# Exceptional Control Flow: Signals and Nonlocal Jumps

15-213 / 18-213: Introduction to Computer Systems
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# 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** (Exceptions, Process Context Switch)

**This Lecture** (Signals, Nonlocal jumps)

# Today

- **Multitasking, shells**
- Signals
- Nonlocal jumps

# The World of Multitasking

- **System runs many processes concurrently**

- **Process: executing program**
  - State includes memory image + register values + program counter

- **Regularly switches from one process to another**
  - Suspend process when it needs I/O resource or timer event occurs
  - Resume process when I/O available or given scheduling priority

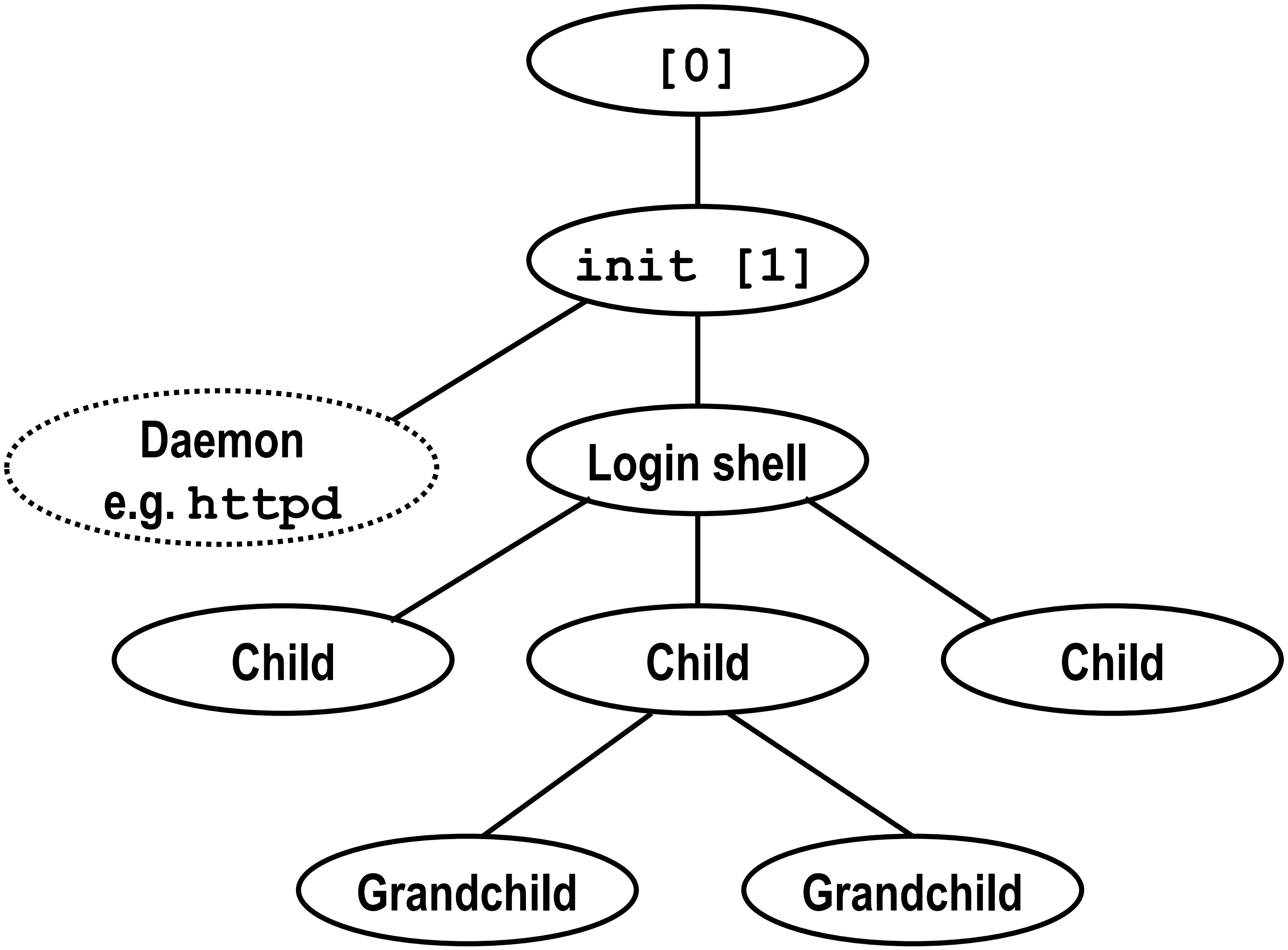
- **Appears to user(s) as if all processes executing simultaneously**
  - Even though systems can only execute one process (or a small number of processes) at a time
  - Except possibly with lower performance than if running alone

# Programmer's Model of Multitasking

- **Basic functions**
  - **`fork`** spawns new process
    - Called once, returns twice
  - **`exit`** terminates own process
    - Called once, never returns
    - Puts it into "zombie" status
  - **`wait`** and **`waitpid`** wait for and reap terminated children
  - **`execve`** runs new program in existing process
    - Called once, (normally) never returns

- **Programming challenge**
  - Understanding the nonstandard semantics of the functions
  - Avoiding improper use of system resources
    - E.g. "Fork bombs" can disable a system

# Unix Process Hierarchy



# 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`** BSD Unix C shell (**`tcsh:`** enhanced `csh` at CMU and elsewhere)
  - **`bash`** "Bourne-Again" Shell

```
int main() {
    char cmdline[MAXLINE];

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

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

*Execution is a sequence of read/evaluate steps*

# Simple Shell `eval` Function

```
void eval(char *cmdline) {
    char *argv[MAXARGS]; /* argv for execve() */
    int bg;              /* should the job run in bg or fg? */
    pid_t pid;           /* process id */

    bg = parseline(cmdline, argv);
    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);
            }
        }

        if (!bg) {   /* parent waits for fg job to terminate */
            int status;
            if (waitpid(pid, &status, 0) < 0)
                unix_error("waitfg: waitpid error");
        }
        else          /* otherwise, don't wait for bg job */
            printf("%d %s", pid, cmdline);
    }
}
```

# What Is a "Background Job"?

- **Users generally run one command at a time**
  - Type command, read output, type another command

- **Some programs run "for a long time"**
  - Example: "delete this file in two hours"

```
unix> sleep 7200; rm /tmp/junk  # shell stuck for 2 hours
```

- **A "background" job is a process we don't want to wait for**

```
unix> (sleep 7200 ; rm /tmp/junk) &
[1] 907
unix> # ready for next command
```

# 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
  - Modern Unix: once you exceed your process quota, your shell can't run any new commands for you: fork() returns -1

```
unix> limit maxproc          # csh syntax
maxproc      202752
unix> ulimit -u              # bash syntax
202752
```

# ECF to the Rescue!

- **Problem**
  - The shell doesn't know when a background job will finish
  - By nature, it could happen at any time
  - The shell's regular control flow can't reap exited background processes in a timely fashion
  - Regular control flow is "wait until running job completes, then reap it"

- **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

- Multitasking, 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 (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

| *ID* | *Name* | *Default Action* | *Corresponding Event* |
|---|---|---|---|
| 2 | SIGINT | Terminate | Interrupt (e.g., ctl-c from keyboard) |
| 9 | SIGKILL | Terminate | Kill program (cannot override or ignore) |
| 11 | SIGSEGV | Terminate & Dump | Segmentation violation |
| 14 | SIGALRM | Terminate | Timer signal |
| 17 | SIGCHLD | Ignore | Child stopped or terminated |

# 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

# 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**

- **Three 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

# 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

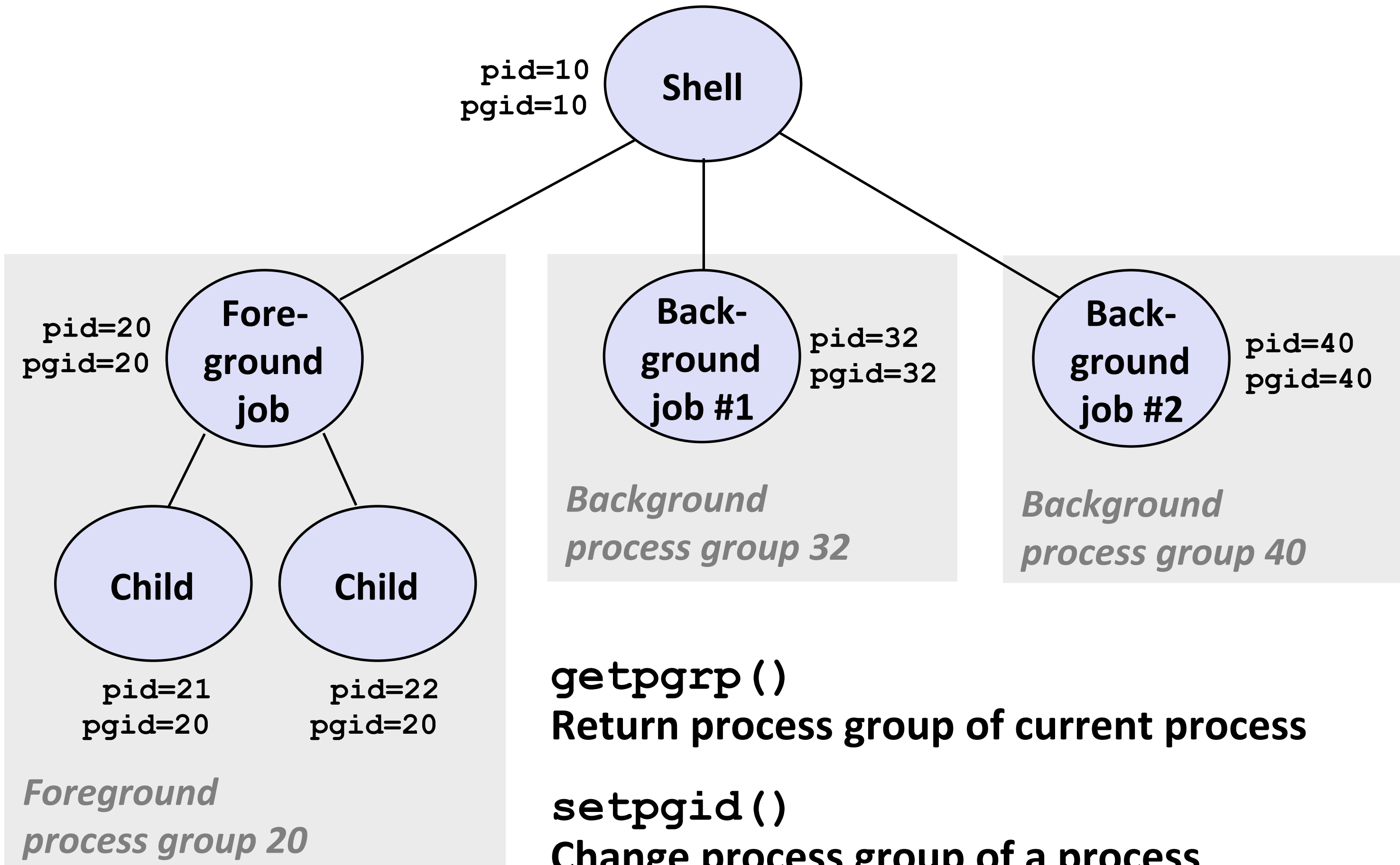
- **A pending signal is received at most once**

# Signal Concepts

- **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

# Process Groups

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




**getpgrp()**
**Return process group of current process**

**setpgid()**
**Change process group of a process**

# Sending Signals with /bin/`kill` Program

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

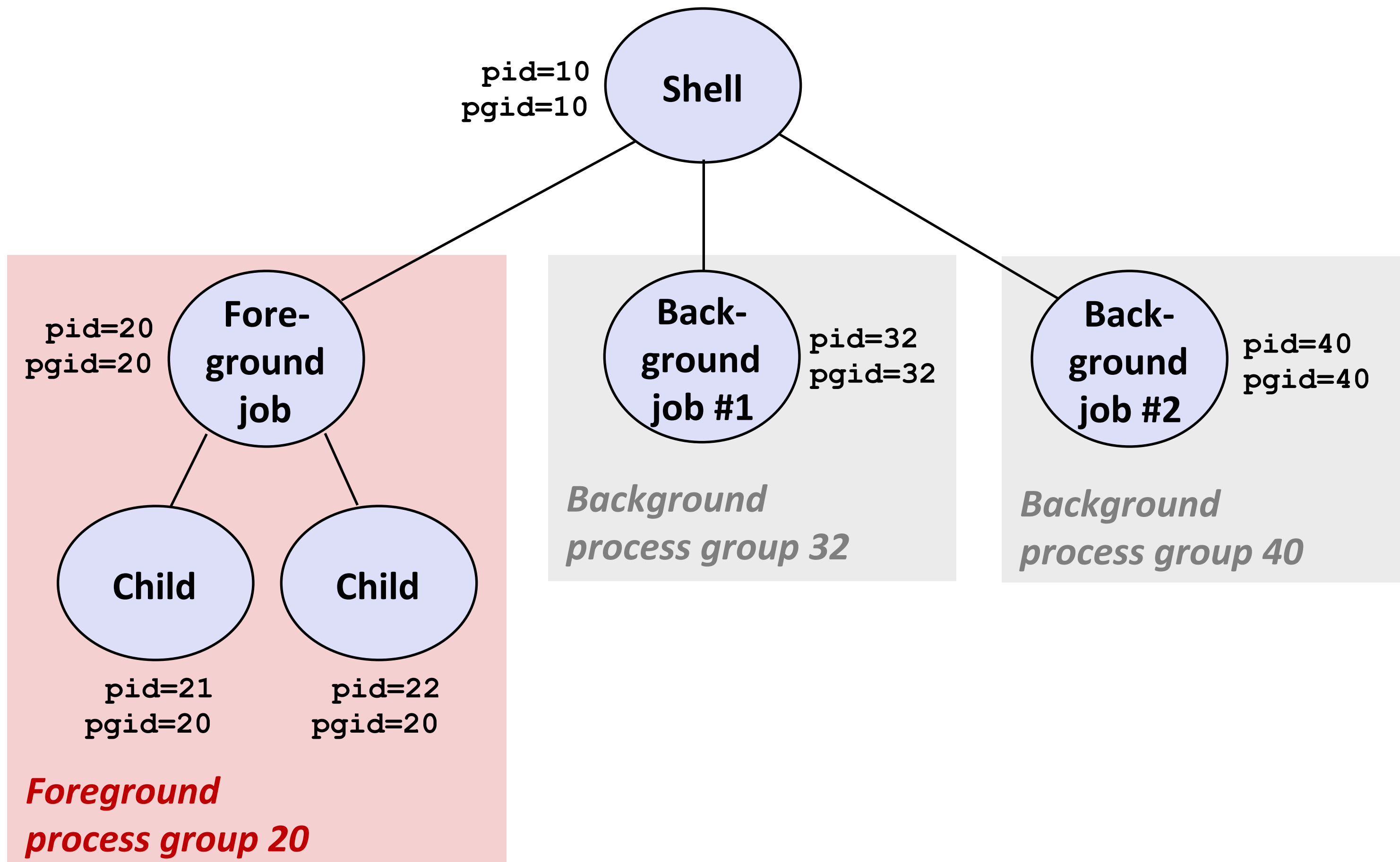
- Examples
  - `/bin/kill -9 24818`
    Send SIGKILL to process 24818
  - `/bin/kill -9 -24817`
    Send SIGKILL to every process in process group 24817

```
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) sends 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

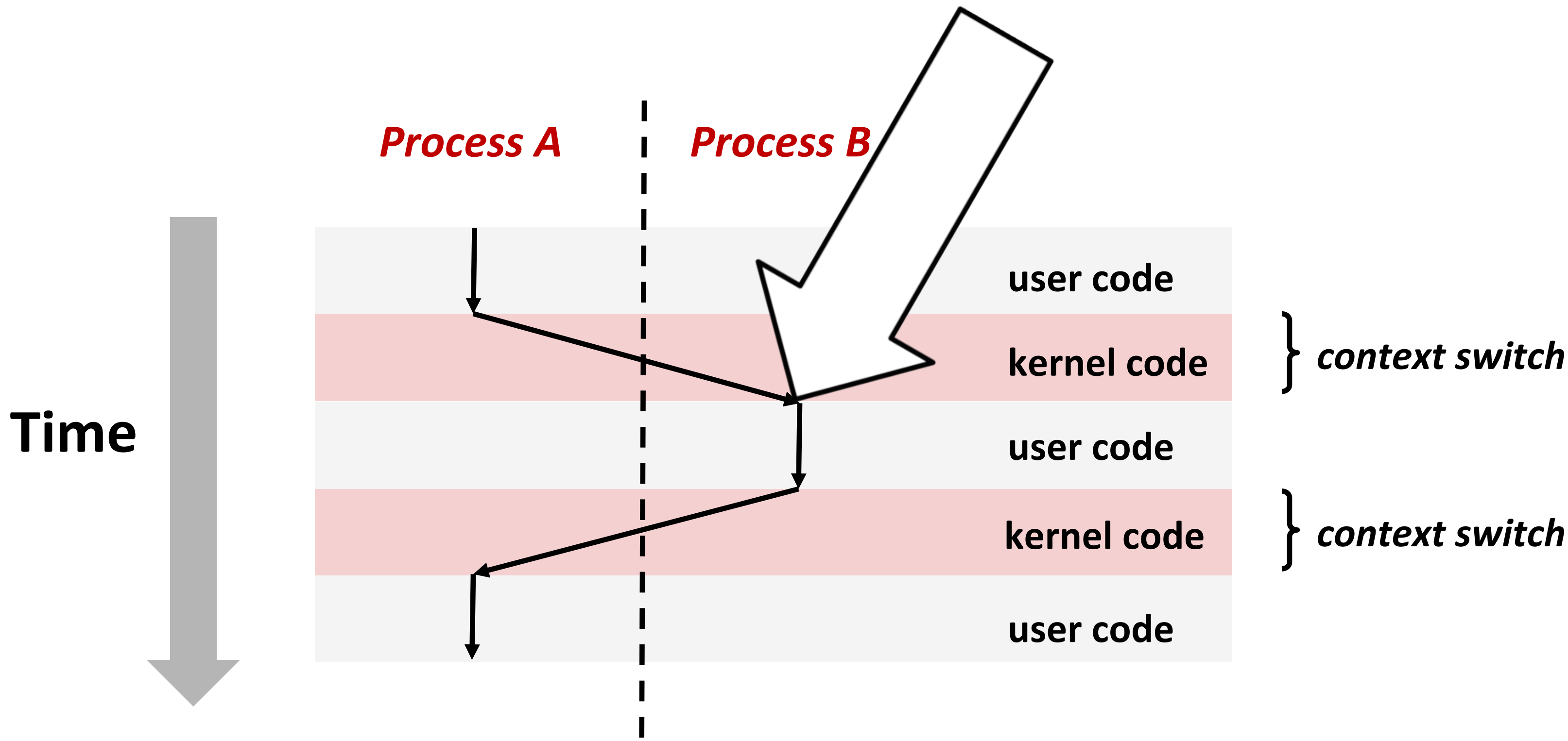
```
void fork12()
{
    pid_t pid[N];
    int i, child_status;
    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0)
            while(1); /* Child infinite loop */

    /* Parent terminates the child processes */
    for (i = 0; i < N; i++) {
        printf("Killing process %d\n", pid[i]);
        kill(pid[i], SIGINT);
    }

    /* Parent reaps terminated children */
    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);
    }
}
```

# Receiving Signals

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




**Important: All context switches are initiated by calling some exceptional hander.**

# Receiving Signals

- **Suppose kernel is returning from an exception handler and is ready to pass control to process *p***
- **Kernel computes `pnb = pending & ~blocked`**
  - The set of pending nonblocked signals for process *p*
- **If (`pnb == 0`)**
  - Pass control to next instruction in the logical flow for *p*
- **Else**
  - Choose least nonzero bit *k* in **`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 **`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 terminates and dumps core
  - 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 ***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 int_handler(int sig) {
    safe_printf("Process %d received signal %d\n", getpid(), sig);
    exit(0);
}

void fork13() {
    pid_t pid[N];
    int i, child_status;
    signal(SIGINT, int_handler);
    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0) {
            while(1); /* child infinite loop
        }
    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);
    }
}
```

# Signal Handling Example

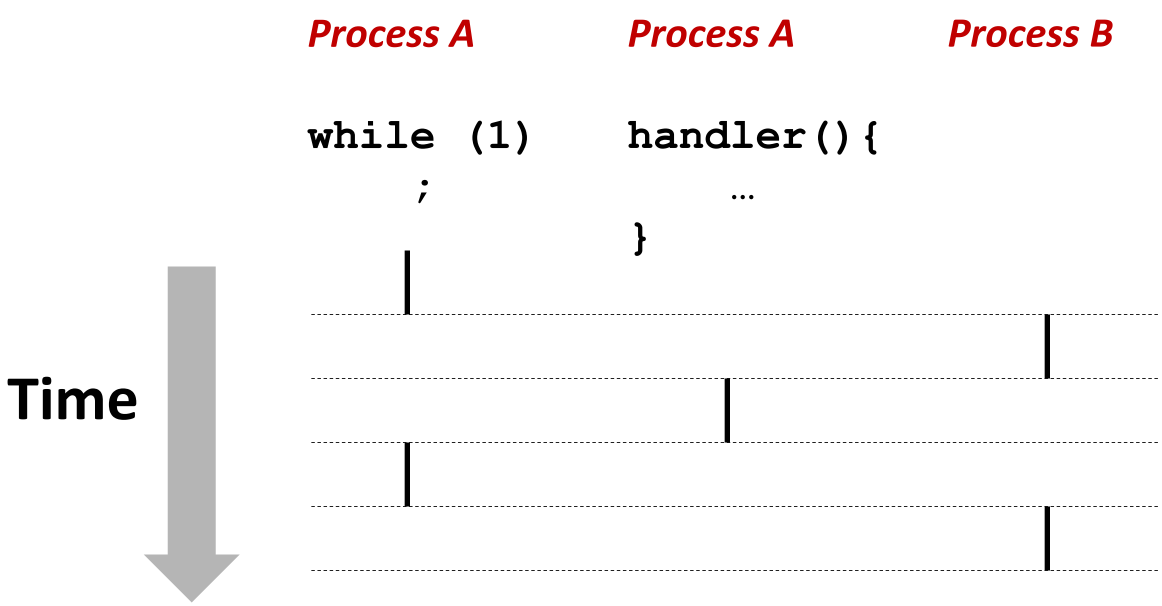
```
void int_handler(int sig) {
    safe_printf("Process %d received signal %d\n", getpid(), sig);
    exit(0);
}

void fork13() {
    pid_t pid[N];
    int i, child_status;
    signal(SIGINT, int_handler);
    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0
            while(1); /* child inf
        }
    for (i = 0; i < N; i++) {
        printf("Killing process %d
        kill(pid[i], SIGINT);
    }
    for (i = 0; i < N; i++) {
        pid_t wpid = wait(&child_s
        if (WIFEXITED(child_status
            printf("Child %d termi
                   wpid, WEXITSTAT
        else
            printf("Child %d termi
    }
}
```

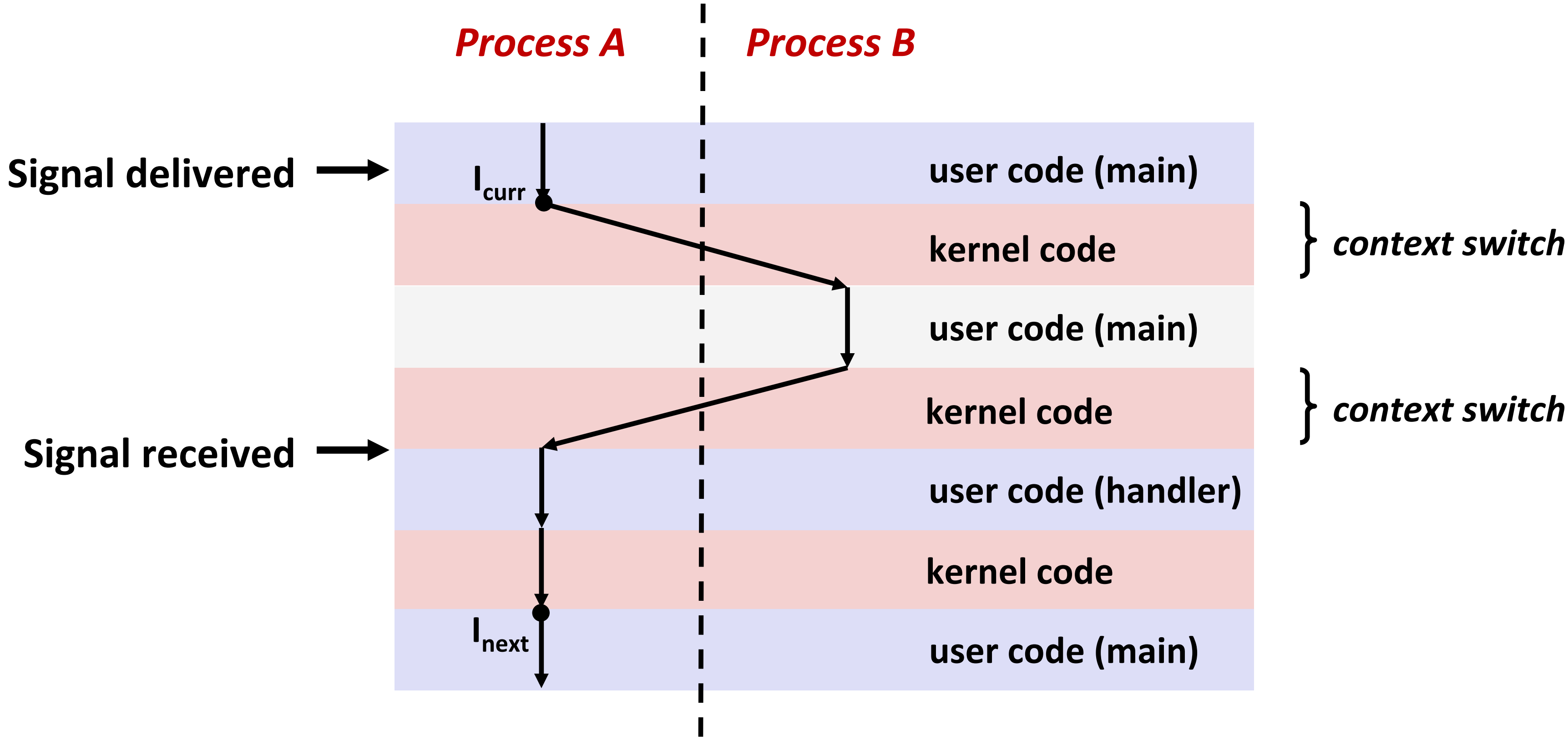
```
linux> ./forks 13
Killing process 25417
Killing process 25418
Killing process 25419
Killing process 25420
Killing process 25421
Process 25417 received signal 2
Process 25418 received signal 2
Process 25420 received signal 2
Process 25421 received signal 2
Process 25419 received signal 2
Child 25417 terminated with exit status 0
Child 25418 terminated with exit status 0
Child 25420 terminated with exit status 0
Child 25419 terminated with exit status 0
Child 25421 terminated with exit status 0
linux>
```

# Signals Handlers as Concurrent Flows

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



# Another View of Signal Handlers as Concurrent Flows



# Signal Handler Funkiness

```
int ccount = 0;
void child_handler(int sig)
{
    int child_status;
    pid_t pid = wait(&child_status);
    ccount--;
    safe_printf(
           "Received signal %d from process %d\n",
           sig, pid);
}

void fork14()
{
    pid_t pid[N];
    int i, child_status;
    ccount = N;
    signal(SIGCHLD, child_handler);
    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0) {
            sleep(1); /* deschedule child */
            exit(0);  /* Child: Exit */
        }
    while (ccount > 0)
        pause(); /* Suspend until signal occurs */
}
```

- **Pending signals are not queued**
  - For each signal type, just have single bit indicating whether or not signal is pending
  - Even if multiple processes have sent this signal
  - This program may get stuck in final loop

# Signal Handler Funkiness

```
int ccount = 0;
void child_handler(int sig)
{
    int child_status;
    pid_t pid = wait(&child_status);
    ccount--;
    safe_printf(
           "Received signal %d from process %d\n",
           sig, pid);
}

void fork14()
{
    pid_t pid[N];
    int i, child_status;
    ccount = N;
    signal(SIGCHLD, child_handler);
    for (i = 0; i < N; i+
        if ((pid[i] = fo
            sleep(1); /*
            exit(0);  /*
        }
    while (ccount > 0)
        pause(); /* Suspend until signal occurs */
}
```

```
linux> ./forks 14
Received SIGCHLD signal 17 for process 21344
Received SIGCHLD signal 17 for process 21345
```

- **Pending signals are not queued**
  - For each signal type, just have single bit indicating whether or not signal is pending
  - Even if multiple processes have sent this signal
  - This program may get stuck in final loop

# Living With Nonqueuing Signals

- **Must wait for all terminated jobs**
  - Have handler loop with **`waitpid`** to get all jobs

```
void child_handler2(int sig)
{
    int child_status;
    pid_t pid;
    int n = 0;
    while ((pid = waitpid(-1, &child_status, WNOHANG)) > 0) {
        ccount--;
        safe_printf("Received signal %d from process %d.  n = %d\n",
                    sig, pid, n++);
    }
}

void fork15()
{
    . . .
    signal(SIGCHLD, child_handler2);
    . . .
}
```

# Living With Nonqueuing Signals

- **Must wait for all terminated jobs**
  - Have handler loop with **`waitpid`** to get all jobs

```
void child_handler2(int sig)
{
    int child_status;
    pid_t pid;
    int n = 0;
    while ((pid = waitpid(-1, &child_status, WNOHANG)) > 0) {
        ccount--;
        safe_printf("Received signal %d from process %d.  n = %d\n",
                    sig, pid, n++);
    }
}

void fork15()
{
    . . .
    signal(SIGC
    . . .
}
```

```
greatwhite> forks 15
Received signal 17 from process 27476.  n = 0
Received signal 17 from process 27477.  n = 0
Received signal 17 from process 27478.  n = 0
Received signal 17 from process 27479.  n = 1
Received signal 17 from process 27480.  n = 0
greatwhite>
```

# More Signal Handler Funkiness

- **Signal arrival during long system calls (say a `read`)**
- **Signal handler interrupts `read` call**
  - Linux: upon return from signal handler, the **`read`** call is restarted automatically
  - Some other flavors of Unix can cause the **`read`** call to fail with an **`EINTR`** error number (**`errno`**)
    in this case, the application program can restart the slow system call

- **Subtle differences like these complicate the writing of portable code that uses signals**
  - Consult your textbook for details

# A Program That Reacts to Externally Generated Events (Ctrl-c)

```
#include <stdlib.h>
#include <stdio.h>
#include <signal.h>

void handler(int sig) {
  safe_printf("You think hitting ctrl-c will stop the bomb?\n");
  sleep(2);
  safe_printf("Well...");
  sleep(1);
  printf("OK\n");
  exit(0);
}

main() {
  signal(SIGINT, handler); /* installs ctl-c handler */
  while(1) {
  }
}
```

```
linux> ./external
<ctrl-c>
You think hitting ctrl-c will stop
the bomb?
Well...OK
linux>
```

external.c

# A Program That Reacts to Internally Generated Events

```
#include <stdio.h>
#include <signal.h>

int beeps = 0;

/* SIGALRM handler */
void handler(int sig) {
  safe_printf("BEEP\n");

  if (++beeps < 5)
    alarm(1);
  else {
    safe_printf("BOOM!\n");
    exit(0);
  }
}
```

internal.c

```
main() {
  signal(SIGALRM, handler);
  alarm(1); /* send SIGALRM in
               1 second */

  while (1) {
    /* handler returns here */
  }
}
```

```
linux> ./internal
BEEP
BEEP
BEEP
BEEP
BEEP
BOOM!
bass>
```

# Async-Signal-Safety

- Function is *async-signal-safe* if either reentrant (all variables stored on stack frame, CS:APP2e 12.7.2) or non-interruptible by signals.
- Posix guarantees 117 functions to be async-signal-safe
  - `write` is on the list, `printf` is not
- One solution: async-signal-safe wrapper for `printf`:

```
void safe_printf(const char *format, ...) {
    char buf[MAXS];
    va_list args;

    va_start(args, format);                       /* reentrant */
    vsnprintf(buf, sizeof(buf), format, args);    /* reentrant */
    va_end(args);                                 /* reentrant */
    write(1, buf, strlen(buf));                   /* async-signal-safe */
}
```

safe_printf.c

# Today

- Multitasking, shells
- Signals
- **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

```
#include <setjmp.h>
jmp_buf buf;

main() {
   if (setjmp(buf) != 0) {
      printf("back in main due to an error\n");
   else
      printf("first time through\n");
   p1(); /* p1 calls p2, which calls p3 */
}
...
p3() {
   <error checking code>
   if (error)
      longjmp(buf, 1)
}
```

# Limitations of Nonlocal Jumps

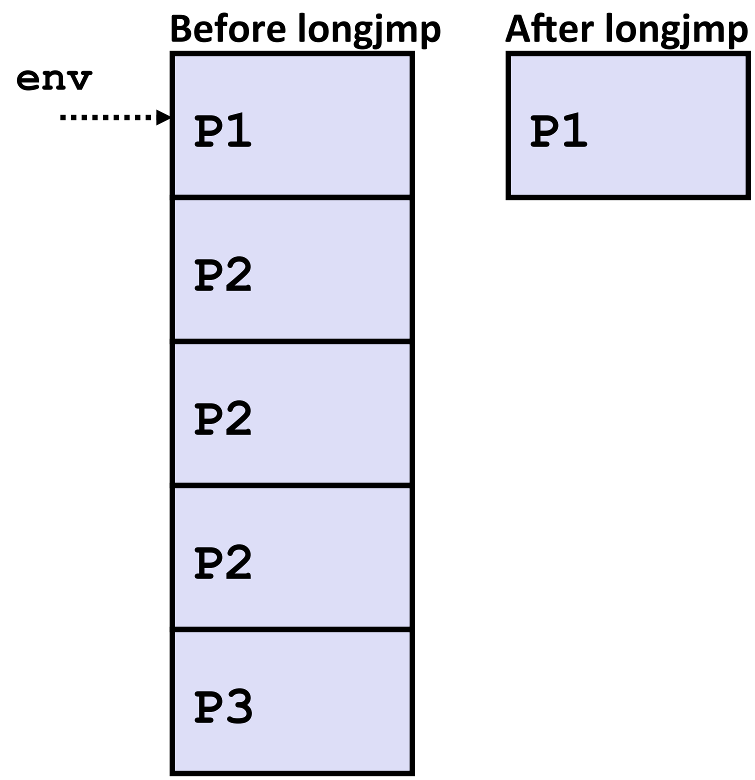
- **Works within stack discipline**
  - Can only long jump to environment of function that has been called but not yet completed

```
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.)

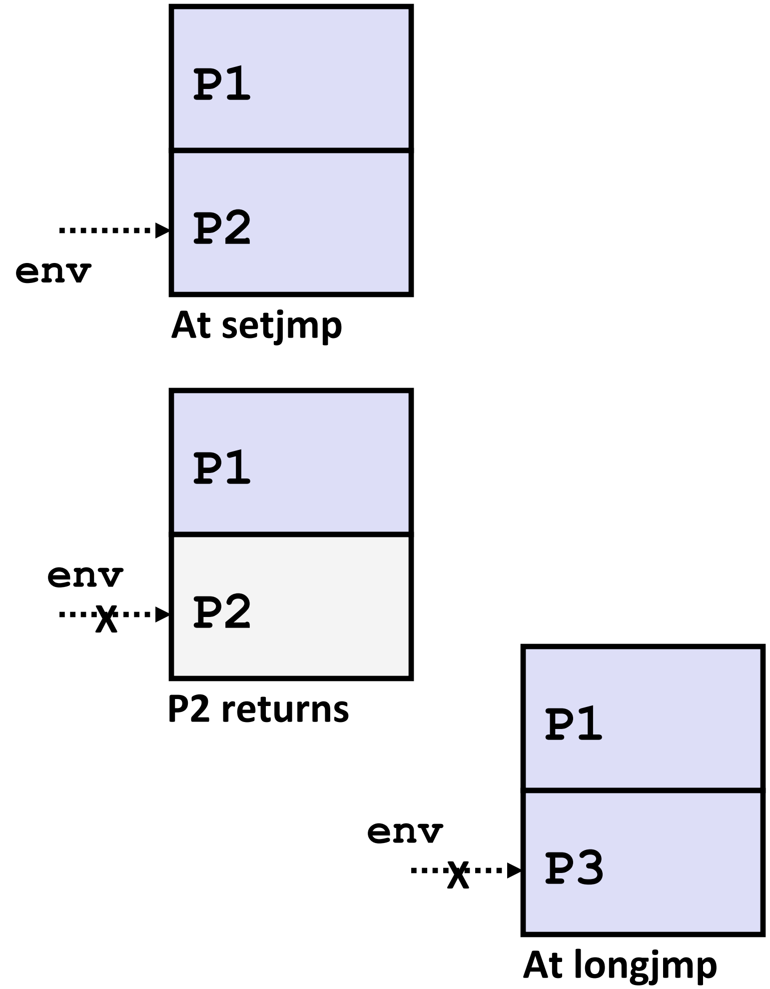
- **Works within stack discipline**
  - Can only long jump to environment of function that has been called but not yet completed

```
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 <stdio.h>
#include <signal.h>
#include <setjmp.h>

sigjmp_buf buf;

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

main() {
  signal(SIGINT, handler);

  if (!sigsetjmp(buf, 1))
    printf("starting\n");
  else
    printf("restarting\n");

  while(1) {
     sleep(1);
     printf("processing...\n");
  }
}
```

restart.c

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

# Summary

- **Signals provide process-level exception handling**
  - Can generate from user programs
  - Can define effect by declaring signal handler
- **Some caveats**
  - Very high overhead
    - >10,000 clock cycles
    - Only use for exceptional conditions
  - Don't have queues
    - Just one bit for each pending signal type
- **Nonlocal jumps provide exceptional control flow within process**
  - Within constraints of stack discipline