

Exceptional Control Flow

COMP402127: Introduction to Computer Systems

Hao Li

Xi'an Jiaotong University

Today

- **Exceptional Control Flow**
- Simple Shell Example
- Signals
- If we have time: Nonlocal Jumps

Printers Used to Catch on Fire



Highly Exceptional Control Flow

```

234 static int lp_check_status(int minor)
235 {
236     int error = 0;
237     unsigned int last = lp_table[minor].last_error;
238     unsigned char status = r_str(minor);
239     if ((status & LP_PERRORP) && !(LP_F(minor) & LP_CAREFUL))
240         /* No error. */
241         last = 0;
242     else if ((status & LP_POUTPA)) {
243         if (last != LP_POUTPA) {
244             last = LP_POUTPA;
245             printk(KERN_INFO "lp%d out of paper\n", minor);
246         }
247         error = -ENOSPC;
248     } else if (!(status & LP_PSELECD)) {
249         if (last != LP_PSELECD) {
250             last = LP_PSELECD;
251             printk(KERN_INFO "lp%d off-line\n", minor);
252         }
253         error = -EIO;
254     } else if (!(status & LP_PERRORP)) {
255         if (last != LP_PERRORP) {
256             last = LP_PERRORP;
257             printk(KERN_INFO "lp%d on fire\n", minor);
258         }
259         error = -EIO;
260     } else {
261         last = 0; /* Come here if LP_CAREFUL is set and no
262                  errors are reported. */
263     }
264
265     lp_table[minor].last_error = last;
266
267     if (last != 0)
268         lp_error(minor);
269
270     return error;
271 }

```

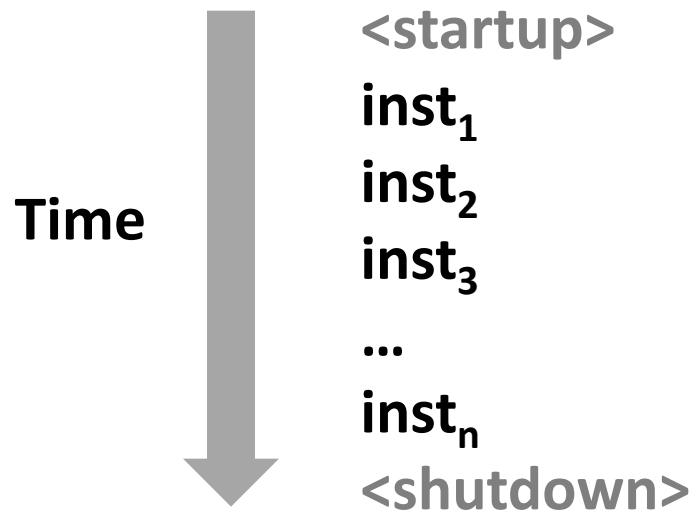
<https://git.kernel.org/pub/scm/linux/kernel/git/torvalds/linux.git/tree/drivers/char/lp.c?h=v5.0-rc3>

Control Flow

■ Processors do only one thing:

- From startup to shutdown, each CPU core simply reads and executes (interprets) a sequence of instructions, one at a time *
- This sequence is the CPU's *control flow* (or *flow of control*)

Physical control flow



- * Externally, from an architectural viewpoint (internally, the CPU may use parallel out-of-order execution)

Altering the Control Flow

■ Up to now: two mechanisms for changing control flow:

- Jumps and branches
- Call and return

React to changes in *program state*

■ Insufficient for a useful system:

Difficult to react to changes in *system state*

- Data arrives from a disk or a network adapter
- Instruction divides by zero
- User hits Ctrl-C at the keyboard
- System timer expires

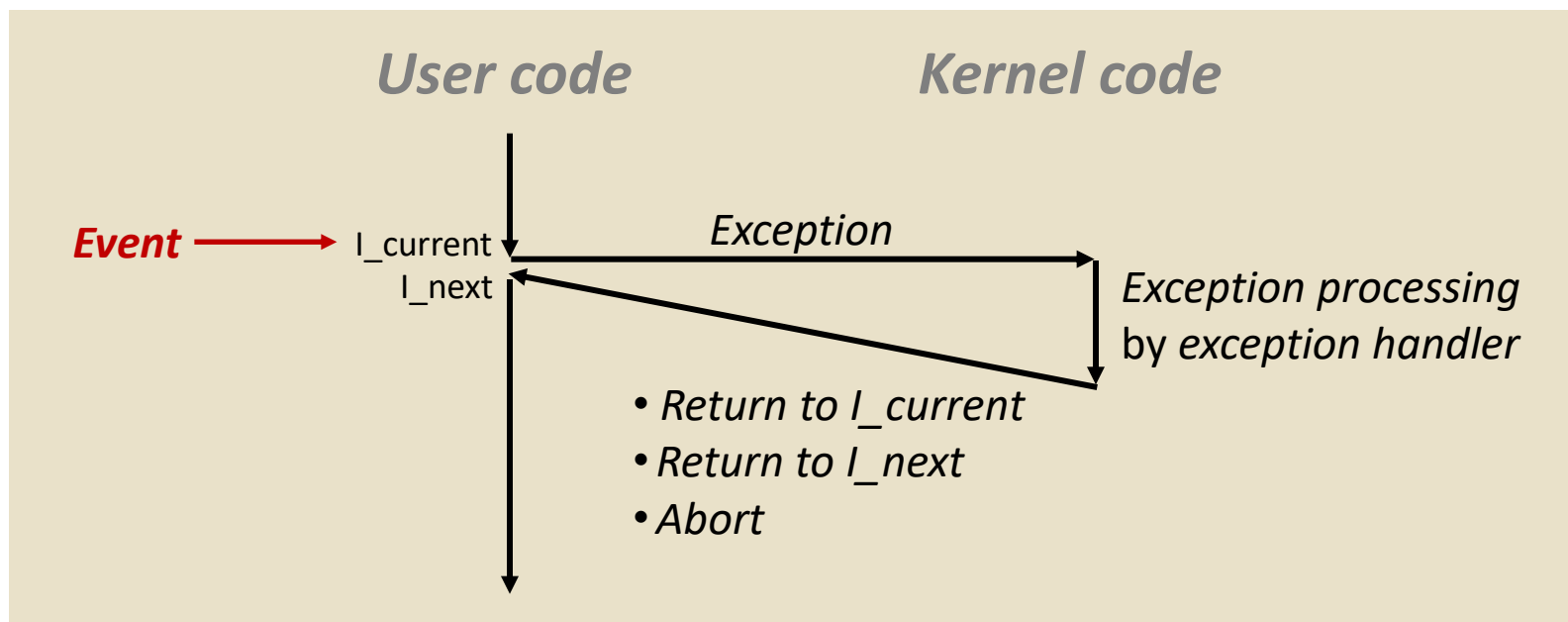
■ System needs mechanisms for “exceptional control flow”

Exceptional Control Flow

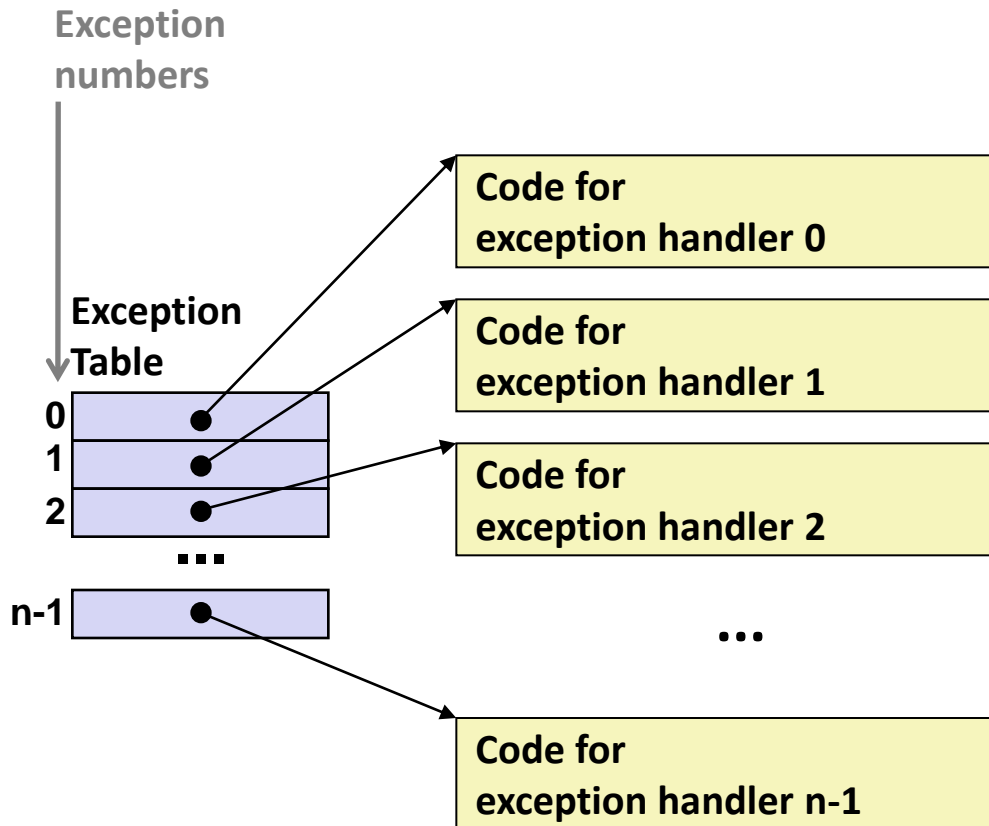
- **Exists at all levels of a computer system**
- **Low level mechanisms**
 - 1. **Exceptions**
 - Change in control flow in response to a system event (i.e., change in system state)
 - Implemented using combination of hardware and OS software
- **Higher level mechanisms**
 - 2. **Process context switch**
 - Implemented by OS software and hardware timer
 - 3. **Signals**
 - Implemented by OS software
 - 4. **Nonlocal jumps**: `setjmp()` and `longjmp()`
 - Implemented by C runtime library

Exceptions

- An **exception** is a transfer of control to the OS *kernel* in response to some *event* (i.e., change in processor state)
 - Kernel is the memory-resident part of the OS
 - Examples of events: Divide by 0, arithmetic overflow, page fault, I/O request completes, typing Ctrl-C

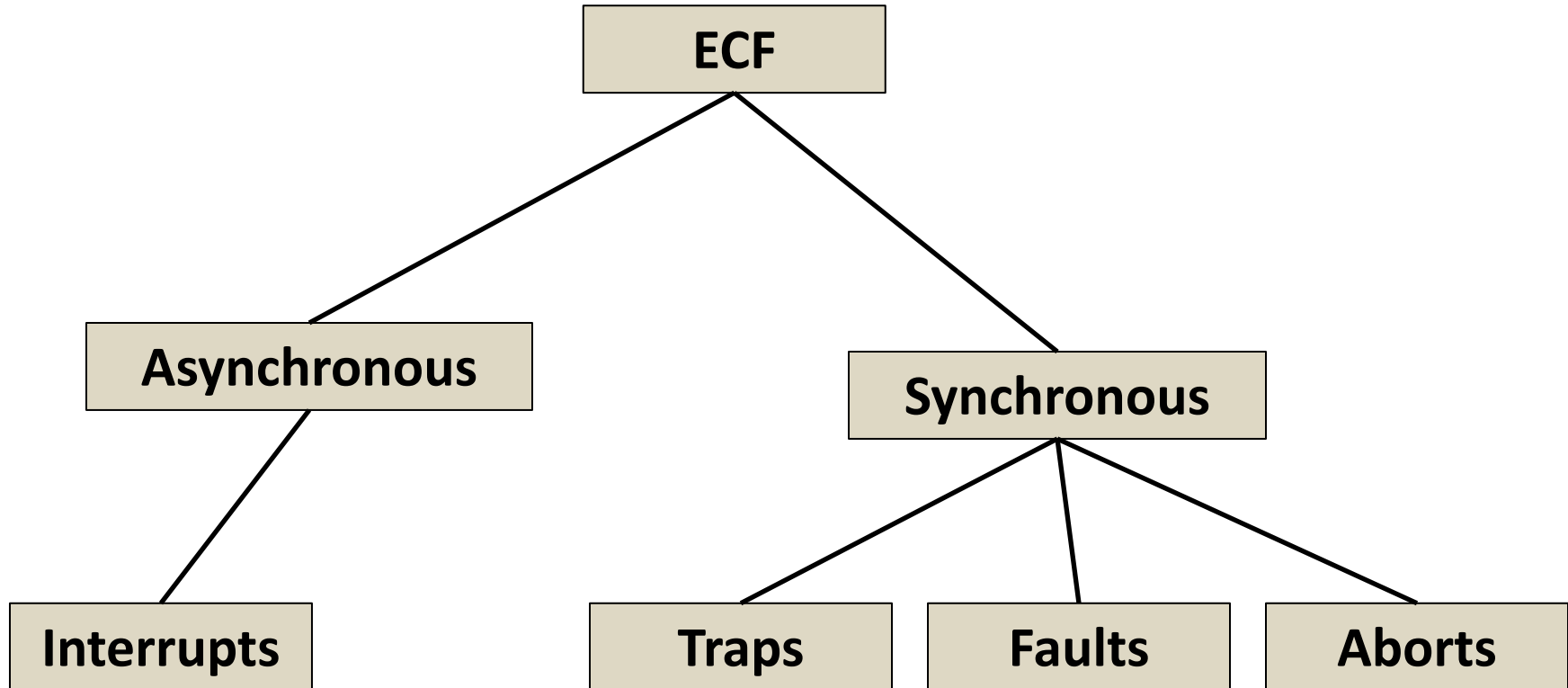


Exception Tables



- Each type of event has a unique exception number k
- k = index into exception table (a.k.a. interrupt vector)
- Handler k is called each time exception k occurs

Taxonomy of Hardware ECF



Asynchronous Exceptions (Interrupts)

■ Caused by events external to the processor

- Indicated by setting the processor's *interrupt pin*
- Handler returns to “next” instruction

■ Examples:

- Timer interrupt
 - Every few ms, an external timer chip triggers an interrupt
 - Used by the kernel to take back control from user programs
- I/O interrupt from external device
 - Hitting Ctrl-C at the keyboard
 - Arrival of a packet from a network
 - Arrival of data from a disk

Synchronous Exceptions

■ Caused by events that occur as a result of executing an instruction:

■ *Traps*

- Intentional, set program up to “trip the trap” and do something
- Examples: ***system calls***, gdb breakpoints
- Returns control to “next” instruction

■ *Faults*

- Unintentional but possibly recoverable
- Examples: page faults (recoverable), protection faults (unrecoverable), floating point exceptions
- Either re-executes faulting (“current”) instruction or aborts

■ *Aborts*

- Unintentional and unrecoverable
- Examples: illegal instruction, parity error, machine check
- Aborts current program

System Calls

- Each x86-64 system call has a unique ID number
- Examples:

<i>Number</i>	<i>Name</i>	<i>Description</i>
0	read	Read file
1	write	Write file
2	open	Open file
3	close	Close file
4	stat	Get info about file
57	fork	Create process
59	execve	Execute a program
60	_exit	Terminate process
62	kill	Send signal to process

System Call Example: Opening File

- User calls: `open(filename, options)`
- Calls `__open` function, which invokes system call instruction `syscall`

0000000000e5d70 <__open>:

...

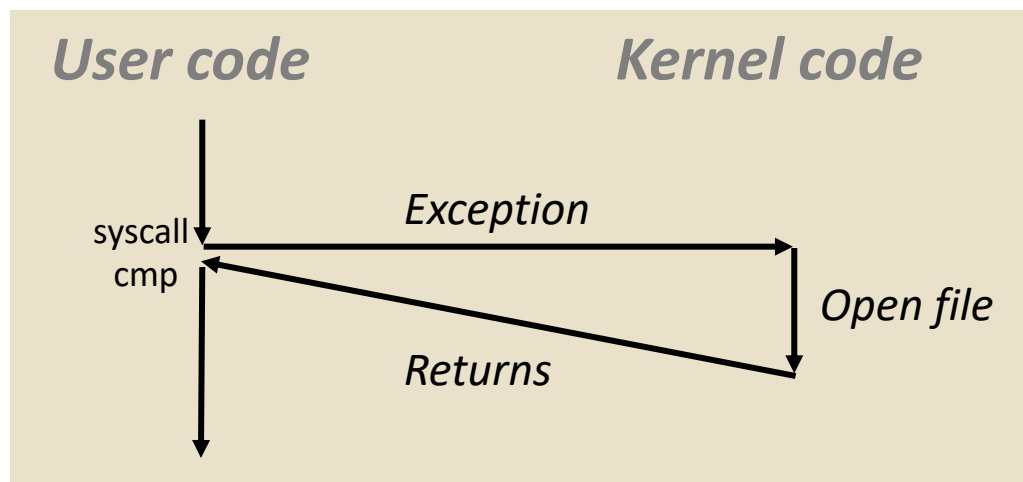
e5d79: b8 02 00 00 00 `mov $0x2,%eax` # open is syscall #2

e5d7e: 0f 05 `syscall` # Return value in %rax

e5d80: 48 3d 01 f0 ff ff `cmp $0xfffffffffff001,%rax`

...

e5dfa: c3 `retq`



- `%rax` contains syscall number
- Other arguments in `%rdi`, `%rsi`, `%rdx`, `%r10`, `%r8`, `%r9`
- Return value in `%rax`
- Negative value is an error corresponding to negative `errno`

System Call

- User calls: `open (filename, flags, mode)`
- Calls `__open` function

```

0000000000e5d70 <__open@libc.so.6>
...
e5d79: b8 02 00 00 00
e5d7e: 0f 05          syscall
e5d80: 48 3d 01 f0 ff ff  cmp     $0xfffffffff, %eax
...
e5dfa: c3            retq
  
```

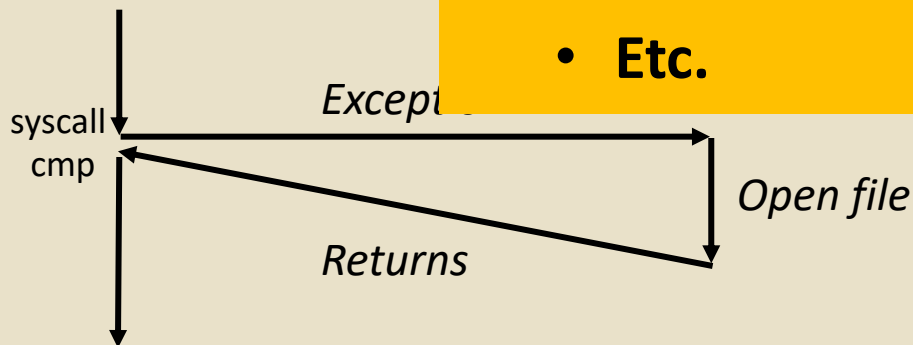
Almost like a function call

- Transfer of control
- On return, executes next instruction
- Passes arguments using calling convention
- Gets result in `%rax`

One Important exception!

- Executed by Kernel
- Different set of privileges
- And other differences:
 - E.g., “address” of “function” is in `%rax`
 - Uses `errno`
 - Etc.

User code



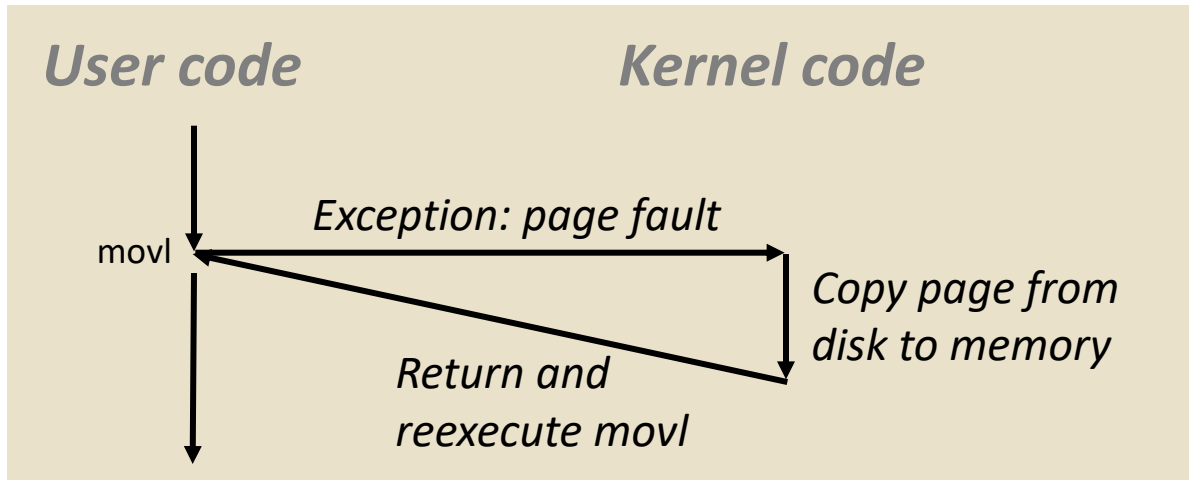
- Return value in `%rax`
- Negative value is an error corresponding to negative `errno`

Fault Example: Page Fault

- User writes to memory location
- That portion (page) of user's memory is currently on disk

```
int a[1000];
main ()
{
    a[500] = 13;
}
```

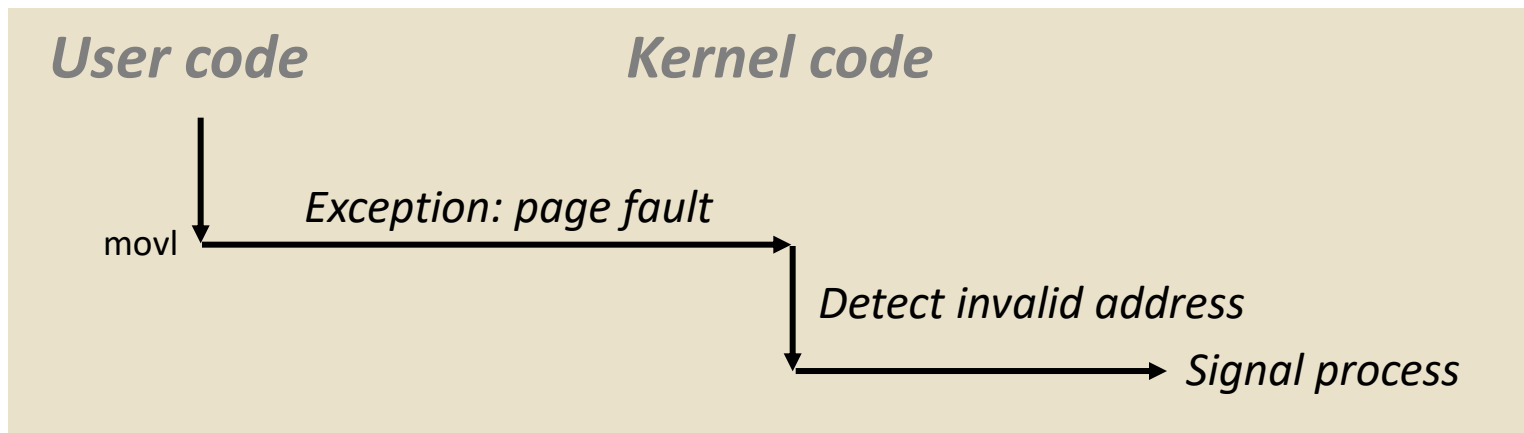
80483b7:	c7 05 10 9d 04 08 0d	movl	\$0xd,0x8049d10
----------	----------------------	------	-----------------



Fault Example: Invalid Memory Reference

```
int a[1000];  
main ()  
{  
    a[5000] = 13;  
}
```

80483b7: c7 05 60 e3 04 08 0d movl \$0xd,0x804e360



- Sends **SIGSEGV** signal to user process
- User process exits with “segmentation fault”

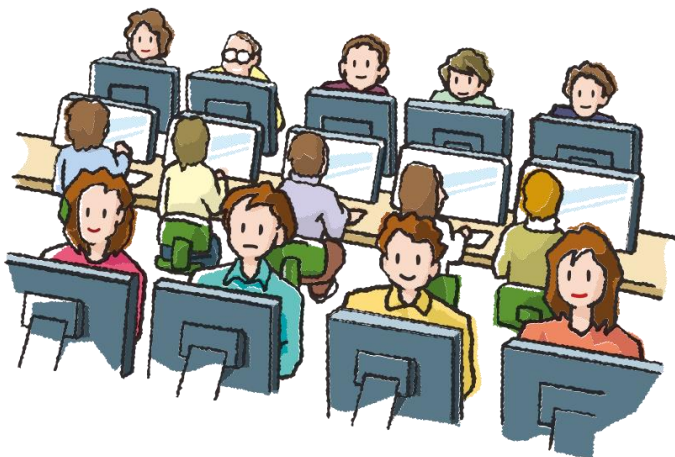
Today

- Exceptional Control Flow
- **Simple Shell Example**
- Signals
- If we have time: Nonlocal Jumps

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)



```
shark.ics.cmu.edu - PuTTY
zweinber@hammerheadshark ~
$ ls
15213      career  kilordle-strats  test      test.o      test.s
15410      gnu     oldFiles         test2.c   test.rs
15410-local iclab   shark-audit.txt  test.c    test.rs~
```

Shell Programs

■ 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    Must give full pathnames for programs
-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 &      Run program in background
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    Sleep is running
 32033 pts/2        00:00:00 ps              in background
> quit
```

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 */
            execve(argv[0], argv, environ);
            // If we get here, execve failed.
            printf("%s: %s\n", argv[0], strerror(errno));
            exit(127);
        }
    }
}
```

Start **argv[0]**.
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 */
            execve(argv[0], argv, environ);
            // If we get here, execve failed.
            printf("%s: %s\n", argv[0], strerror(errno));
            exit(127);
        }

        /* 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.

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 */
            execve(argv[0], argv, environ);
            // If we get here, execve failed.
            printf("%s: %s\n", argv[0], strerror(errno));
            exit(127);
        }

        /* 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\n", 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 */
            execve(argv[0], argv, environ);
            // If we get here, execve failed.
            printf("%s: %s\n", argv[0], strerror(errno));
            exit(127);
        }

        /* 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.

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
 - Could run the entire computer out of memory
 - More likely, run out of PIDs

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

- Exceptional Control Flow
- Simple Shell Example
- **Signals**
- If we have time: Nonlocal Jumps

Signals

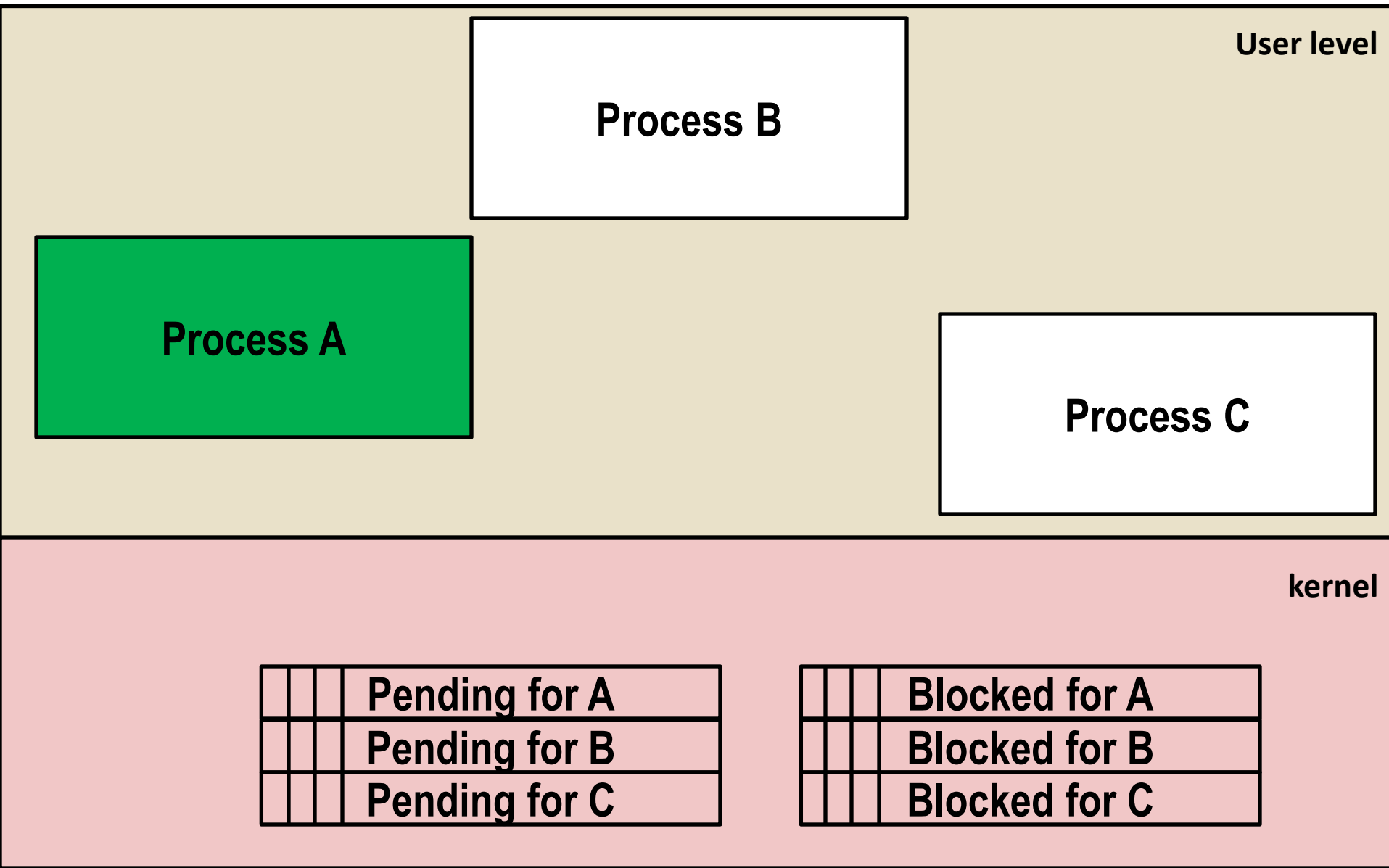
- A **signal** is a small message that notifies a process that an event of some type has occurred in the system
 - Akin to exceptions and interrupts
 - Sent from the kernel (sometimes at the request of another process) to a process
 - Signal type is identified by small integer ID's (1-30)
 - Only information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

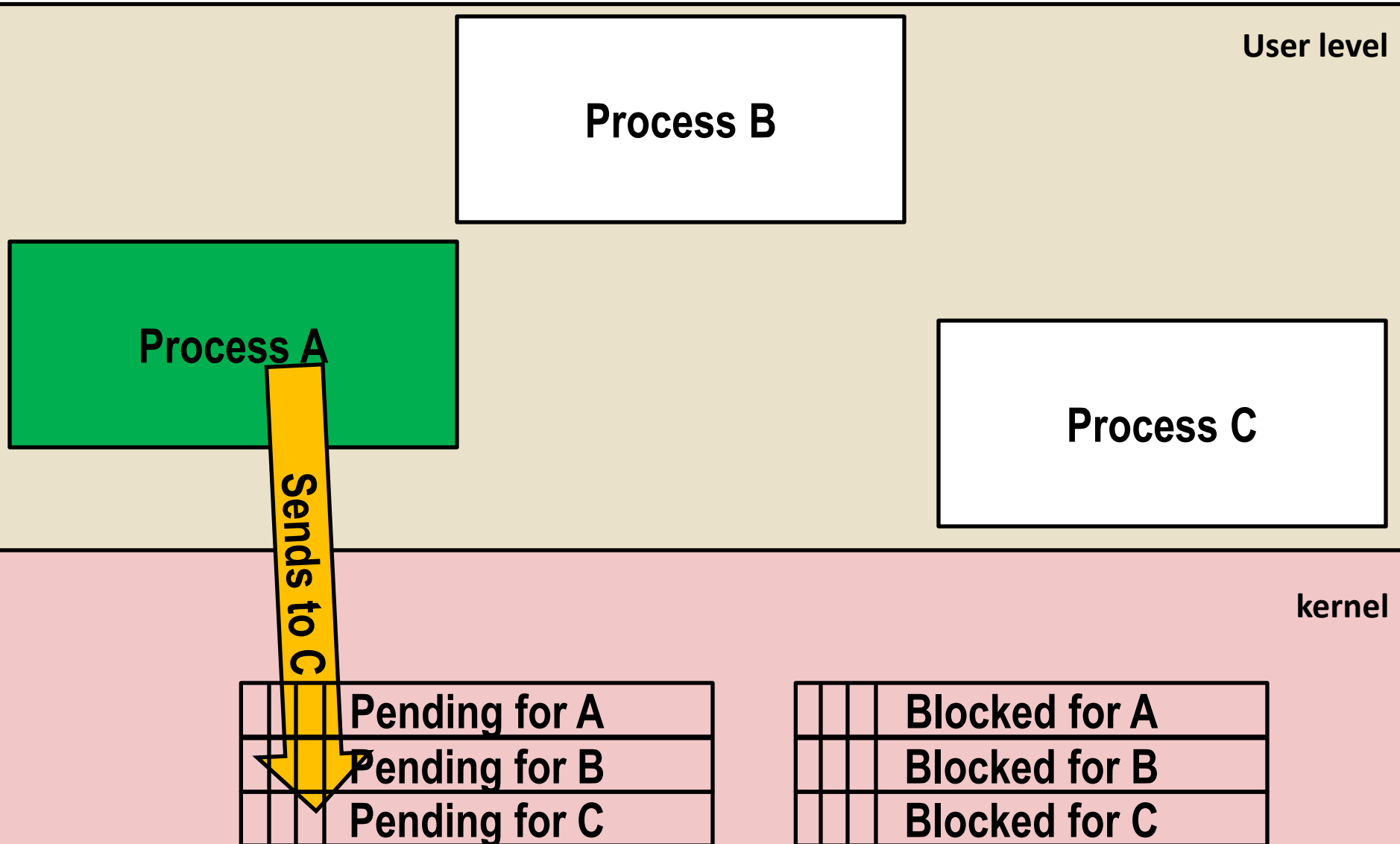
Signal Concepts: Sending a Signal

- Kernel *sends* 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

User level

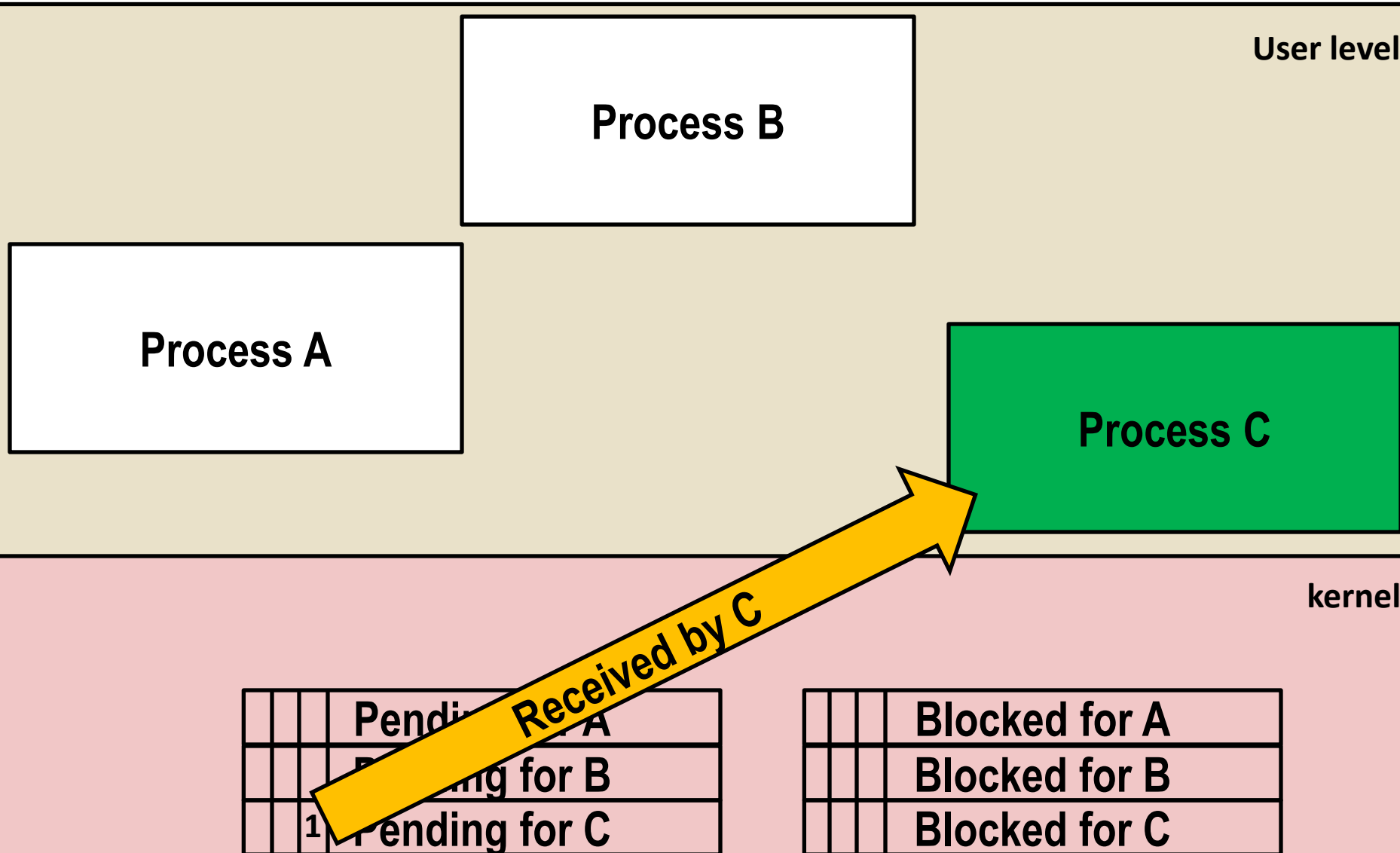
Process B**Process A****Process C**

kernel

			Pending for A
			Pending for B
		1	Pending for C

			Blocked for A
			Blocked for B
			Blocked for C

Signal Concepts: Sending a Signal



Signal Concepts: Sending a Signal

User level

Process B

Process A

Process C

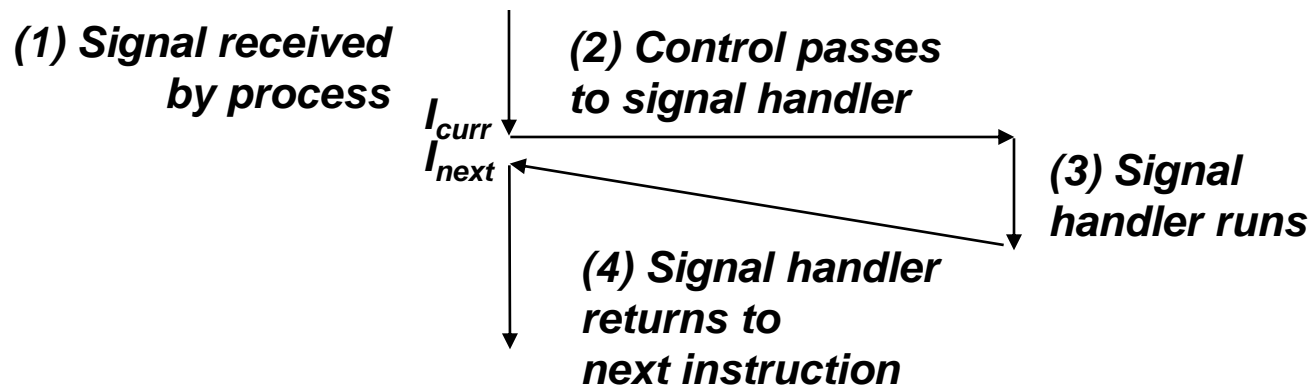
kernel

			Pending for A
			Pending for B
		0	Pending for C

			Blocked for A
			Blocked for B
			Blocked for C

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 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:



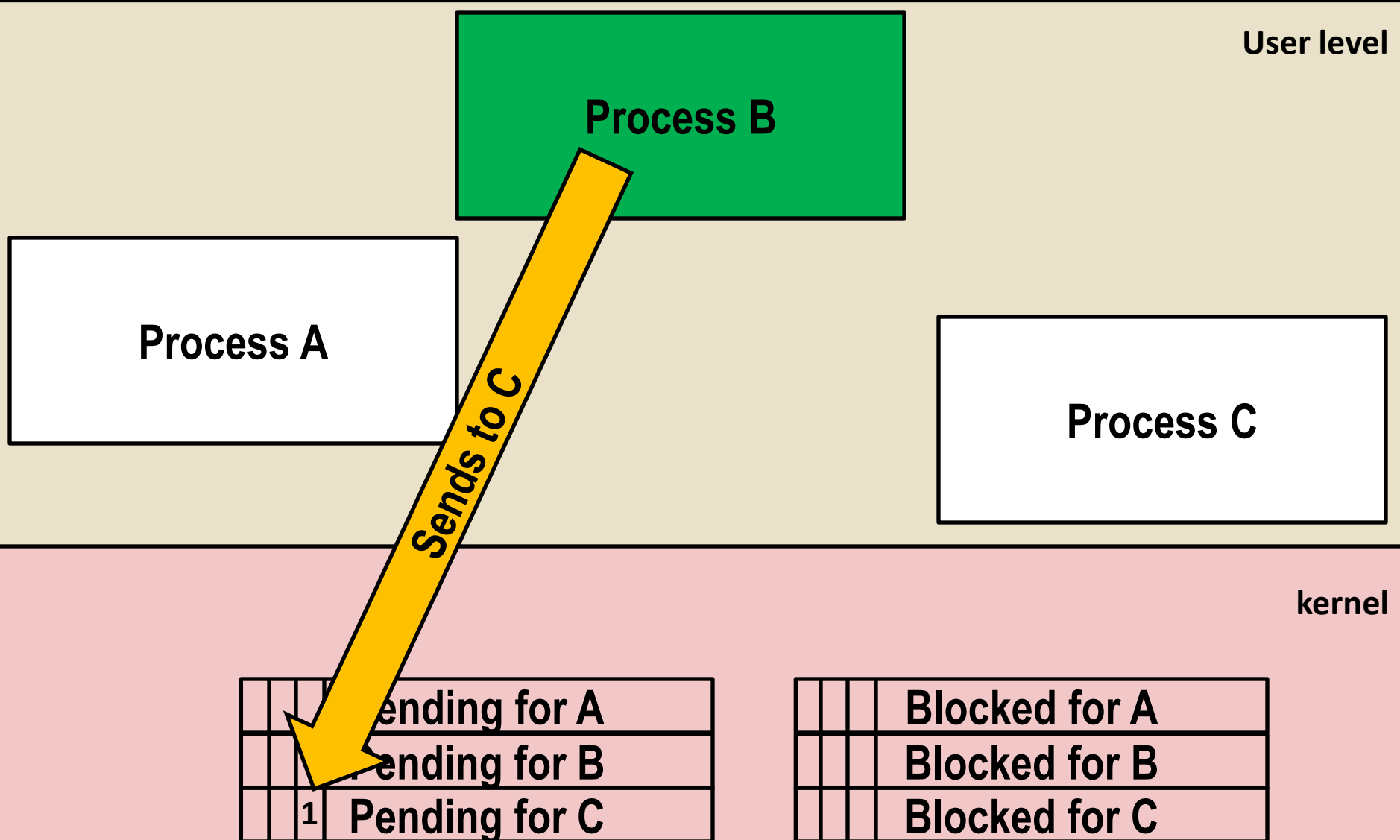
Signal Concepts: Pending and Blocked Signals

- A signal is ***pending*** if sent but not yet received
 - There can be at most one pending signal of each 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 sent, but will not be received until the signal is unblocked
 - Some signals cannot be blocked (SIGKILL, SIGSTOP) or can only be blocked when sent by other processes (SIGSEGV, SIGILL, etc)
- A pending signal is received at most once

Signal Concepts: Pending/Blocked Bits

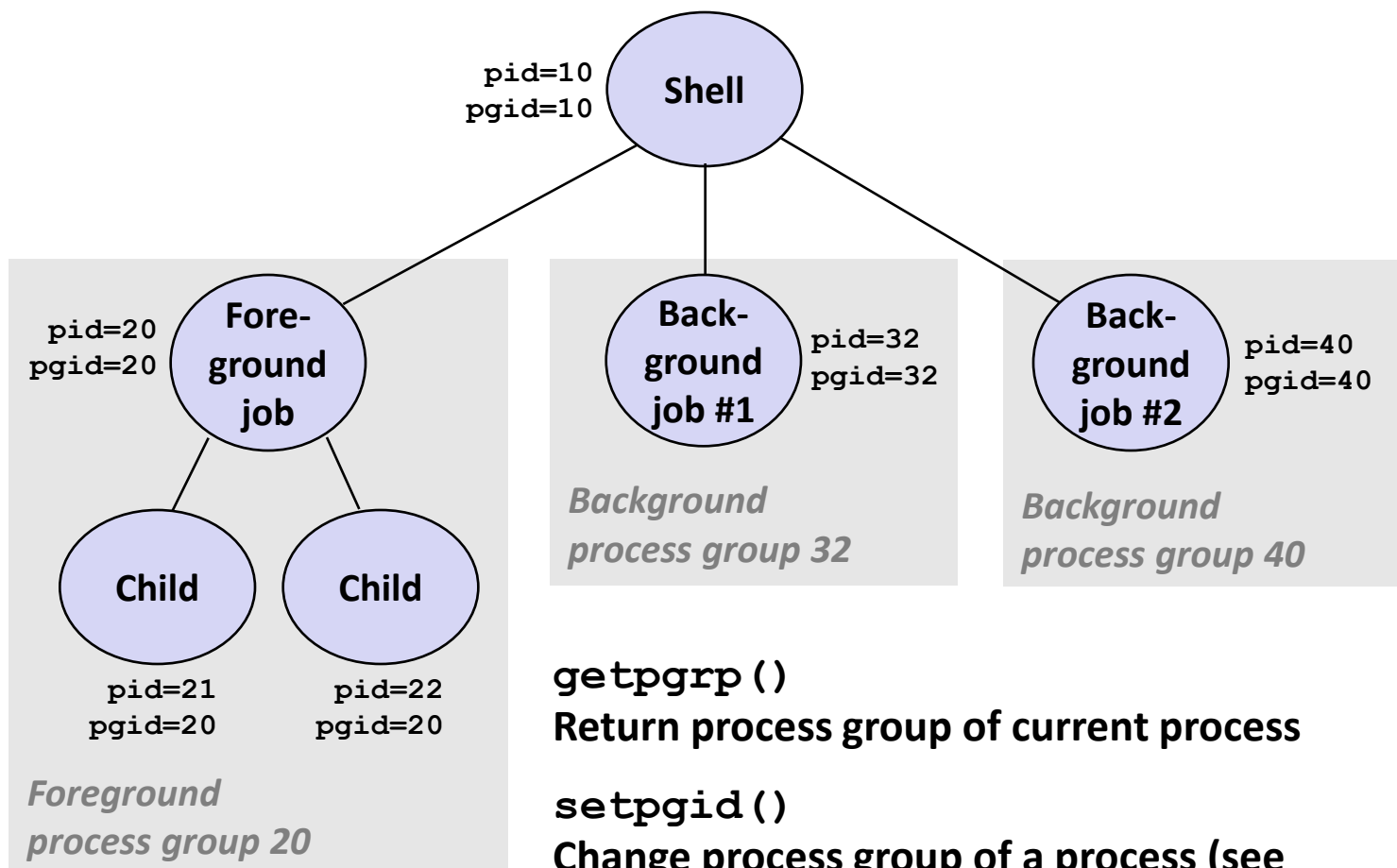
- Kernel maintains **pending** and **blocked** bit vectors in the context of each process
 - **pending**: represents the set of pending signals
 - Kernel sets bit k in **pending** when a signal of type k is sent
 - Kernel clears bit k in **pending** when a signal of type k is received
 - **blocked**: 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



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
```

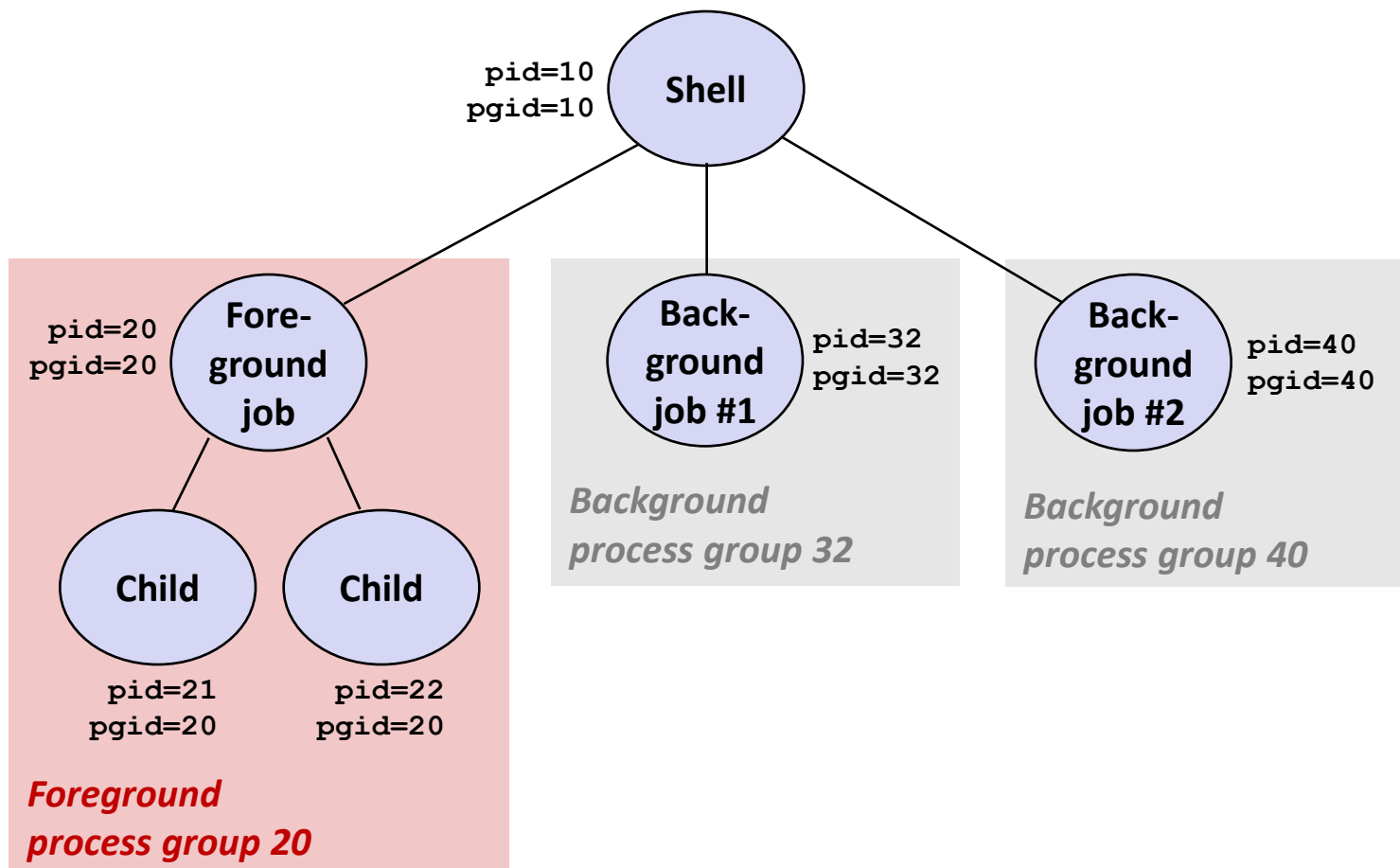
```
linux> ps
  PID TTY          TIME CMD
24788 pts/2        00:00:00 tcsh
24818 pts/2        00:00:02 forks
24819 pts/2        00:00:02 forks
24820 pts/2        00:00:00 ps
```

```
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)
                ;
        }

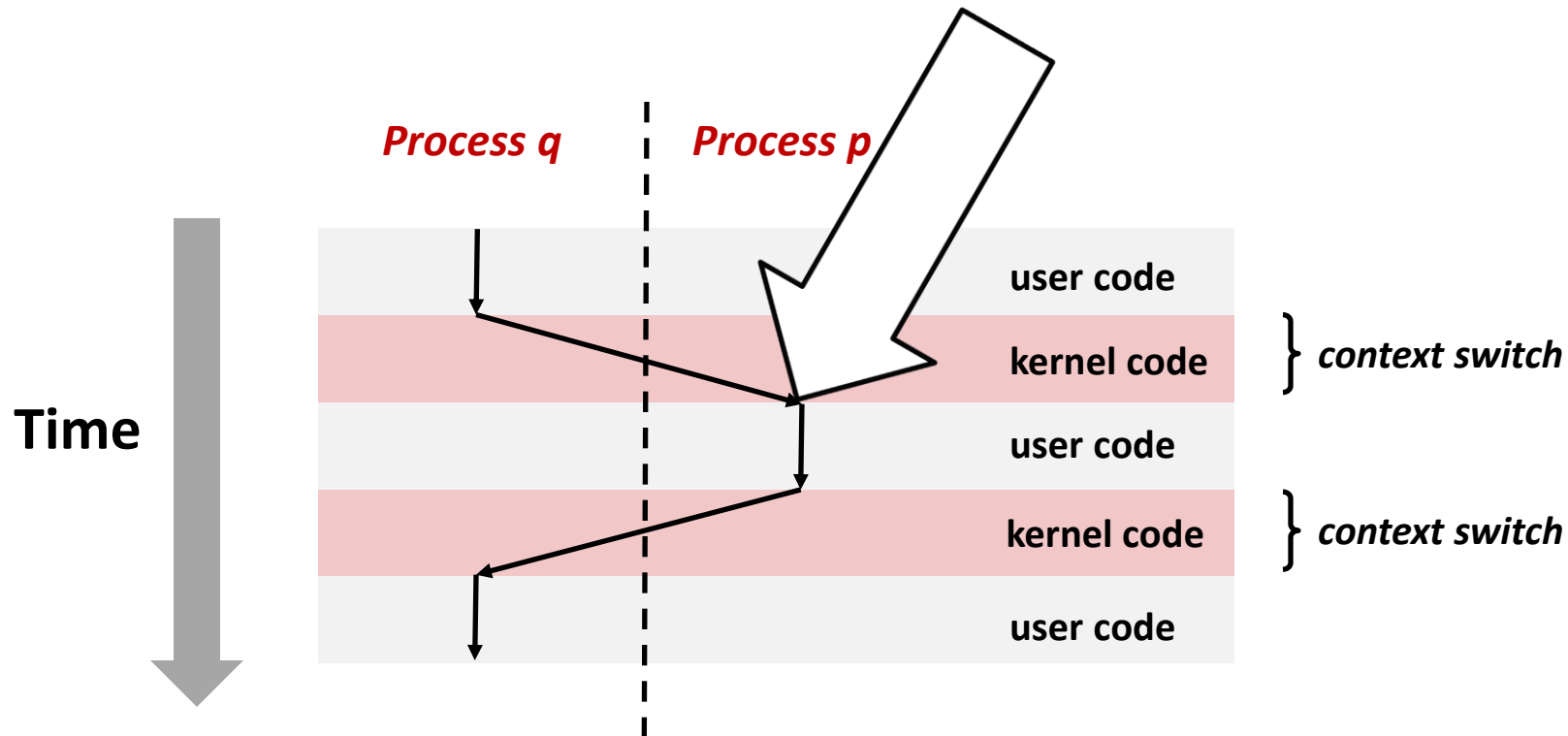
    for (i = 0; i < N; i++) {
        printf("Killing process %d\n", pid[i]);
        kill(pid[i], SIGINT);
    }

    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...\n");
    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");

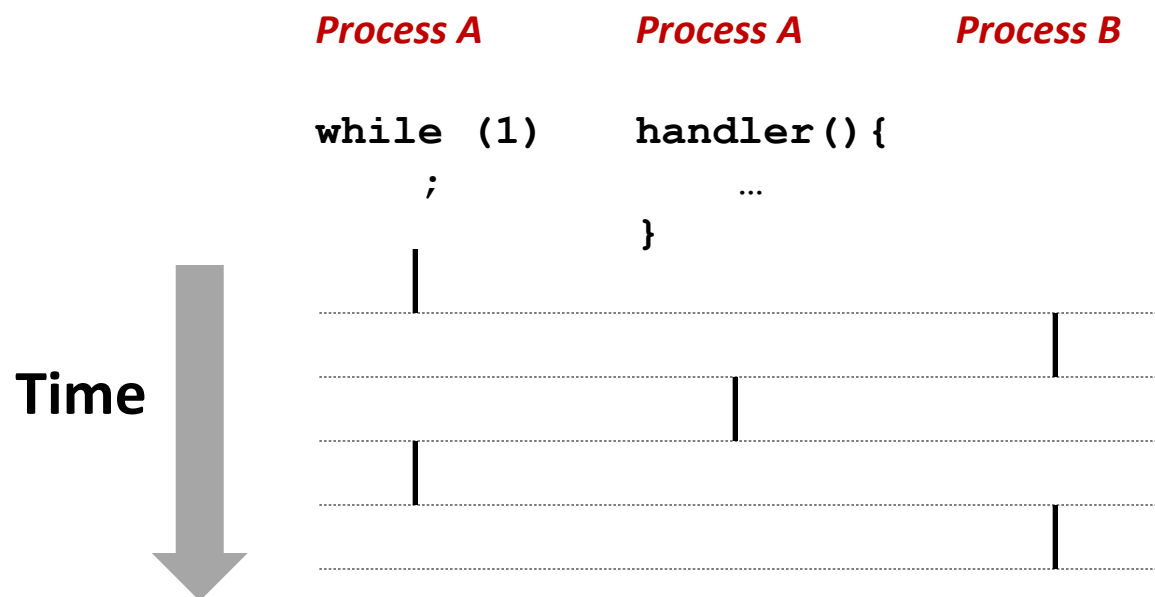
    /* Wait for the receipt of a signal */
    pause();

    return 0;
}
```

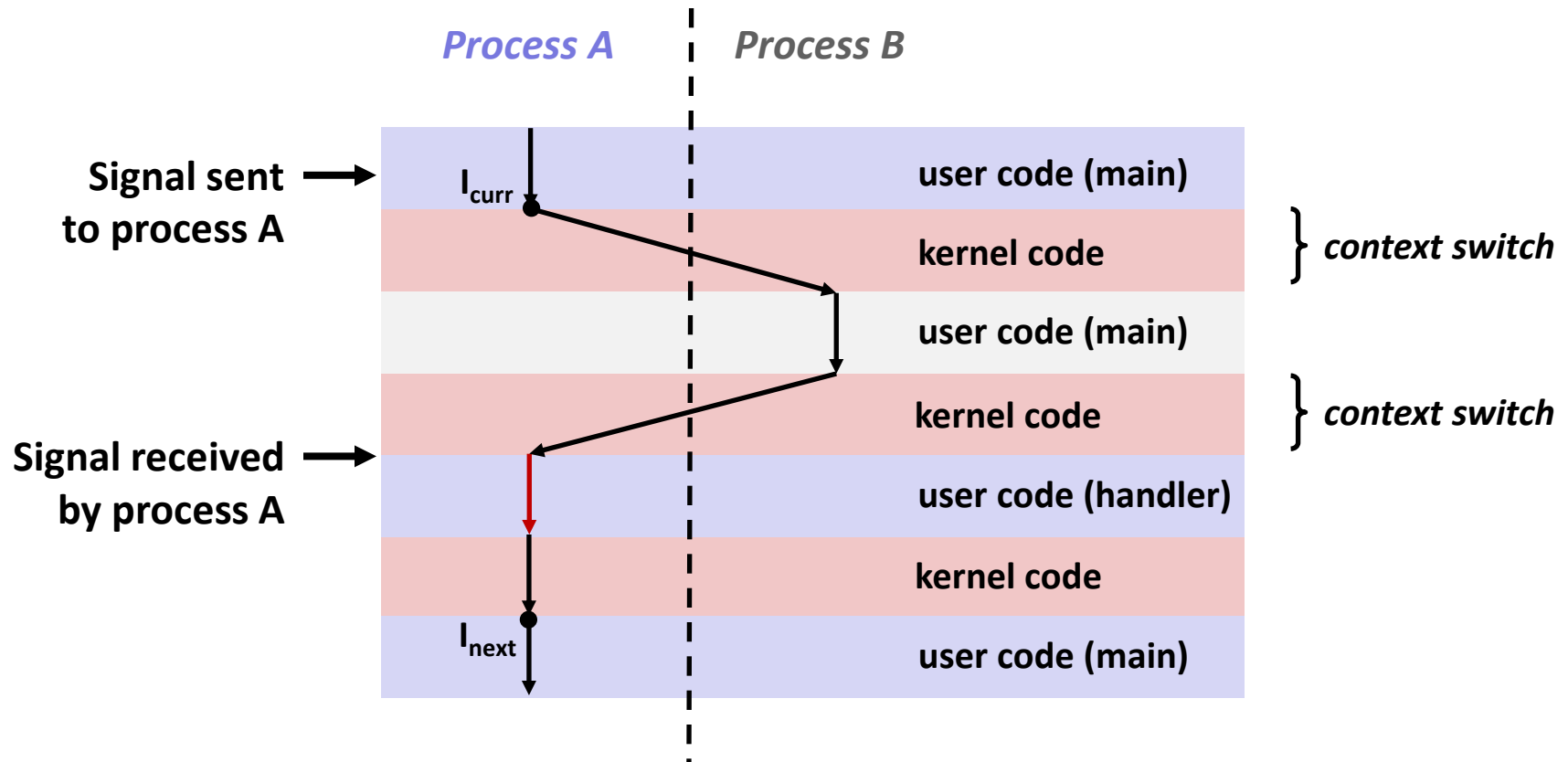
sigint.c

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

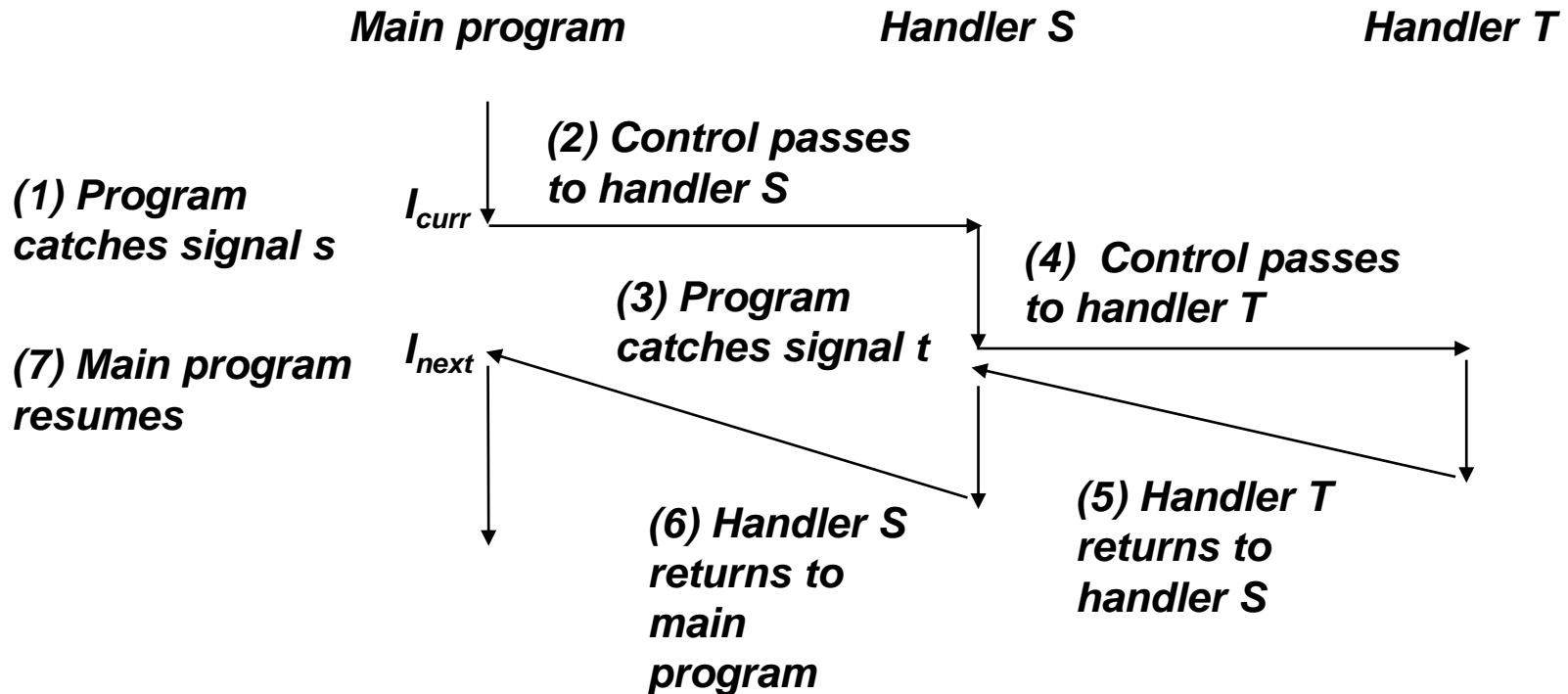


Another View of Signal Handlers as Concurrent Flows



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;
}
```

This code is incorrect!

```
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 */
        ;
}
```

N == 5

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

forks.c

- 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.

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;
}
```

```
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 (pid != 0 && 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);
}
```

procmask2.c

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.

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--) {
        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);
}
```

Today

- Exceptional Control Flow
- Signals
- **If we have time: Nonlocal Jumps**

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);

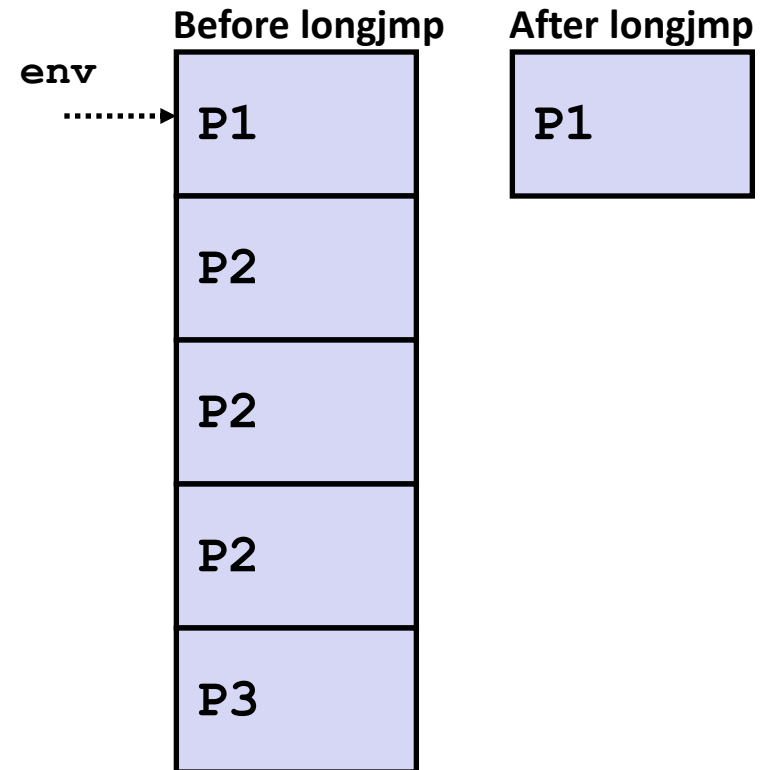
int main()
{
    switch(setjmp(buf)) {
        case 0:
            foo();
            break;
        case 1:
            printf("Detected an error1 condition in foo\n");
            break;
        case 2:
            printf("Detected an error2 condition in foo\n");
            break;
        default: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

```
    }
```

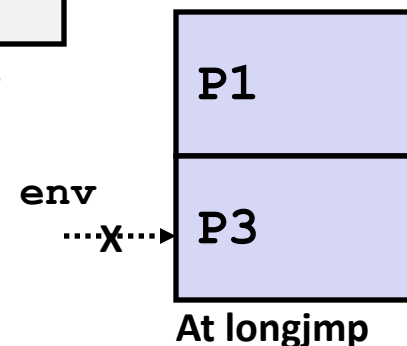
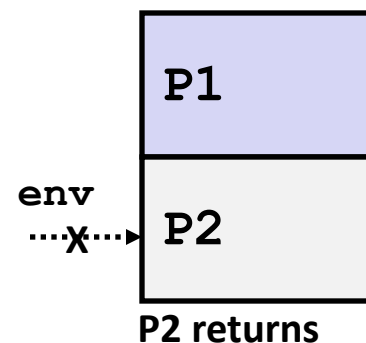
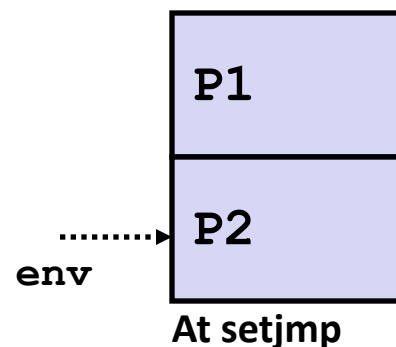
```
}
```

```
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