Announcement

- **Please fill out the course evaluation.**

Exceptional Control Flow: Processes and Signals (Cont.)

B&O Readings: 8.4-8.8
CSE 361: Introduction to Systems Software

Instructor:
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`fork` Example: Nested `forks` in parent

```
void fork2()
{
    printf("L0\n");
    if (Fork() != 0) {
        printf("L1\n");
        if (Fork() != 0) {
            printf("L2\n");
        }
    }
    printf("Bye\n");
}
```

forks.c

Feasible output?

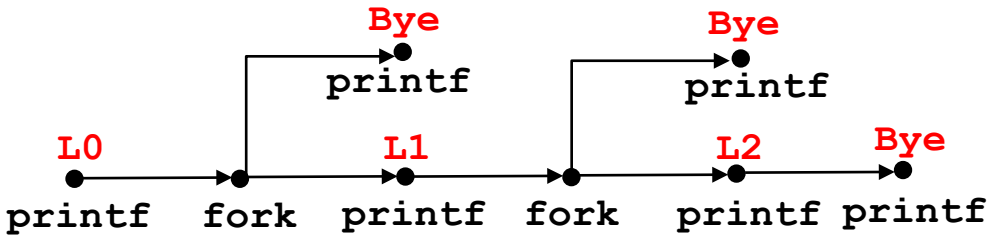
L0
L1
Bye
Bye
L2
Bye

Feasible output?

L0
Bye
L1
Bye
Bye
L2

`fork` Example: Nested `forks` in parent

```
void fork2()
{
    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

Yes

Feasible output?

L0
Bye
L1
Bye
Bye
L2

No

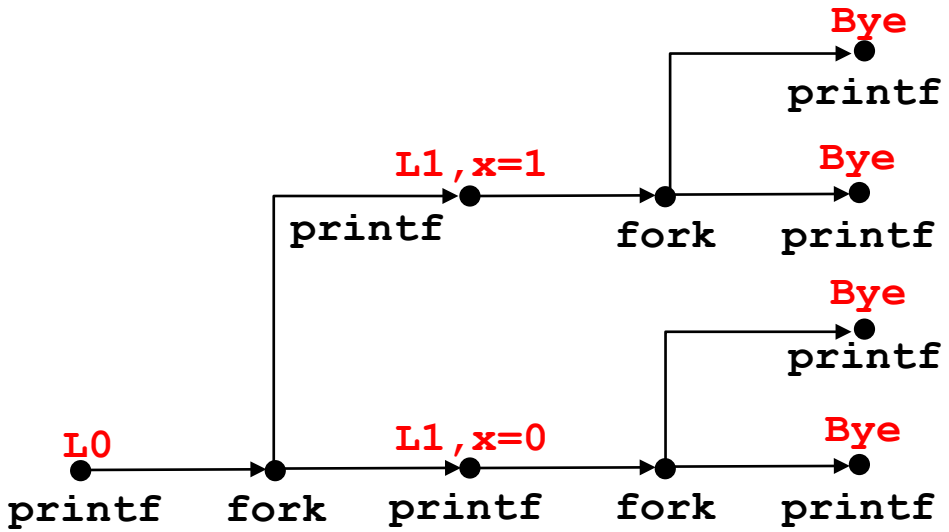
`fork` Example: Two consecutive `forks`

```
void fork4()
{
    int x = 0;
    printf("L0\n");
    if(Fork() == 0) x++;
    printf("L1,%d\n", x);
    Fork();
    printf("Bye\n");
}
```
forks.c

- What does the process graph look like?
- How many Bye does this program print?

`fork` Example: Two consecutive `forks`

```
void fork4()
{
    int x = 0;
    printf("L0\n");
    if(fork() == 0) x++;
    printf("L1,%d\n", x);
    fork();
    printf("Bye\n");
}
```
forks.c

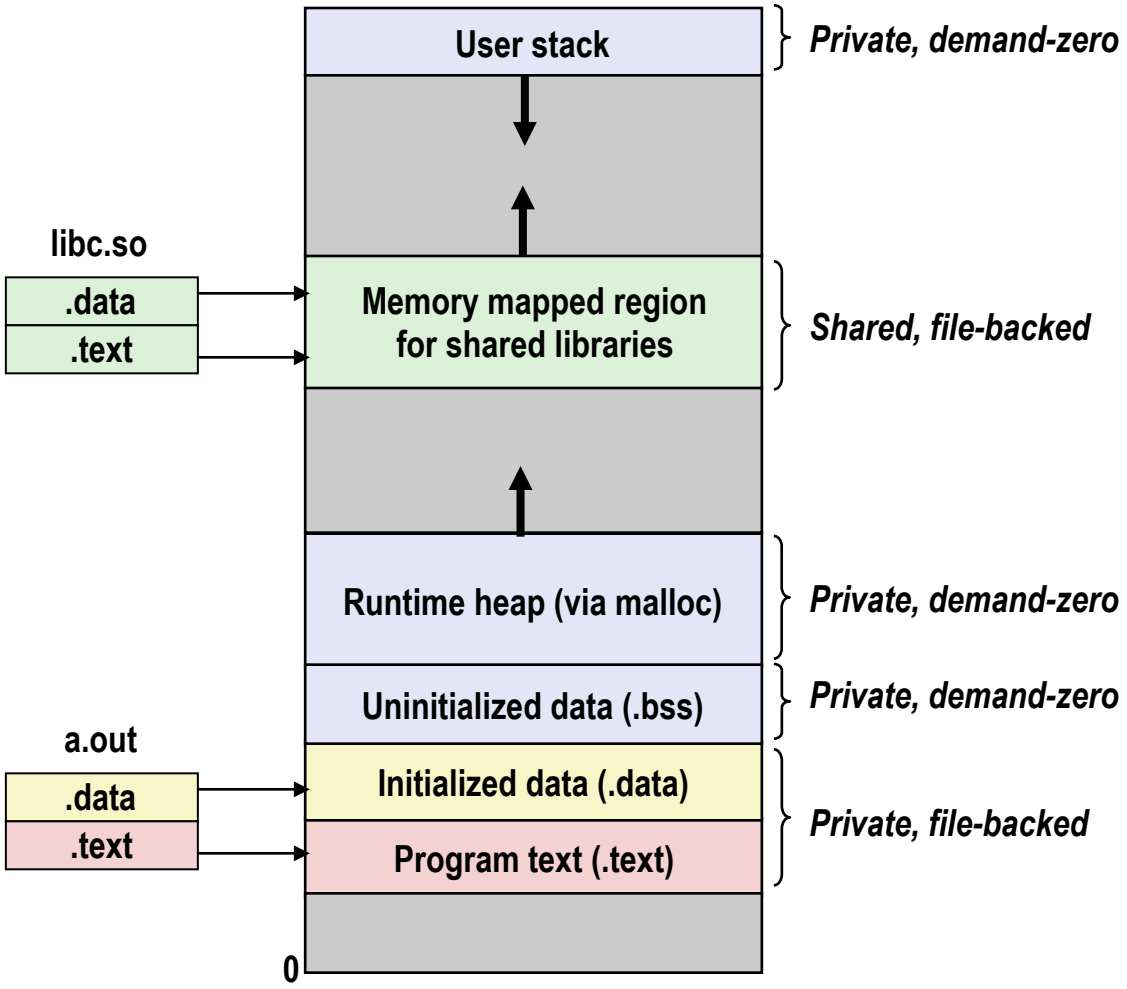


- What does the process graph look like?
- How many Bye does this program print?

`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 (e.g., `#!/bin/bash`)
  - with argument list **`argv`**
    - By convention **`argv[0]==filename`**
  - and environment variable list **`envp`**
    - "name=value" strings (e.g., **`USER=angelee`**)
    - **`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

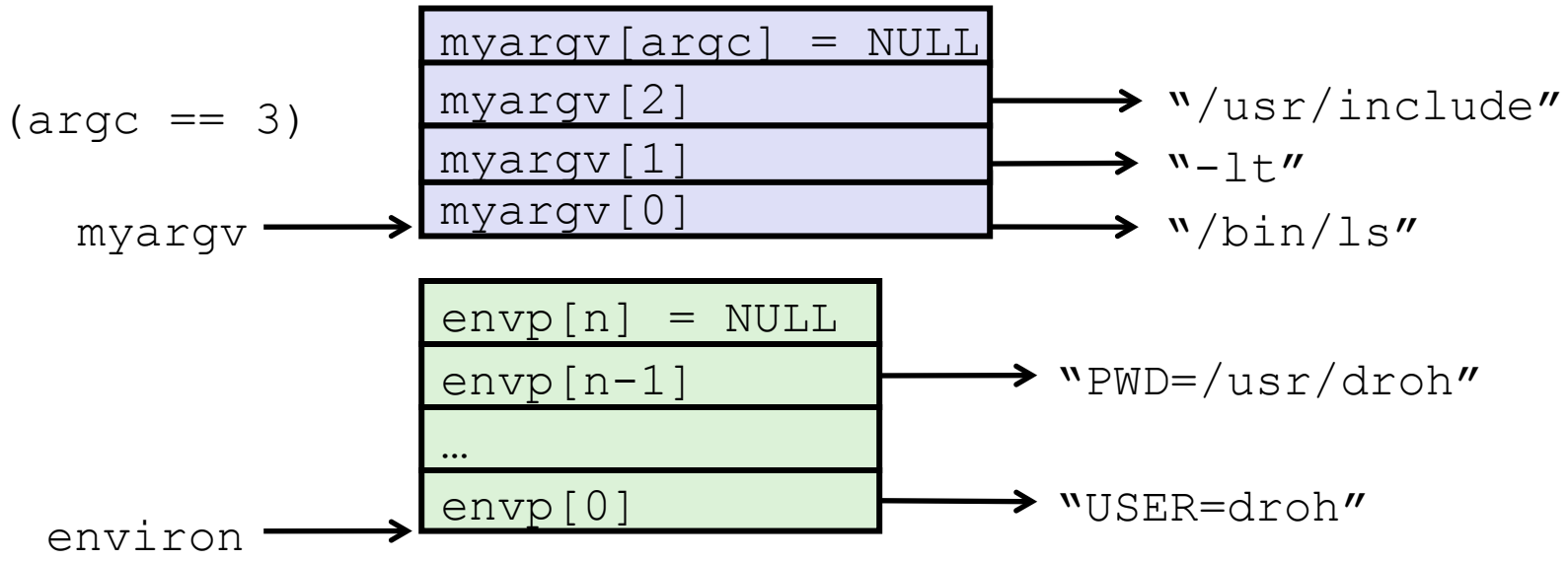
The execve Function



- **To load and run a new program `a.out` in the current process using `execve`:**
- **Free `vm_area_struct`'s and page tables for old user areas**
- **Create `vm_area_struct`'s and page tables for new areas**
  - Programs and initialized data backed by object files.
  - `.bss` and stack backed by anonymous files .
- **Set PC to entry point in `.text`**
  - Linux will fault in code and data pages as needed.

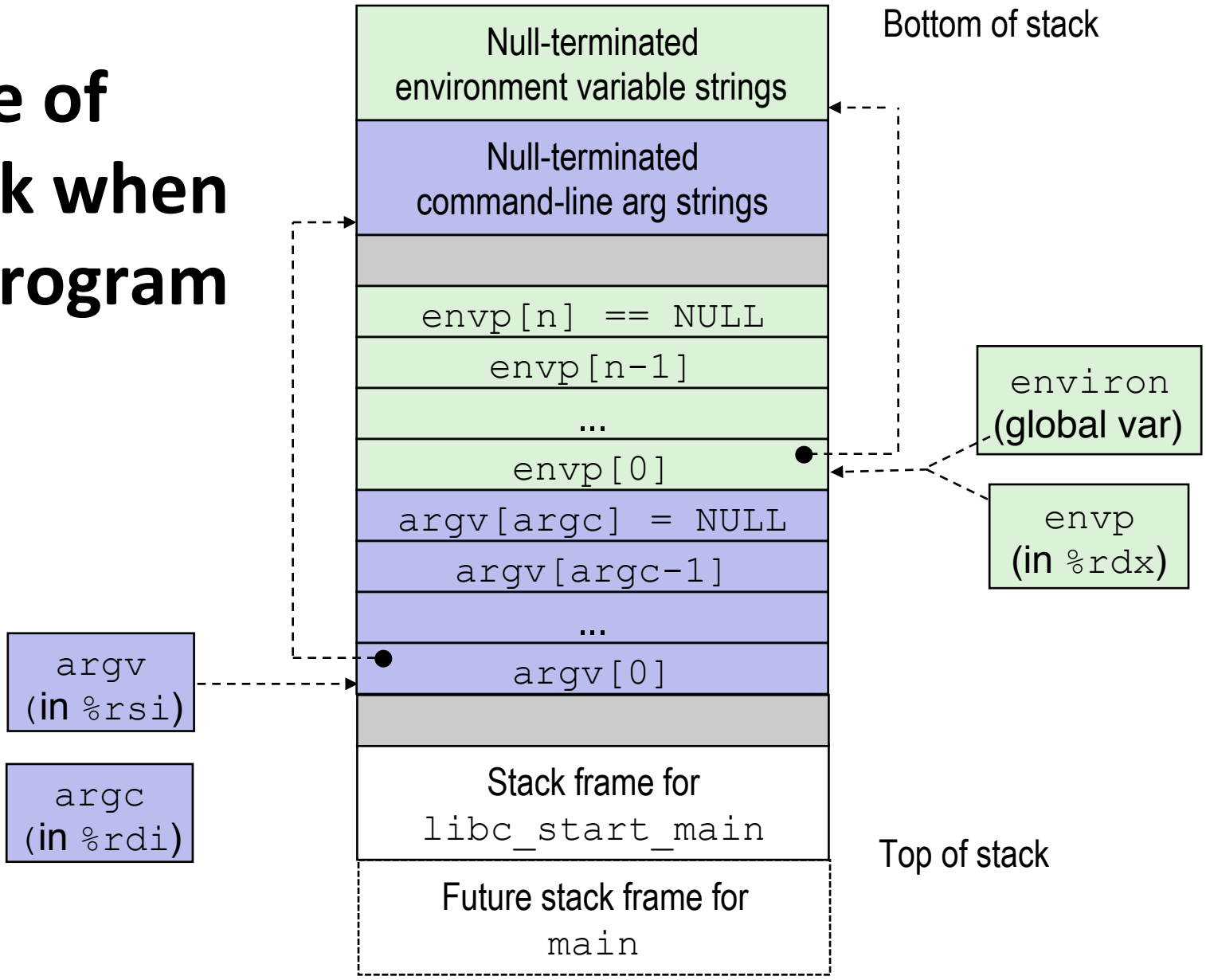
execve Example

- **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);
    }
}
```

Structure of the stack when a new program starts



Reaping Child Processes

- **Idea**
  - When process terminates, it still consumes system resources
    - Examples: Exit status, various OS data structures
  - Called a “zombie”
    - Living corpse, half alive and half dead
- **Reaping**
  - Performed by parent on terminated child to get child's exit status (using `wait` or `waitpid`)
  - 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, should reap children explicitly 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

```
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 -9 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

```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

Synchronizing with Children

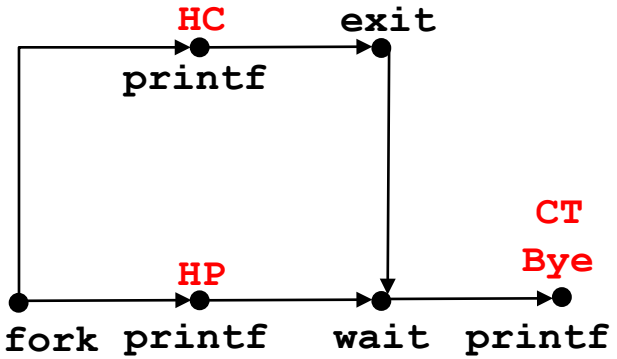
- **Parent reaps a child by calling the `wait/waitpid` function**

- **`pid_t wait(int *child_status)`**
- **`pid_t waitpid(pid_t pid, int *child_status, int option);`**
  - 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`
    - 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 or man page)

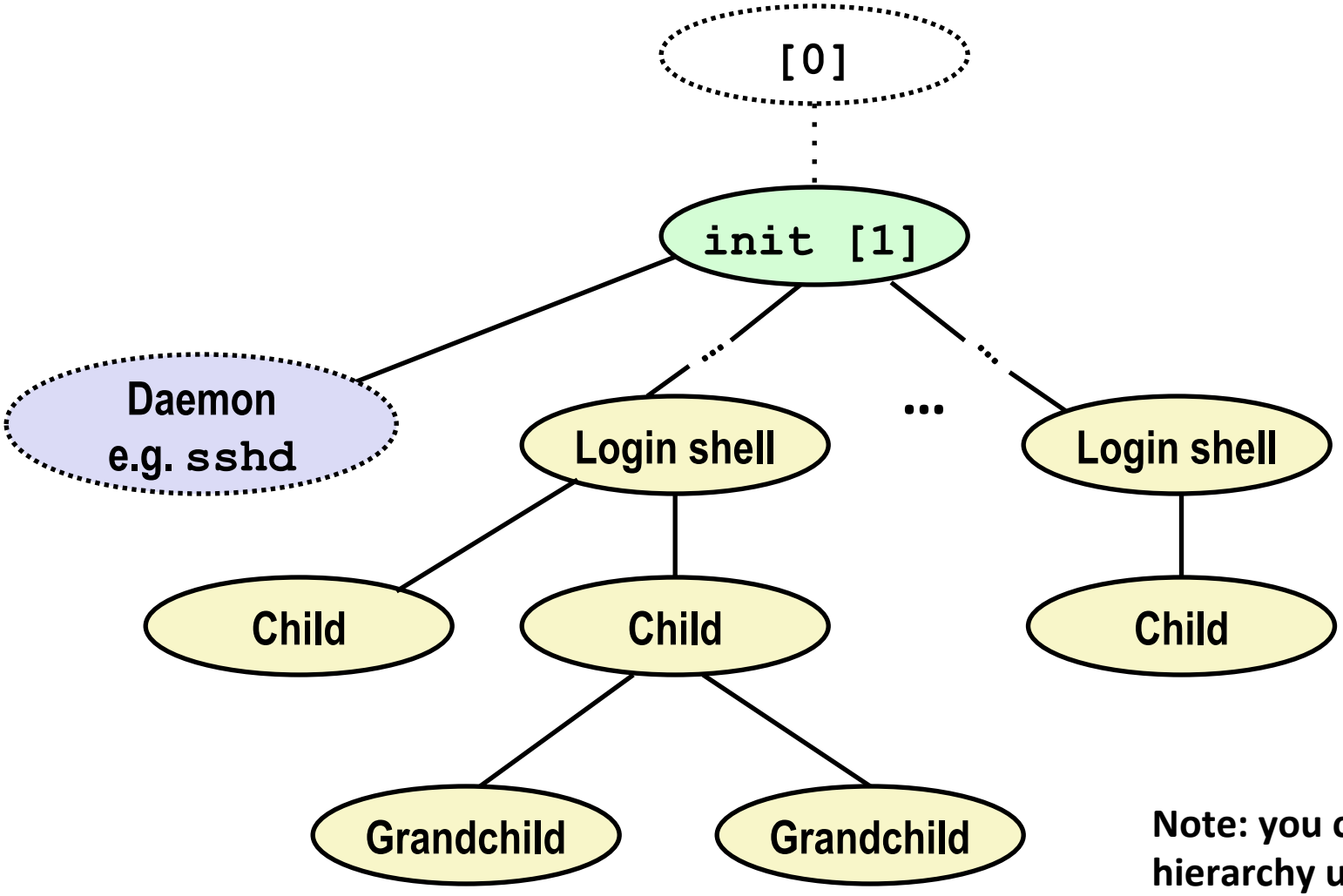
```
void fork11() {
    pid_t pid[N];
    int i, child_status;

    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0)
            exit(100+i); /* Child */
    for (i = 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

Today

- Process Control
- **Shells**
- Signals
- Nonlocal jumps

Linux Process Hierarchy



Note: you can view the hierarchy using the Linux `pstree` command

Shell Programs

- **A *shell* is an application program that runs programs on behalf of the user.**
  - `sh` Original Unix shell (Stephen Bourne, AT&T Bell Labs, 1977)
  - `csh/tcsh` BSD Unix C shell
  - `bash` "Bourne-Again" Shell (default Linux shell)
- **Simple shell**
  - Described in the textbook, starting at p. 753
  - Implementation of a very elementary shell
  - Purpose
    - Understand what happens when you type commands
    - Understand use and operation of process control operations

Simple Shell Example

```
linux> ./shellex
> /bin/ls -l csapp.c
-rw-r--r-- 1 bryant users 23053 Jun 15  2015 csapp.c
> /bin/ps
  PID TTY          TIME CMD
31542 pts/2    00:00:01 tcsh
32017 pts/2    00:00:00 shellex
32019 pts/2    00:00:00 ps
> /bin/sleep 10 &
32031 /bin/sleep 10 &
> /bin/ps
 PID TTY          TIME CMD
31542 pts/2    00:00:01 tcsh
32024 pts/2    00:00:00 emacs
32030 pts/2    00:00:00 shellex
32031 pts/2    00:00:00 sleep
32033 pts/2    00:00:00 ps
> quit
```

Must give full pathnames for programs

Run program in background

Sleep is running in background

Simple Shell Implementation

- **Basic loop**
  - Read line from command line
  - Execute the requested operation
    - Built-in command (only one implemented is **`quit`**)
    - Load and execute program from file

```
int main(int argc, char** argv)
{
    char cmdline[MAXLINE]; /* command line */

    while (1) {
        /* read */
        printf("> ");
        Fgets(cmdline, MAXLINE, stdin);
        if (feof(stdin))
            exit(0);

        /* evaluate */
        eval(cmdline);
    }
   ...
```

shellex.c

Execution is a sequence of read/ evaluate steps

Simple Shell `eval` Function

```
void eval(char *cmdline)
{
    char *argv[MAXARGS]; /* Argument list execve() */
    char buf[MAXLINE];   /* Holds modified command line */
    int bg;              /* Should the job run in bg or fg? */
    pid_t pid;           /* Process id */

    strcpy(buf, cmdline);
    bg = parseline(buf, argv);
```

`parseline` will parse ‘buf’ into ‘argv’ and return whether or not input line ended in ‘&’

shellex.c

Simple Shell `eval` Function

```
void eval(char *cmdline)
{
    char *argv[MAXARGS]; /* Argument list execve() */
    char buf[MAXLINE];   /* Holds modified command line */
    int bg;              /* Should the job run in bg or fg? */
    pid_t pid;           /* Process id */

    strcpy(buf, cmdline);
    bg = parseline(buf, argv);
    if (argv[0] == NULL)
        return;   /* Ignore empty lines */
```

Ignore empty lines.

shellex.c

Simple Shell `eval` Function

```
void eval(char *cmdline)
{
    char *argv[MAXARGS]; /* Argument list execve() */
    char buf[MAXLINE];   /* Holds modified command line */
    int bg;              /* Should the job run in bg or fg? */
    pid_t pid;           /* Process id */

    strcpy(buf, cmdline);
    bg = parseline(buf, argv);
    if (argv[0] == NULL)
        return;   /* Ignore empty lines */

    if (!builtin_command(argv)) {
```

If it is a 'built in' command, then handle it here in this program. Otherwise fork/exec the program specified in argv[0]

shellex.c

Simple Shell `eval` Function

```
void eval(char *cmdline)
{
    char *argv[MAXARGS]; /* Argument list execve() */
    char buf[MAXLINE];   /* Holds modified command line */
    int bg;              /* Should the job run in bg or fg? */
    pid_t pid;           /* Process id */

    strcpy(buf, cmdline);
    bg = parseline(buf, argv);
    if (argv[0] == NULL)
        return;   /* Ignore empty lines */

    if (!builtin_command(argv)) {
        if ((pid = Fork()) == 0) {   /* Child runs user job */
```

Create child

shellex.c

Simple Shell `eval` Function

```
void eval(char *cmdline)
{
    char *argv[MAXARGS]; /* Argument list execve() */
    char buf[MAXLINE];   /* Holds modified command line */
    int bg;              /* Should the job run in bg or fg? */
    pid_t pid;           /* Process id */

    strcpy(buf, cmdline);
    bg = parseline(buf, argv);
    if (argv[0] == NULL)
        return;   /* Ignore empty lines */

    if (!builtin_command(argv)) {
        if ((pid = Fork()) == 0) {   /* Child runs user job */
            if (execve(argv[0], argv, environ) < 0) {
                printf("%s: Command not found.\n", argv[0]);
                exit(0);
            }
        }
```

Start **`argv[0]`**.
Remember **`execve`** only returns on error.

shellex.c

Simple Shell `eval` Function

```
void eval(char *cmdline)
{
    char *argv[MAXARGS]; /* Argument list execve() */
    char buf[MAXLINE];   /* Holds modified command line */
    int bg;              /* Should the job run in bg or fg? */
    pid_t pid;           /* Process id */

    strcpy(buf, cmdline);
    bg = parseline(buf, argv);
    if (argv[0] == NULL)
        return;   /* Ignore empty lines */

    if (!builtin_command(argv)) {
        if ((pid = Fork()) == 0) {   /* Child runs user job */
            if (execve(argv[0], argv, environ) < 0) {
                printf("%s: Command not found.\n", argv[0]);
                exit(0);
            }
        }

        /* Parent waits for foreground job to terminate */
       if (!bg) {
            int status;
            if (waitpid(pid, &status, 0) < 0)
                unix_error("waitfg: waitpid error");
        }
```

If running child in foreground, wait until it is done.

shellex.c

Simple Shell `eval` Function

```
void eval(char *cmdline)
{
    char *argv[MAXARGS]; /* Argument list execve() */
    char buf[MAXLINE];   /* Holds modified command line */
    int bg;              /* Should the job run in bg or fg? */
    pid_t pid;           /* Process id */

    strcpy(buf, cmdline);
    bg = parseline(buf, argv);
    if (argv[0] == NULL)
        return;   /* Ignore empty lines */

    if (!builtin_command(argv)) {
        if ((pid = Fork()) == 0) {   /* Child runs user job */
            if (execve(argv[0], argv, environ) < 0) {
                printf("%s: Command not found.\n", argv[0]);
                exit(0);
            }
        }

        /* Parent waits for foreground job to terminate */
       if (!bg) {
            int status;
            if (waitpid(pid, &status, 0) < 0)
                unix_error("waitfg: waitpid error")
        }
        else
            printf("%d %s", pid, cmdline);
    }
    return;
}
```

If running child in background, print pid and continue doing other stuff.

shellex.c

Simple Shell `eval` Function

```
void eval(char *cmdline)
{
    char *argv[MAXARGS]; /* Argument list execve() */
    char buf[MAXLINE];   /* Holds modified command line */
    int bg;              /* Should the job run in bg or fg? */
    pid_t pid;           /* Process id */

    strcpy(buf, cmdline);
    bg = parseline(buf, argv);
    if (argv[0] == NULL)
        return;   /* Ignore empty lines */

    if (!builtin_command(argv)) {
        if ((pid = Fork()) == 0) {   /* Child runs user job */
            if (execve(argv[0], argv, environ) < 0) {
                printf("%s: Command not found.\n", argv[0]);
                exit(0);
            }
        }

        /* Parent waits for foreground job to terminate */
       if (!bg) {
            int status;
            if (waitpid(pid, &status, 0) < 0)
                unix_error("waitfg: waitpid error");
        }
        else
            printf("%d %s", pid, cmdline);
    }
    return;
}
```

Oops. *There is a problem with this code.*

shellex.c

Problem with Simple Shell Example

- **Our example shell correctly waits for and reaps foreground jobs**

- **But what about background jobs?**
  - Will become zombies when they terminate
  - Will never be reaped because shell (typically) will not terminate
  - Will create a memory leak that could run the kernel out of memory

ECF to the Rescue!

- **Solution: Exceptional control flow**
  - The kernel will interrupt regular processing to alert us when a background process completes
  - In Unix / Linux, the alert mechanism is called a ***signal***

ECF Exists at All Levels of a System

- **Exceptions**
  - Hardware and operating system kernel software
- **Process Context Switch**
  - Hardware timer and kernel software
- **Signals**
  - Kernel software and application software
- **Nonlocal jumps**
  - Application code

Previous Lecture

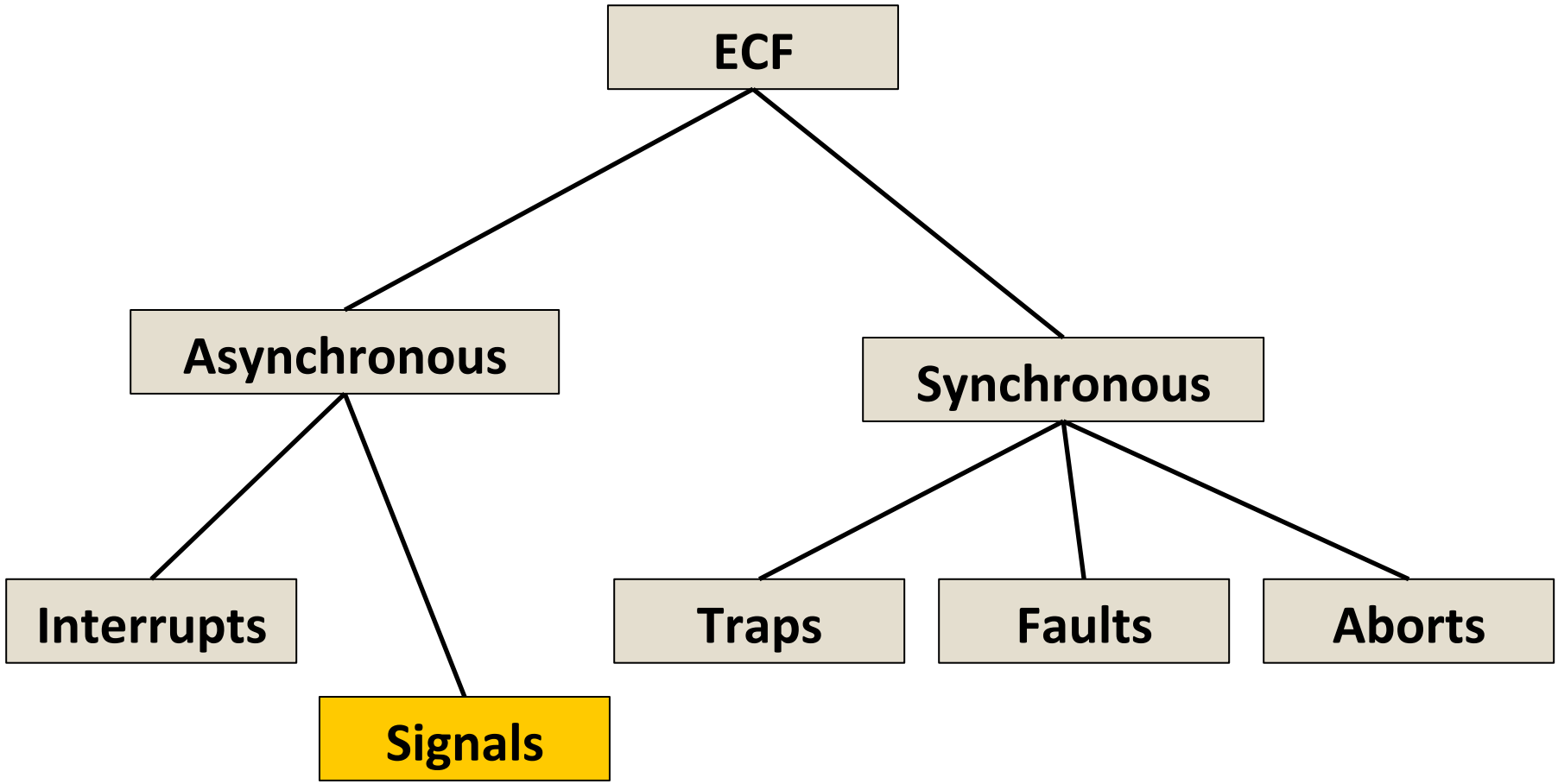
This Lecture

Textbook and supplemental slides

Taxonomy

Handled in kernel

Handled in user process



Today

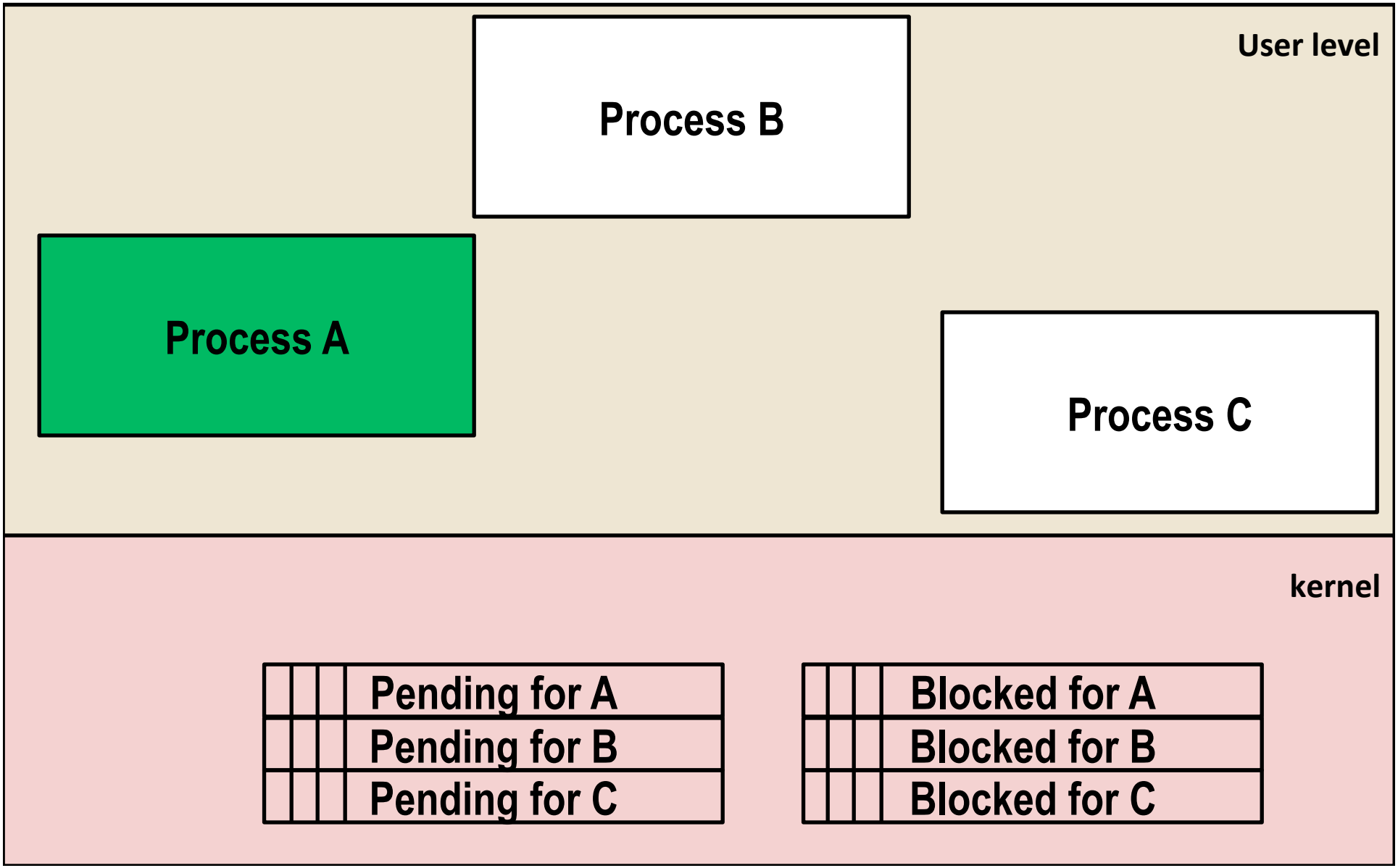
- Process
- Shells
- **Signals**
- Nonlocal jumps

Signals

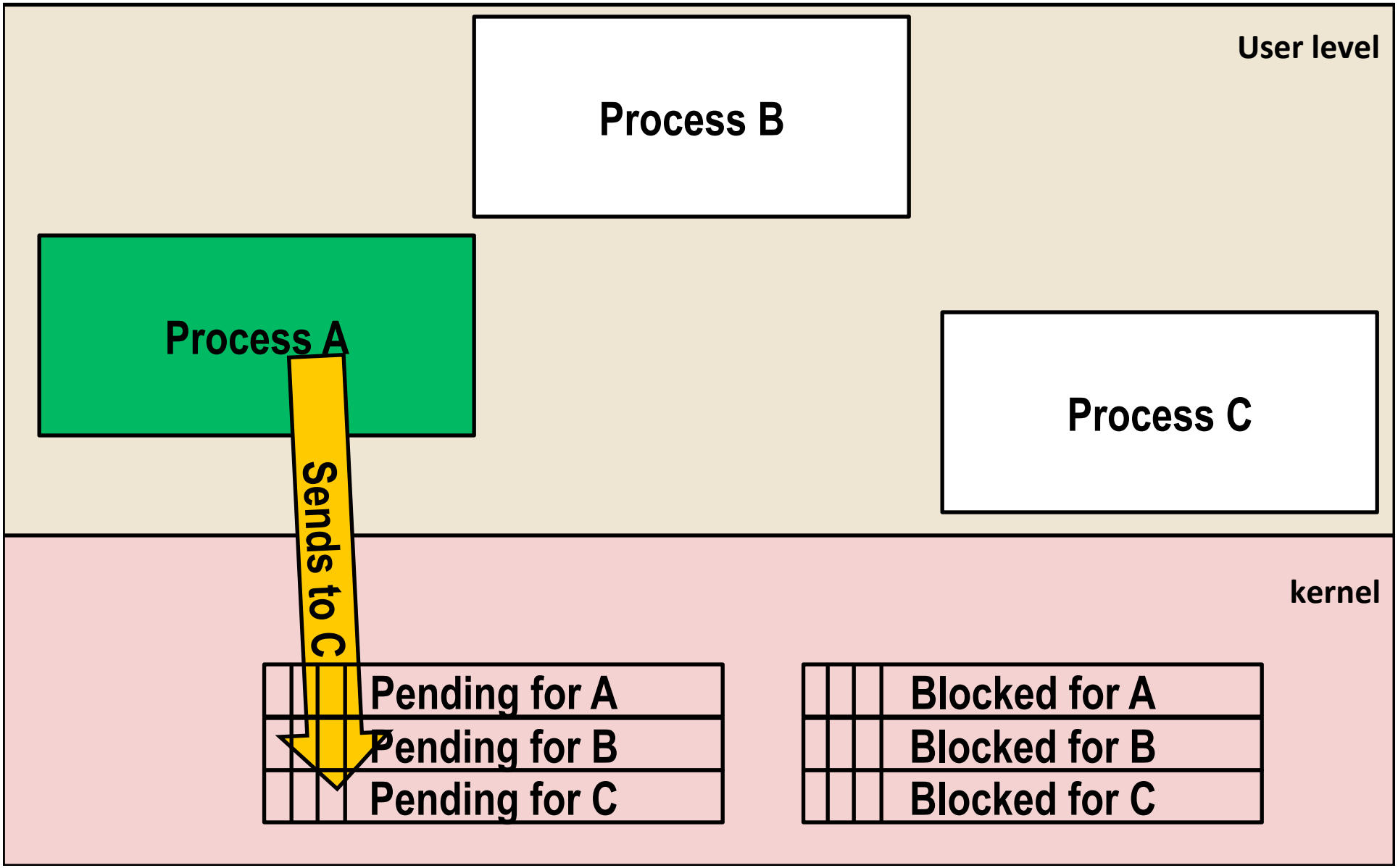
- **A *signal* is a small message that notifies a process that an event of some type has occurred in the system**
  - Akin to exceptions and interrupts
  - Sent from the kernel to a process
  - A process can also ask the kernel to send signals to a different process
  - Signal type is identified by small integer ID's (1-30)
  - Only information in a signal is its ID and the fact that it arrived

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

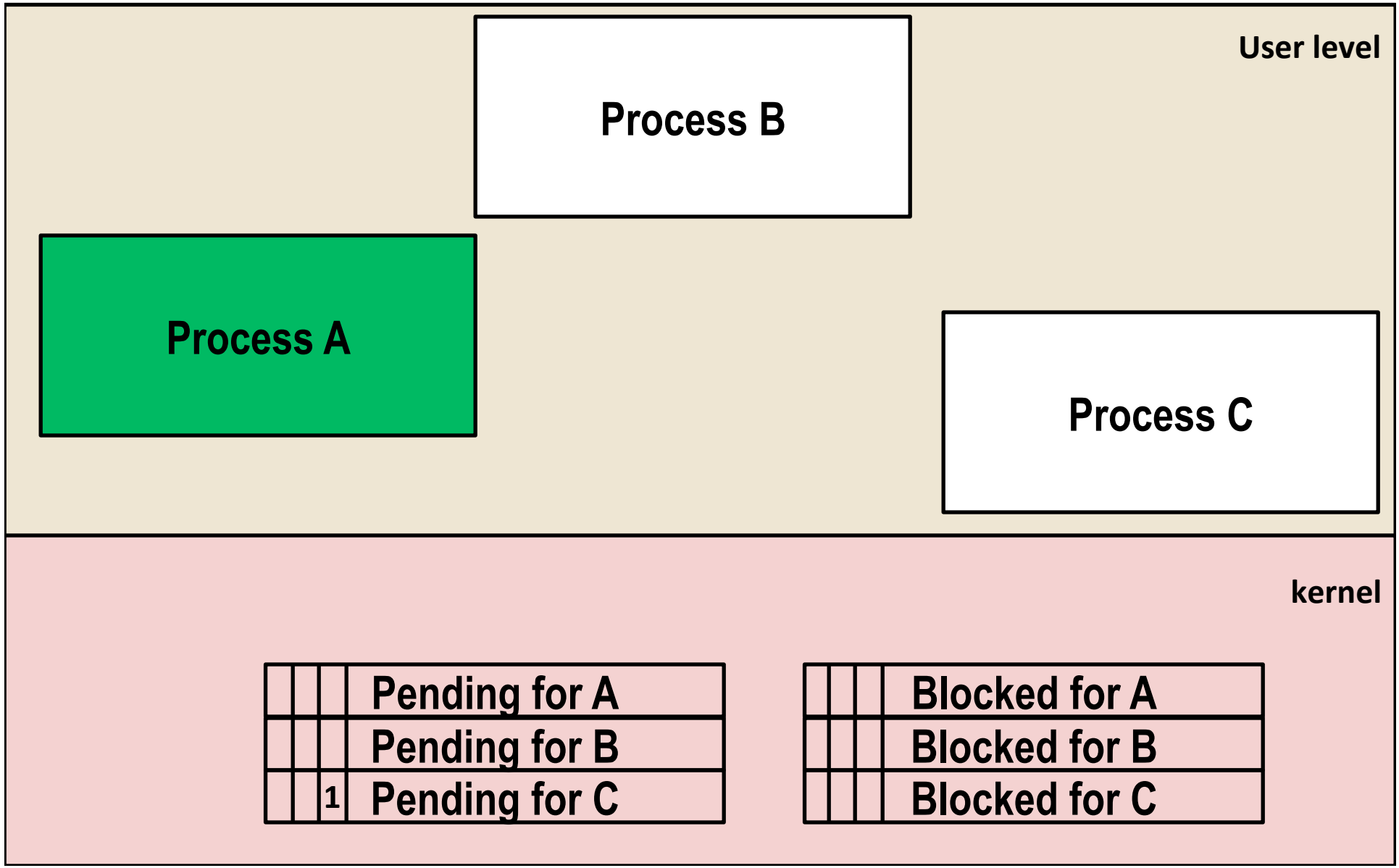
Signal Concepts: Sending a Signal



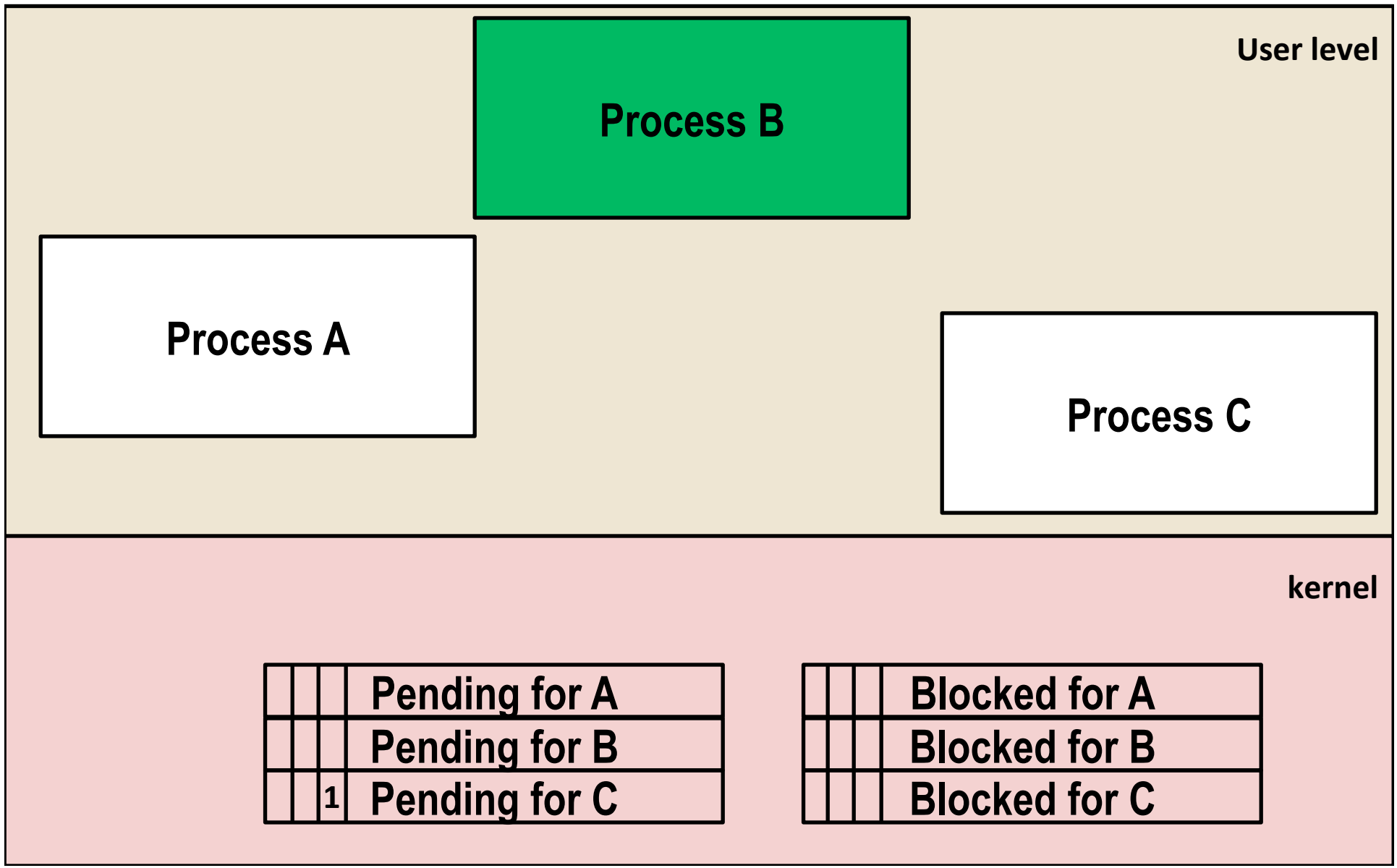
Signal Concepts: Sending a Signal



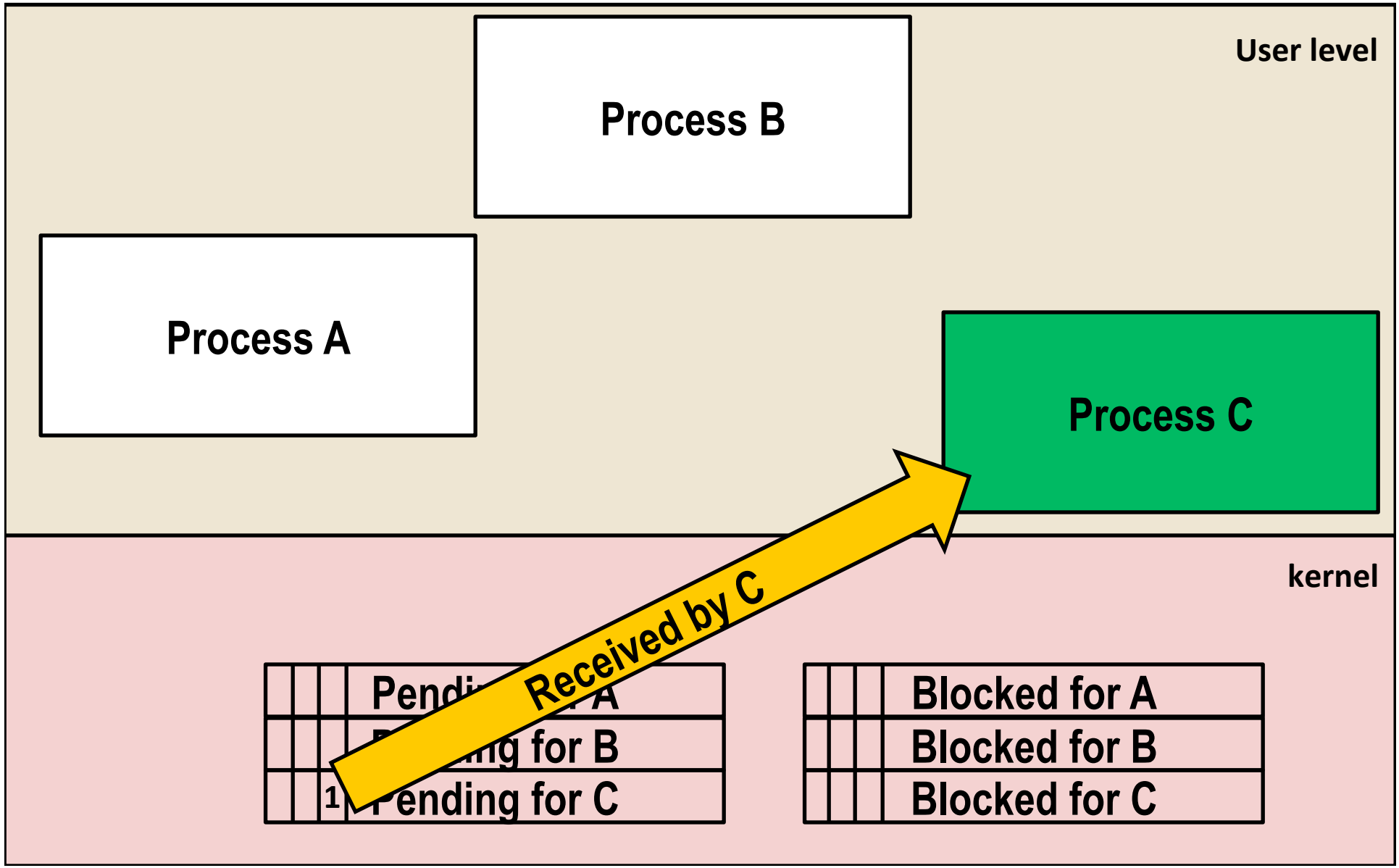
Signal Concepts: Sending a Signal



Signal Concepts: Sending a Signal



Signal Concepts: Receiving a Signal



Signal Concepts: Sending a Signal

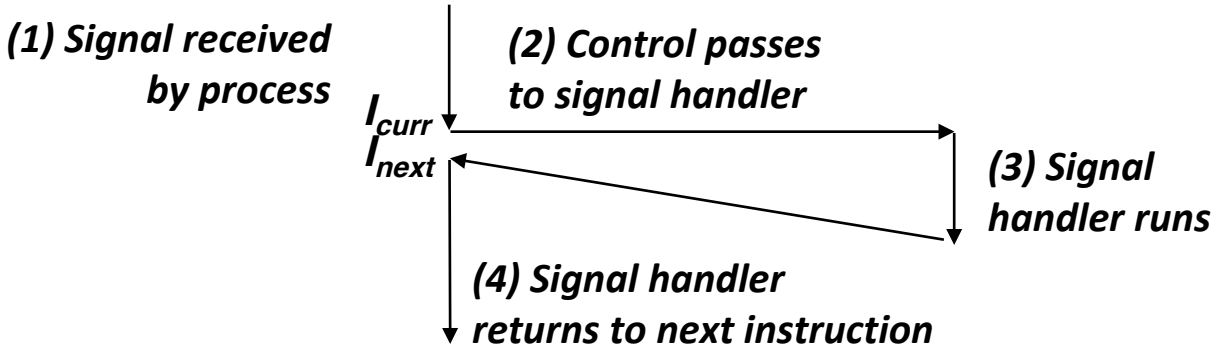
- **Kernel *sends* (delivers) a signal to a *destination process* by updating some state in the context of the destination process**

- **Kernel sends a signal for one of the following reasons:**
  - Kernel has detected a system event such as divide-by-zero (SIGFPE) or the termination of a child process (SIGCHLD)
  - Another process has invoked the **`kill`** system call to explicitly request the kernel to send a signal to the destination process

- **Note that a signal is sent, but the kernel may not process it immediately, and the destination process may not receive it immediately.**

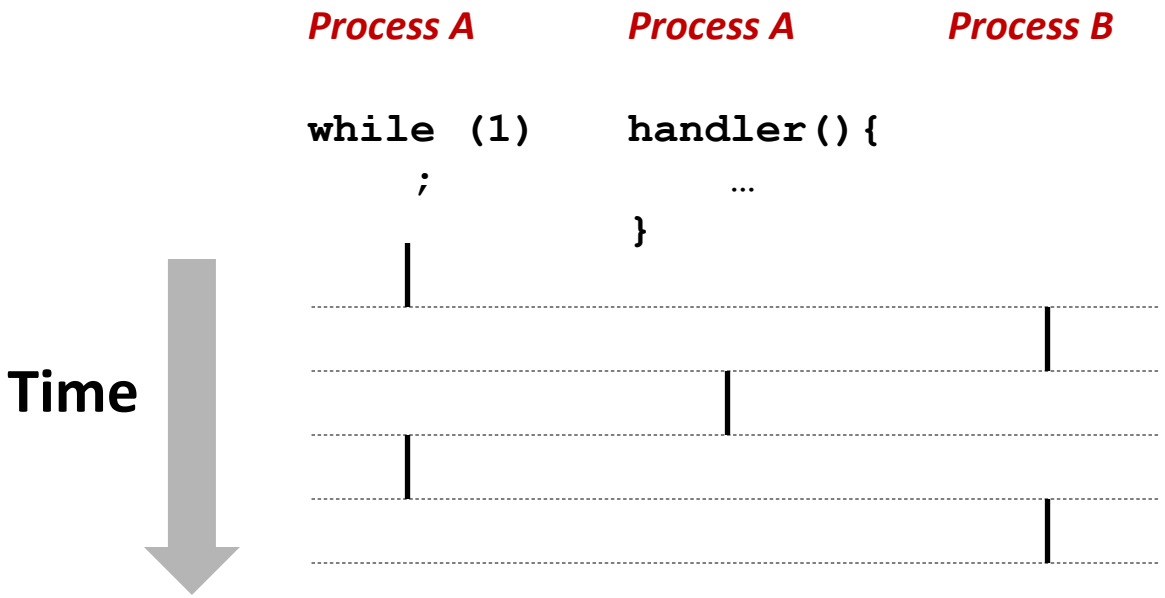
Signal Concepts: Receiving a Signal

- **The kernel processes signals sent to a destination process when it is about to resume / pass control back to the process.**
- **The destination process *receives* a signal when it is forced by the kernel to react in some way to the delivery of the signal**
  - The receipt of the signal triggers some ***action*** by the destination process
- **Some possible ways to react:**
  - ***Ignore*** the signal (do nothing)
  - ***Terminate*** the process (with optional core dump)
  - ***Catch*** the signal by executing a user-level function called ***signal handler***
    - Akin to other ECF mechanisms we talked about

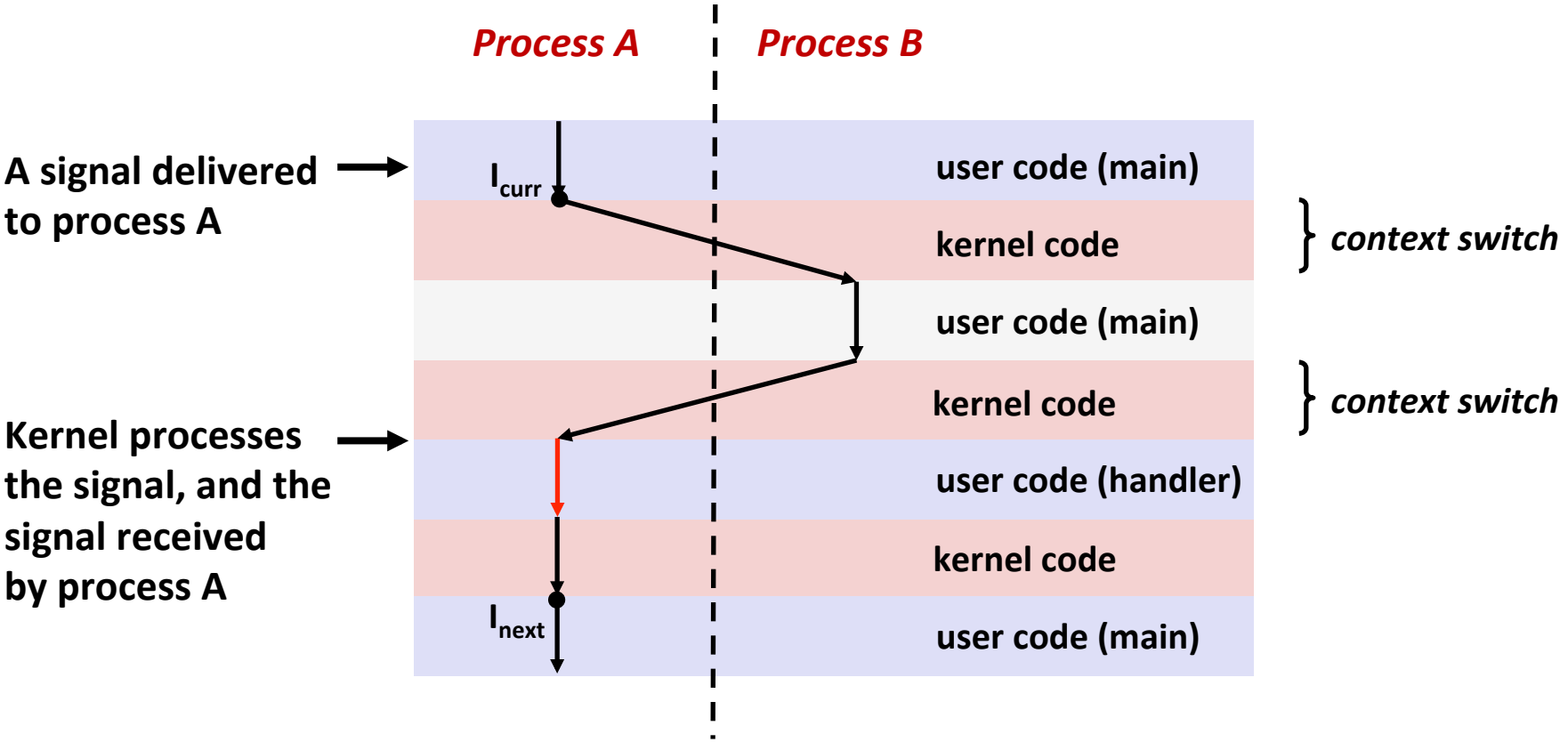


Signals Handlers as Concurrent Flows

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



Another View of Signal Handlers as Concurrent Flows



Signal Concepts: 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
  - **Important: Signals are not queued**
    - If a process has a pending signal of type k, then subsequent signals of type k that are sent to that process are discarded
  - A pending signal is received at most once

- **A process can *block* the receipt of certain signals**
  - Blocked signals can be delivered, but will not be received until the signal is unblocked

Signal Concepts: Pending/Blocked Bits

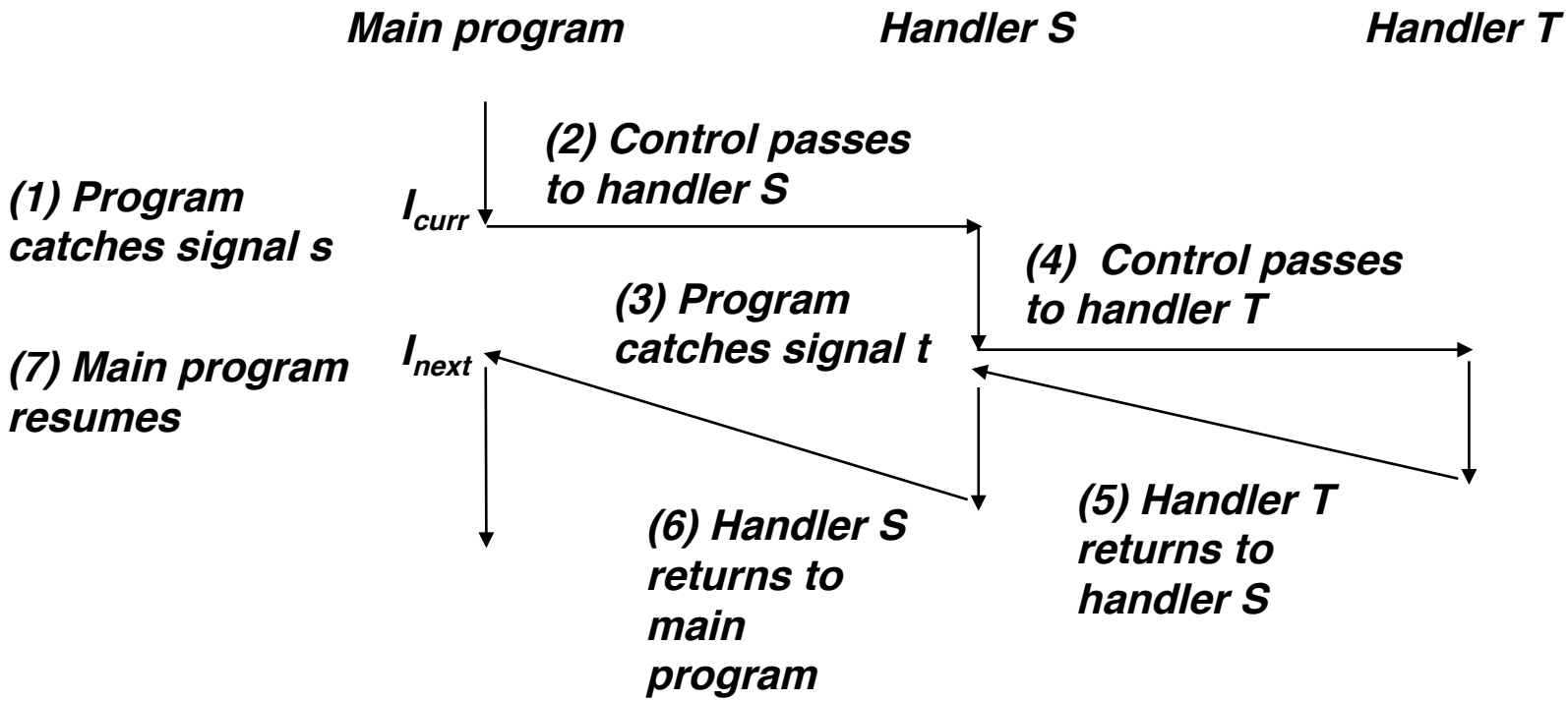
- **Kernel maintains `pending` and `blocked` bit vectors in the context of each process**
  - **`pending`**: represents the set of pending signals
    - Kernel sets bit k in **`pending`** when a signal of type k is delivered
    - Kernel clears bit k in **`pending`** when a signal of type k is received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

How Kernel Processes Signals

- **Suppose kernel is returning from an exception handler and is ready to pass control to process *A***
- **Kernel computes `pnb = pending & ~blocked`**
  - The set of pending nonblocked signals for process *A*
- **If `(pnb == 0)`**
  - Pass control to next instruction in the logical flow for *A*
- **Else**
  - Choose least nonzero bit *k* in **`pnb`** and force process *A* to ***receive*** signal *k*
  - The receipt of the signal triggers some ***action*** by *A*
  - Repeat for all nonzero *k* in **`pnb`**
  - Pass control to next instruction in logical flow for *A*

Nested Signal Handlers

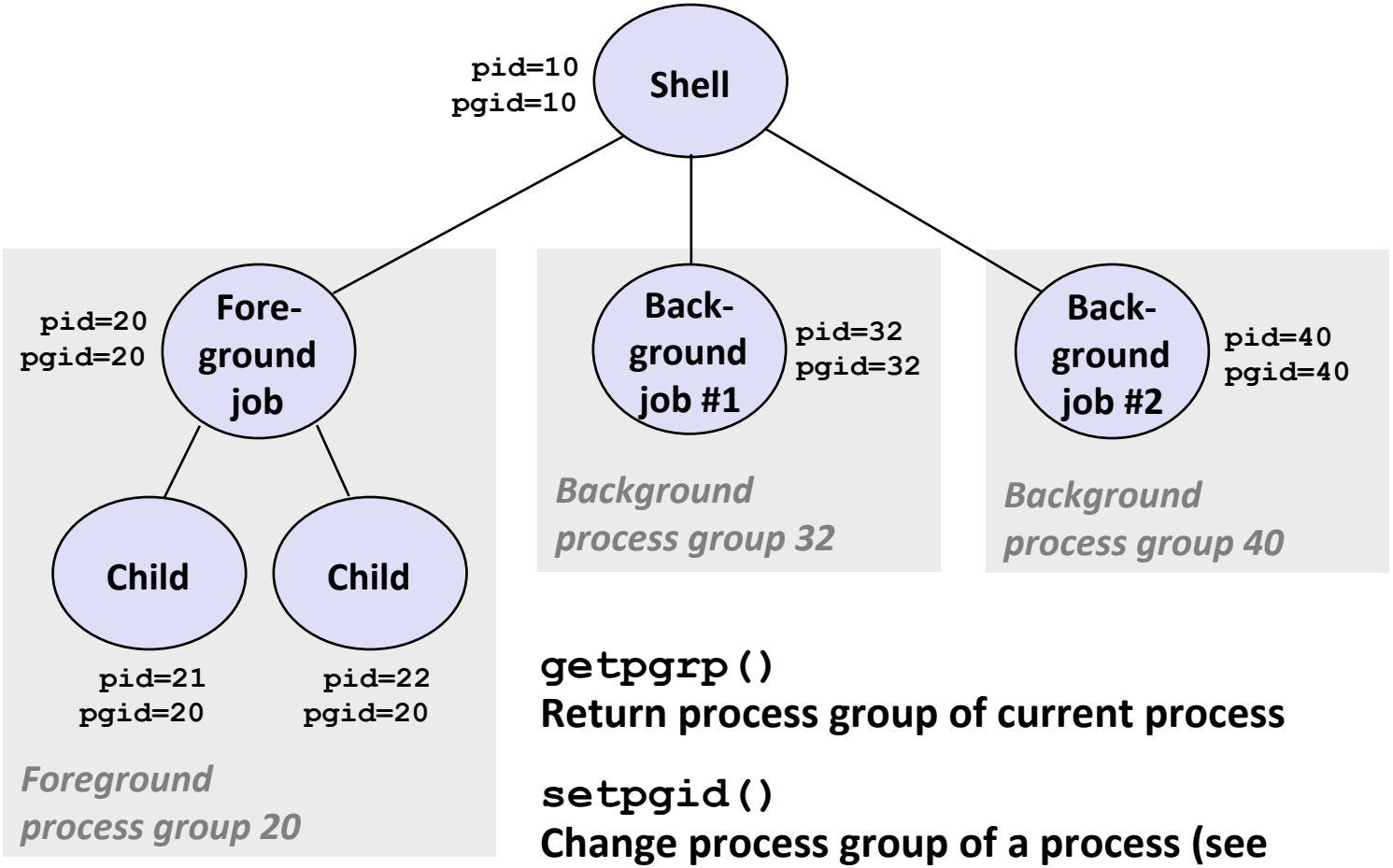
- Handlers can be interrupted by other handlers



- Although execution of a handler cannot be interrupted by another handler of the same type.

Sending Signals: Process Groups

- **Every process belongs to exactly one process group**

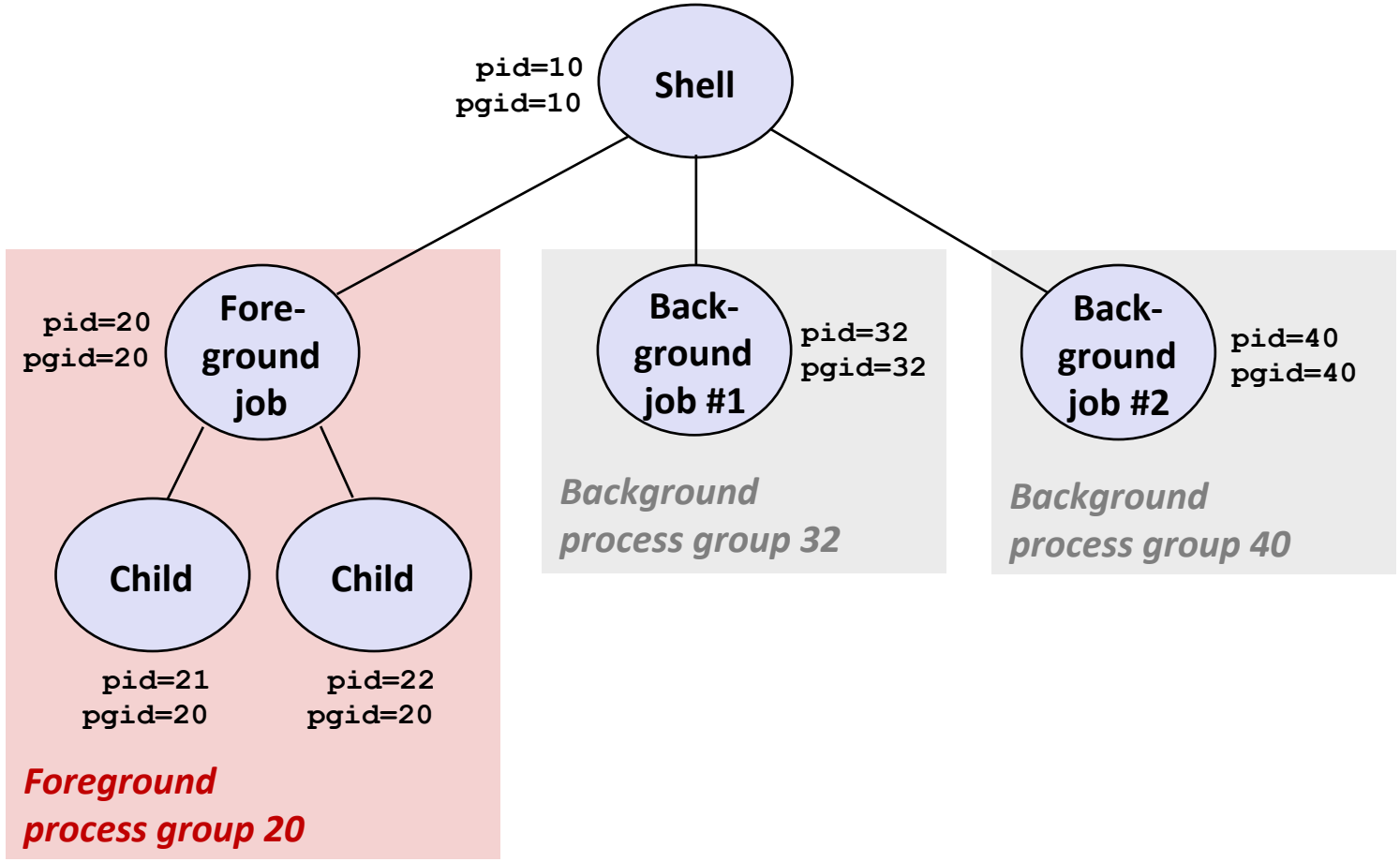


`getpgrp()`
Return process group of current process

`setpgid()`
Change process group of a process (see text for details)

Sending Signals from the Keyboard

- **Typing ctrl-c (ctrl-z) causes the kernel to send a SIGINT (SIGTSTP) to every job in the foreground process group.**
  - SIGINT – default action is to terminate each process
  - 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
27699 pts/8    Ss     0:00 -tcsh
28110 pts/8    R+     0:00 ps w
```

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 `/bin/kill` Program

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

- **Examples**
  - **`/bin/kill -9 24818`**
    Send SIGKILL to process 24818
  - **`/bin/kill -9 -24817`**
    Send SIGKILL to every process in process group 24817

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

linux> ps
  PID TTY          TIME CMD
24788 pts/2    00:00:00 tcsh
24818 pts/2    00:00:02 forks
24819 pts/2    00:00:02 forks
24820 pts/2    00:00:00 ps
linux> /bin/kill -9 -24817
linux> ps
  PID TTY          TIME CMD
24788 pts/2    00:00:00 tcsh
24823 pts/2    00:00:00 ps
linux>
```

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 Signal Handler

- **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`:**
  - **`handler_t *signal(int signum, handler_t *handler)`**
  - Though **`signal`** is not very portable, so use **`sigaction`** instead (see textbook example pg 775).

- **Different values for `handler`:**
  - SIG_IGN: ignore signals of type **`signum`**
  - SIG_DFL: revert to the default action on receipt of signals of type **`signum`**
  - Otherwise, **`handler`** is the address of a user-level ***signal handler***
    - Called when process receives signal of type **`signum`**

Signal Handling Example

```
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, see textbook pg 750 */
    Signal(SIGINT, sigint_handler);
    ... /* do something else */

    return 0;
}
```

Buggy Code!
Not safe to use `printf` in handler

sigint.c

Safe Signal Handling

- **Proceed with caution: signal-handling is a tricky business**
  - The handler executes concurrently with the main program.
  - Shared data structures can become corrupted.
  - Can have nested signal handlers.
  - Certain library functions are ***NOT SAFE*** to invoke within a signal handler!

Guidelines for Writing Safe Handlers

- **G0: Keep your handlers as simple as possible**
  - e.g., Set a global flag and return
- **G1: Call only async-signal-safe functions in your handlers**
  - **`printf`**, **`sprintf`**, **`malloc`**, and **`exit`** are not safe!
- **G2: Save and restore `errno` on entry and exit**
  - So that this or other handlers don't overwrite the value of **`errno`** used by the application code
- **G3: Protect accesses to shared data structures by temporarily blocking all signals.**
  - To prevent possible corruption
- **G4: Declare global variables as `volatile`**
  - To prevent compiler from storing them in a register
- **G5: Declare global flags (integer) as `sig_atomic_t`**
  - Individual read / write will be atomic (e.g. flag = 1, not flag++)