15-213

“The course that gives CMU its Zip!”

Exceptional Control Flow Part II October 7, 2008

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

Previous Lecture (Exceptions, Concurrent processes)

This Lecture (Signals, Non-local jumps)

The World of Multi<u>task</u>ing

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
- `execl()` and `execve()` run 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

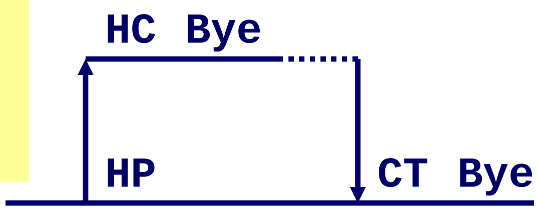
`wait`: Synchronizing with Children

`int wait(int *child_status)`

- suspends current process until one of its children terminates
- return value is the `pid` of the child process that terminated
- if `child_status != NULL`, then the object it points to will be set to a status indicating why the child process terminated

wait: Synchronizing with Children

```
void fork9() {
   int child_status;

   if (fork() == 0) {
      printf("HC: hello from child\n");
   }
   else {
      printf("HP: hello from parent\n");
      wait(&child_status);
      printf("CT: child has terminated\n");
   }
   printf("Bye\n");
   exit();
}
```



wait() Example

- If multiple children completed, will take in arbitrary order
- Can use macros WIFEXITED and WEXITSTATUS to get information about exit status

```
void fork10()
{
    pid_t pid[N];
    int i;
    int child_status;
    for (i = 0; i < N; i++)
       if ((pid[i] = fork()) == 0)
           exit(100+i); /* Child */
    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);
    }
}
```

waitpid(): Waiting for a Specific Process

- **waitpid(pid, &status, options)**
  - suspends current process until specific process terminates
  - various options (that we won't talk about)

```
void fork11()
{
    pid_t pid[N];
    int i;
    int child_status;
    for (i = 0; i < N; i++)
       if ((pid[i] = fork()) == 0)
           exit(100+i); /* Child */
    for (i = 0; i < N; i++) {
       pid_t wpid = waitpid(pid[i], &child_status, 0);
       if (WIFEXITED(child_status))
           printf("Child %d terminated with exit status %d\n",
                  wpid, WEXITSTATUS(child_status));
       else
           printf("Child %d terminated abnormally\n", wpid);
    }
```

exec: Loading and Running Programs

```
int execl(char *path, char *arg0, char *arg1, …, 0)
```

- Loads and runs executable at `path` with args `arg0`, `arg1`, …
  - `path` is the complete path of an executable object file
  - By convention, `arg0` is the name of the executable object file
  - "Real" arguments to the program start with `arg1`, etc.
  - List of args is terminated by a `(char *)0` argument
  - Environment taken from `char **environ`, which points to an array of "name=value" strings:
    - » USER=droh
    - » LOGNAME=droh
    - » HOME=/afs/cs.cmu.edu/user/droh
- Returns `-1` if error, otherwise doesn't return!

- Family of functions includes `execv`, `execve` (base function), `execvp`, `execl`, `execle`, and `execlp`

exec：Loading and Running Programs

```
main() {
   if (fork() == 0) {
      execl("/usr/bin/cp", "cp", "foo", "bar", 0);
   }
   wait(NULL);
   printf("copy completed\n");
   exit();
}
```

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: csh enhanced 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);
    }
}
```

"Background Job"?

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"

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

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

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

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
- Will create a memory leak that could theoretically run the kernel out of memory
  - In modern Unix: once you exceed your *process quota*, your shell can't run any new commands for you; `fork()` returns -1

```
% limit maxproc          # csh syntax
maxproc      3574
$ ulimit -u              # bash syntax
3574
```

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***

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

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 (continued)

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 (continued)

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

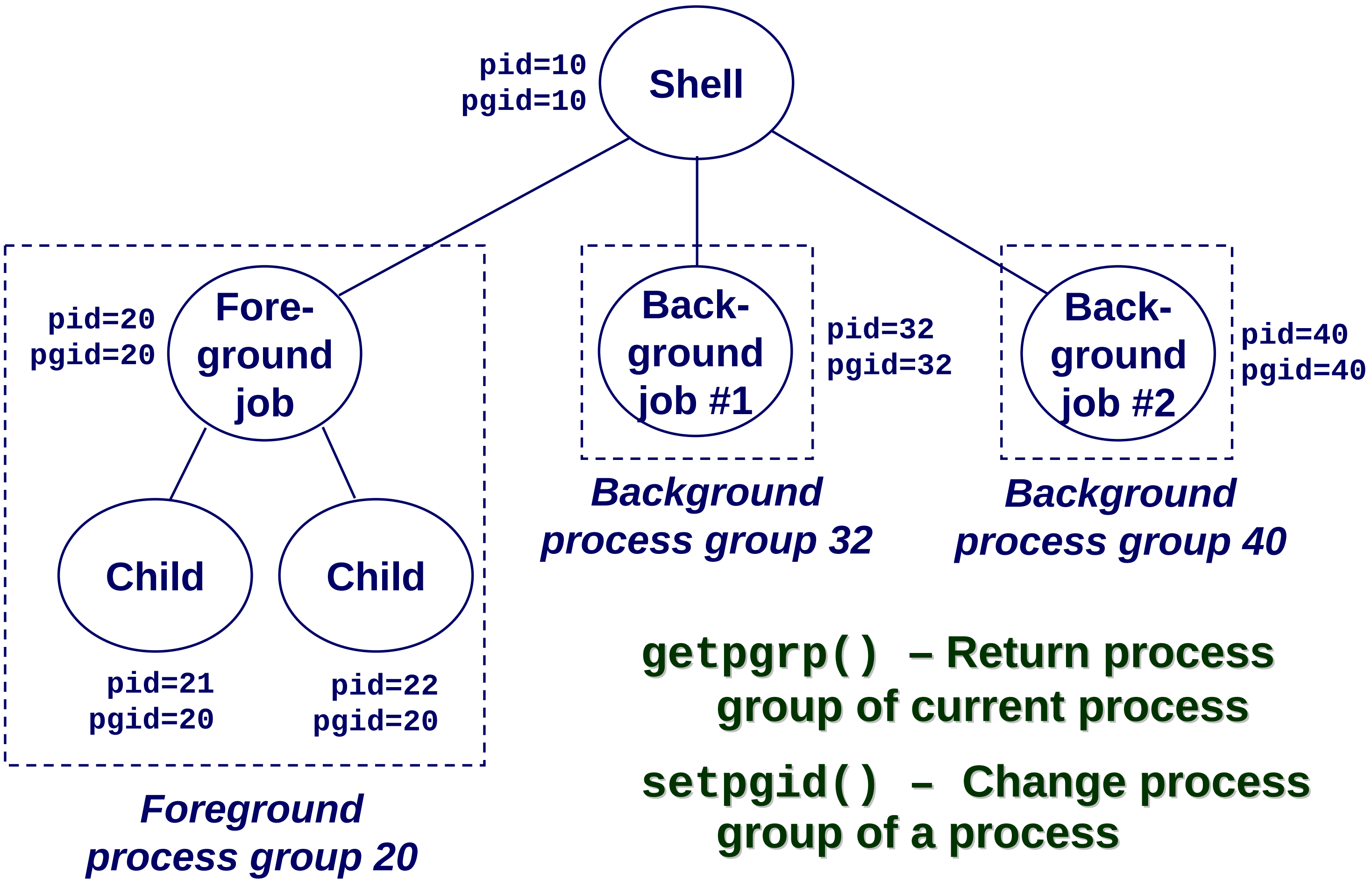
Signal Concepts

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 `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    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> 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 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*

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

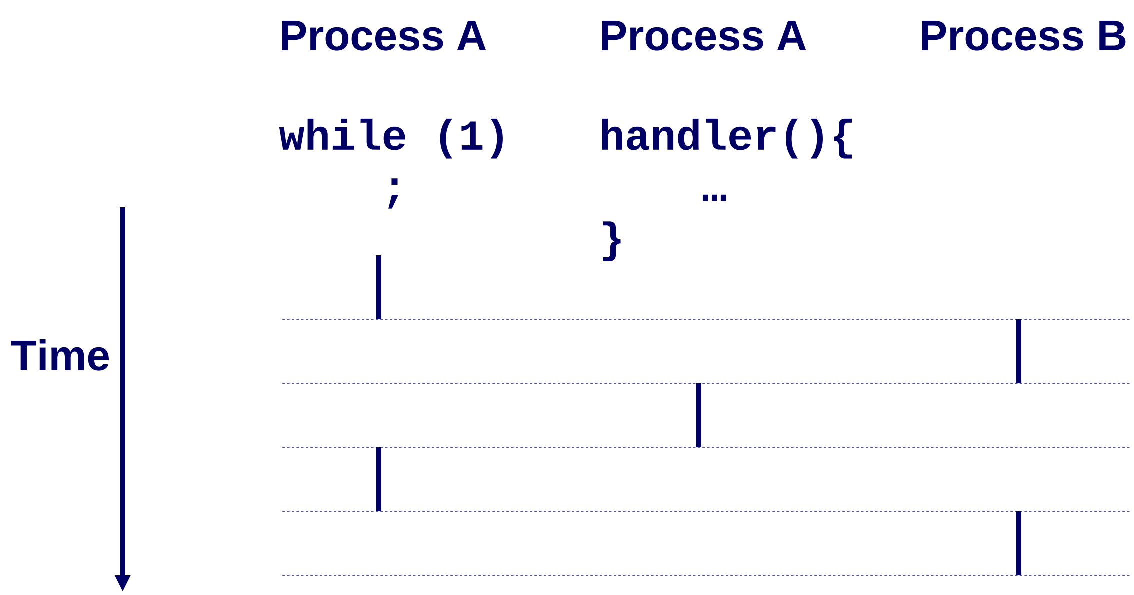
```
void int_handler(int sig)
{
    printf("Process %d received signal %d\n",
            getpid(), sig);
    exit(0);
}

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
linux>
```

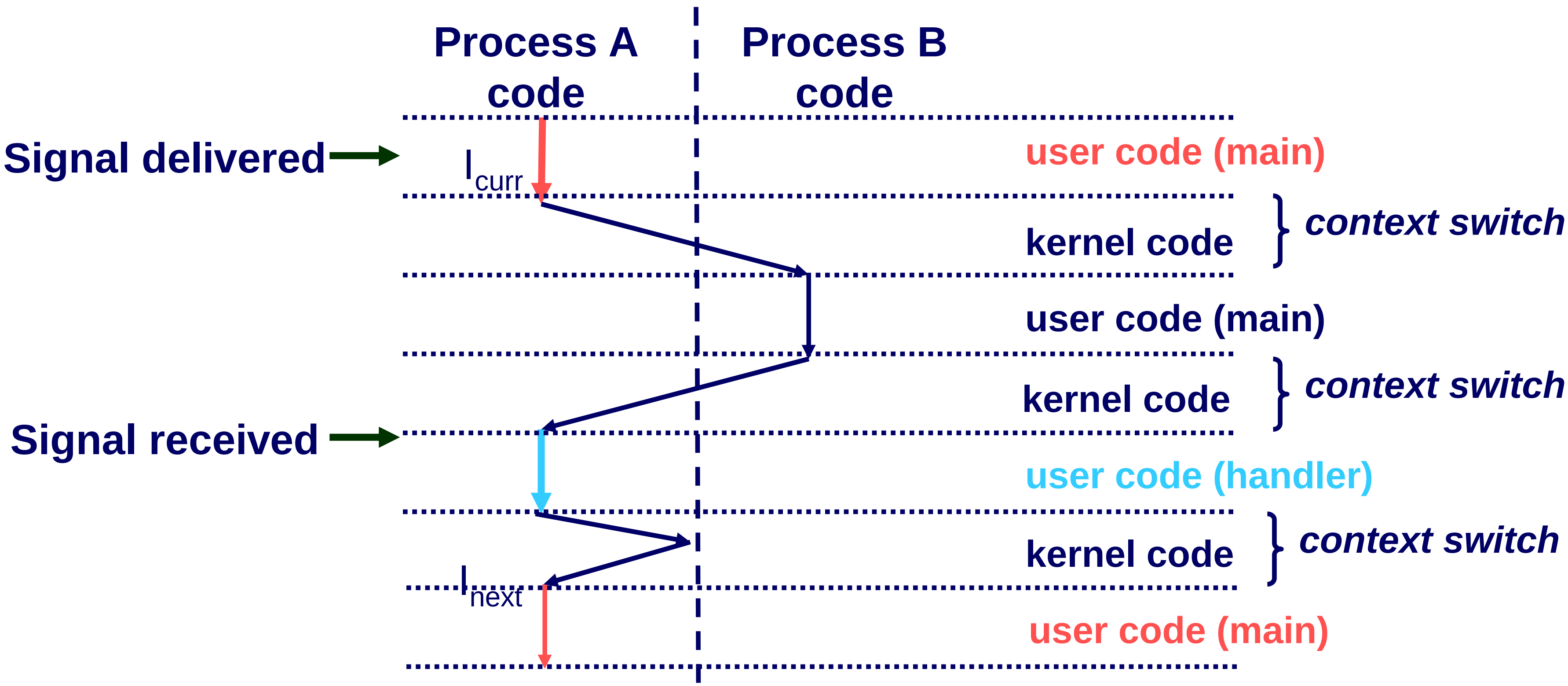
Signals Handlers as Concurrent Flows

A signal handler is a separate logical flow (thread) that runs concurrently with the main program

- "concurrently", in the "not sequential" sense



Another View of Signal Handlers as Concurrent Flows



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 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

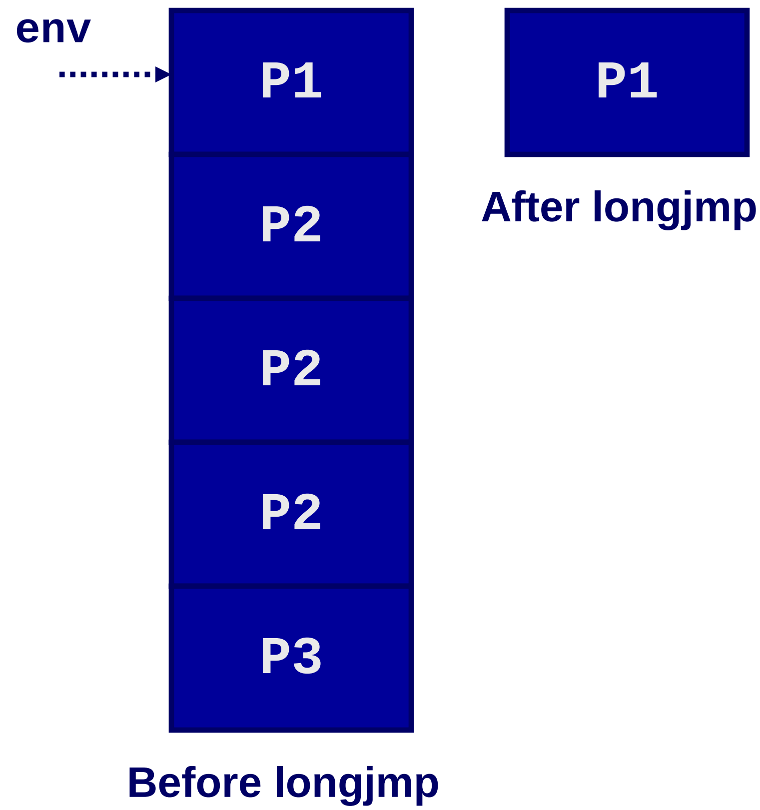
```
#include <setjmp.h>
jmp_buf buf;

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);
}
```

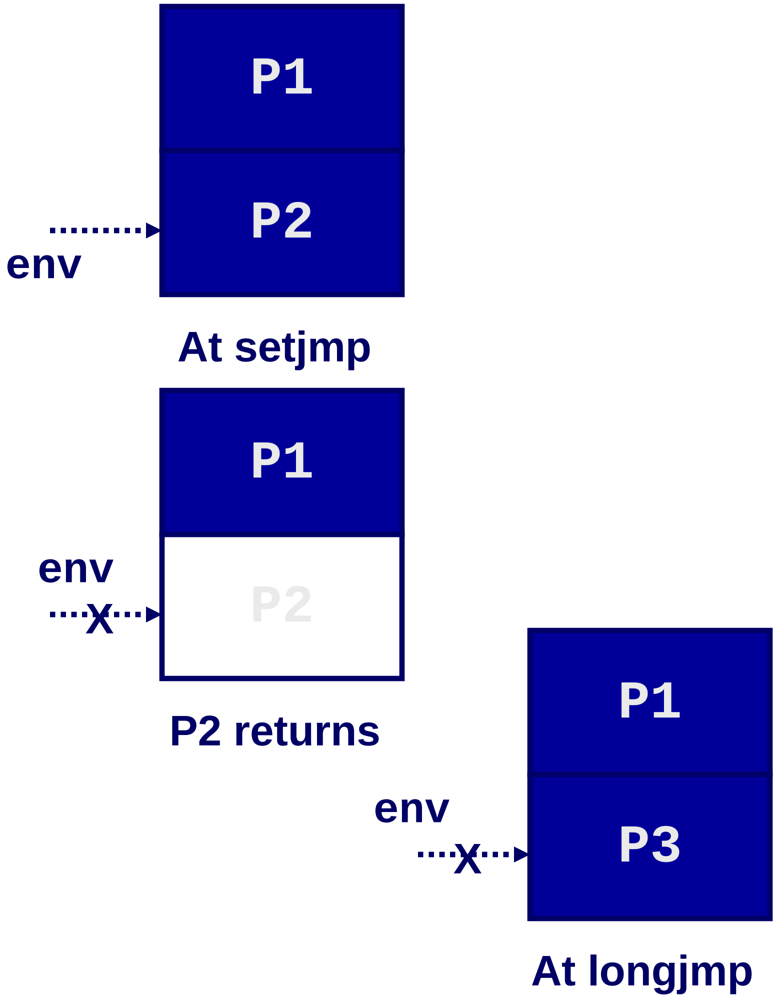


Limitations of Long Jumps (cont.)

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");
  }
}
```

```
bass> a.out
starting
processing...
processing...
restarting        <- Ctrl-c
processing...
processing...
restarting        <- Ctrl-c
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

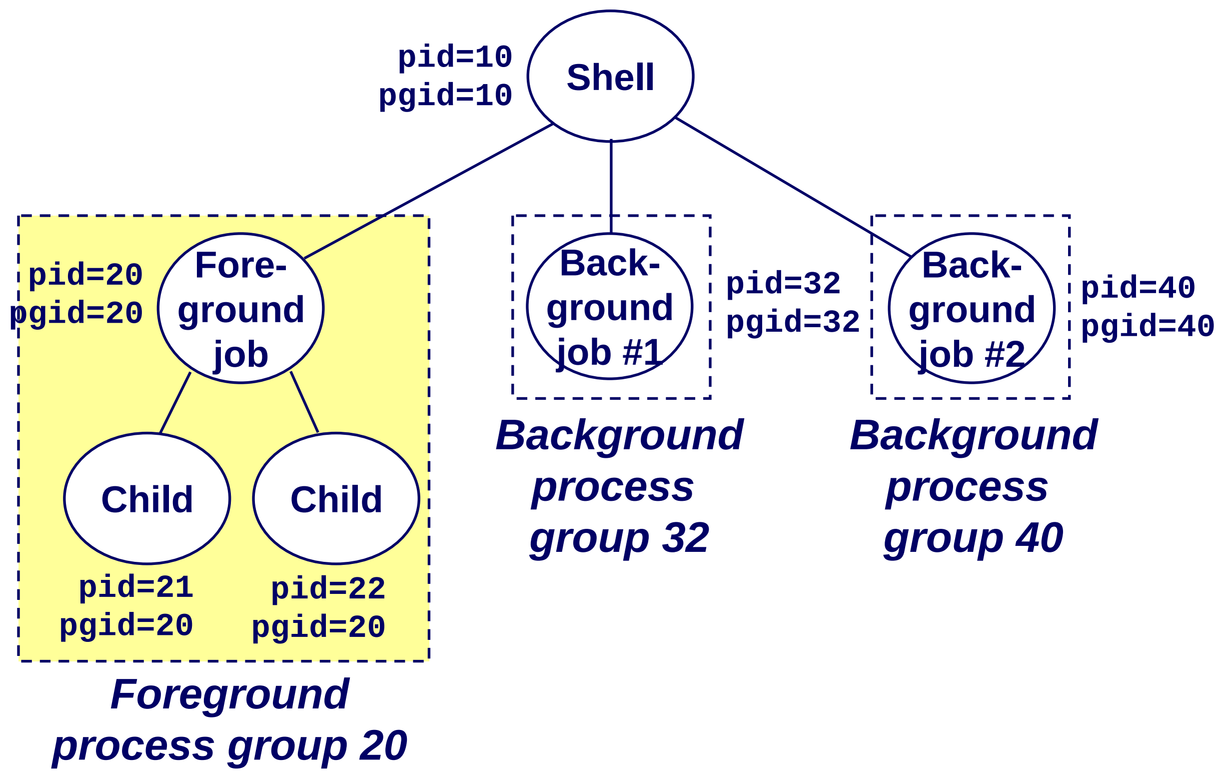
Nonlocal jumps provide exceptional control flow within process

- Within constraints of stack discipline

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

Signal Handler Funkiness

```
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) {
            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

Living With Nonqueuing Signals

Must check for all terminated jobs

- Typically loop with `wait`

```
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 `EINTER` 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)

```
#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 ctl-c handler */
  while(1) {
  }
}
```

A Program That Reacts to Internally Generated Events

```
#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
BEEP
BOOM!
bass>
```