15-213
“The course that gives CMU its Zip!”

Exceptional Control Flow
Part II
October 16, 2003

Topics
- Process Hierarchy
- Shells
- Signals
- Nonlocal jumps
ECF Exists at All Levels of a System

Exceptions
- Hardware and operating system kernel software

Concurrent processes
- Hardware timer and kernel software

Signals
- Kernel software

Non-local jumps
- Application code
The World of Multitasking

System Runs Many Processes Concurrently

- Process: executing program
  - State consists of memory image + register values + program counter

- Continually 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
- **exec1()** and **execve()** run a new program in an 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

[0]

init [1]

Daemon
e.g. httpd

Login shell

Child

Grandchild

Child

Grandchild

Child
The `ps` command

Unix> `ps aux -w --forest`  
(output edited to fit slide)

<table>
<thead>
<tr>
<th>USER</th>
<th>PID</th>
<th>TTY</th>
<th>STAT</th>
<th>COMMAND</th>
</tr>
</thead>
<tbody>
<tr>
<td>root</td>
<td>1</td>
<td>?</td>
<td>S</td>
<td>init [3]</td>
</tr>
<tr>
<td>root</td>
<td>2</td>
<td>?</td>
<td>SW</td>
<td>[keventd]</td>
</tr>
<tr>
<td>root</td>
<td>3</td>
<td>?</td>
<td>SWN</td>
<td>[ksoftirqd_CPU0]</td>
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<tr>
<td>root</td>
<td>4</td>
<td>?</td>
<td>SW</td>
<td>[kswapd]</td>
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<td>root</td>
<td>5</td>
<td>?</td>
<td>SW</td>
<td>[bdflush]</td>
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<td>root</td>
<td>6</td>
<td>?</td>
<td>SW</td>
<td>[kupupdated]</td>
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<td>root</td>
<td>9</td>
<td>?</td>
<td>SW&lt;</td>
<td>[mdrecoveryd]</td>
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<td>root</td>
<td>12</td>
<td>?</td>
<td>SW</td>
<td>[scsi_eh_0]</td>
</tr>
<tr>
<td>root</td>
<td>397</td>
<td>?</td>
<td>S</td>
<td>/sbin/pump -i eth0</td>
</tr>
<tr>
<td>root</td>
<td>484</td>
<td>?</td>
<td>S&lt;</td>
<td>/usr/local/sbin/afsd -nosetime</td>
</tr>
<tr>
<td>root</td>
<td>533</td>
<td>?</td>
<td>S</td>
<td>syslogd -m 0</td>
</tr>
<tr>
<td>root</td>
<td>538</td>
<td>?</td>
<td>S</td>
<td>klogd -2</td>
</tr>
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<td>rpc</td>
<td>563</td>
<td>?</td>
<td>S</td>
<td>portmap</td>
</tr>
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<td>rpcuser</td>
<td>578</td>
<td>?</td>
<td>S</td>
<td>rpc.statd</td>
</tr>
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<td>daemon</td>
<td>696</td>
<td>?</td>
<td>S</td>
<td>/usr/sbin/atd</td>
</tr>
<tr>
<td>root</td>
<td>713</td>
<td>?</td>
<td>S</td>
<td>/usr/local/etc/nanny -init /etc/nanny.conf</td>
</tr>
<tr>
<td>mmdif</td>
<td>721</td>
<td>?</td>
<td>S</td>
<td>-- /usr/local/etc/deliver -b -csmtpcmu</td>
</tr>
<tr>
<td>root</td>
<td>732</td>
<td>?</td>
<td>S</td>
<td>-- /usr/local/sbin/named -f</td>
</tr>
<tr>
<td>root</td>
<td>738</td>
<td>?</td>
<td>S&lt;</td>
<td>-- /usr/local/sbin/sshd -D</td>
</tr>
<tr>
<td>root</td>
<td>739</td>
<td>?</td>
<td>S&lt;</td>
<td>-- /usr/local/etc/ntpd -n</td>
</tr>
<tr>
<td>root</td>
<td>752</td>
<td>?</td>
<td>S&lt;</td>
<td>-- /usr/local/etc/ntpd -n</td>
</tr>
<tr>
<td>root</td>
<td>753</td>
<td>?</td>
<td>S&lt;</td>
<td>-- /usr/local/etc/ntpd -n</td>
</tr>
<tr>
<td>root</td>
<td>744</td>
<td>?</td>
<td>S</td>
<td>-- /usr/local/sbin/zhm -n zephyr-1.srv.cm</td>
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<tr>
<td>root</td>
<td>774</td>
<td>?</td>
<td>S</td>
<td>gpm -t ps/2 -m /dev/mouse</td>
</tr>
<tr>
<td>root</td>
<td>786</td>
<td>?</td>
<td>S</td>
<td>crond</td>
</tr>
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</table>
### The `ps` Command (cont.)

<table>
<thead>
<tr>
<th>USER</th>
<th>PID</th>
<th>TTY</th>
<th>STAT</th>
<th>COMMAND</th>
</tr>
</thead>
<tbody>
<tr>
<td>root</td>
<td>889</td>
<td>tty1</td>
<td>S</td>
<td>/bin/login -- agn</td>
</tr>
<tr>
<td>agn</td>
<td>900</td>
<td>tty1</td>
<td>S</td>
<td>xinit -- :0</td>
</tr>
<tr>
<td>root</td>
<td>921</td>
<td>?</td>
<td>SL</td>
<td>/etc/X11/X -auth /usr/local/Xauthority :0</td>
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<tr>
<td>agn</td>
<td>948</td>
<td>tty1</td>
<td>S</td>
<td>/bin/sh /afs/cs.cmu.edu/user/agn/.xinitrc</td>
</tr>
<tr>
<td>agn</td>
<td>958</td>
<td>tty1</td>
<td>S</td>
<td>xterm -geometry 80x45+1+1 -C -j -ls -n</td>
</tr>
<tr>
<td>agn</td>
<td>966</td>
<td>pts/0</td>
<td>S</td>
<td>-tcsh</td>
</tr>
<tr>
<td>agn</td>
<td>1184</td>
<td>pts/0</td>
<td>S</td>
<td>/usr/local/bin/wish8.0 -f /usr</td>
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<td>agn</td>
<td>1212</td>
<td>pts/0</td>
<td>S</td>
<td>aspell -a -S</td>
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<tr>
<td>agn</td>
<td>1191</td>
<td>pts/0</td>
<td>S</td>
<td>/bin/sh /usr/local/libexec/moz</td>
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<td>pts/0</td>
<td>S</td>
<td>/usr/local/libexec/mozilla</td>
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<tr>
<td>agn</td>
<td>1207</td>
<td>pts/0</td>
<td>S</td>
<td>/usr/local/libexec/moz</td>
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<tr>
<td>agn</td>
<td>1208</td>
<td>pts/0</td>
<td>S</td>
<td>/usr/local/libexec/moz</td>
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<tr>
<td>agn</td>
<td>1209</td>
<td>pts/0</td>
<td>S</td>
<td>/usr/local/libexec/moz</td>
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<td>pts/0</td>
<td>S</td>
<td>java_vm</td>
</tr>
<tr>
<td>agn</td>
<td>2469</td>
<td>pts/0</td>
<td>S</td>
<td>java_vm</td>
</tr>
<tr>
<td>agn</td>
<td>2483</td>
<td>pts/0</td>
<td>S</td>
<td>java_vm</td>
</tr>
<tr>
<td>agn</td>
<td>2484</td>
<td>pts/0</td>
<td>S</td>
<td>java_vm</td>
</tr>
<tr>
<td>agn</td>
<td>2485</td>
<td>pts/0</td>
<td>S</td>
<td>java_vm</td>
</tr>
<tr>
<td>agn</td>
<td>3042</td>
<td>pts/0</td>
<td>S</td>
<td>java_vm</td>
</tr>
<tr>
<td>agn</td>
<td>959</td>
<td>tty1</td>
<td>S</td>
<td>/bin/sh /usr/local/libexec/kde/bin/sta</td>
</tr>
<tr>
<td>agn</td>
<td>1020</td>
<td>tty1</td>
<td>S</td>
<td>kwrapper ksmserver</td>
</tr>
</tbody>
</table>
Unix Startup: Step 1

1. Pushing reset button loads the PC with the address of a small bootstrap program.
2. Bootstrap program loads the boot block (disk block 0).
3. Boot block program loads kernel binary (e.g., /boot/vmlinux).
4. Boot block program passes control to kernel.
5. Kernel handcrafts the data structures for process 0.

![Process Diagram]

- [0]: Process 0: handcrafted kernel process
- init [1]: Process 0 forks child process 1
- Child process 1 execs /sbin/init
Some PC Start-up Details

Boot Disk / CD / Floppy

Power OK
Deassert Reset

BIOS ROM

CPU

Start Execution at 0xfffffffff0

The Linux kernel is loaded and begins initialization
CPU executes LILO

BIOS verifies MBR and jumps to 0x00007c00

Copy

Master Boot Record into memory

LILO (or GRUB) is loaded from first sector of active partition

0xffffffff
0xffffffff
0xffff0000
0x00007c00
0x00000000
Unix Startup: Step 2

init forks and execs daemons per /etc/inittab, and forks and execs a getty program for the console

/etc/inittab

init [1]

Daemons
e.g. ftpd, httpd

getty

[0]
Unix Startup: Step 3

[0]

init [1]

login

The getty process execs a login program
Unix Startup: Step 4

- login reads login-ID and passwd.
  - if OK, it execs a shell.
  - if not OK, it execs another getty

In case of login on the console, xinit may be used instead of a shell to start the window manager.
A **shell** is an application program that runs programs on behalf of the user.

- `sh` – Original Unix Bourne Shell
- `csh` – BSD Unix C Shell, `tcsh` – Enhanced C Shell
- `bash` – Bourne-Again Shell

```c
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

```c
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);
}
```
Problem with Simple Shell 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.
- Creates a memory leak that will eventually crash the kernel when it runs out of memory.

Solution: Reaping background jobs requires a mechanism called a signal.
Signals

A *signal* is a small message that notifies a process that an event of some type has occurred in the system.

- Kernel abstraction for exceptions and interrupts.
- Sent from the kernel (sometimes at the request of another process) to a process.
- Different signals are identified by small integer ID’s (1-30)
- The only information in a signal is its ID and the fact that it arrived.

<table>
<thead>
<tr>
<th>ID</th>
<th>Name</th>
<th>Default Action</th>
<th>Corresponding Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>SIGINT</td>
<td>Terminate</td>
<td>Interrupt from keyboard (ctl-c)</td>
</tr>
<tr>
<td>9</td>
<td>SIGKILL</td>
<td>Terminate</td>
<td>Kill program (cannot override or ignore)</td>
</tr>
<tr>
<td>11</td>
<td>SIGSEGV</td>
<td>Terminate &amp; Dump</td>
<td>Segmentation violation</td>
</tr>
<tr>
<td>14</td>
<td>SIGALRM</td>
<td>Terminate</td>
<td>Timer signal</td>
</tr>
<tr>
<td>17</td>
<td>SIGCHLD</td>
<td>Ignore</td>
<td>Child stopped or terminated</td>
</tr>
</tbody>
</table>
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 (cont)

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 a signal handler.
    - Akin to a hardware exception handler being called in response to an asynchronous interrupt.
Signal Concepts (cont)

A signal is **pending** if it has been 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 whenever a signal of type k is delivered.
  - Kernel clears bit k in pending whenever a signal of type k is received
- **blocked** – represents the set of blocked signals
  - Can be set and cleared by the application using the `sigprocmask` function.
Process Groups

Every process belongs to exactly one process group

- **Shell**
  - **Foreground job** (pid=20, pgid=20)
    - Child (pid=21, pgid=20)
    - Child (pid=22, pgid=20)
  - **Background job #1** (pid=32, pgid=32)
  - **Background job #2** (pid=40, pgid=40)

- **Foreground process group 20**
- **Background process group 32**
- **Background process group 40**

- `getpgid()` — Return process group of current process
- `setpgid()` — Change process group of a process
Sending Signals with kill Program

**kill** program sends arbitrary signal to a process or process group

**Examples**

- **kill -9 24818**
  - Send SIGKILL to process 24818

- **kill -9 -24817**
  - Send SIGKILL to every process in process group 24817.

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

linux> ps
   PID   TTY TIME CMD
24788 pts/2   0:00:00 tcsh
24818 pts/2   0:00:02 forks
24819 pts/2   0:00:02 forks
24820 pts/2   0:00:00 ps

linux> kill -9 -24817

linux> ps
   PID   TTY TIME CMD
24788 pts/2   0:00:00 tcsh
24823 pts/2   0:00:00 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

```
- Shell
  - Foreground job
    - Child
      - PID: 20
        - PGID: 20
  - Background job #1
    - PID: 32
      - PGID: 32
      - Background process group 32
  - Background job #2
    - PID: 40
      - PGID: 40
      - Background process group 40
```

Foreground process group 20
Example of `ctrl-c` and `ctrl-z`

```bash
linux> ./forks 17
Child: pid=24868 pgrp=24867
Parent: pid=24867 pgrp=24867
  <typed ctrl-z>
Suspended
linux> ps a
    PID  TTY   STAT   TIME COMMAND
 24788 pts/2  S  0:00   -usr/local/bin/tcsh -i
 24867 pts/2  T  0:01   ./forks 17
 24868 pts/2  T  0:01   ./forks 17
 24869 pts/2  R  0:00   ps a
bass> fg
./forks 17
  <typed ctrl-c>
linux> ps a
    PID  TTY   STAT   TIME COMMAND
 24788 pts/2  S  0:00   -usr/local/bin/tcsh -i
 24870 pts/2  R  0:00   ps a
```
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 $p$.

Kernel computes $\text{pnb} = \text{pending} \& \sim \text{blocked}$

- The set of pending nonblocked signals for process $p$

If $(\text{pnb} == 0)$

- Pass control to next instruction in the logical flow for $p$.

Else

- Choose least nonzero bit $k$ in $\text{pnb}$ and force process $p$ to receive signal $k$.
- The receipt of the signal triggers some action by $p$
- Repeat for all nonzero $k$ in $\text{pnb}$.
- 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 `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

```c
void int_handler(int sig)
{
    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);
...
}
```

```
linux> ./forks 13
Killing process 24973
Killing process 24974
Killing process 24975
Killing process 24976
Killing process 24977
Process 24977 received signal 2
Child 24977 terminated with exit status 0
Process 24976 received signal 2
Child 24976 terminated with exit status 0
Process 24975 received signal 2
Child 24975 terminated with exit status 0
Process 24974 received signal 2
Child 24974 terminated with exit status 0
Process 24973 received signal 2
Child 24973 terminated with exit status 0
```
Signal Handler Funkiness

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

```c
int ccount = 0;
void child_handler(int sig)
{
    int child_status;
    pid_t pid = wait(&child_status);
    ccount--;
    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) {
            /* Child: Exit */
            exit(0);
        }
    while (ccount > 0)
        pause(); /* Suspend until signal occurs */
}
Living With Nonqueuing Signals

Must check for all terminated jobs

- Typically loop with `wait`

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

void fork15()
{
    . . .
    signal(SIGCHLD, child_handler2);
    . . .
}
Signal Handler Funkiness (Cont.)

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 `EINVAL` 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.
A Program That Reacts to Externally Generated Events (ctrl-c)

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

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

main() {
    signal(SIGINT, handler); /* installs ctrl-c handler */
    while(1) {
    }
}
```
A Program That Reacts to Internally Generated Events

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

int beeps = 0;

/* SIGALRM handler */
void handler(int sig) {
    printf("BEEP\n");
    fflush(stdout);

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

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

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

```
linux> a.out
BEEP
BEEP
BEEP
BEEP
BOOM!
bass>
```
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

```c
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 from jump buffer \( j \)
- Set %eax (the return value) to \( i \)
- Jump to the location indicated by the PC stored in jump buf \( j \).
#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)
    }
}
Putting It All Together: A Program That Restarts Itself When `ctrl-c’d`

```c
#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");
}
```

bass> a.out
starting
processing...
processing...
restarting
processing...
processing...
CTRL-C
CTRL-C

15-213, F’03
Limitations of Nonlocal Jumps

Works within stack discipline

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

```c
jmp_buf env;

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

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

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

Before longjmp

After longjmp
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

```c
jmp_buf env;

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

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

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