Exceptional Control Flow II

Today
- Process Hierarchy
- Shells
- Signals
- Nonlocal jumps

Next time
- I/O

Chris Riesbeck, Fall 2011
Original: Fabian Bustamante

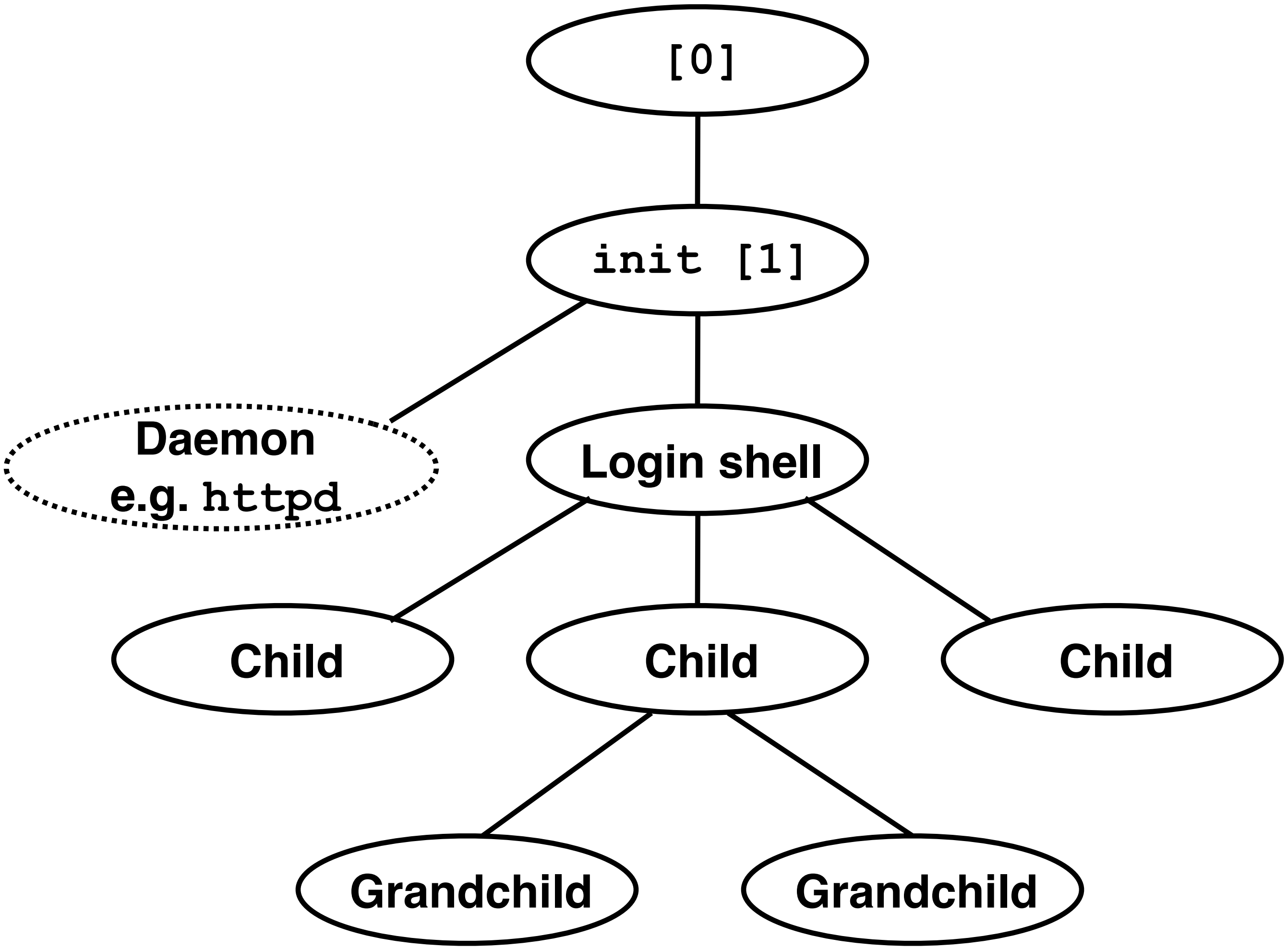
The world of multitasking

- 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
    - Except possibly with lower performance
    - Even though most systems can only execute one at a time

Programmer's model of multitasking

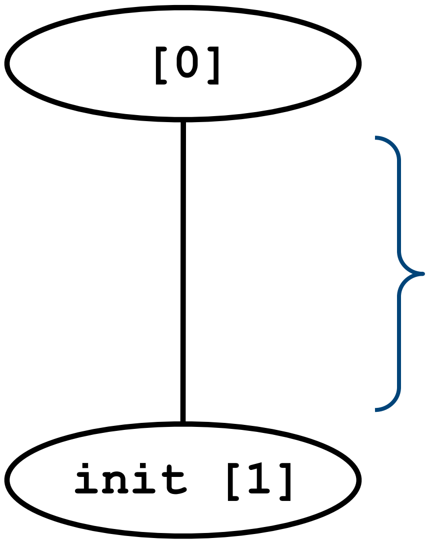
- Basic functions
  - `fork()` spawns new process
    - Called once, returns twice
  - `exit()` terminates own process
    - Called once, never returns
    - Puts it into "zombie" status
  - `wait()` and `waitpid()` wait for and reap terminated children
  - `execl()` and `execve()` run a new program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



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.

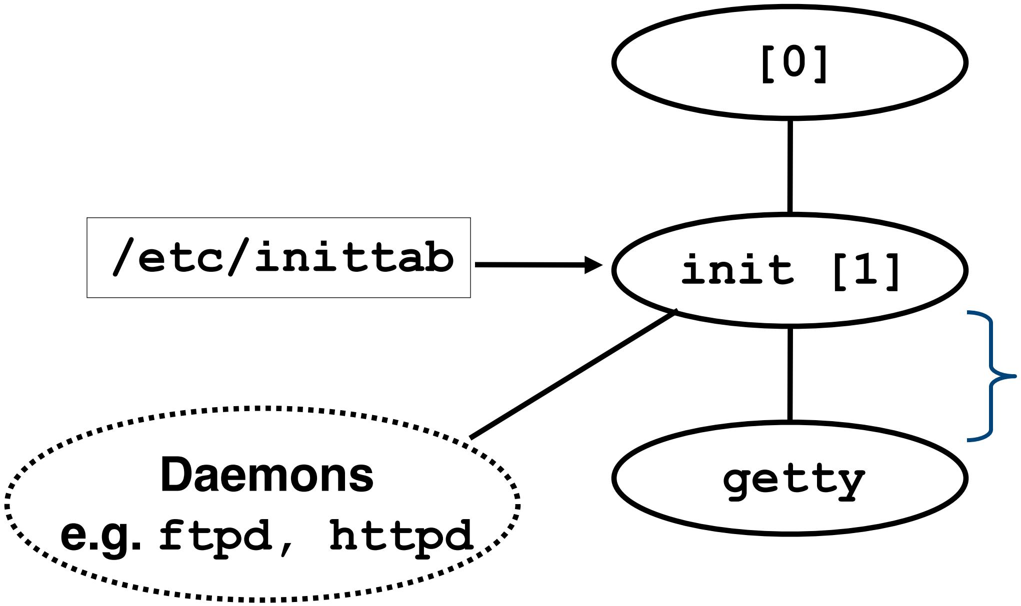


Process 0: handcrafted kernel process

Process 0 forks child process 1

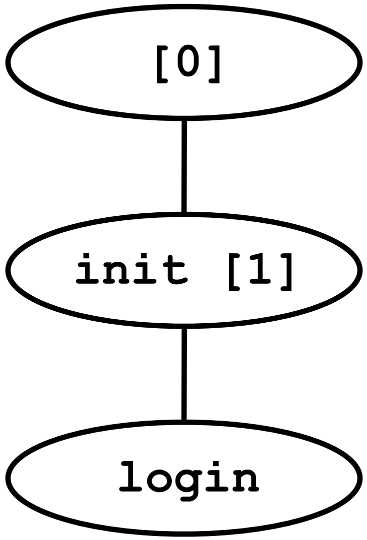
Child process 1 execs `/sbin/init`

Unix startup: Step 2



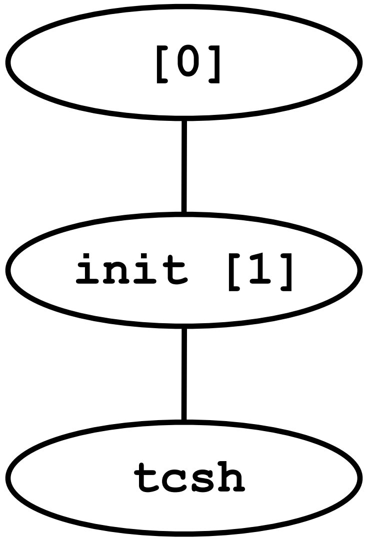
`init` forks and execs daemons per `/etc/inittab`, and forks and execs a `getty` program for the console

Unix startup: Step 3



The `getty` process execs a `login` program

Unix startup: Step 4



`login` **reads login and passwd.**
if OK, it execs a *shell.*
if not OK, it execs another `getty`

Shell programs

- 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

```
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);
    }
}
```

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
  - The only information in a signal is its ID and the fact that it arrived.

ID	Name	Default Action	Corresponding Event
2	`SIGINT`	Terminate	Interrupt from keyboard (`ctl-c`)
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 (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.
    - *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)

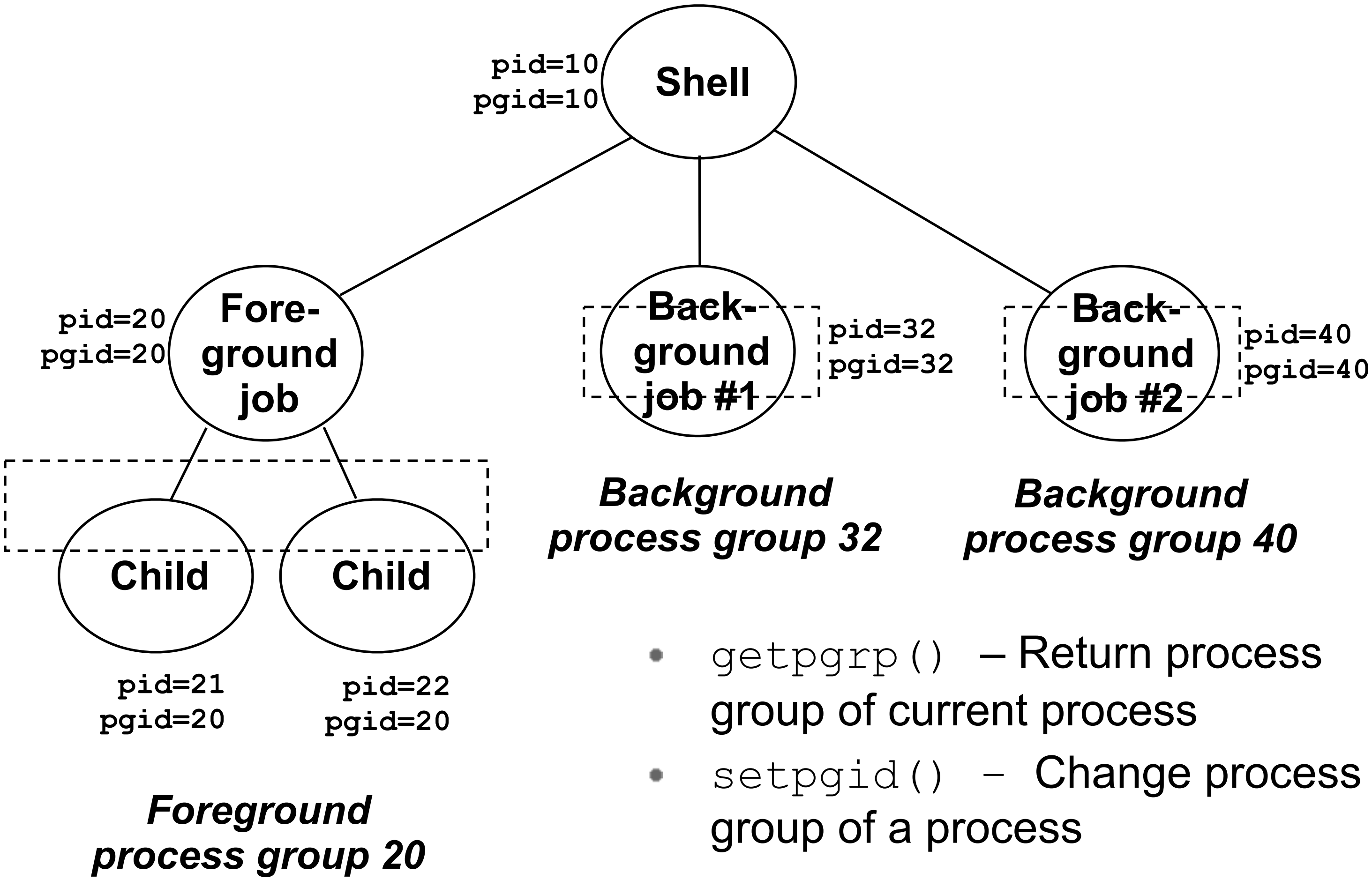
- A signal is *pending* if it has been sent but not yet received.
  - There can be at most one pending signal of any type.
  - Important: Signals are not queued
    - If a process has a pending signal of type k, then subsequent signals of type k that are sent to that process are discarded.
- A process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

- All mechanisms for sending signals to processes rely on the notion of process group
- 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

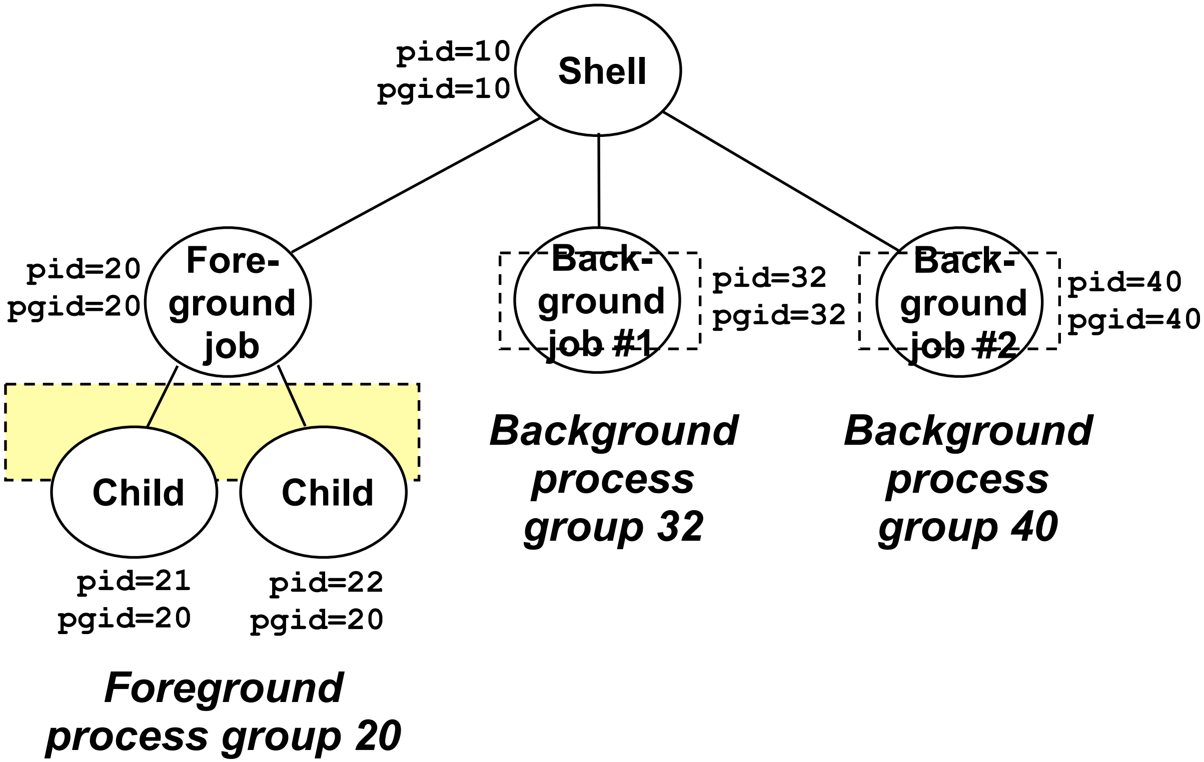
- `kill` program sends arbitrary signal to a process or process group
- Examples
  - `kill -9 24818`
    - Send SIGKILL to process 24818
  - `kill -9 -24817`
    - Send SIGKILL to every process in process group 24817.

```
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 from the keyboard

- Typing ctrl-c (ctrl-z) sends a SIGTERM (SIGTSTP) to every job in the foreground process group.
  - SIGTERM – default action is to terminate each process
  - SIGTSTP – default action is to stop (suspend) each process



Example of `ctrl-c` and `ctrl-z`

```
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
```

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 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>
```

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) {
            /* Child: Exit */
            exit(0);
        }
    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
  - Code on left will miss signals if 2 or more sent while processing the first

Living with nonqueuing signals

- Must check for all terminated jobs
  - Typically loop with wait
  - Similar code used for web servers, shells, …
  - See Figure 8.30 in textbook for another problem with interrupted system calls

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

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

External event handling

- 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) {
  }
}
```

Internal event handling

```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);
  }
}
```

```c
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!
linux>
```

Checkpoint

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
  - Used 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:
  - Store 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` stored in jump buffer `j` again...
    - …but return i this time `i` instead of 0
  - Called after `setjmp`
  - Called once, but never returns
- 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) { /* buf gets reg data */
      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); /* return 1 from setjmp */
}
```

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");
  }
}
```

```
linux> a.out
starting
processing...
processing...
restarting            Ctrl-c
processing...
processing...
processing...
restarting            Ctrl-c
processing...
restarting            Ctrl-c
processing...
processing...
```

Limitations of nonlocal jumps

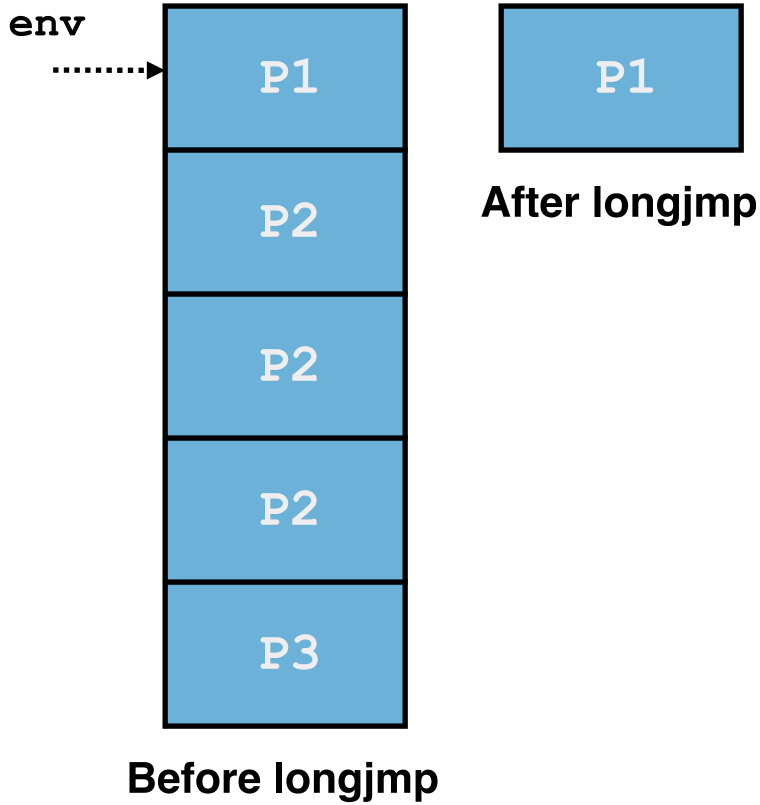
- Works within stack discipline
  - Can only long jump to environment of function that has been called but not yet completed

```
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.)

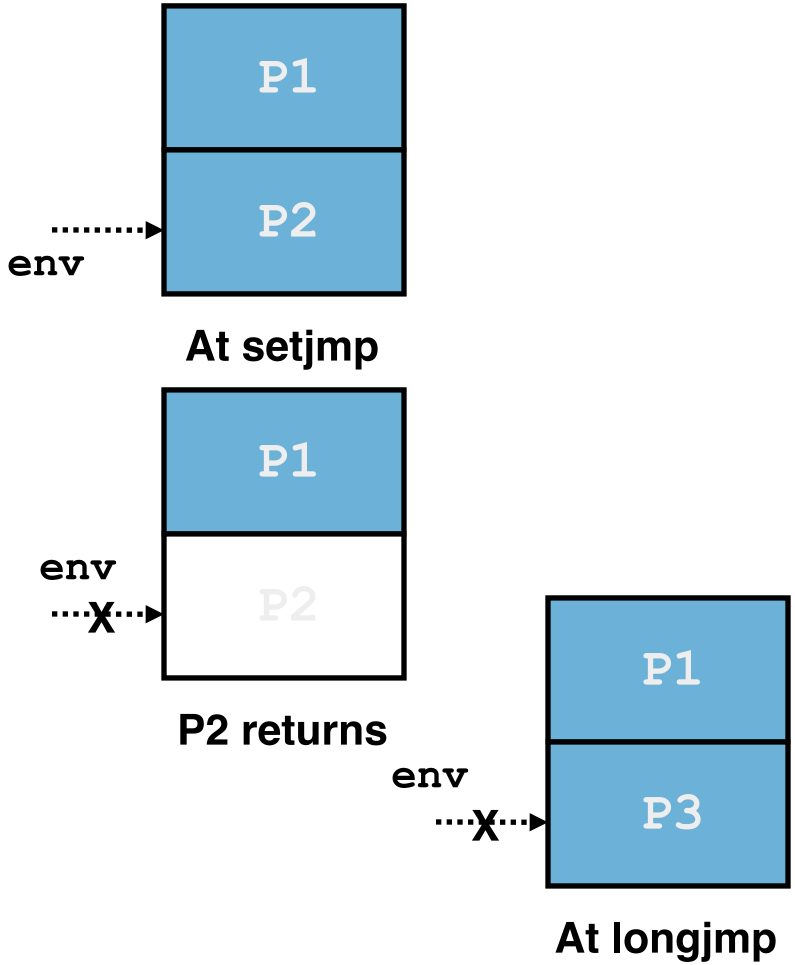
- Works within stack discipline
  - Can only long jump to environment of function that has been called but not yet completed

```
jmp_buf env;

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

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

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



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