



# Exceptional Control Flow: Signals

18-213/18-613: Introduction to Computer Systems  
18<sup>th</sup> Lecture, Spring 2026

# 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 should be reaped by `init` process (`pid == 1`)
  - Unless `ppid == 1`! Then need to reboot...
- 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 */
    }
}
```

```
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
```

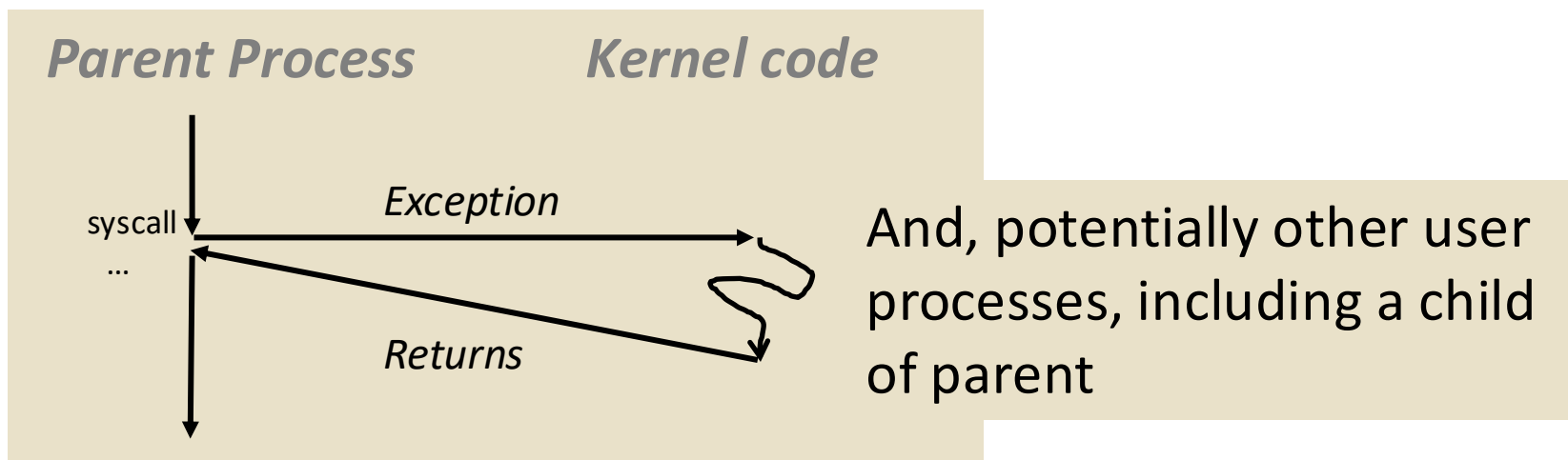
PID	TTY	TIME	CMD
6585	ttyp9	00:00:00	tcsh
6642	ttyp9	00:00:00	ps

■ **ps** shows child process as “defunct” (i.e., a zombie)

■ Killing parent allows child to be reaped by **init**

# 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
  - Implemented as syscall



# `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

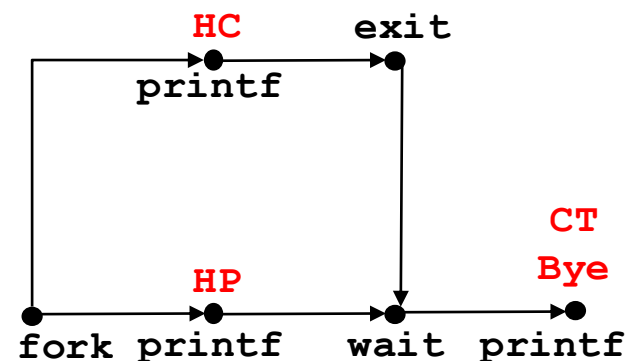
```

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(s):

HC      HP  
 HP      HC  
 CT      CT  
 Bye     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*

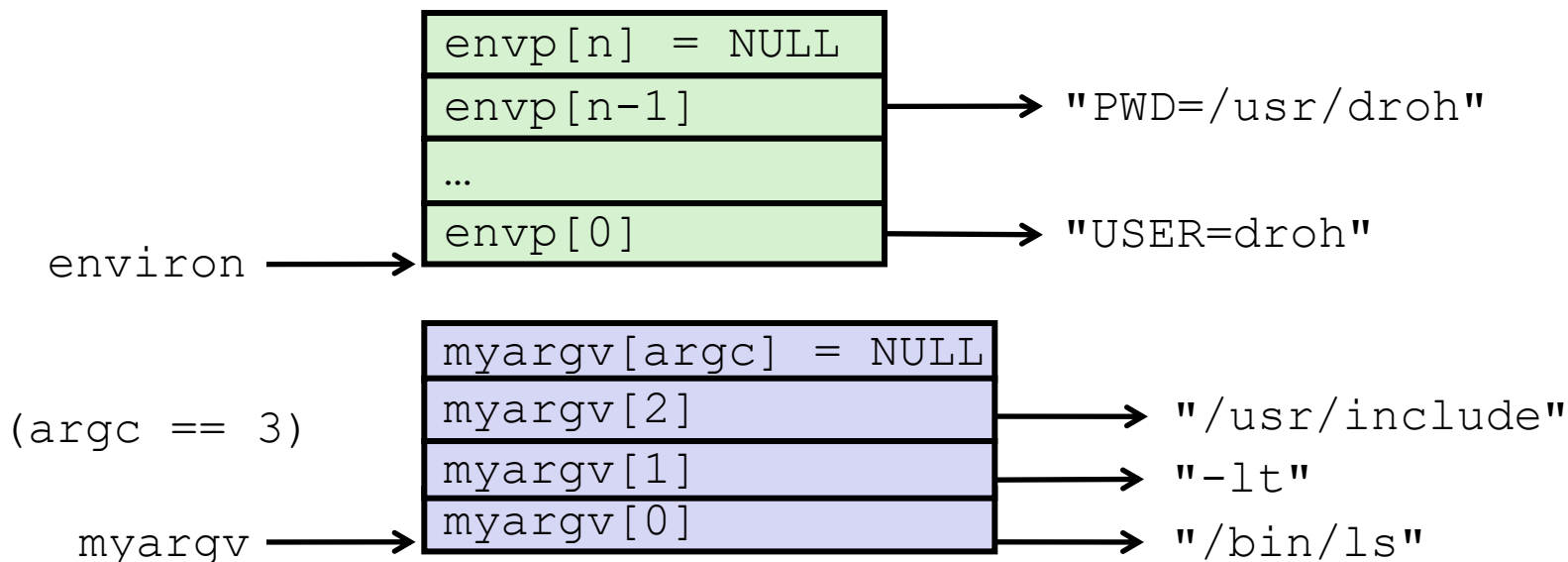
`waitpid(-1, &child_status, 0)`  
is equivalent to  
`wait(&child_status);`

# 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

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

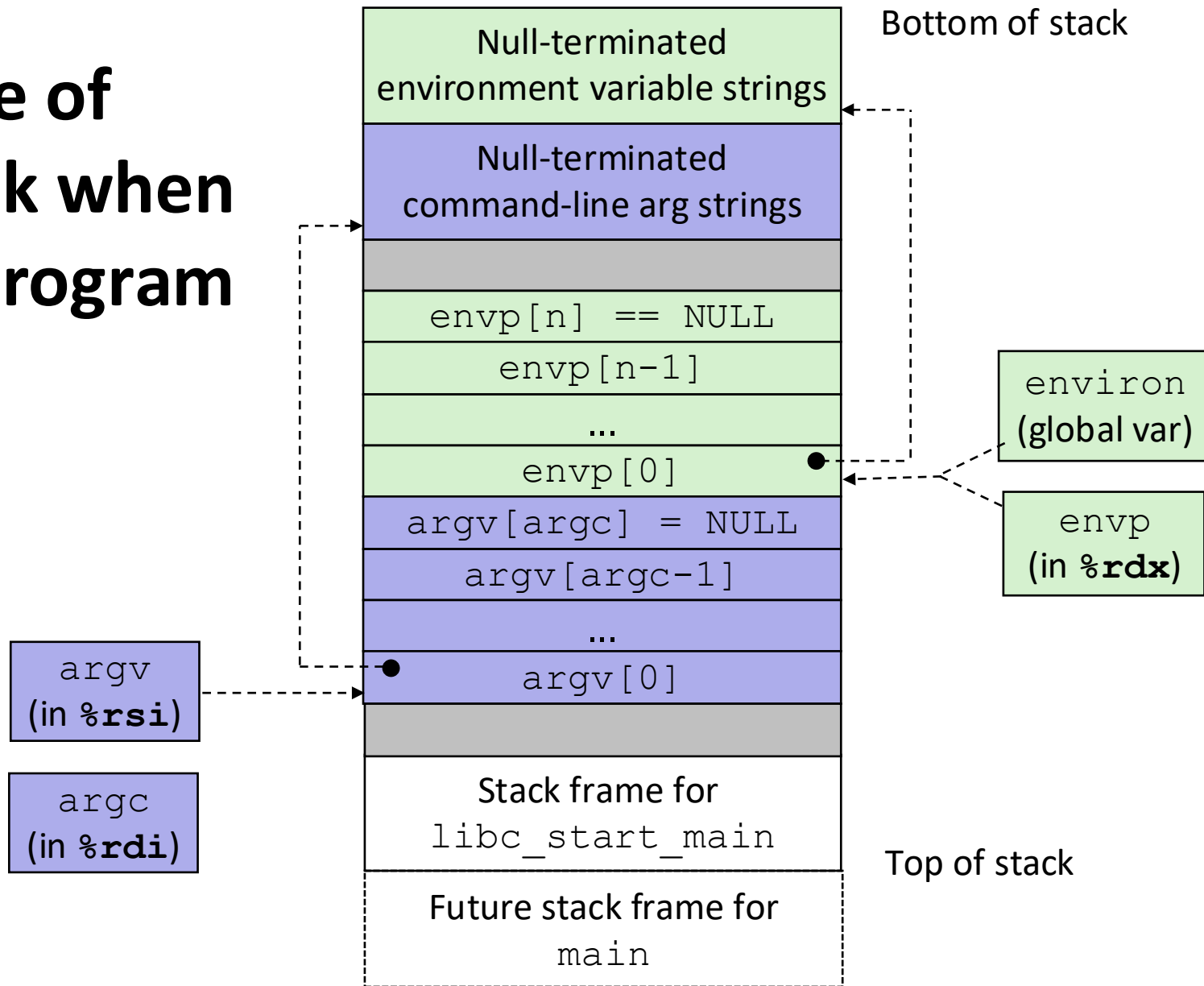


```

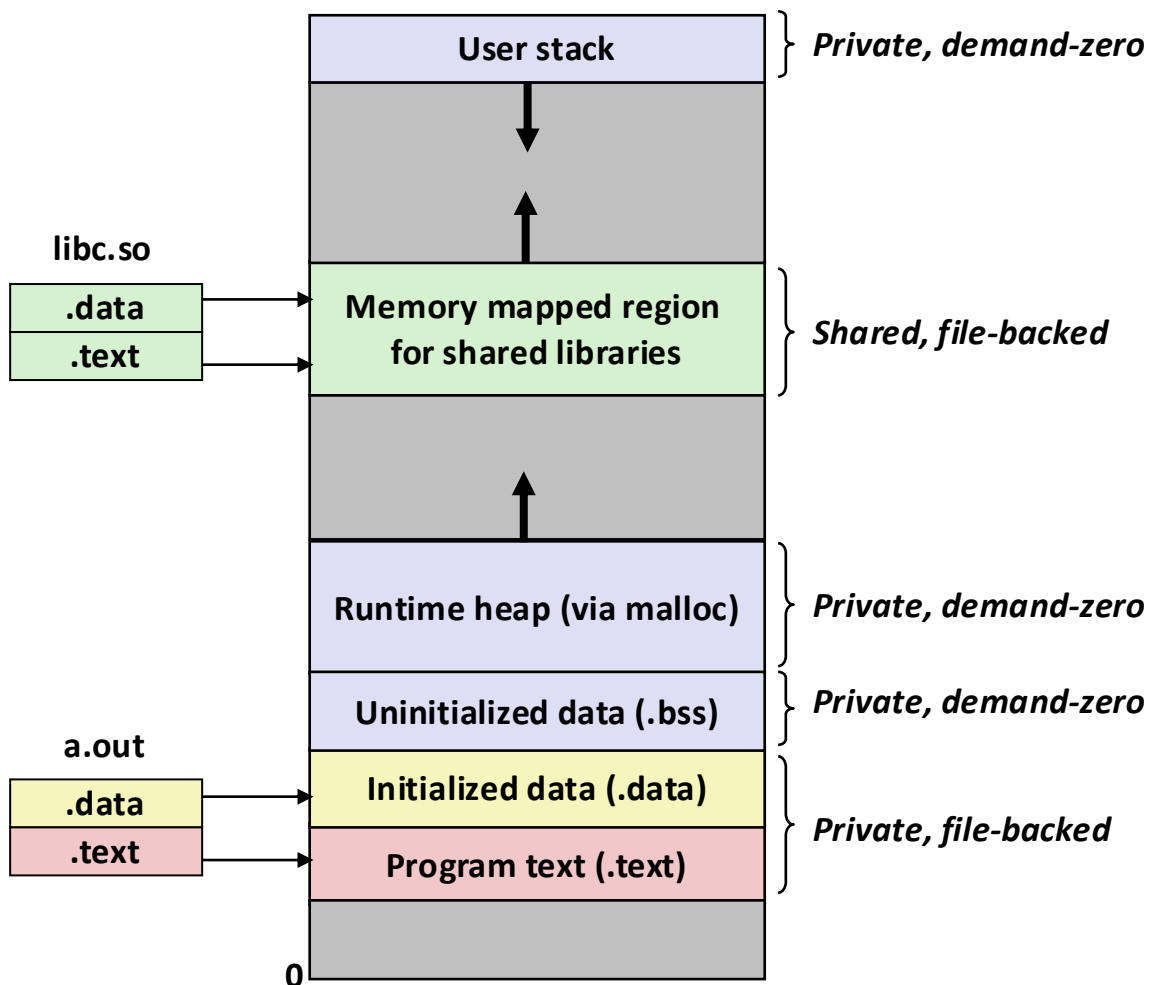
if ((pid = Fork()) == 0) { /* Child runs program */
    if (execve(myargv[0], myargv, environ) < 0) {
        printf("%s: Command not found.\n", myargv[0]);
        exit(1);
    }
}

```

# Structure of the stack when a new program starts



# The `execve` Function Revisited



- 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 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.

# Exceptions & Processes - 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 any single core
- Each process appears to have total control of processor + private memory space

# Today

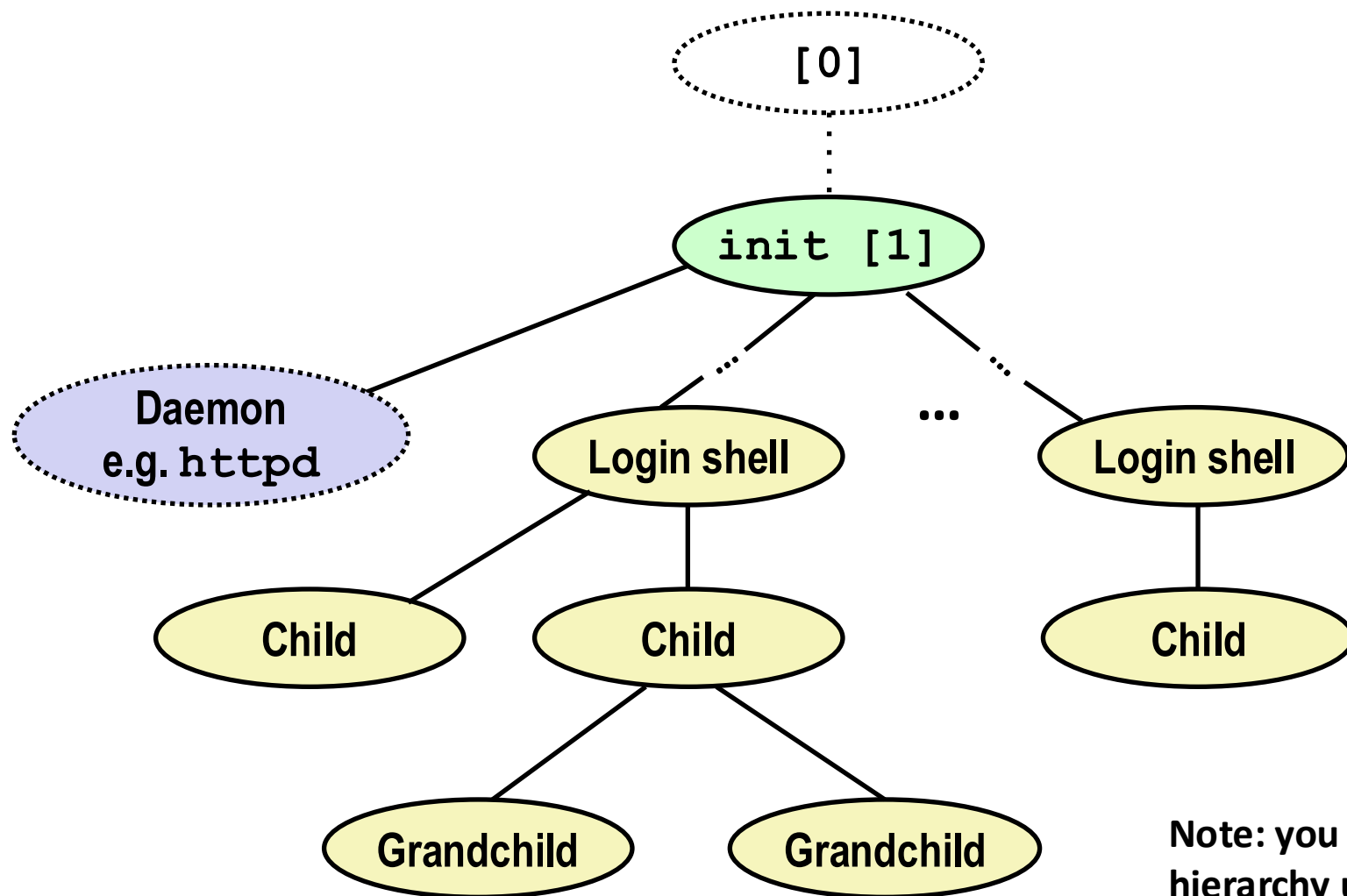
- Shells

CSAPP 8.4.6

- Signals

CSAPP 8.5

# 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
```

**Note: 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 '&'

# 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.

# 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]

# 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

# 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.

# 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.

# 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

- **Shell designed to run indefinitely**
  - Should not accumulate unneeded resources
    - Memory
    - Child processes
    - File descriptors
- **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, the alert mechanism is called a *signal*

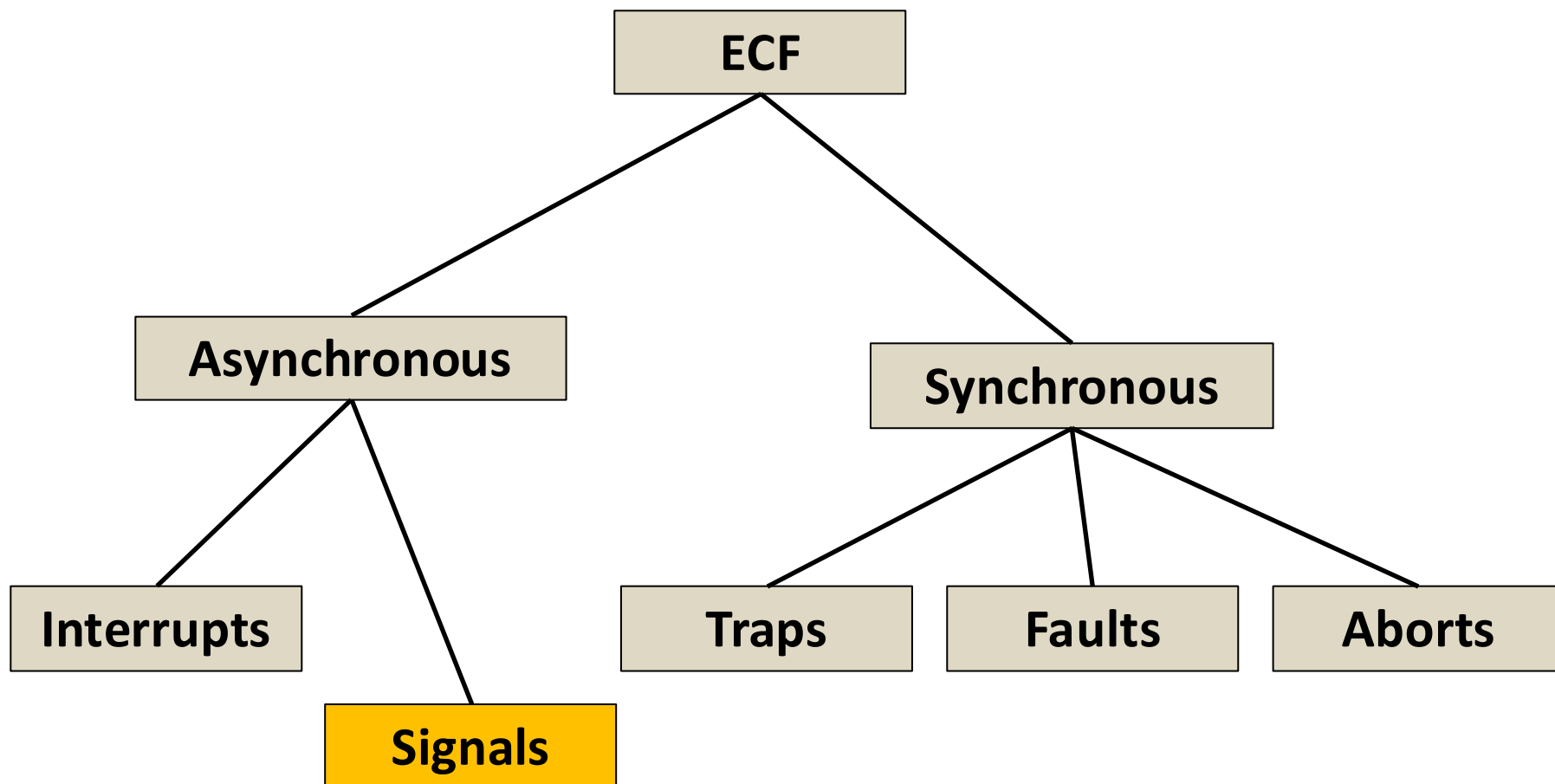
# Today

- Shells
- **Signals**

Handled in kernel

Handled in user process

# (partial) Taxonomy



# Signals

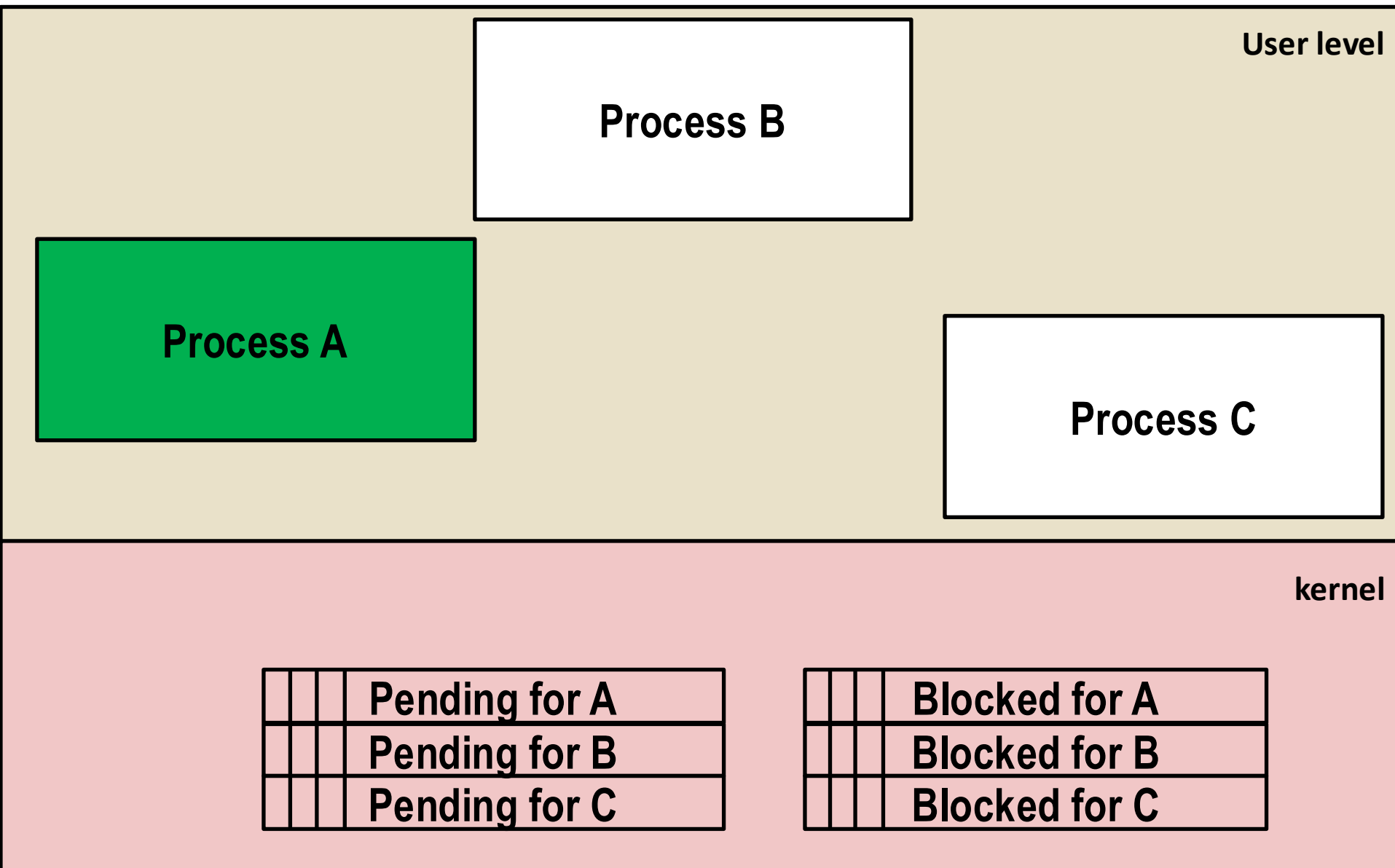
- A *signal* is a small message that notifies a process that an event of some type has occurred in the system
  - Akin to exceptions and interrupts
  - Sent from the kernel (sometimes at the request of another process) to a process
  - Signal type is identified by small integer ID's (1-30)
  - Only information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

<i>ID</i>	<i>Name</i>	<i>Default Action</i>	<i>Corresponding Event</i>
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

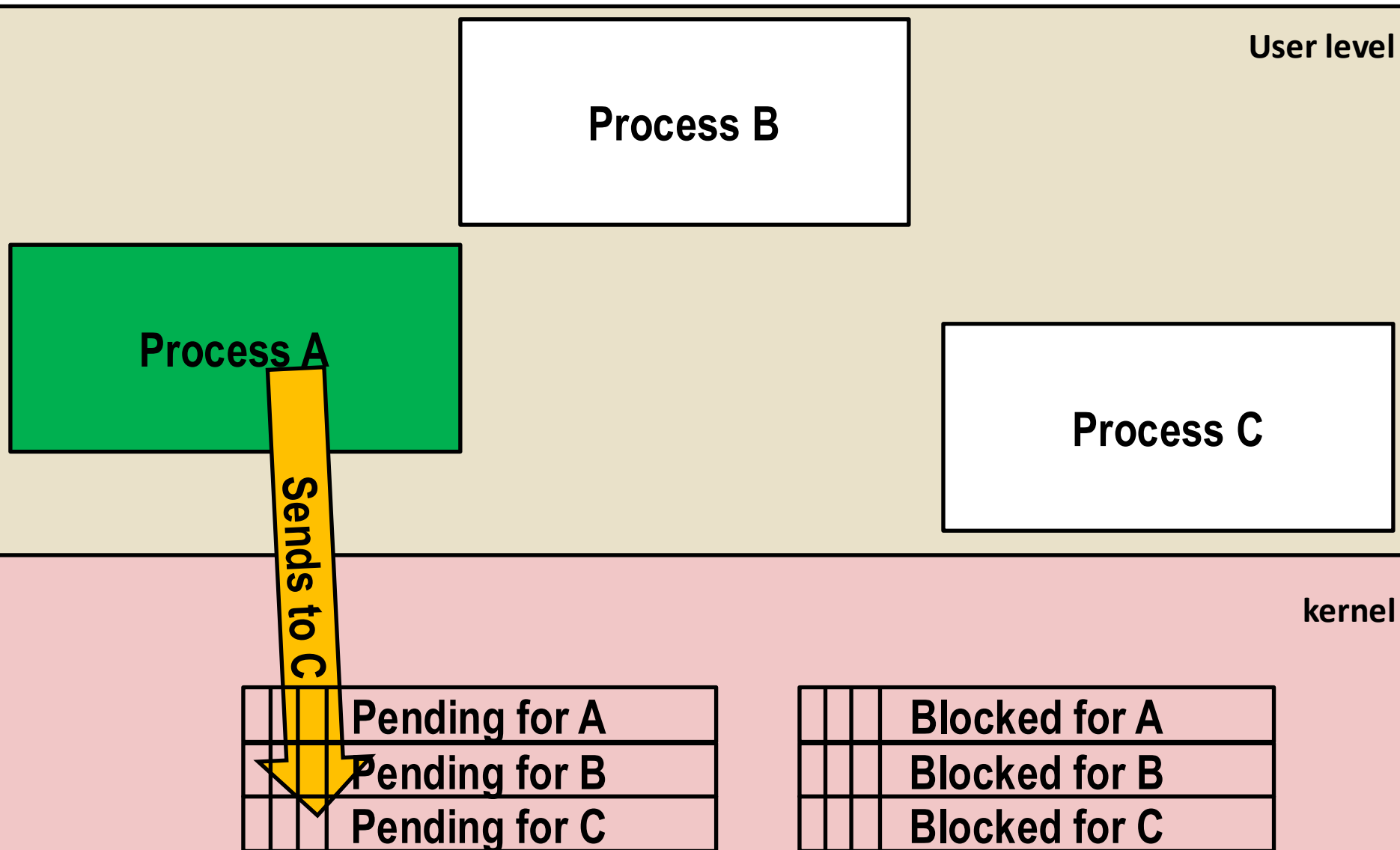
# Signal Concepts: Sending a Signal

- 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

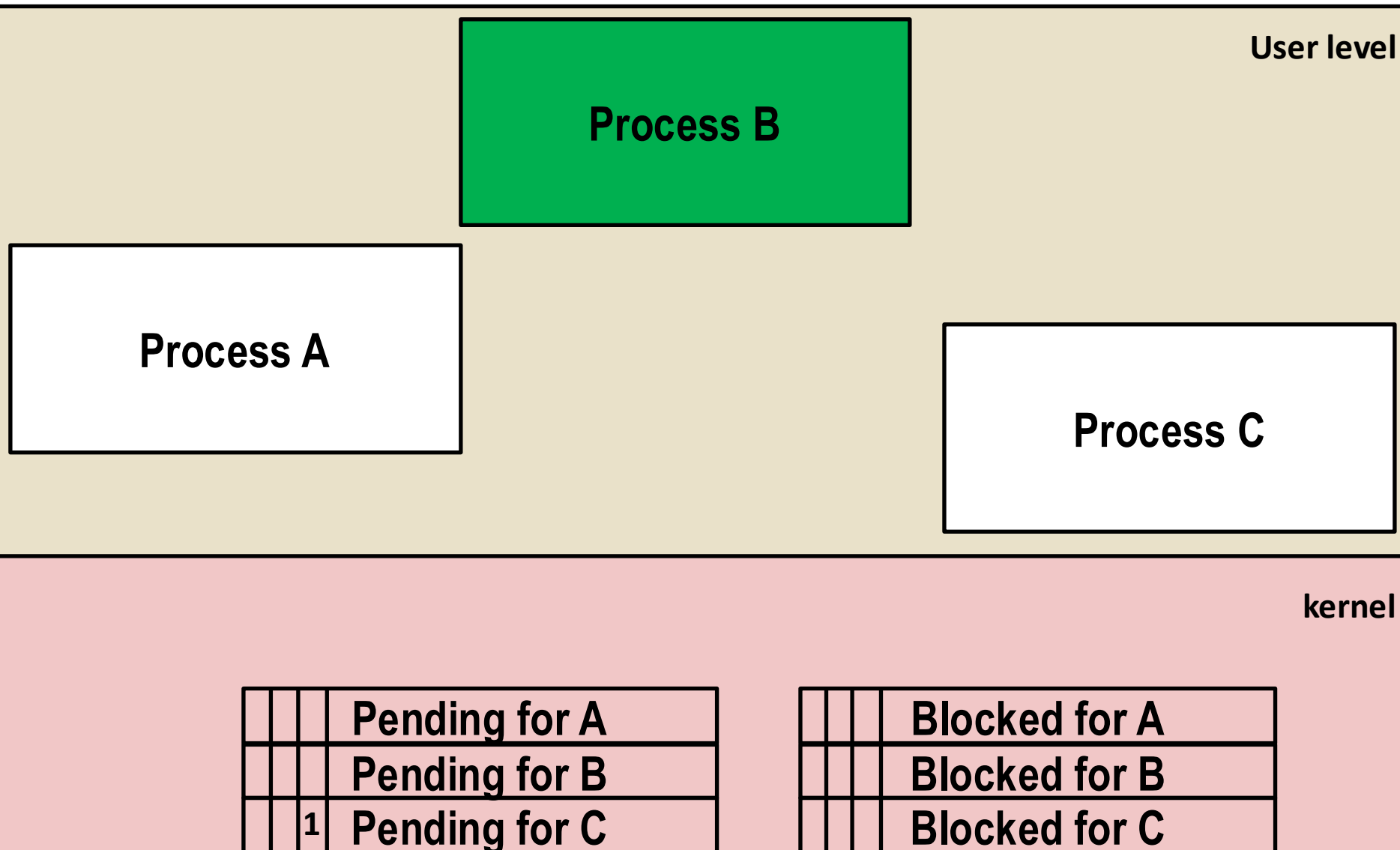
# Signal Concepts: Sending a Signal



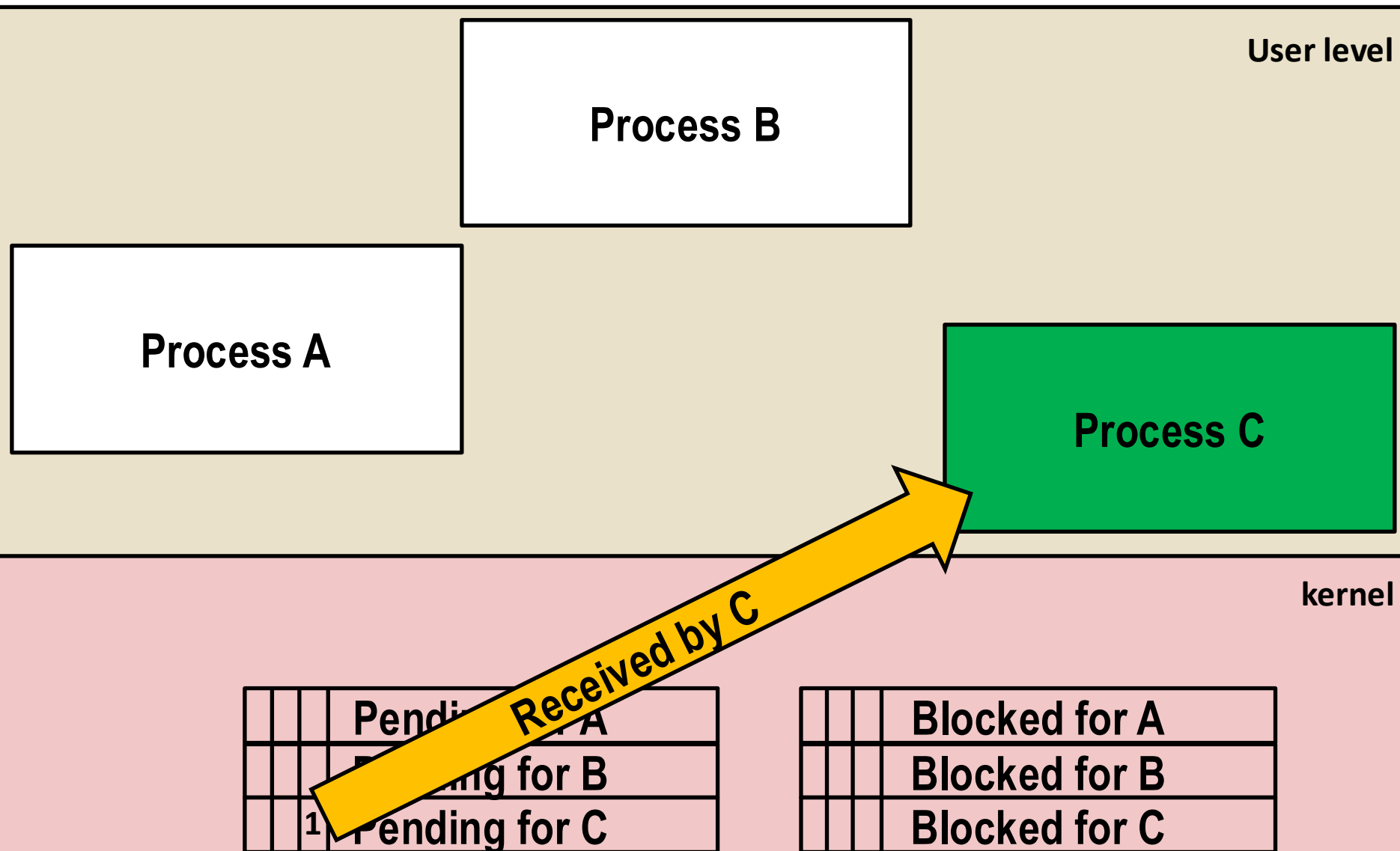
# Signal Concepts: Sending a Signal



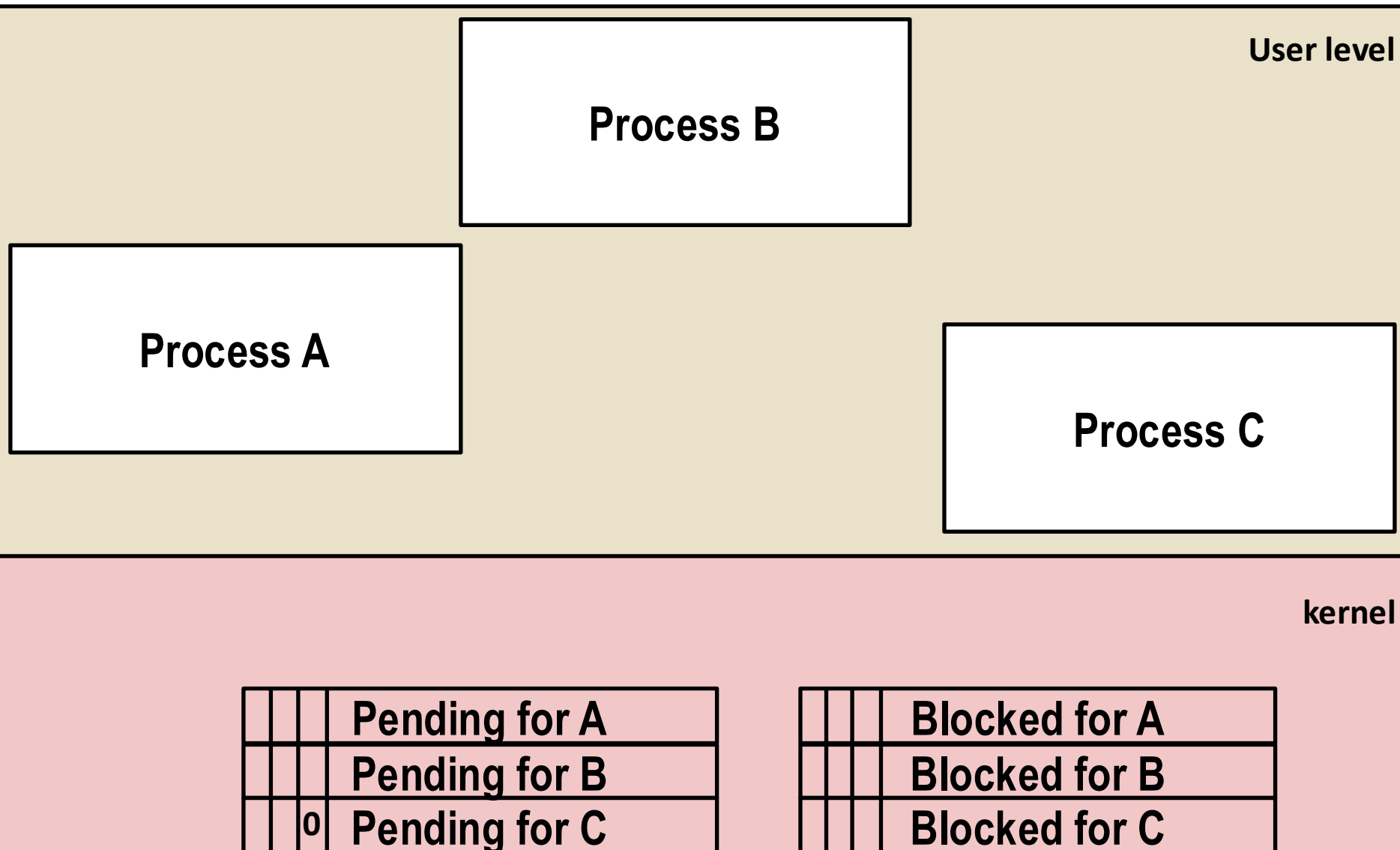
# Signal Concepts: Sending a Signal



# Signal Concepts: Sending a Signal

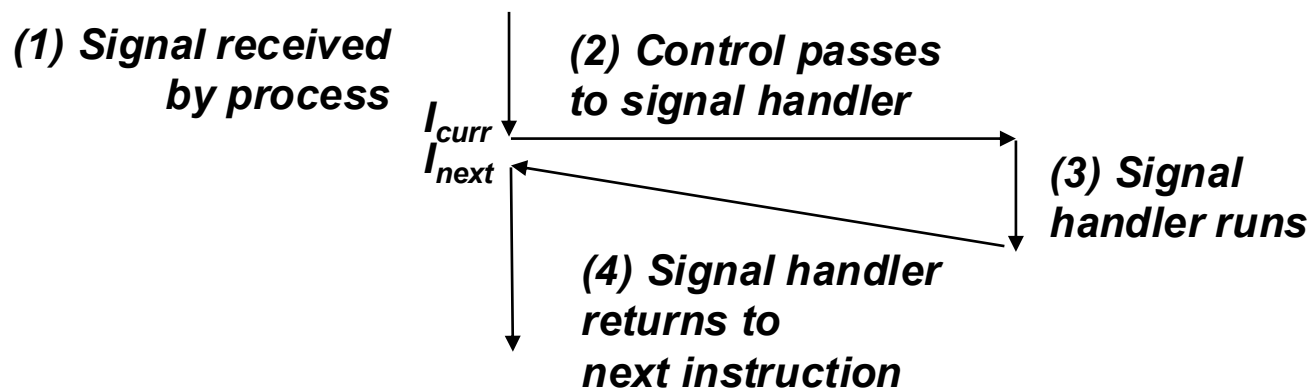


# Signal Concepts: Sending a Signal



# Signal Concepts: Receiving a Signal

- A destination process *receives* a signal when it is forced by the kernel to react in some way to the delivery of the signal
- 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 a hardware exception handler being called in response to an asynchronous interrupt:



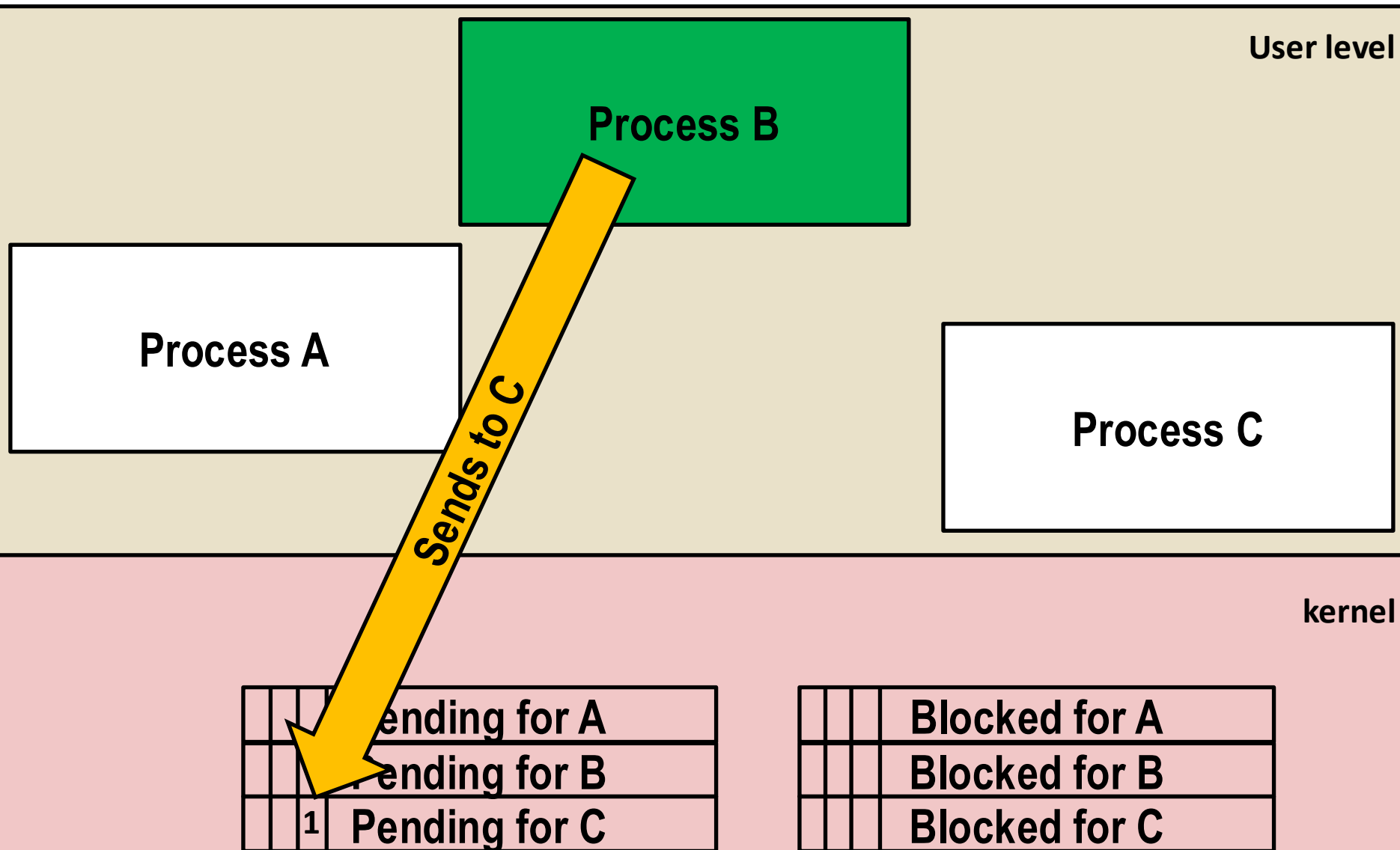
# Signal Concepts: Pending and Blocked Signals

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

# Signal Concepts: Pending/Blocked Bits

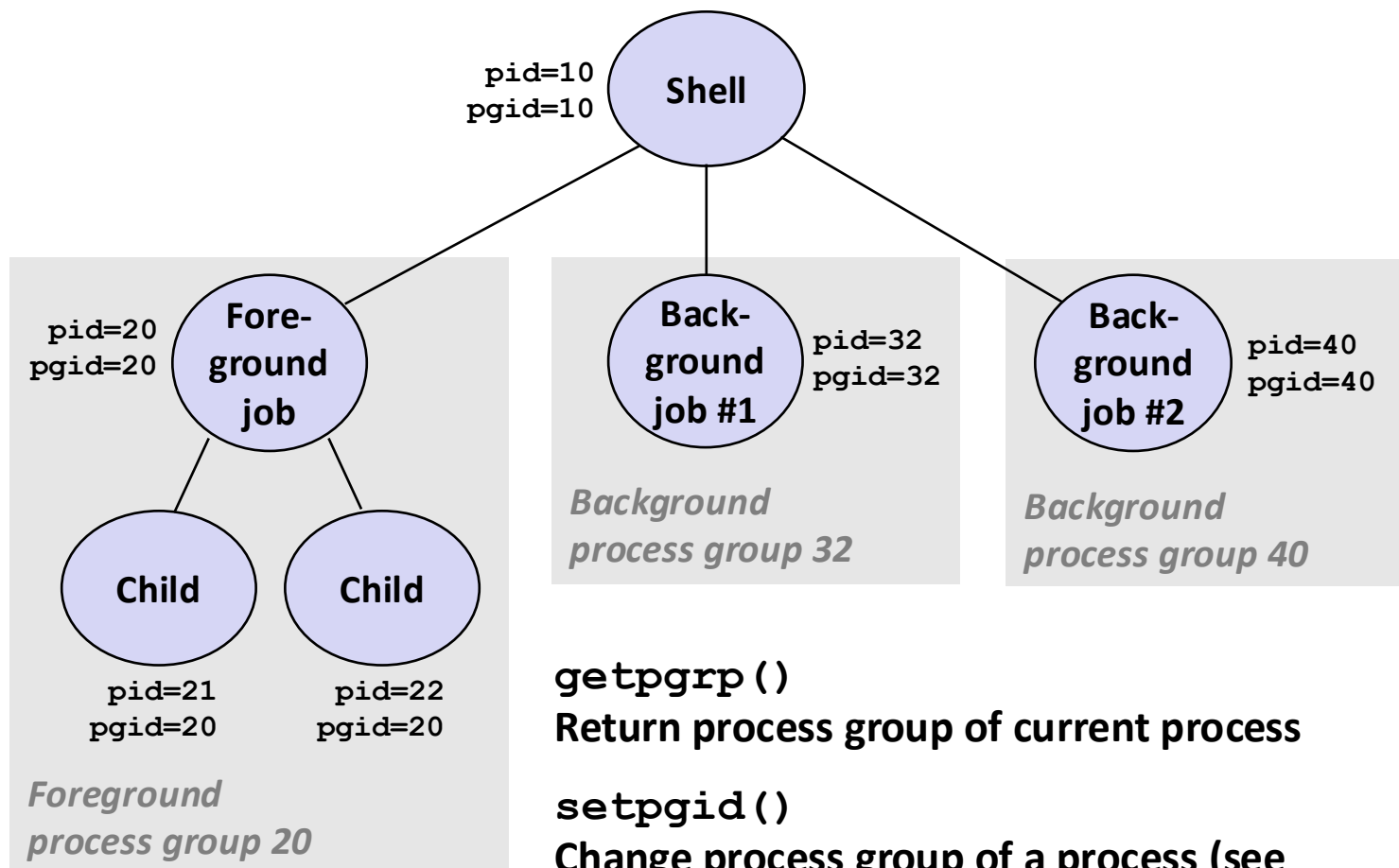
- Kernel maintains **pending** and **blocked** bit vectors in the context of each process
  - **pending**: represents the set of pending signals
    - Kernel sets bit *k* in **pending** when a signal of type *k* is delivered
    - Kernel clears bit *k* in **pending** when a signal of type *k* is received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

# Signal Concepts: Sending a Signal



# 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 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

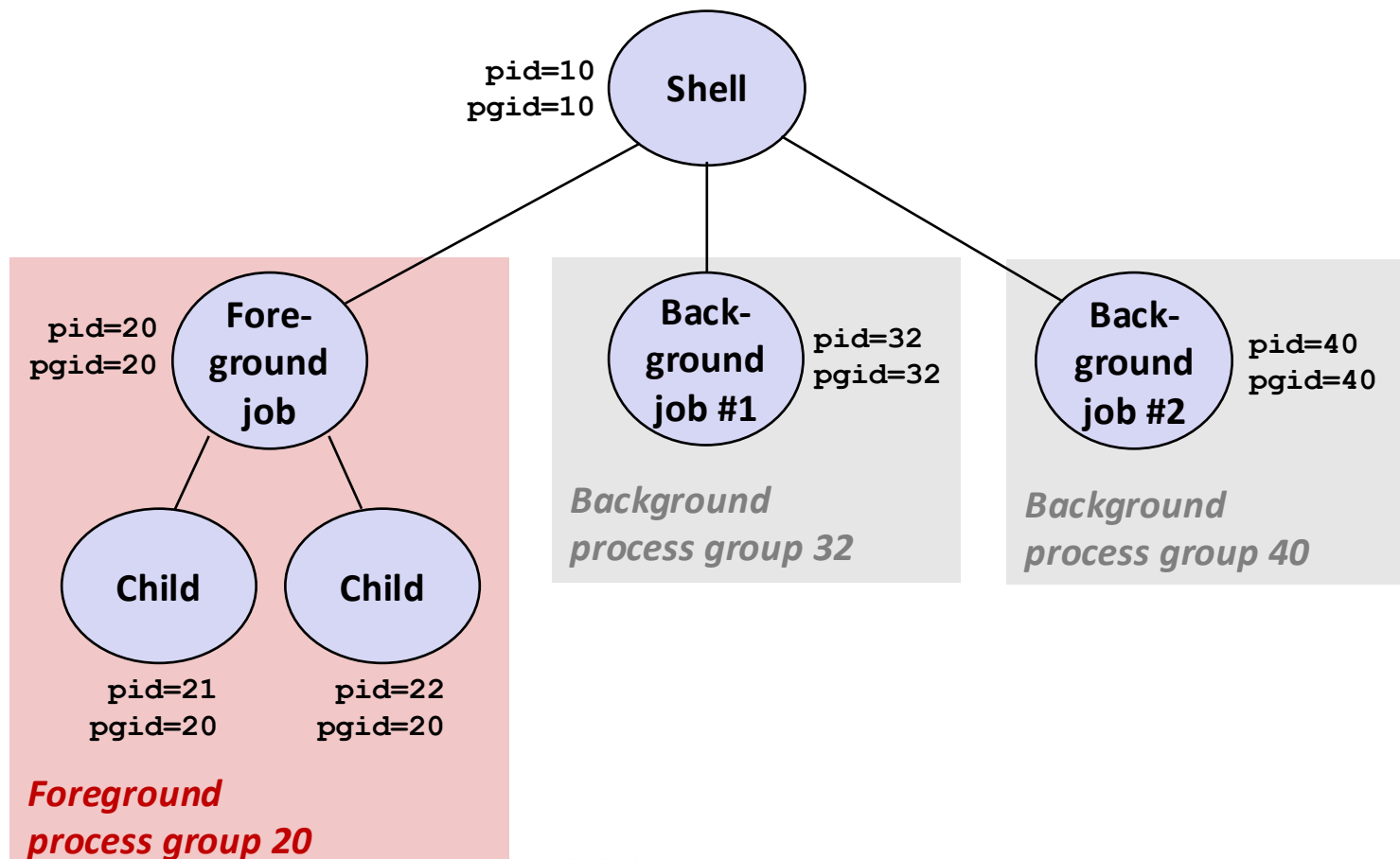
- `/bin/kill -9 -24817`  
Send SIGKILL to every process in process group 24817

```
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 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 `kill` Function

```
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)
                ;
        }

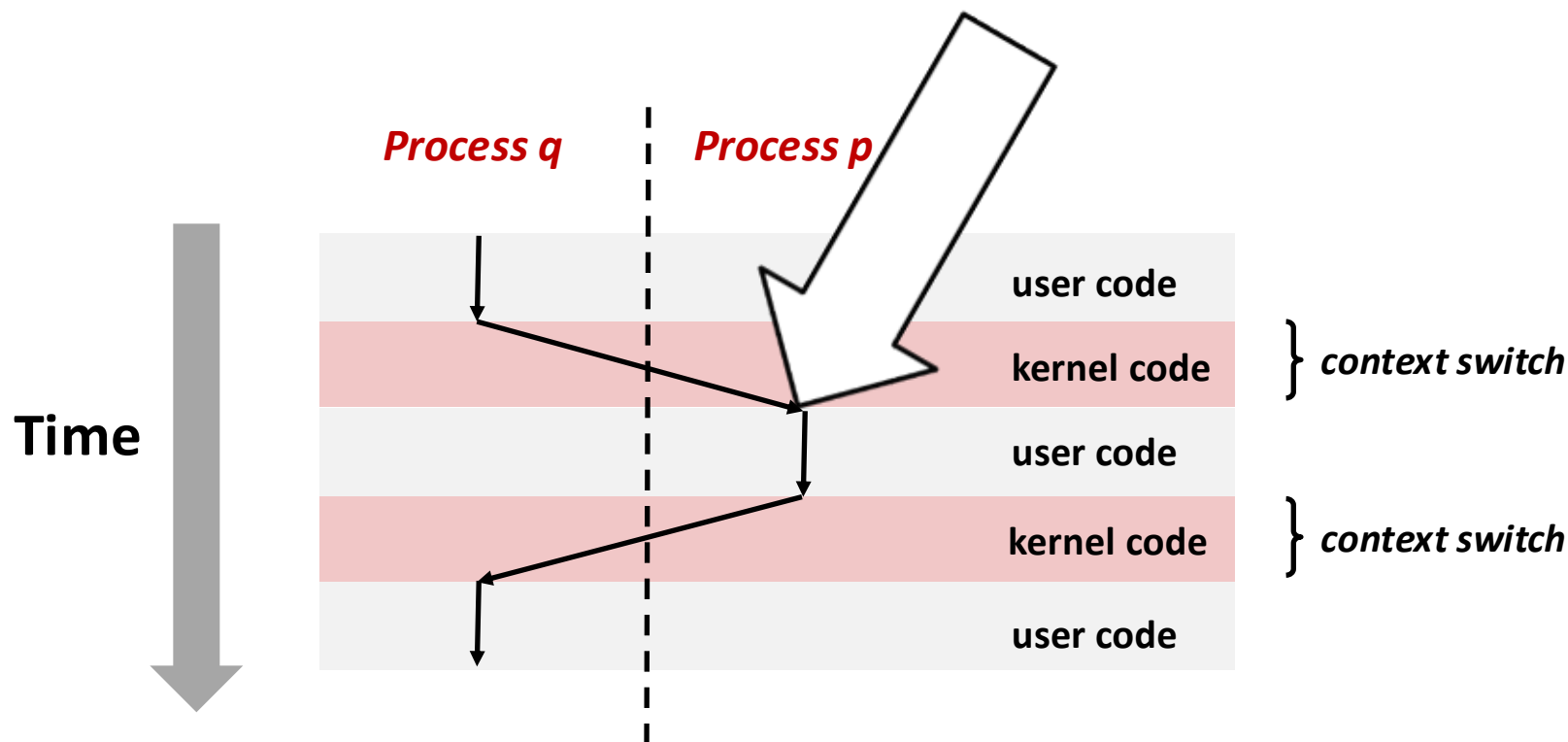
    for (i = 0; i < N; i++) {
        printf("Killing process %d\n", pid[i]);
        kill(pid[i], SIGINT);
    }

    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*

# Receiving Signals

- Suppose kernel is returning from an exception handler and is ready to pass control to process  $p$



# Receiving Signals

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

# Default Actions

- 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)`
- 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`
    - Referred to as *“installing”* the handler
    - Executing handler is called *“catching”* or *“handling”* the signal
    - 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

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

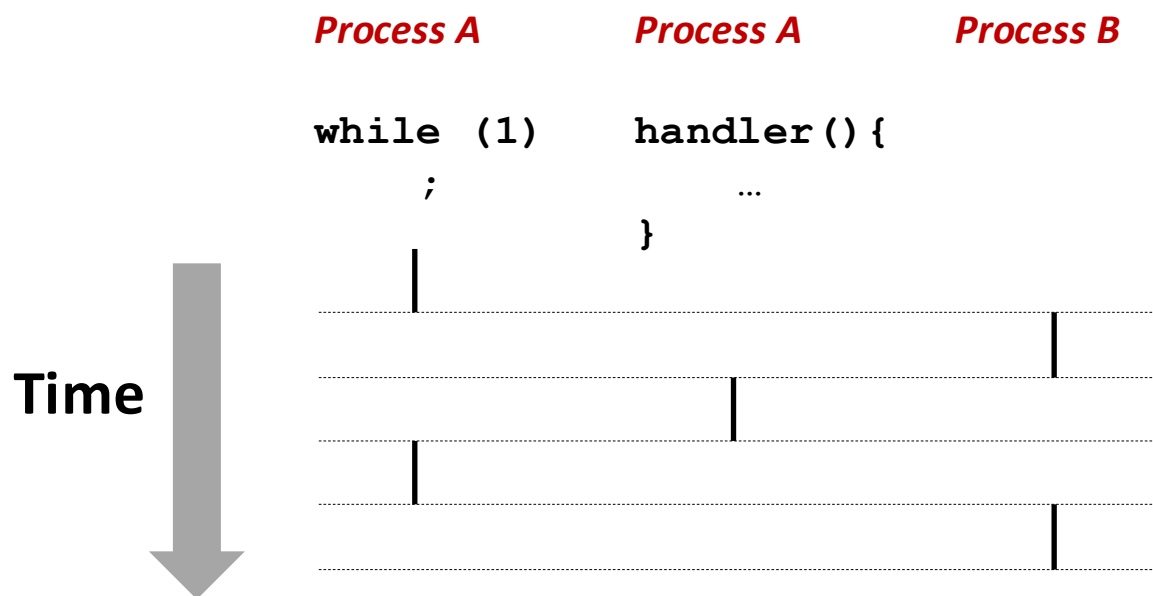
    /* Wait for the receipt of a signal */
    pause();

    return 0;
}
```

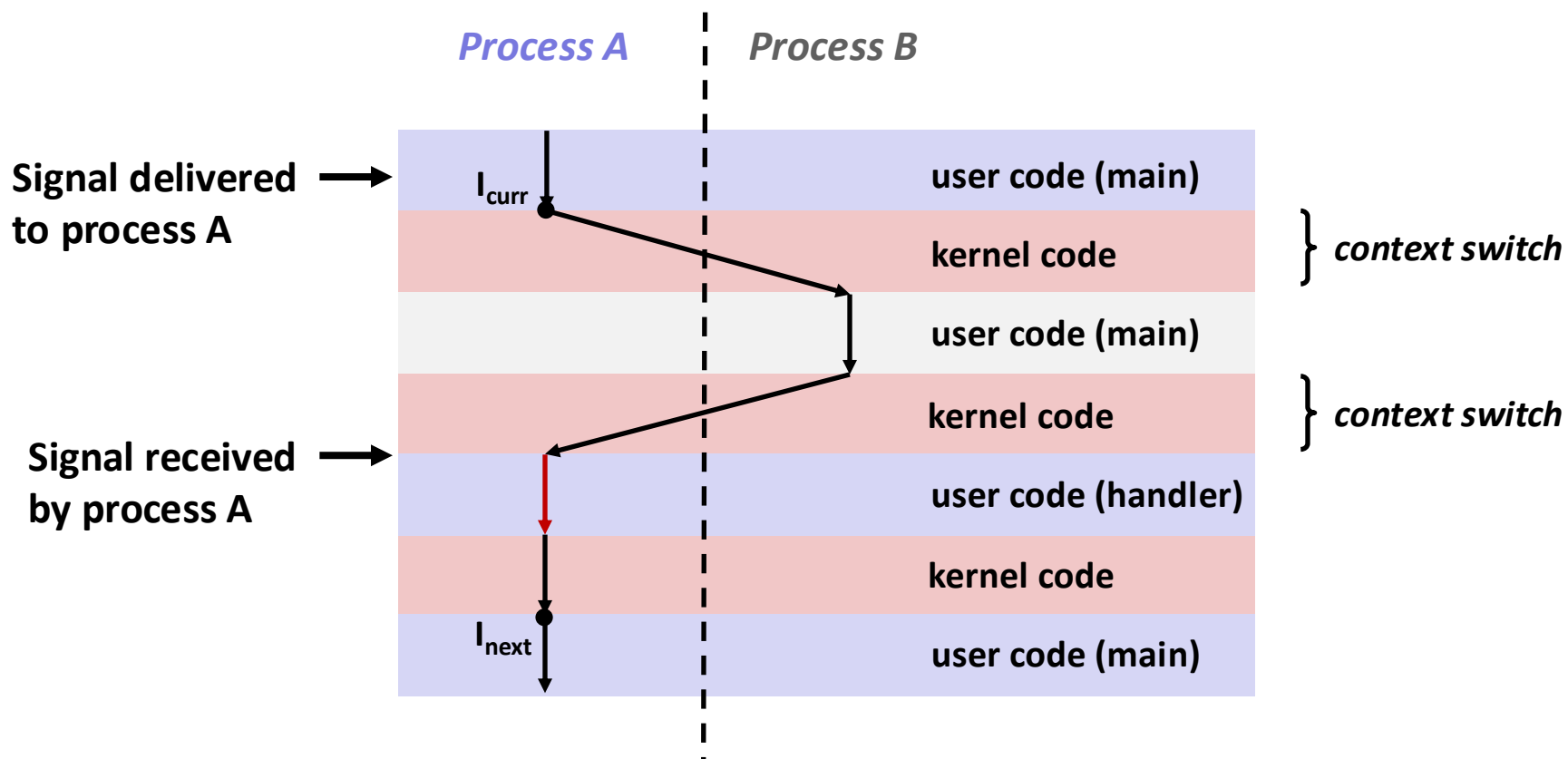
sigint.c

# Signals Handlers as Concurrent Flows

- A signal handler is a separate logical flow (not process) that runs concurrently with the main program
- But, this flow exists only until returns to main program

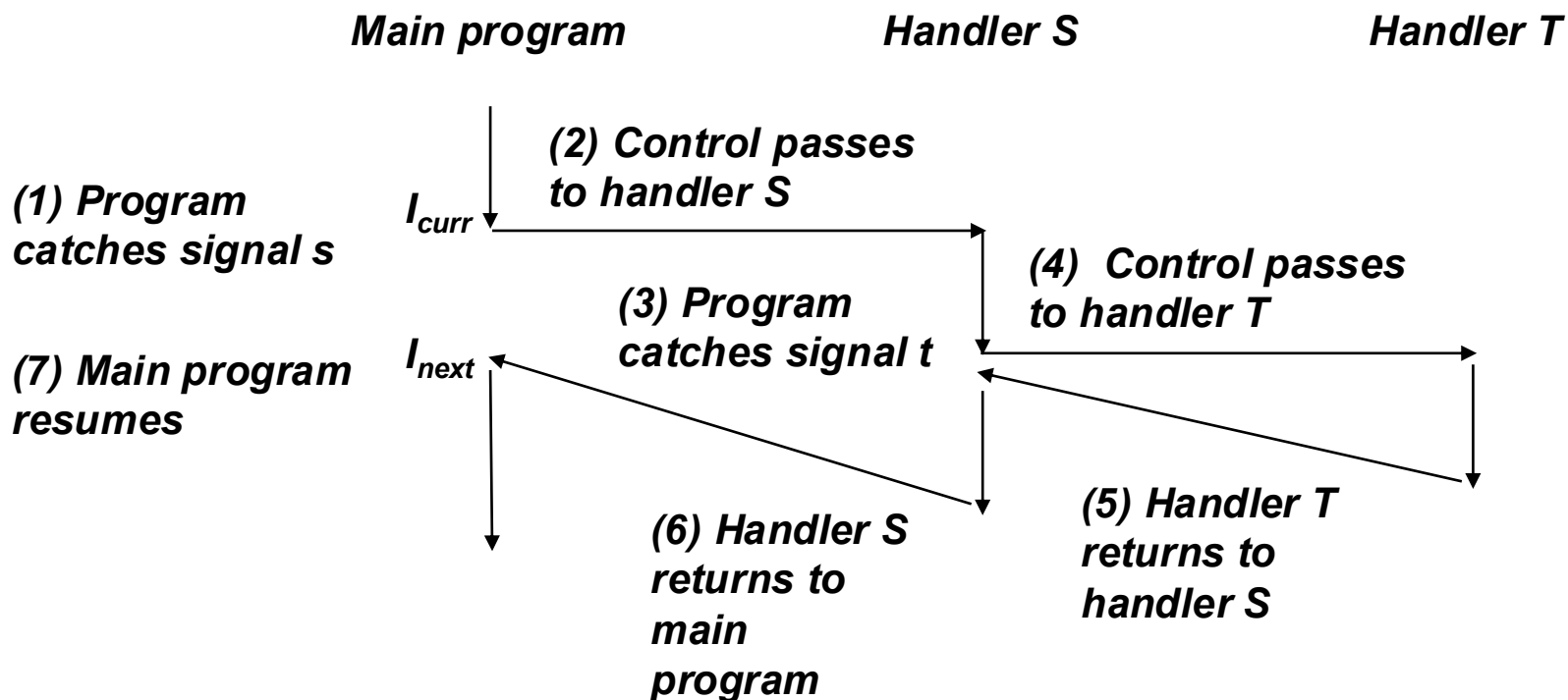


# Another View of Signal Handlers as Concurrent Flows



# Nested Signal Handlers

- Handlers can be interrupted by other handlers



# Blocking and Unblocking Signals

## ■ Implicit blocking mechanism

- Kernel blocks any pending signals of type currently being handled.
- E.g., A SIGINT handler can't be interrupted by another SIGINT

## ■ Explicit blocking and unblocking mechanism

- `sigprocmask` function

## ■ Supporting functions

- `sigemptyset` – Create empty set
- `sigfillset` – Add every signal number to set
- `sigaddset` – Add signal number to set
- `sigdelset` – Delete signal number from set

# Temporarily 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);
```

# Safe Signal Handling

- **Handlers are tricky because they are concurrent with main program and share the same global data structures.**
  - Shared data structures can become corrupted.
- **We'll explore concurrency issues later in the term.**
- **For now here are some guidelines to help you avoid trouble.**

# 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 other handlers don't overwrite your value of `errno`
- **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 as `volatile sig_atomic_t`**
  - *flag*: variable that is only read or written (e.g. `flag = 1`, not `flag++`)
  - Flag declared this way does not need to be protected like other globals

# Async-Signal-Safety

- Function is *async-signal-safe* if either reentrant (e.g., all variables stored on stack frame, CS:APP3e 12.7.2) or non-interruptible by signals.
- Posix guarantees 117 functions to be async-signal-safe
  - Source: “man 7 signal-safety”
  - 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

# Safe Formatted Output: Option #1

- Use the reentrant SIO (Safe I/O library) from `csapp.c` in your handlers.

- `ssize_t sio_puts(char s[]) /* Put string */`
- `ssize_t sio_putl(long v) /* Put long */`
- `void sio_error(char s[]) /* Put msg & exit */`

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

sigintsafe.c

# Safe Formatted Output: Option #2

- Use the new & improved reentrant `sio_printf` !
  - Handles restricted class of printf format strings
    - Recognizes: `%c %s %d %u %x %%`
    - Size designators `'l'` and `'z'`

```
void sigint_handler(int sig) /* Safe SIGINT handler */
{
    Sio_printf("So you think you can stop the bomb"
              " (process %d) with ctrl-%c, do you?\n",
              (int) getpid(), 'c');

    sleep(2);
    Sio_puts("Well...");
    sleep(1);
    Sio_puts("OK. :-)\n");
    _exit(0);
}
```

sigintsafe.c

# Correct Signal Handling

```
volatile int ccount = 0;
void child_handler(int sig) {
    int olderrno = errno;
    pid_t pid;
    if ((pid = wait(NULL)) < 0)
        Sio_error("wait error");
    ccount--;
    Sio_puts("Handler reaped child ");
    Sio_putl((long)pid);
    Sio_puts(" \n");
    sleep(1);
    errno = olderrno;
}

void fork14() {
    pid_t pid[N];
    int i;
    ccount = N;
    Signal(SIGCHLD, child_handler);

    for (i = 0; i < N; i++) {
        if ((pid[i] = Fork()) == 0) {
            Sleep(1);
            exit(0); /* Child exits */
        }
    }
    while (ccount > 0) /* Parent spins */
        ;
}
```

**This code is incorrect!**

- Pending signals are not queued
  - For each signal type, one bit indicates whether or not signal is pending...
  - ...thus at most one pending signal of any particular type.
- You can't use signals to count events, such as children terminating.

```
whaleshark> ./forks 14
Handler reaped child 23240
Handler reaped child 23241
...(hangs)
```

forks.c

# Correct Signal Handling

- **Must wait for all terminated child processes**
  - Put `wait` in a loop to reap all terminated children

```
void child_handler2(int sig)
{
    int olderrno = errno;
    pid_t pid;
    while ((pid = wait(NULL)) > 0) {
        ccount--;
        Sio_puts("Handler reaped child ");
        Sio_putl((long)pid);
        Sio_puts(" \n");
    }
    if (errno != ECHILD)
        Sio_error("wait error");
    errno = olderrno;
}
```

(Here N = 5)

```
whaleshark> ./forks 15
Handler reaped child 23246
Handler reaped child 23247
Handler reaped child 23248
Handler reaped child 23249
Handler reaped child 23250
whaleshark>
```

# Synchronizing Flows to Avoid Races

## ■ SIGCHLD handler for a simple shell

- Blocks all signals while running critical code

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

    Sigfillset(&mask_all);
    while ((pid = waitpid(-1, NULL, 0)) > 0) { /* Reap child */
        Sigprocmask(SIG_BLOCK, &mask_all, &prev_all);
        deletejob(pid); /* Delete the child from the job list */
        Sigprocmask(SIG_SETMASK, &prev_all, NULL);
    }
    if (errno != ECHILD)
        Sio_error("waitpid error");
    errno = olderrno;
}
```

procmask1.c

# Synchronizing Flows to Avoid Races

- Simple shell with a subtle synchronization error because it assumes parent runs before child.

```
int main(int argc, char **argv)
{
    int pid;
    sigset_t mask_all, prev_all;
    int n = N; /* N = 5 */
    Sigfillset(&mask_all);
    Signal(SIGCHLD, handler);
    initjobs(); /* Initialize the job list */

    while (n-- > 0) {
        if ((pid = Fork()) == 0) { /* Child */
            Execve("/bin/date", argv, NULL);
        }
        Sigprocmask(SIG_BLOCK, &mask_all, &prev_all); /* Parent */
        addjob(pid); /* Add the child to the job list */
        Sigprocmask(SIG_SETMASK, &prev_all, NULL);
    }
    exit(0);
}
```

procmask1.c

# Corrected Shell Program without Race

```
int main(int argc, char **argv)
{
    int pid;
    sigset_t mask_all, mask_one, prev_one;
    int n = N; /* N = 5 */
    Sigfillset(&mask_all);
    Sigemptyset(&mask_one);
    Sigaddset(&mask_one, SIGCHLD);
    Signal(SIGCHLD, handler);
    initjobs(); /* Initialize the job list */

    while (n--) {
        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);
        }
        Sigprocmask(SIG_BLOCK, &mask_all, NULL); /* Parent process */
        addjob(pid); /* Add the child to the job list */
        Sigprocmask(SIG_SETMASK, &prev_one, NULL); /* Unblock SIGCHLD */
    }
    exit(0);
}
```

# Explicitly Waiting for Signals

- Handlers for program explicitly waiting for SIGCHLD to arrive.

```
volatile sig_atomic_t pid;

void sigchld_handler(int s)
{
    int olderrno = errno;
    pid = Waitpid(-1, NULL, 0); /* Main is waiting for nonzero pid */
    errno = olderrno;
}

void sigint_handler(int s)
{
}
```

waitforsignal.c

# Explicitly Waiting for Signals

```

int main(int argc, char **argv) {
    sigset_t mask, prev;
    int n = N; /* N = 10 */
    Signal(SIGCHLD, sigchld_handler);
    Signal(SIGINT, sigint_handler);
    Sigemptyset(&mask);
    Sigaddset(&mask, SIGCHLD);

    while (n--) {
        Sigprocmask(SIG_BLOCK, &mask, &prev); /* Block SIGCHLD */
        if (Fork() == 0) /* Child */
            exit(0);
        /* Parent */
        pid = 0;
        Sigprocmask(SIG_SETMASK, &prev, NULL); /* Unblock SIGCHLD */

        /* Wait for SIGCHLD to be received (wasteful!) */
        while (!pid)
            ;
        /* Do some work after receiving SIGCHLD */
        printf(".");
    }
    printf("\n");
    exit(0);
}

```

Similar to a shell waiting for a foreground job to terminate.

waitforsignal.c

# Explicitly Waiting for Signals

```
while (!pid)
    ;
```

## ■ Program is correct, but very wasteful

- Program in busy-wait loop

```
while (!pid) /* Race! */
    pause();
```

## ■ Possible race condition

- Between checking pid and starting pause, might receive signal

```
while (!pid) /* Too slow! */
    sleep(1);
```

## ■ Safe, but slow

- Will take up to one second to respond

# Waiting for Signals with `sigsuspend`

- `int sigsuspend(const sigset_t *mask)`
- Equivalent to atomic (uninterruptable) version of:

```
sigprocmask(SIG_SETMASK, &mask, &prev);  
pause();  
sigprocmask(SIG_SETMASK, &prev, NULL);
```

# Waiting for Signals with `sigsuspend`

```
int main(int argc, char **argv) {
    sigset_t mask, prev;
    int n = N; /* N = 10 */
    Signal(SIGCHLD, sigchld_handler);
    Signal(SIGINT, sigint_handler);
    Sigemptyset(&mask);
    Sigaddset(&mask, SIGCHLD);
    while (n-- > 0) {
        Sigprocmask(SIG_BLOCK, &mask, &prev); /* Block SIGCHLD */
        if (Fork() == 0) /* Child */
            exit(0);

        /* Wait for SIGCHLD to be received */
        pid = 0;
        while (!pid)
            Sigsuspend(&prev);
        /* Optionally unblock SIGCHLD */
        Sigprocmask(SIG_SETMASK, &prev, NULL);
        /* Do some work after receiving SIGCHLD */
        printf(".");
    }
    printf("\n");
    exit(0);
}
```

sigsuspend.c

# Summary

- **Signals provide process-level exception handling**
  - Can generate from user programs
  - Can define effect by declaring signal handler
  - Be very careful when writing signal handlers

# Additional slides

# Nonlocal Jumps: `setjmp/longjmp`

- **Powerful (but dangerous) user-level mechanism for transferring control to an arbitrary location**
  - Controlled to way to break the procedure call / return discipline
  - Useful for error recovery and signal handling
- **`int setjmp(jmp_buf j)`**
  - Must be called before `longjmp`
  - Identifies a return site for a subsequent `longjmp`
  - Called **once**, returns **one or more** times
- **Implementation:**
  - Remember where you are by storing the current **register context**, **stack pointer**, and **PC value** in `jmp_buf`
  - Return 0

# setjmp/longjmp (cont)

- `void longjmp(jmp_buf j, int i)`
  - Meaning:
    - return from the `setjmp` remembered by jump buffer `j` again ...
    - ... this time returning `i` instead of 0
  - Called after `setjmp`
  - Called **once**, but **never** returns
- **longjmp Implementation:**
  - Restore register context (stack pointer, base pointer, PC value) from jump buffer `j`
  - Set `%eax` (the return value) to `i`
  - Jump to the location indicated by the PC stored in jump buf `j`

# setjmp/longjmp Example

- Goal: return directly to original caller from a deeply-nested function

```
/* Deeply nested function foo */  
void foo(void)  
{  
    if (error1)  
        longjmp(buf, 1);  
    bar();  
}  
  
void bar(void)  
{  
    if (error2)  
        longjmp(buf, 2);  
}
```

## setjmp/longjmp Example (cont)

```
jmp_buf buf;

int error1 = 0;
int error2 = 1;

void foo(void), bar(void);

int main()
{
    switch(setjmp(buf)) {
        case 0:
            foo();
            break;
        case 1:
            printf("Detected an error1 condition in foo\n");
            break;
        case 2:
            printf("Detected an error2 condition in foo\n");
            break;
        default:
            printf("Unknown error condition in foo\n");
    }
    exit(0);
}
```

# Limitations of Nonlocal Jumps

## ■ Works within stack discipline

- Can only long jump to environment of function that has been called but not yet completed

```

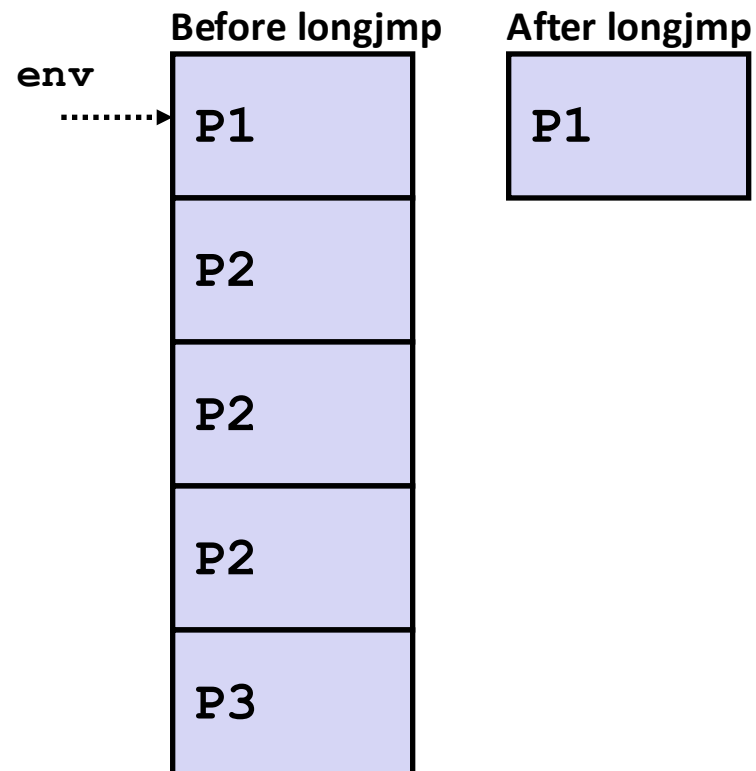
jmp_buf env;

P1()
{
    if (setjmp(env)) {
        /* Long Jump to here */
    } else {
        P2();
    }
}

P2()
{ . . . P2(); . . . P3(); }

P3()
{
    longjmp(env, 1);
}

```



# Limitations of Long Jumps (cont.)

## ■ Works within stack discipline

- Can only long jump to environment of function that has been called but not yet completed

```

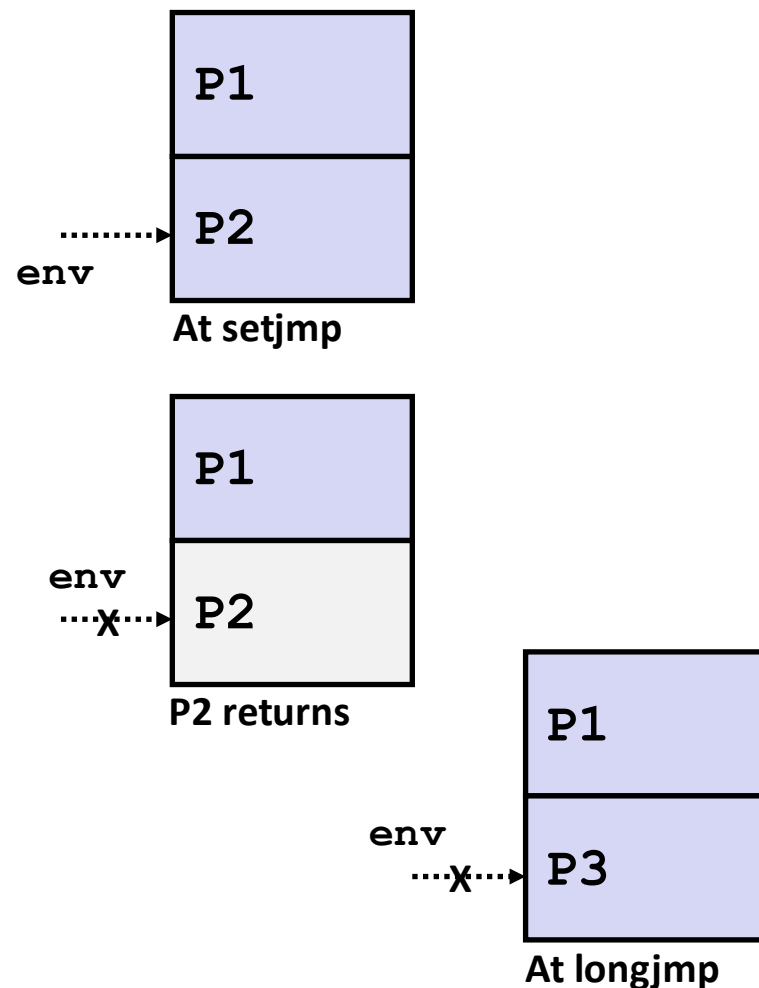
jmp_buf env;

P1 ()
{
    P2 (); P3 ();
}

P2 ()
{
    if (setjmp(env)) {
        /* Long Jump to here */
    }
}

P3 ()
{
    longjmp(env, 1);
}

```



# Putting It All Together: A Program That Restarts Itself When `ctrl-c`'d

```
#include "csapp.h"

sigjmp_buf buf;

void handler(int sig)
{
    siglongjmp(buf, 1);
}

int main()
{
    if (!sigsetjmp(buf, 1)) {
        Signal(SIGINT, handler);
        Sio_puts("starting\n");
    }
    else
        Sio_puts("restarting\n");

    while(1) {
        Sleep(1);
        Sio_puts("processing...\n");
    }
    exit(0); /* Control never reaches here */
}
```

```
greatwhite> ./restart
starting
processing...
processing...
processing...
restarting
processing... ← Ctrl-c
processing...
restarting
processing... ← Ctrl-c
processing...
processing...
```

restart.c