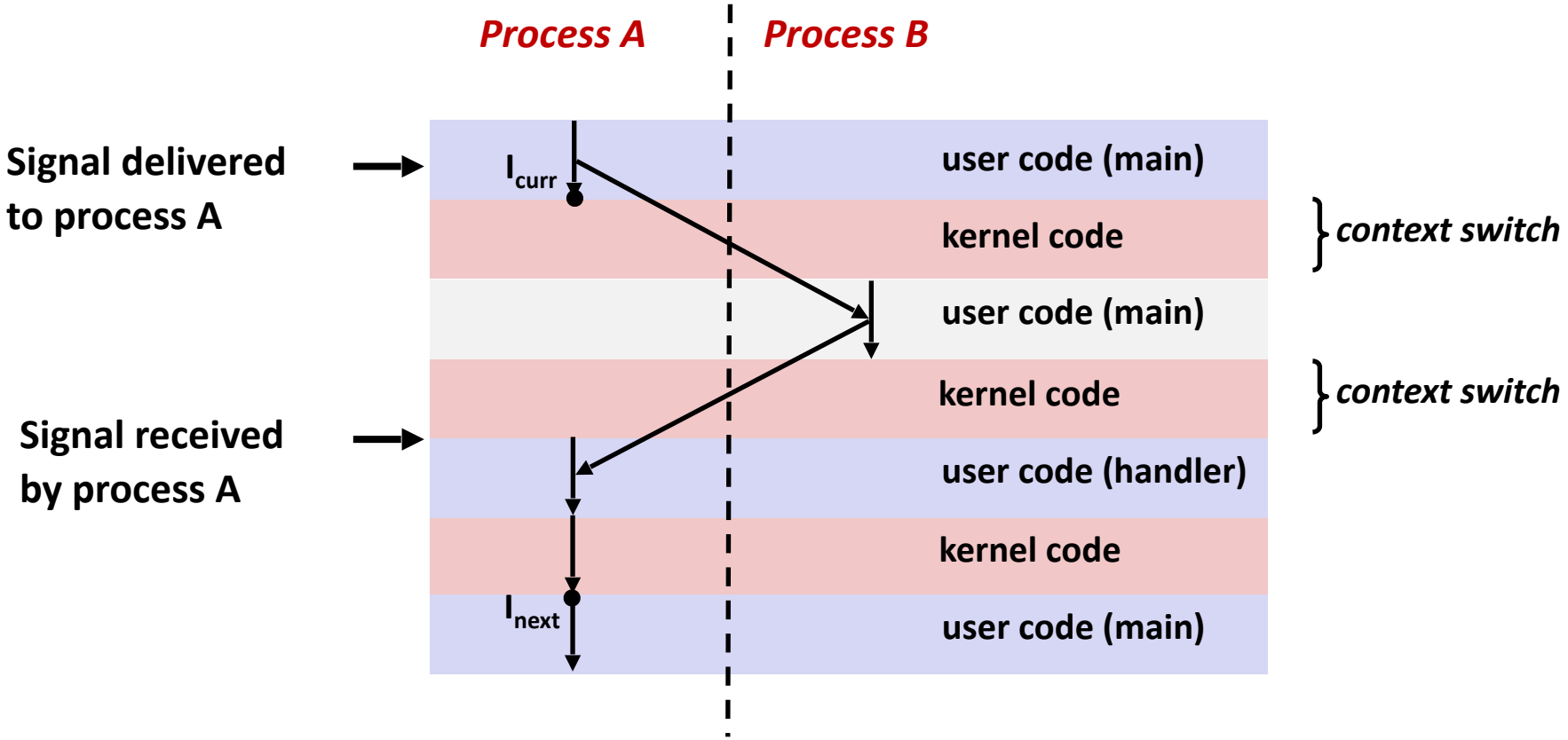

Pending and Blocked Signals

- A signal is pending if sent but not yet received
  - There can be at most one pending signal of any particular type for a process
  - That is: *Signals are not queued*
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- A process can block/mask the receipt of certain signals
  - Blocked signals can be delivered, i.e., in the pending state, but will not be received/responded to *until the signal is unblocked*

Pending/Blocked Bits

- Kernel maintains pending and masked bit vectors in the context of each process
  - pending: represents the set of pending signals
    - Kernel sets bit k in pending when a signal of type k is delivered
    - Kernel clears bit k in pending when a signal of type k is received
  - masked: represents the set of blocked signals
    - Can be set and cleared by using the `sigprocmask` function
    - Also referred to as the signal mask.

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Blocking Signals

```
sigset_t mask, prev_mask;

sigemptyset(&mask);
sigaddset(&mask, SIGINT);

/* Block SIGINT and save previous blocked set */
sigprocmask(SIG_BLOCK, &mask, &prev_mask);

/* Code region that will not be interrupted by SIGINT */

/* Restore previous blocked set, unblocking SIGINT */
sigprocmask(SIG_SETMASK, &prev_mask, NULL);
```

- Explicit blocking and unblocking signal
  - `sigprocmask` function
  - `sigemptyset` – Create empty set
  - `sigfillset` – Add every signal number to set
  - `sigaddset` – Add signal number to set
  - `sigdelset` – Delete signal number from set

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static int x = 5;
void handler(int sig)
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{
    int pid, y = 0;
    Signal(SIGCHLD, handler);

    if ((pid = Fork()) == 0) { /* Child */
        Execve("/bin/date", argv, NULL);
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    if (x == 5)
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    exit(0);
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- When return to parent process, **y == 20**!

Safe Signal Handling

- Handlers are tricky because they are concurrent with main program and may share the same global data structures.
  - Programmers have no control over the execution ordering between the main program and the signal handler, that is:
    - when a signal happens/delivers (depends on user or other process)
    - when the signal handler will be executed (depends on kernel)
  - If not careful, shared data structures can be corrupted

Fixing the Signal Handling Bug

```
static int x = 5;
void handler(int sig)
{
    x = 10;
}

int main(int argc, char **argv)
{
    int pid;
    sigset_t mask_all, prev_all;
    sigfillset(&mask_all);
    signal(SIGCHLD, handler);

    if ((pid = Fork()) == 0) { /* Child */
        Execve("/bin/date", argv, NULL);
    }

    Sigprocmask(SIG_BLOCK, &mask_all, &prev_all);
    if (x == 5)
        y = x * 2; // You'd expect y == 10
    Sigprocmask(SIG_SETMASK, &prev_all, NULL);

    exit(0);
}
```

- Block all signals before accessing a shared, global data structure.
- Can't use a lock (later in this course)

Async-Signal-Safety

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  - Source: “man 7 signal”
  - Popular functions on the list:
    - `_exit`, `write`, `wait`, `waitpid`, `sleep`, `kill`
  - Popular functions that are not on the list:
    - `printf`, `sprintf`, `malloc`, `exit`
    - Unfortunate fact: `write` is the only async-signal-safe output function

Another Unsafe Signal Handler Example

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  - When each child process is created, add the child PID to a queue
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  - The parent creates multiple child processes
  - When each child process is created, add the child PID to a queue
  - When a child process terminates, the parent process removes the child PID from the queue
- One possible implementation:
  - An array for keeping the child PIDs
  - Use a loop to fork child, and add PID to the array after fork
  - Install a handler for SIGCHLD in parent process
  - The SIGCHLD handler removes the child PID

First Attempt

```
void handler(int sig)
{
    pid_t pid;

    while ((pid = wait(NULL)) > 0) { /* Reap child */
        /* Delete the child from the job list */
        deletejob(pid);
    }
}

int main(int argc, char **argv)
{
    int pid;

    Signal(SIGCHLD, handler);
    initjobs(); /* Initialize the job list */

    while (1) {
        if ((pid = Fork()) == 0) { /* Child */
            Execve("/bin/date", argv, NULL);
        }
        /* Add the child to the job list */
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- Context switch to parent, which executes the SIGCHLD handler before **`addjob(pid)`** is executed

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- Context switch to parent, which executes the SIGCHLD handler before **`addjob(pid)`** is executed
- The handler deletes the job, which isn't in the queue yet!

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The following can happen:

- The first child runs, and terminates
- Kernel sends SIGCHLD
- Context switch to parent, which executes the SIGCHLD handler before **`addjob(pid)`** is executed
- The handler deletes the job, which isn't in the queue yet!
- The parent process resumes and adds a terminated child to job list

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Key in this example: creating a child and adding its PID to the job list must be an *atomic unit:* either both happen or neither happen; there can't be anything else that separates the two.

Second Attempt

```
void handler(int sig)
{
    sigset_t mask_all, prev_all;
    pid_t pid;

    sigfillset(&mask_all);
    while ((pid = wait(NULL)) > 0) {
        sigprocmask(SIG_BLOCK, &mask_all, &prev_all);
        deletejob(pid);
        sigprocmask(SIG_SETMASK, &prev_all, NULL);
    }
}
int main(int argc, char **argv)
{
    int pid;
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    sigfillset(&mask_all);
    signal(SIGCHLD, handler);
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        sigprocmask(SIG_BLOCK, &mask_all, &prev_all);
        addjob(pid);
        sigprocmask(SIG_SETMASK, &prev_all, NULL);
    }
    exit(0);
}
```

Third Attempt (The Correct One)

```
int main(int argc, char **argv)
{
    int pid;
    sigset_t mask_all, mask_one, prev_one;

    Sigfillset(&mask_all);
    Sigemptyset(&mask_one);
    Sigaddset(&mask_one, SIGCHLD);
    Signal(SIGCHLD, handler);
    initjobs(); /* Initialize the job list */

    while (1) {
        Sigprocmask(SIG_BLOCK, &mask_one, &prev_one); /* Block SIGCHLD */
        if ((pid = Fork()) == 0) { /* Child process */
            Sigprocmask(SIG_SETMASK, &prev_one, NULL); /* Unblock SIGCHLD */
            Execve("/bin/date", argv, NULL);
        }
        addjob(pid);  /* Add the child to the job list */
        Sigprocmask(SIG_SETMASK, &prev_one, NULL);  /* Unblock SIGCHLD */
    }
    exit(0);
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    }
    exit(0);
}
```

Why this? →

Thinking in Parallel is Hard

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Maybe Thinking is Hard