Signals

15-213/18-243: Introduction to Computer Systems

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ECF Exists at All Levels of a System

- **Exceptions**
  - Hardware
  - Operating system (kernel software)
- **Signals**
  - Kernel software
- **Non-local jumps**
  - Application code

Previous Lecture

This Lecture

Today

- Multitasking, shells
- Signals
- Long jumps
- More on signals

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
  - **`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

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);
  }
}
```

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 hrs
```

- **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
  - 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***

Today

- Multitasking, shells
- **Signals**
- Long jumps
- More on signals

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

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

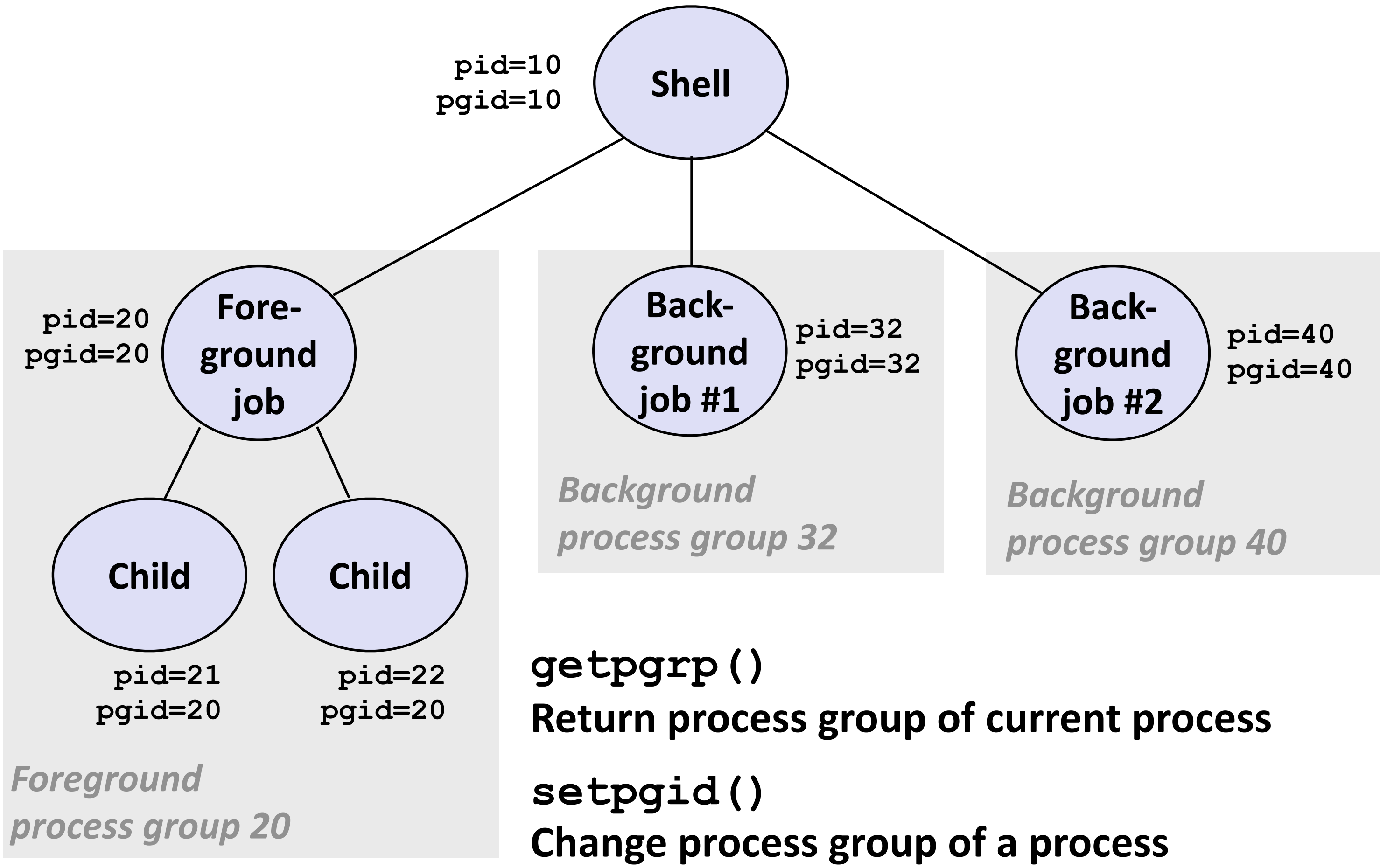
- **A pending signal is received at most once**

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

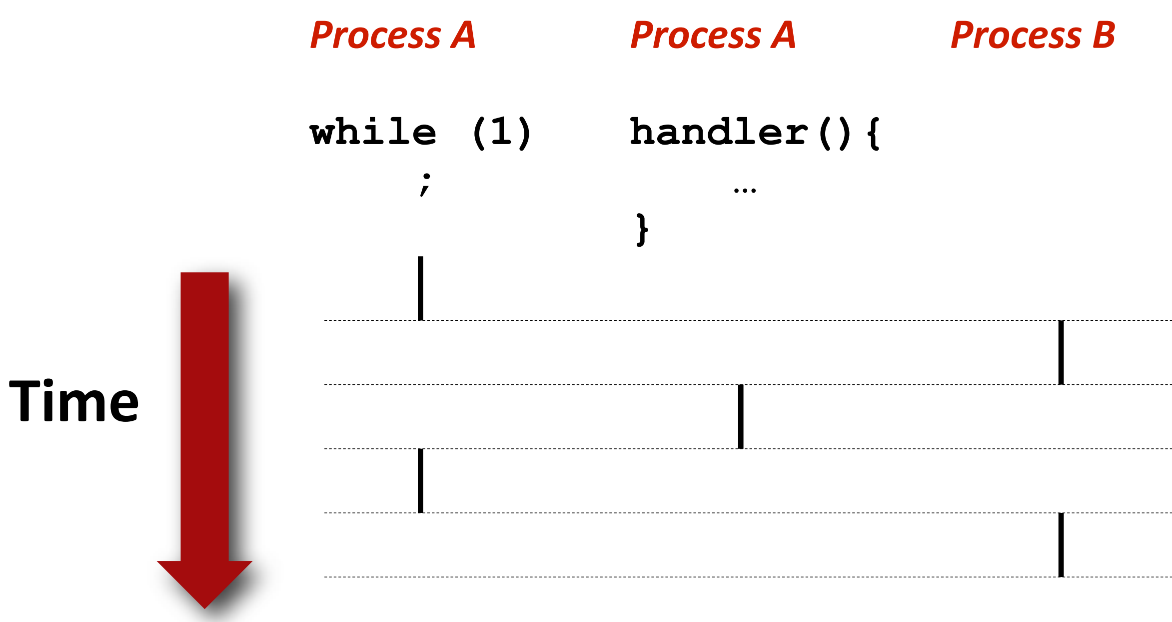
```
void int_handler(int sig)
{
  printf("Process %d received signal %d\n",
         getpid(), sig);
  exit(0);
}

void fork13()
{
  pid_t pid[N];
  int i, child_status;
  signal(SIGINT, int_handler);

  . . .
}
```

User: Ctrl-C (once)

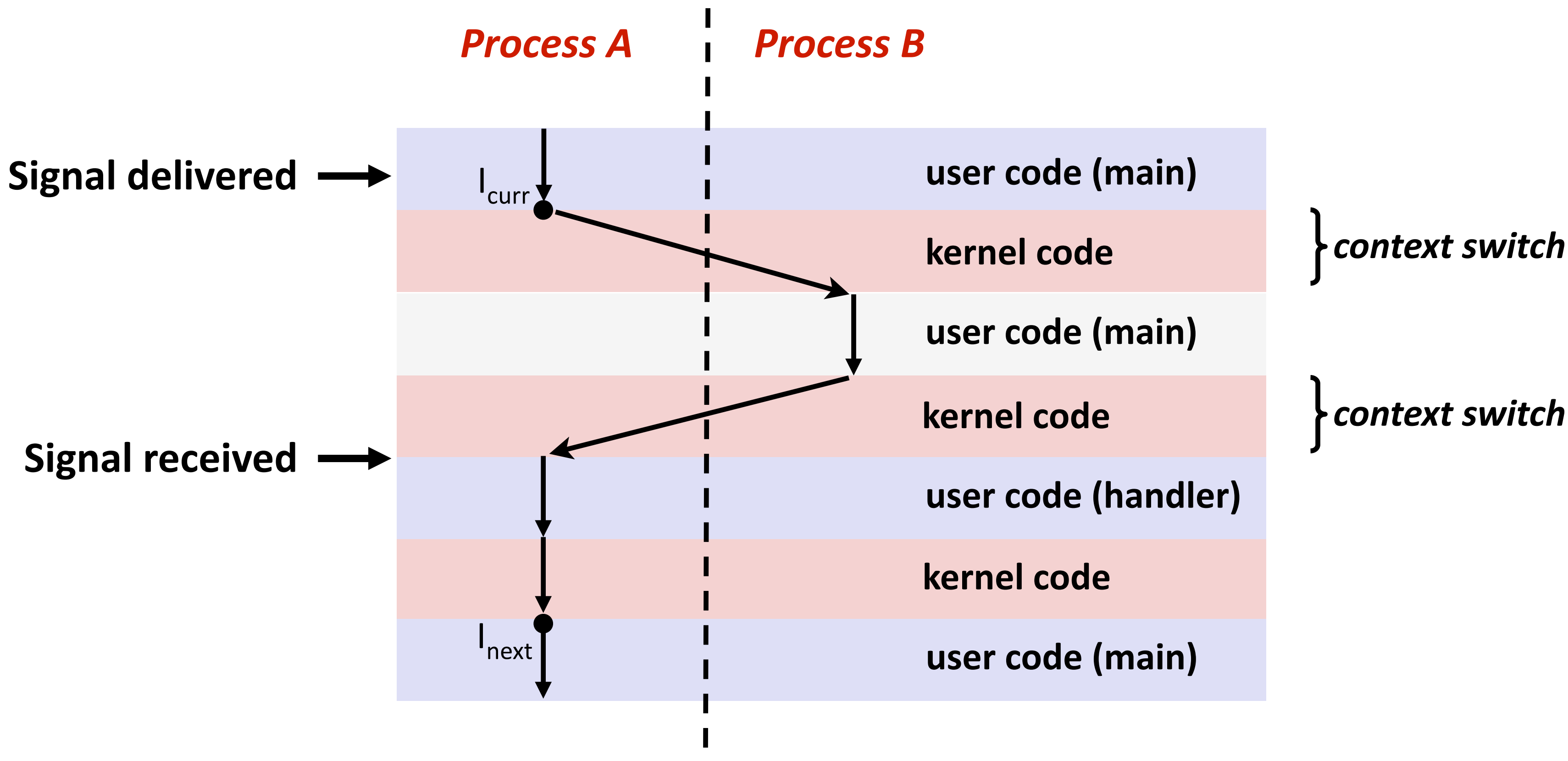
```
linux> ./forks 13
Killing process 24973
Killing process 24974
Killing process 24975
Killing process 24976
Killing process 24977
Process 24977 received signal 2
Child 24977 terminated with exit status 0
Process 24976 received signal 2
Child 24976 terminated with exit status 0
Process 24975 received 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 (not process) that runs concurrently with the main program**
  - "concurrently" in the "not sequential" sense



Another View of Signal Handlers as Concurrent Flows



Today

- Multitasking, shells
- Signals
- **Long jumps**
- More on signals

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`**

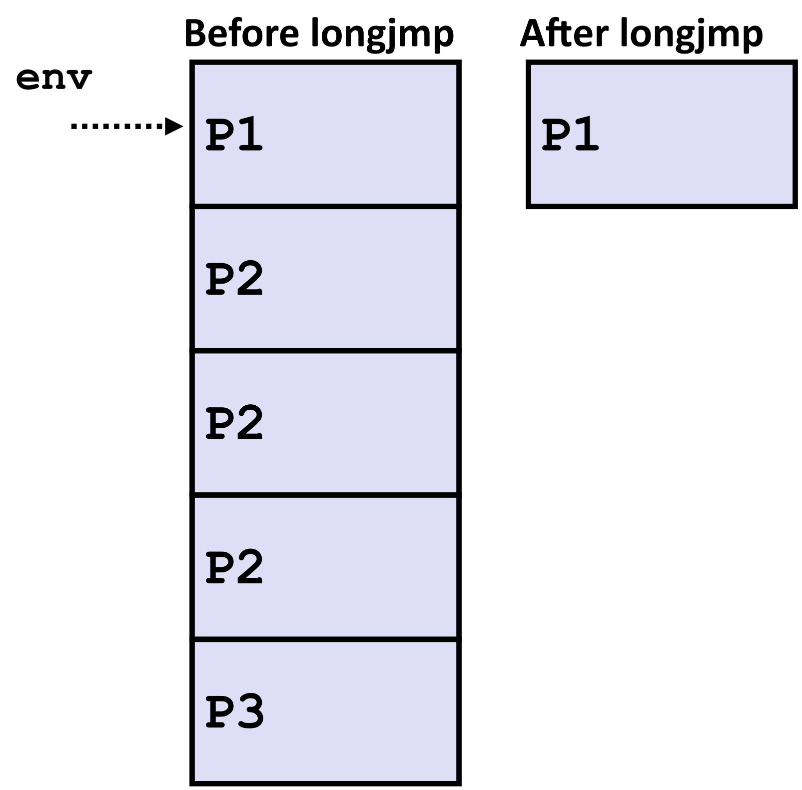
setjmp/longjmp Example

```
#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

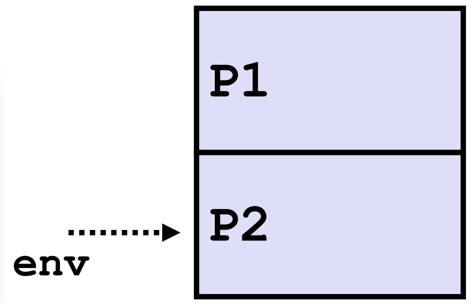
```
jmp_buf env;

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

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

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);
}
```



At 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");
  }
}
```

Summary

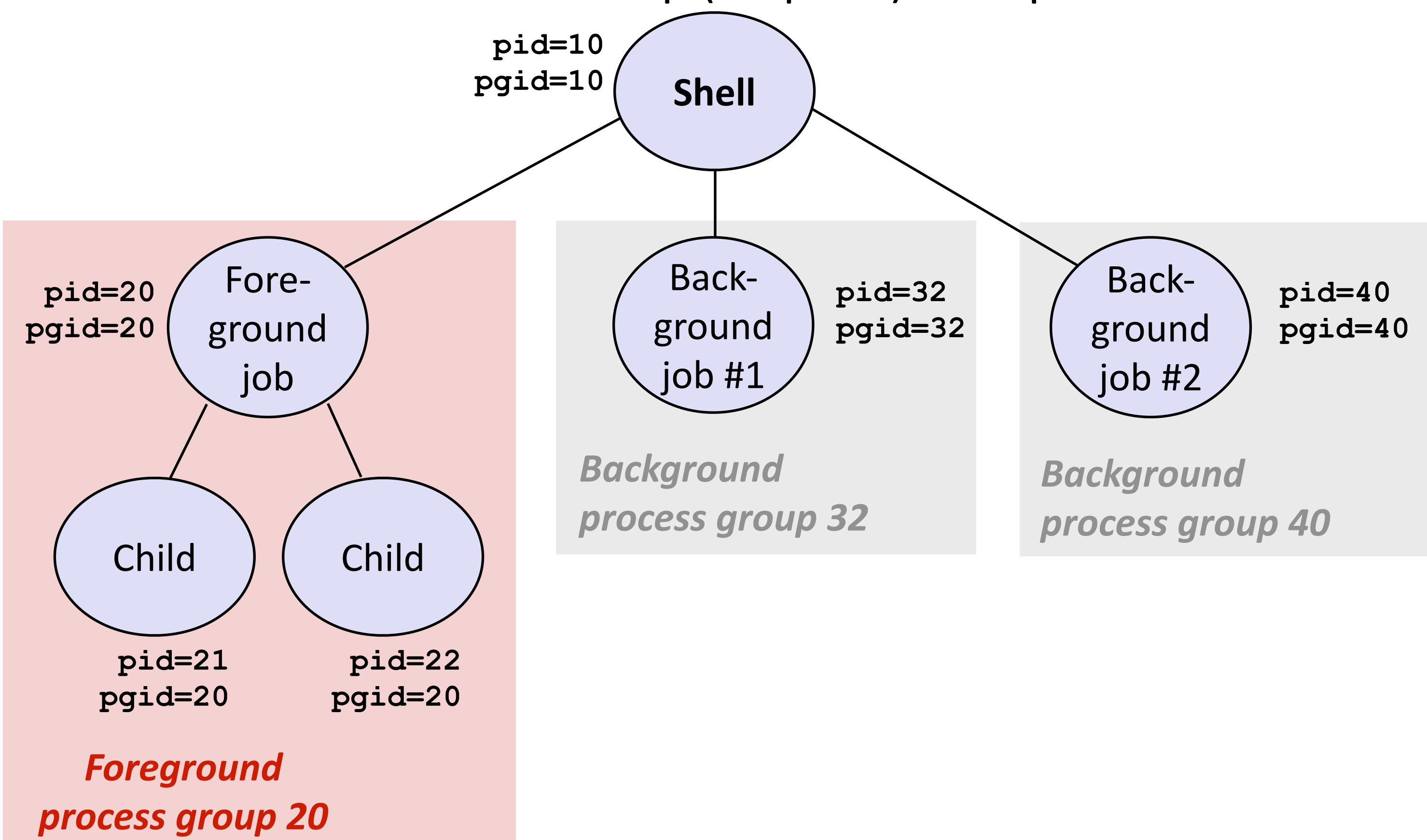
- **Signals provide process-level exception handling**
  - Can generate from user programs
  - Can define effect by declaring signal handler
- **Some caveats**
  - Very high overhead
    - >10,000 clock cycles
    - Only use for exceptional conditions
  - Don't have queues
    - Just one bit for each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

Today

- Multitasking, shells
- Signals
- Long jumps
- **More on signals**

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 proc %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 sig 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>
```

Summary

- **Multitasking, shells**
- **Signals**
  - Pending, Blocked
  - Handlers
- **Long jumps**
  - setjmp / longjmp
  - Signal variants
- **More on signals**

- **Next Time: Spring Break**
- **After Next Time: Virtual Memory I**
  - Virtual and Physical Addresses
  - Memory pages