

# Exceptional Control Flow: Signals and Nonlocal Jumps

15-213 / 18-213: Introduction to Computer Systems  
14<sup>th</sup> Lecture, Feb. 27, 2014

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# Exam Next Week!

## ■ Exam Format

- Designed for normal class period, we give you 4 hours
- You can bring 1 double-side notes sheet
- Take it in the comfort of a proctored computer cluster

## ■ Tentative Test Taking Times (locations TBA)

- Monday 9-midnight
- Tuesday 9-midnight
- Wednesday 9-midnight
- Thursday 5pm-midnight

## ■ Topics Include

- Bits, Bytes, Integers, Floats
- Assembly
- Stack Discipline
- Cache
- Linking

# ECF Exists at All Levels of a System

## ■ Exceptions

- Hardware and operating system kernel software

## ■ Process Context Switch

- Hardware timer and kernel software

## ■ Signals

- Kernel software and application software

## ■ Nonlocal jumps

- Application code

**Previous Lecture**

**This Lecture**

# 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 most systems can only execute one process at a time
  - Except possibly with lower performance than if running alone

# Programmer's Model of Multitasking

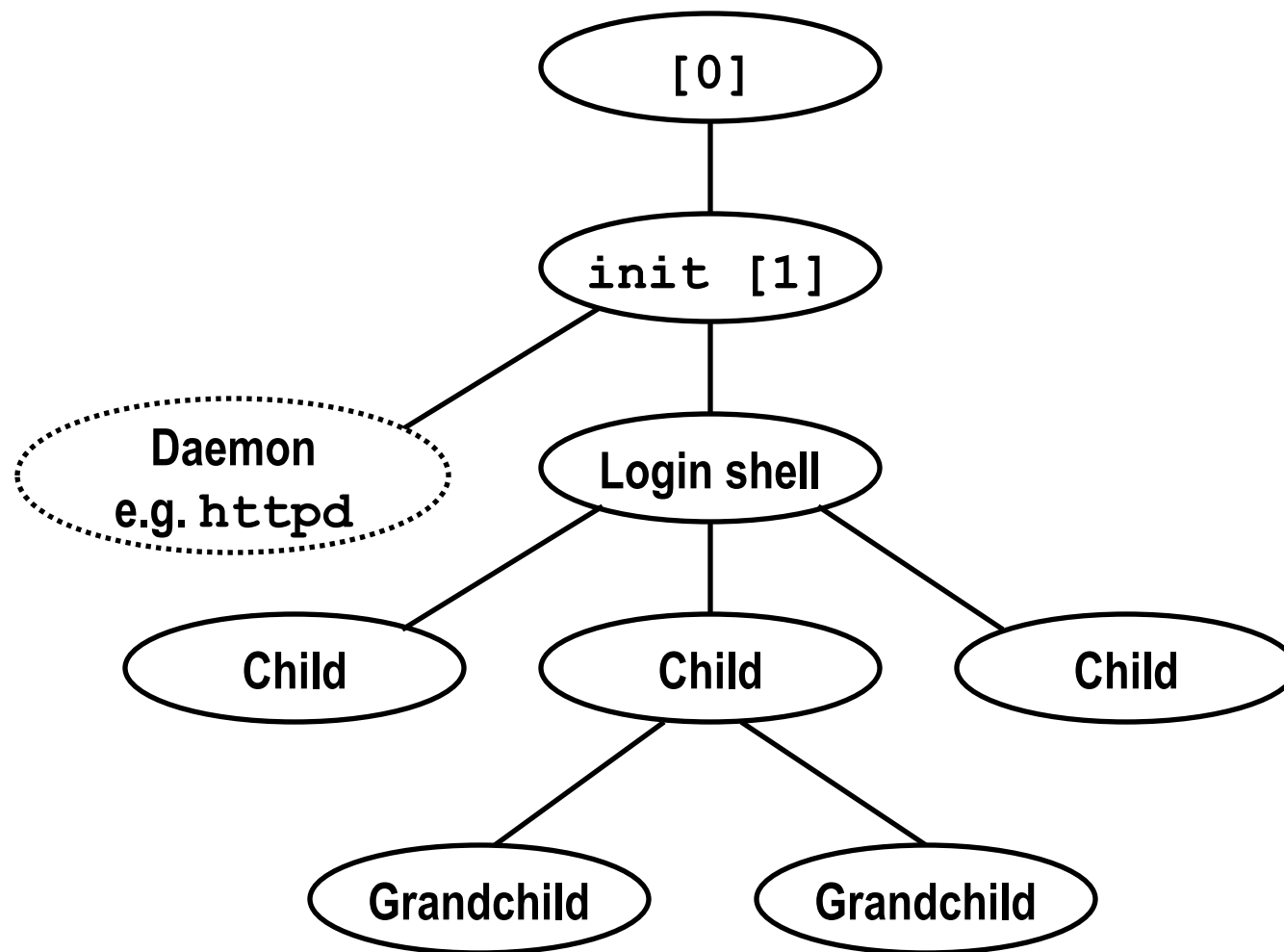
## ■ Basic functions

- **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

<i>ID</i>	<i>Name</i>	<i>Default Action</i>	<i>Corresponding Event</i>
2	SIGINT	Terminate	Interrupt (e.g., ctrl-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

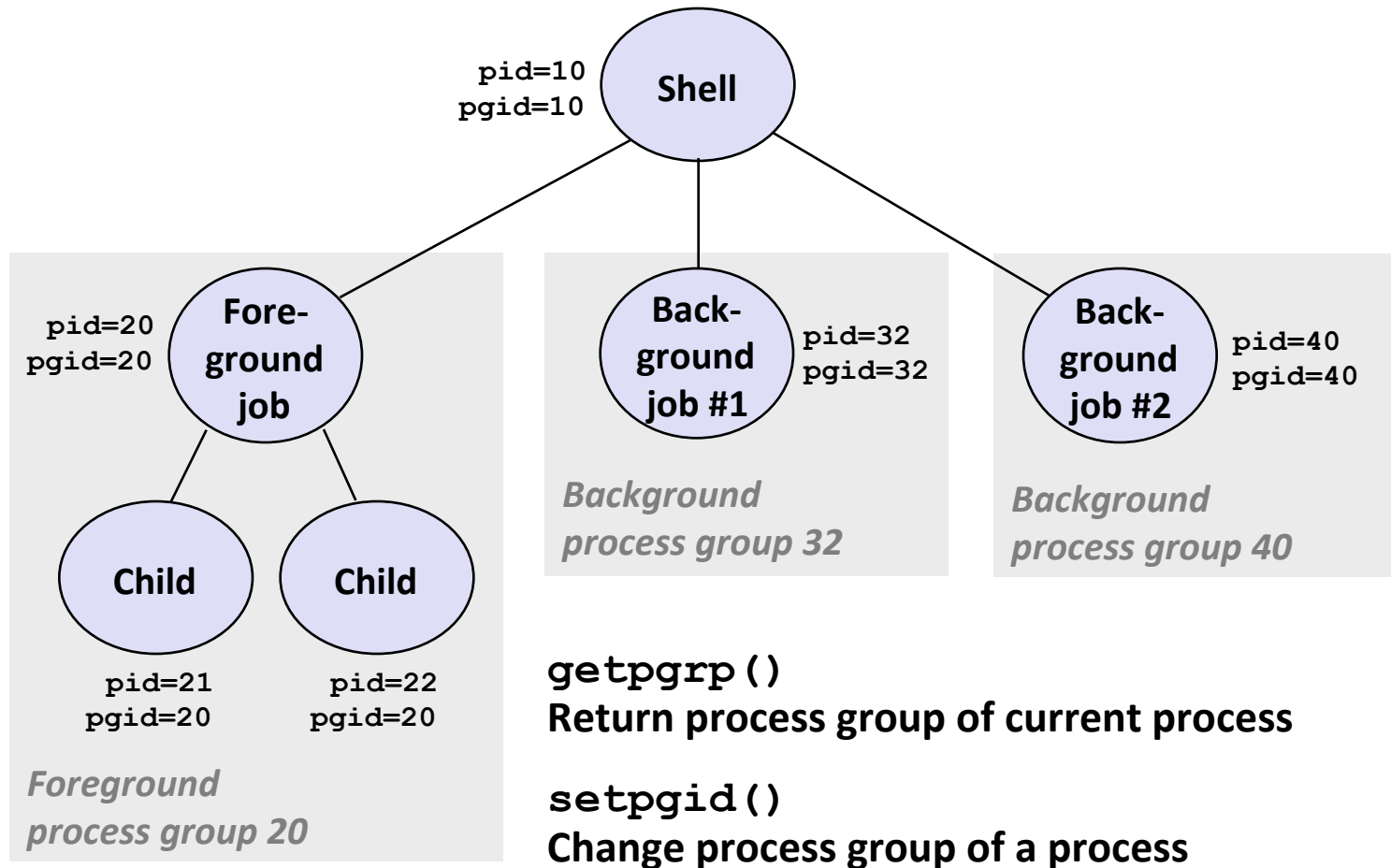
- A signal is *pending* if sent but not yet received
  - There can be at most one pending signal of any particular type
  - Important: Signals are not queued
    - If a process has a pending signal of type k, then subsequent signals of type k that are sent to that process are discarded
- A process can *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



# 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
```

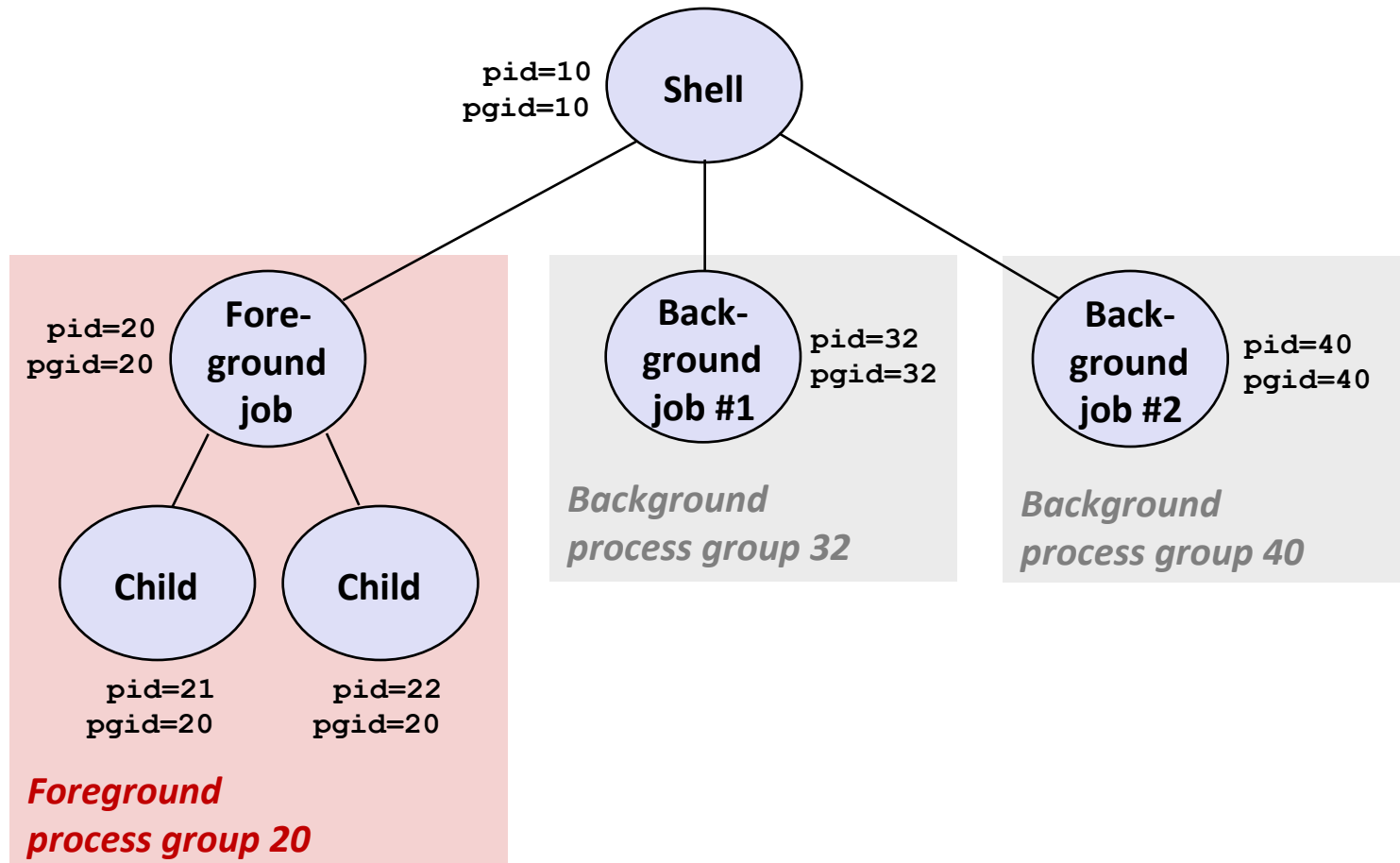
```
linux> ps
  PID TTY          TIME CMD
24788 pts/2        00:00:00 tcsh
24818 pts/2        00:00:02 forks
24819 pts/2        00:00:02 forks
24820 pts/2        00:00:00 ps
```

```
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

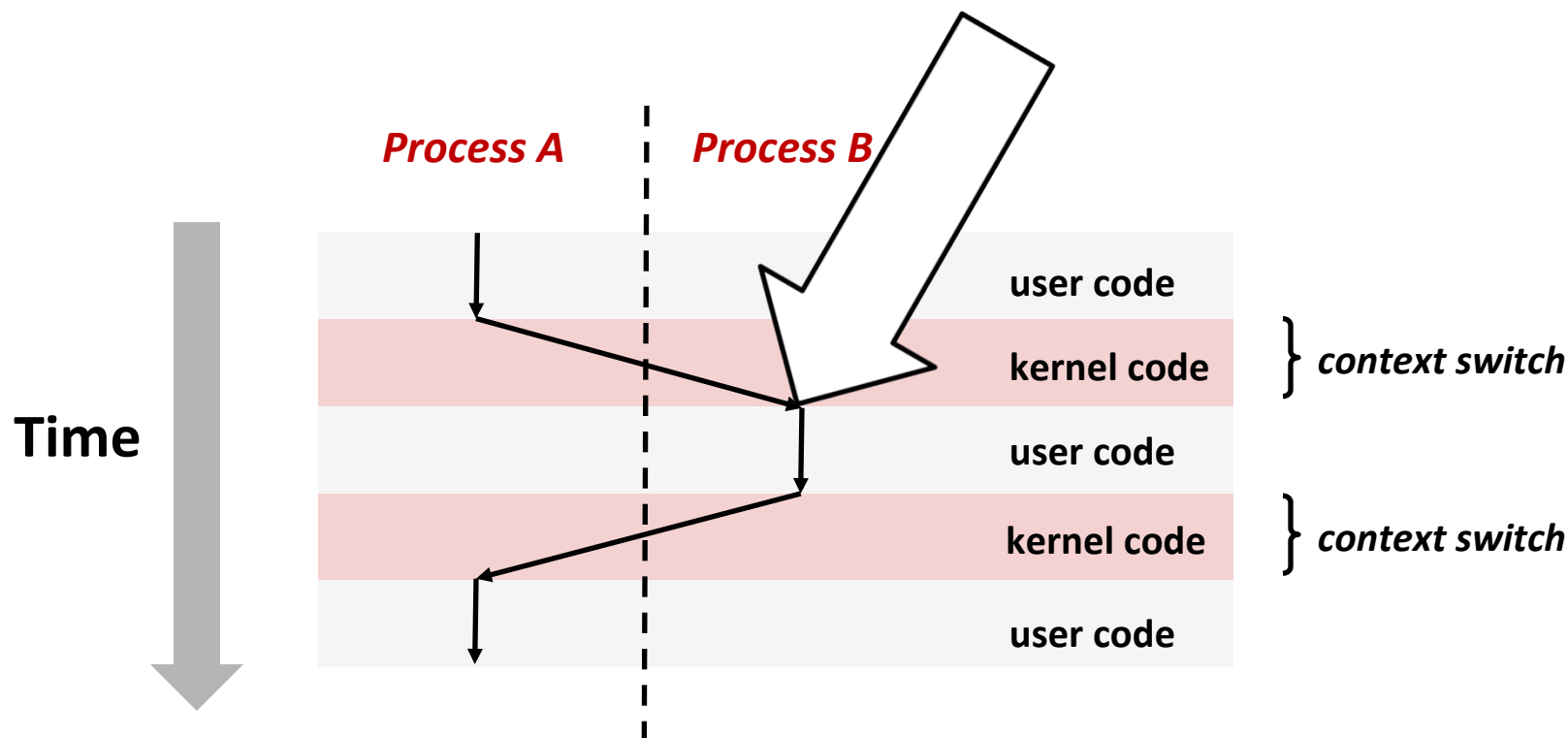
```
void fork12()
{
    pid_t pid[N];
    int i, child_status;
    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0)
            while(1); /* Child infinite loop */

    /* 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 handler.**



# 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 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

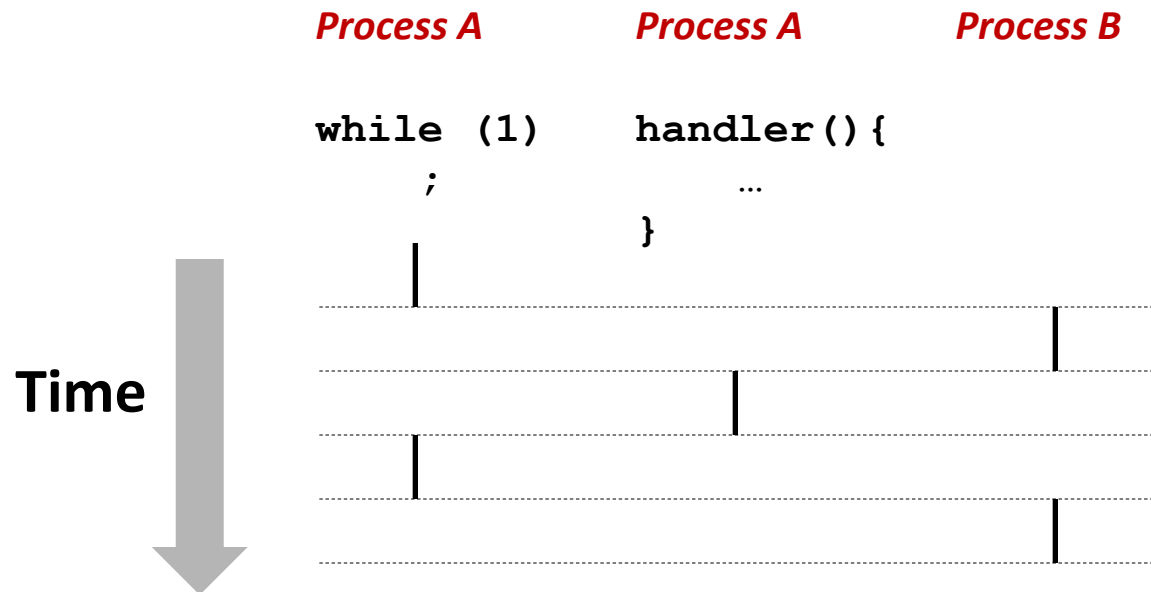
```
void int_handler(int sig) {
    safe_printf("Process %d received signal %d\n", getpid(), sig);
    exit(0);
}
```

```
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 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
        }
    }
}
```

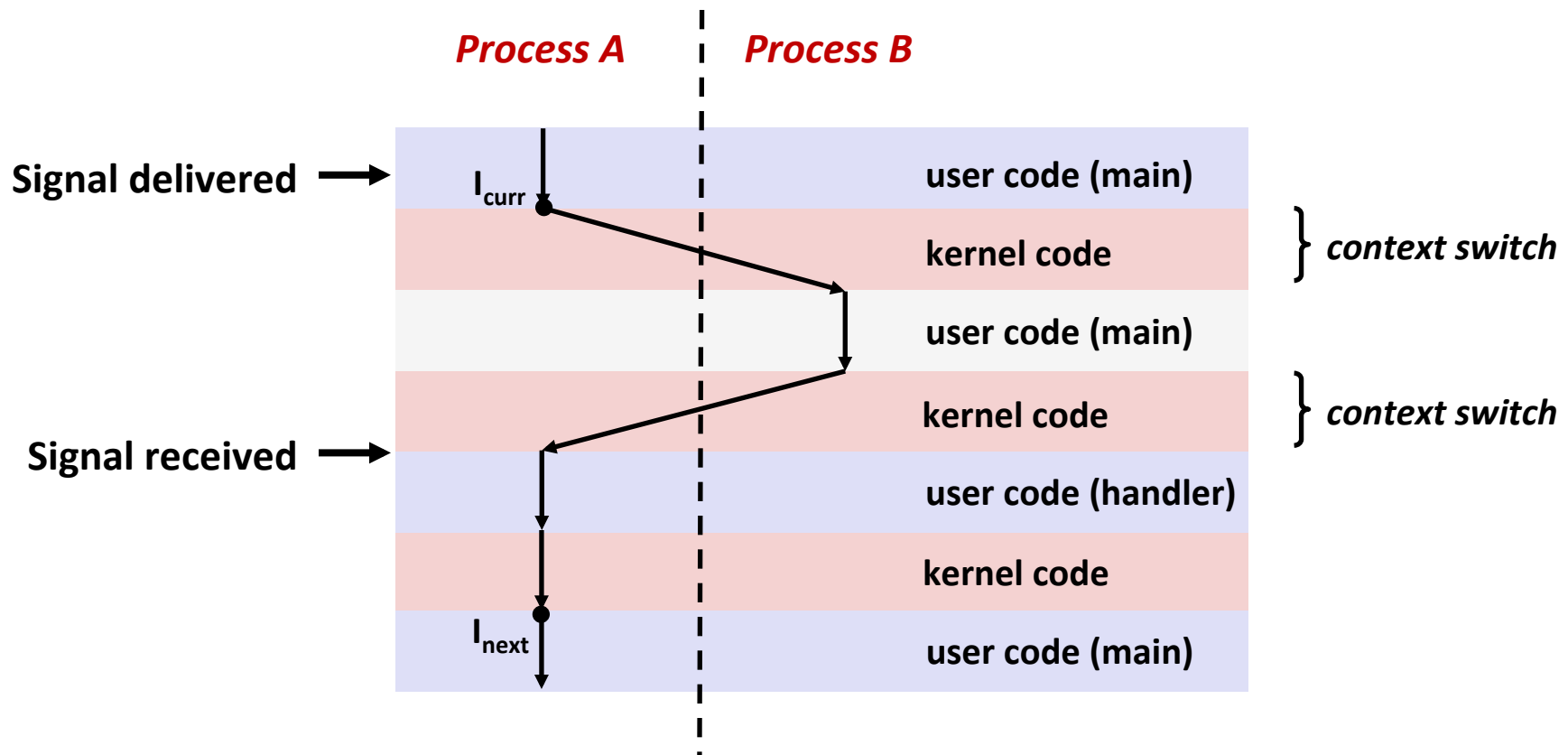
```
linux> ./forks 13
Killing process 25417
Killing process 25418
Killing process 25419
Killing process 25420
Killing process 25421
Process 25417 received signal 2
Process 25418 received signal 2
Process 25420 received signal 2
Process 25421 received signal 2
Process 25419 received signal 2
Child 25417 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); /* Suspend until signal occurs */
            exit(0); /* Suspend until signal occurs */
    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

```

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

```

# Living With Nonqueuing Signals

- Must check for all terminated jobs
  - Typically loop with `waitpid`

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

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

greatwhite> forks 15
Received signal 17 from process 27476
Received signal 17 from process 27477
. . .
Received signal 17 from process 27478
Received signal 17 from process 27479
. . .
Received signal 17 from process 27480
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 ctrl-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 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)
    }
}
```

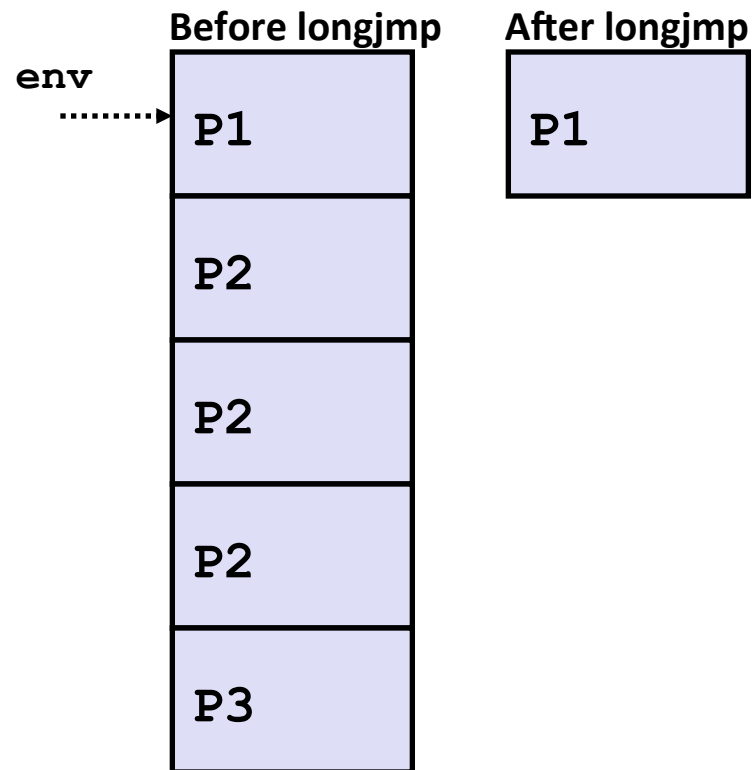


# Limitations of Nonlocal Jumps

## ■ 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(); }
```



# 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

```

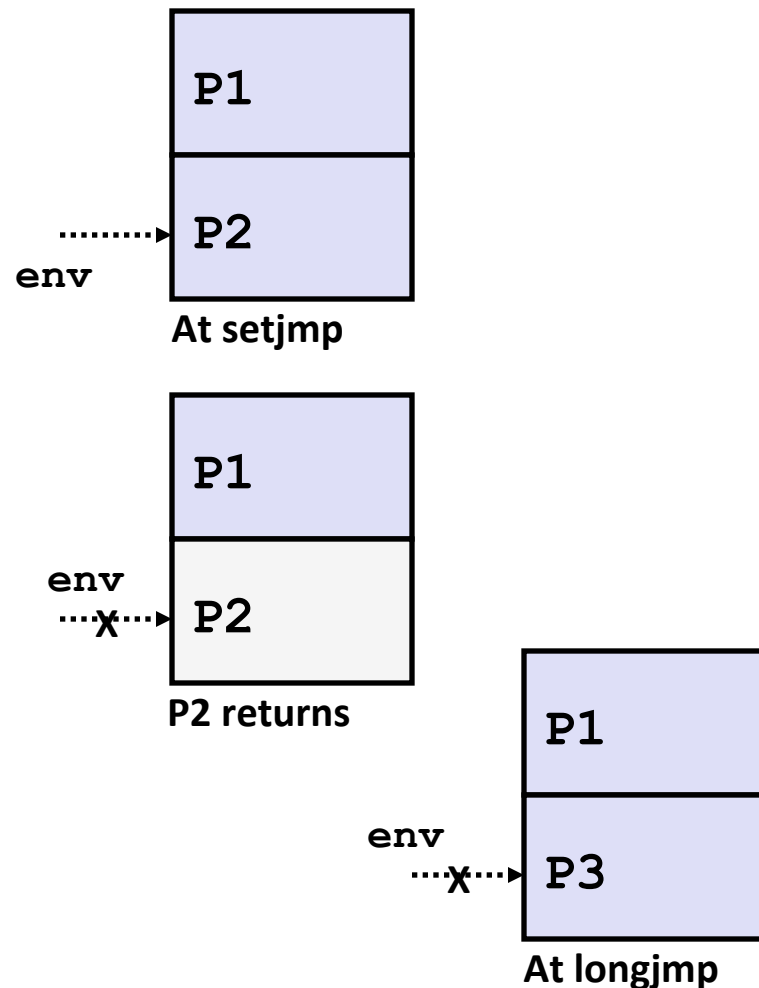
jmp_buf env;

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");
    }
}
```

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

restart.c

# 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