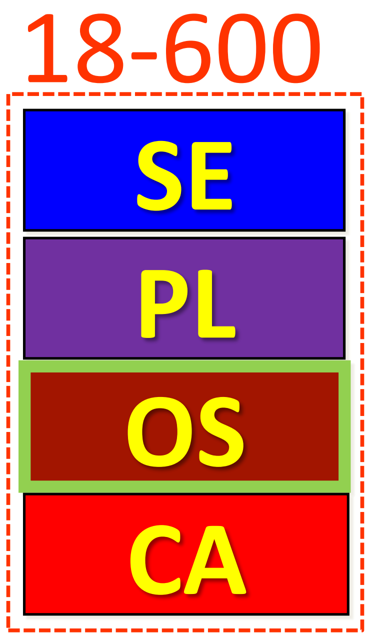
18-600 Foundations of Computer Systems

Lecture 13: "Exceptional Control Flow II: Signals and Nonlocal Jumps"

October 11, 2017



- Required Reading Assignment:
  - **Chapter 8 of CS:APP (3rd edition) by Randy Bryant & Dave O'Hallaron.**

Electrical & Computer ENGINEERING

Carnegie Mellon University

Socrative Experiment (Continuing)

- Pittsburgh Students (18600PGH): https://api.socrative.com/rc/icJVVC
- Silicon Valley Students (18600SV): https://api.socrative.com/rc/iez85z
- Microphone/Speak out/Raise Hand: Still G-R-E-A-T!
- Socrative:
  - Let's me open floor for electronic questions, putting questions into a visual queue so I don't miss any
  - Let's me do flash polls, etc.
  - Prevents cross-talk and organic discussions in more generalized forums from pulling coteries out of class discussion into parallel question space.
    - Keeps focus and reduces distraction while adding another vehicle for classroom interactivity.
  - Won't allow more than 150 students per "room"
    - So, I created one room per campus
    - May later try random assignment to a room, etc.

Reaping Child Processes

- Idea
  - When process terminates, it still consumes system resources
    - Examples: Exit status, various OS tables
  - Called a "zombie"
    - Living corpse, half alive and half dead
- Reaping
  - Performed by parent on terminated child (using `wait` or `waitpid`)
  - Parent is given exit status information
  - Kernel then deletes zombie child process
- What if parent doesn't reap?
  - If any parent terminates without reaping a child, then the orphaned child will be reaped by **`init`** process (pid == 1)
  - So, only need explicit reaping in long-running processes
    - e.g., shells and servers

Zombie Example

```
void fork7() {
   if (fork() == 0) {
      /* Child */
      printf("Terminating Child, PID = %d\n", getpid());
      exit(0);
   } else {
      printf("Running Parent, PID = %d\n", getpid());
      while (1)
         ; /* Infinite loop */
   }
}
```

forks.c

```
linux> ./forks 7 &
[1] 6639
Running Parent, PID = 6639
Terminating Child, PID = 6640
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6639 ttyp9    00:00:03 forks
 6640 ttyp9    00:00:00 forks <defunct>
 6641 ttyp9    00:00:00 ps
linux> kill 6639
[1]    Terminated
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6642 ttyp9    00:00:00 ps
```

- `ps` shows child process as "defunct" (i.e., a zombie)
- Killing parent allows child to be reaped by `init`

Non-terminating Child Example

```
void fork8()
{
   if (fork() == 0) {
      /* Child */
      printf("Running Child, PID = %d\n",
             getpid());
      while (1)
         ; /* Infinite loop */
   } else {
      printf("Terminating Parent, PID = %d\n",
             getpid());
      exit(0);
   }
}
```

forks.c

```
linux> ./forks 8
Terminating Parent, PID = 6675
Running Child, PID = 6676
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6676 ttyp9    00:00:06 forks
 6677 ttyp9    00:00:00 ps
linux> kill 6676
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6678 ttyp9    00:00:00 ps
```

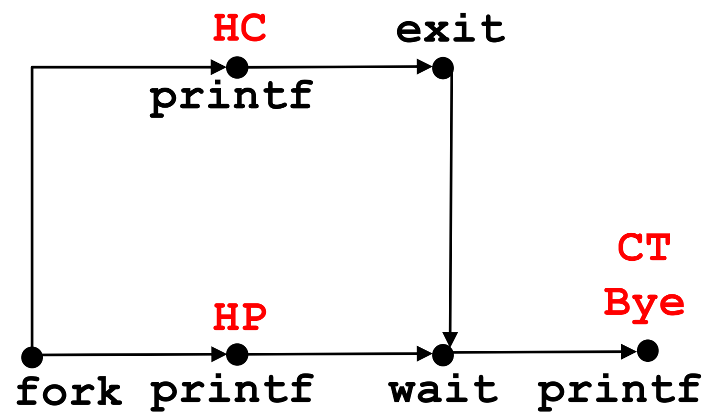
- Child process still active even though parent has terminated
- Must kill child explicitly, or else will keep running indefinitely

`wait`: Synchronizing with Children

- Parent reaps a child by calling the `wait` function
- `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 integer it points to will be set to a value that indicates reason the child terminated and the exit status:
    - Checked using macros defined in `wait.h`
      - `WIFEXITED, WEXITSTATUS, WIFSIGNALED, WTERMSIG, WIFSTOPPED, WSTOPSIG, WIFCONTINUED`
      - See textbook for details

wait: Synchronizing with Children

```
void fork9() {
   int child_status;

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



forks.c

Feasible output:	Infeasible output:
HC	HP
HP	CT
CT	Bye
Bye	HC

Another 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, child_status;

    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0) {
            exit(100+i); /* Child */
        }
    for (i = 0; i < N; i++) { /* Parent */
        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 terminate abnormally\n", wpid);
    }
}
```

forks.c

`waitpid`: Waiting for a Specific Process

- `pid_t waitpid(pid_t pid, int &status, int options)`
  - Suspends current process until specific process terminates
  - Various options (see textbook)

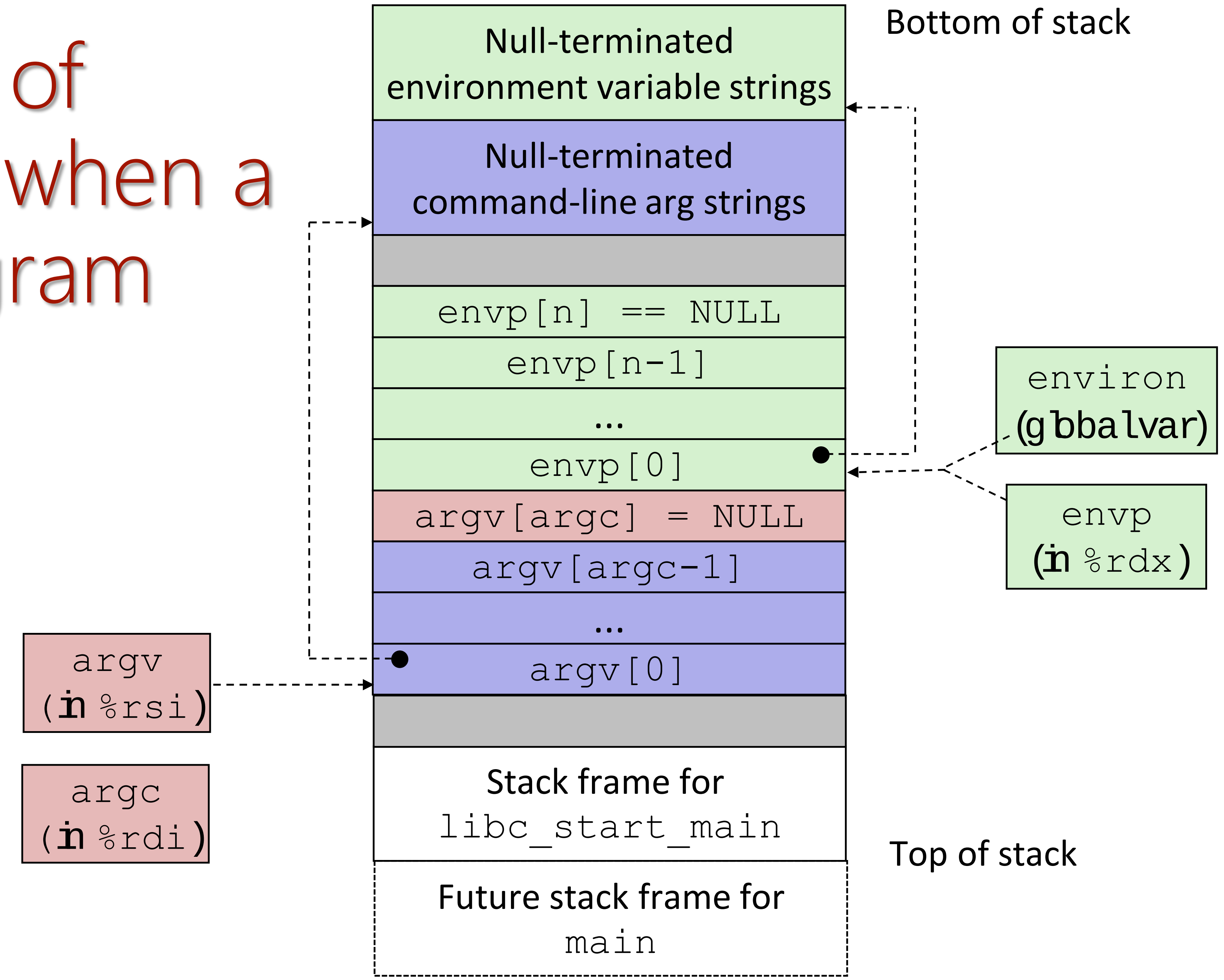
```
void fork11() {
   pid_t pid[N];
   int i;
   int child_status;

   for (i = 0; i < N; i++)
      if ((pid[i] = fork()) == 0)
         exit(100+i); /* Child */
   for (i = N-1; i >= 0; 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 terminate abnormally\n", wpid);
   }
}
```

forks.c

`execve`: Loading and Running Programs

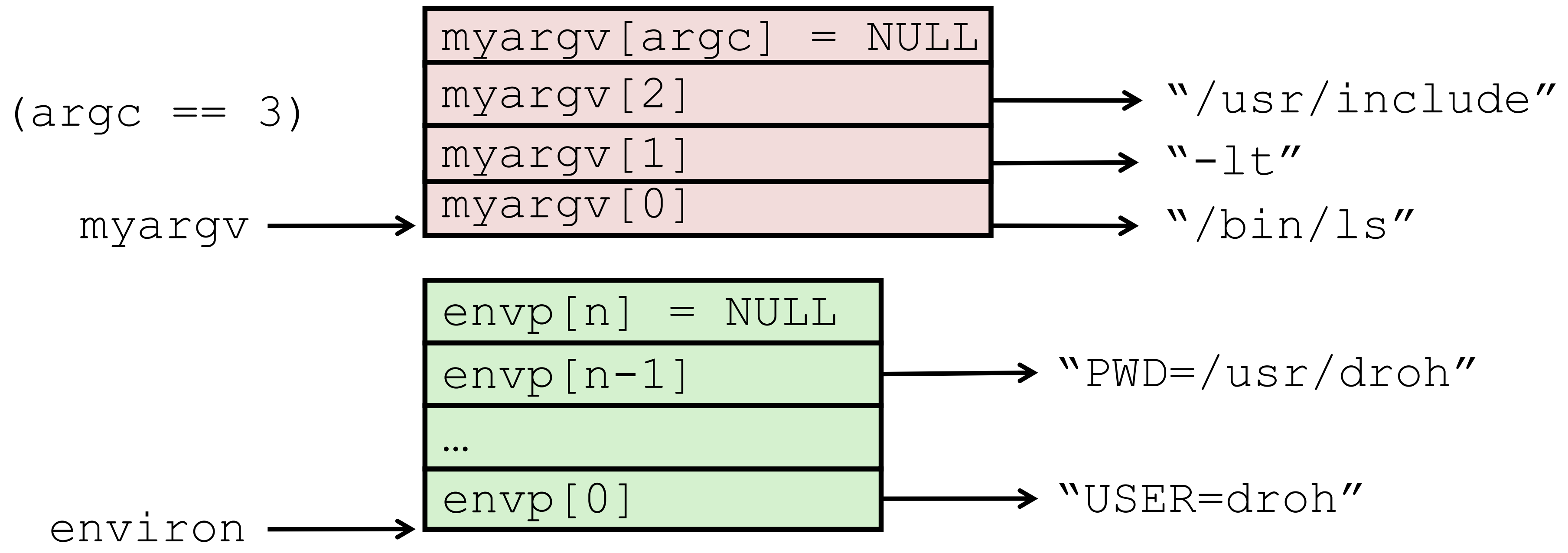
- `int execve(char *filename, char *argv[], char *envp[])`
- Loads and runs in the current process:
  - Executable file **`filename`**
    - Can be object file or script file beginning with `#!interpreter` (e.g., `#!/bin/bash`)
  - …with argument list **`argv`**
    - By convention **`argv[0]==filename`**
  - …and environment variable list **`envp`**
    - "name=value" strings (e.g., `USER=droh`)
    - `getenv, putenv, printenv`
- Overwrites code, data, and stack
  - Retains PID, open files and signal context
- Called once and never returns
  - …except if there is an error

Structure of the stack when a new program starts



execve Example

- **Executes** `"/bin/ls -lt /usr/include"` **in child process using current environment:**



```
if ((pid = Fork()) == 0) {   /* Child runs program */
   if (execve(myargv[0], myargv, environ) < 0) {
      printf("%s: Command not found.\n", myargv[0]);
      exit(1);
   }
}
```

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Lecture 13:
"Exceptional Control Flow II: Signals and Nonlocal Jumps"

- **Shells**
- Signals
- Nonlocal jumps

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ECF Exists at All Levels of a System

- **Exceptions**
  - Hardware and operating system kernel software
- **Process Context Switch**
  - Hardware timer and kernel software

} **Previous Lecture**

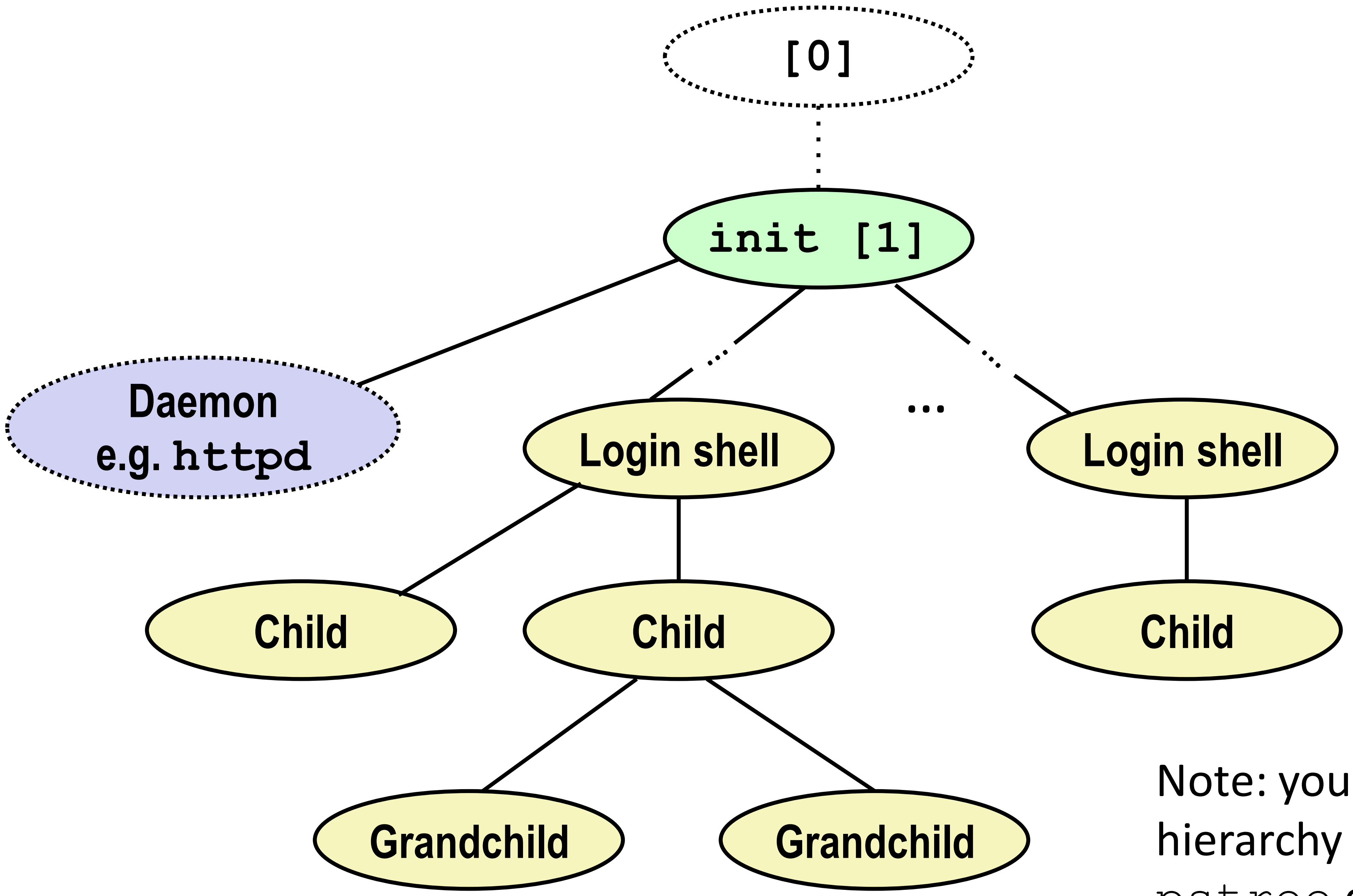
- **Signals**
  - Kernel software and application software

} **This Lecture**

- **Nonlocal jumps**
  - Application code

} **Textbook and** supplemental slides

Linux Process Hierarchy



Note: you can view the hierarchy using the Linux `pstree` command

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/tcsh`** BSD Unix C shell
  - **`bash`** "Bourne-Again" Shell (default Linux shell)

```
int main()
{
   char cmdline[MAXLINE]; /* command line */

   while (1) {
      /* read */
      printf("> ");
      Fgets(cmdline, MAXLINE, stdin);
      if (feof(stdin))
         exit(0);

      /* evaluate */
      eval(cmdline);
   }
}
```

shellex.c

Execution is a sequence of read/evaluate steps

Simple Shell **eval** Function

```
void eval(char *cmdline)
{
   char *argv[MAXARGS]; /* Argument list execve() */
   char buf[MAXLINE];   /* Holds modified command line */
   int bg;              /* Should the job run in bg or fg? */
   pid_t pid;           /* Process id */

   strcpy(buf, cmdline);
   bg = parseline(buf, argv);
   if (argv[0] == NULL)
      return;   /* Ignore empty lines */

   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);
         }
      }

      /* Parent waits for foreground job to terminate */
            if (!bg) {
         int status;
         if (waitpid(pid, &status, 0) < 0)
            unix_error("waitfg: waitpid error");
      }
      else
         printf("%d %s", pid, cmdline);
   }
   return;
}
```

shellex.c

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

ECF to the Rescue!

- **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***

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Lecture 13:
"Exceptional Control Flow II: Signals and Nonlocal Jumps"

- 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

ID	*Name*	*Default Action*	*Corresponding Event*
2	SIGINT	Terminate	User typed ctrl-c
9	SIGKILL	Terminate	Kill program (cannot override or ignore)
11	SIGSEGV	Terminate	Segmentation violation
14	SIGALRM	Terminate	Timer signal
17	SIGCHLD	Ignore	Child stopped or terminated

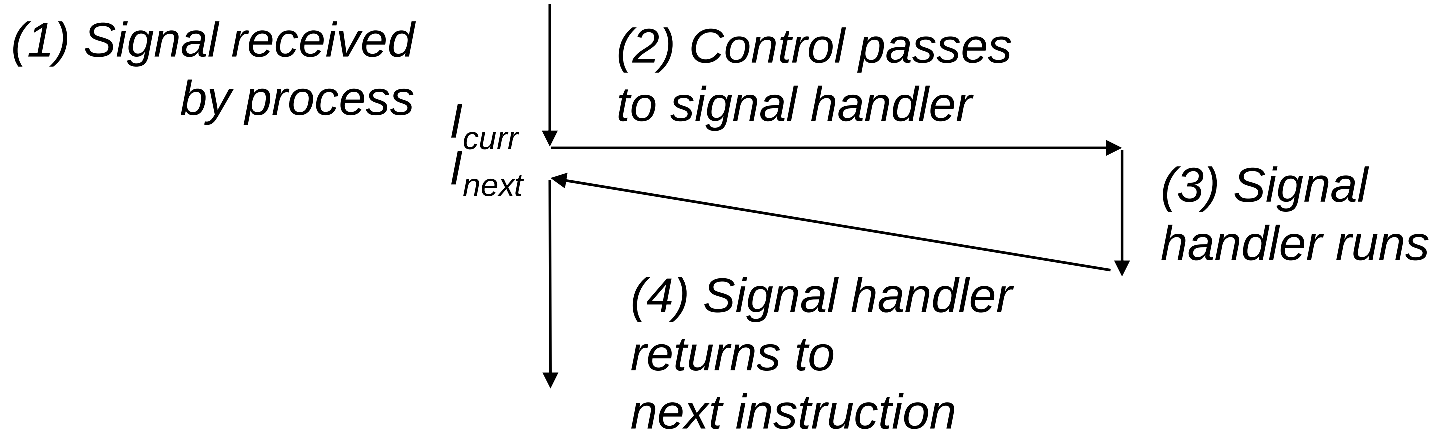
Signal Concepts: Sending a Signal

- **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: 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**
- **Some 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:


(1) Signal received by process
I_{curr}
I_{next}
(2) Control passes to signal handler
(3) Signal handler runs
(4) Signal handler returns to next instruction

Signal Concepts: Pending and Blocked Signals

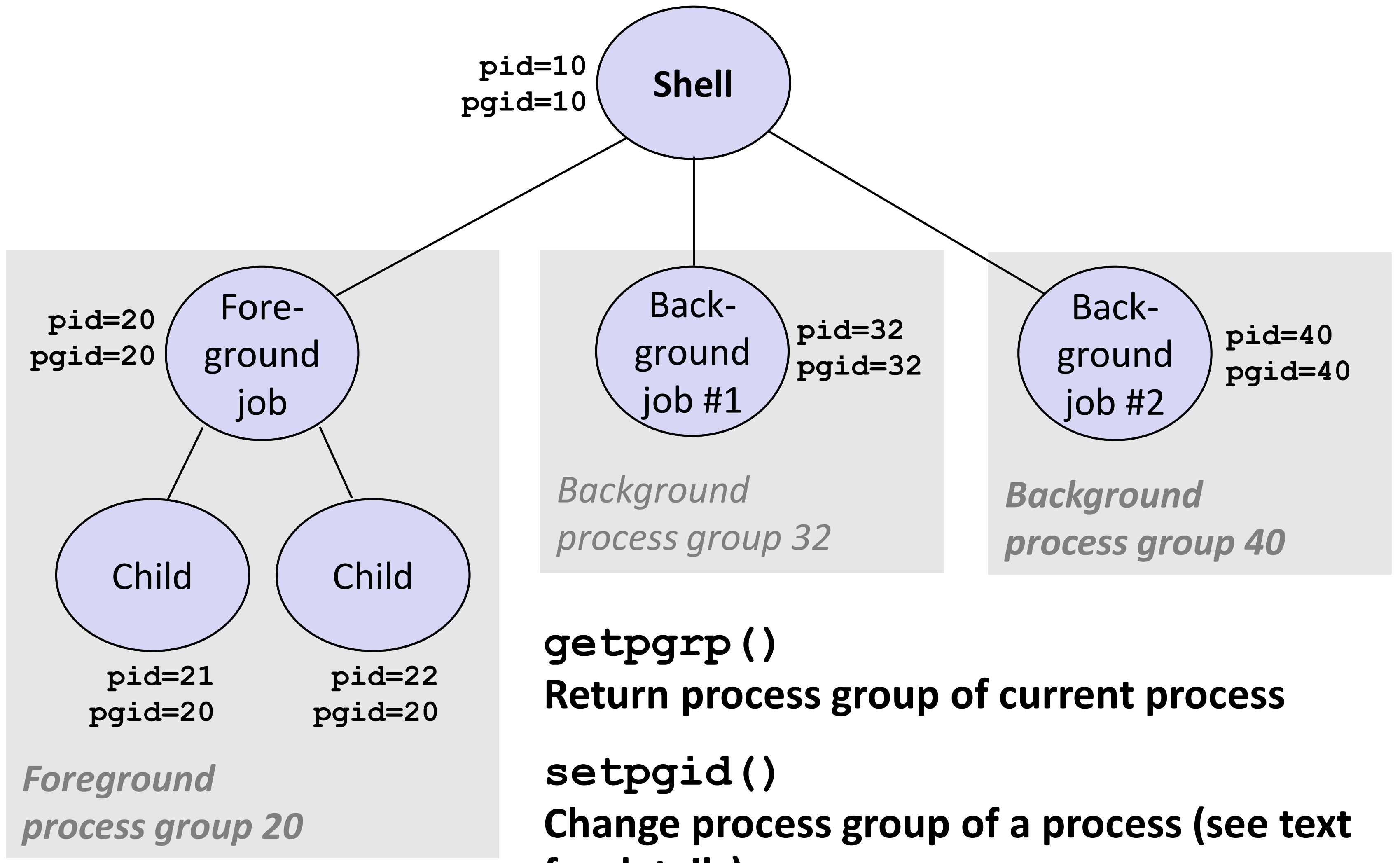
- **A signal is *pending* if sent but not yet received**
  - There can be at most one pending signal of any particular type
  - Important: Signals are not queued
    - If a process has a pending signal of type k, then subsequent signals of type k that are sent to that process are discarded
- **A process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

- **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
    - Also referred to as the *signal mask*.

Sending Signals: Process Groups

- Every process belongs to exactly one process group



`getpgrp()`
Return process group of current process

`setpgid()`
Change process group of a process (see text for details)

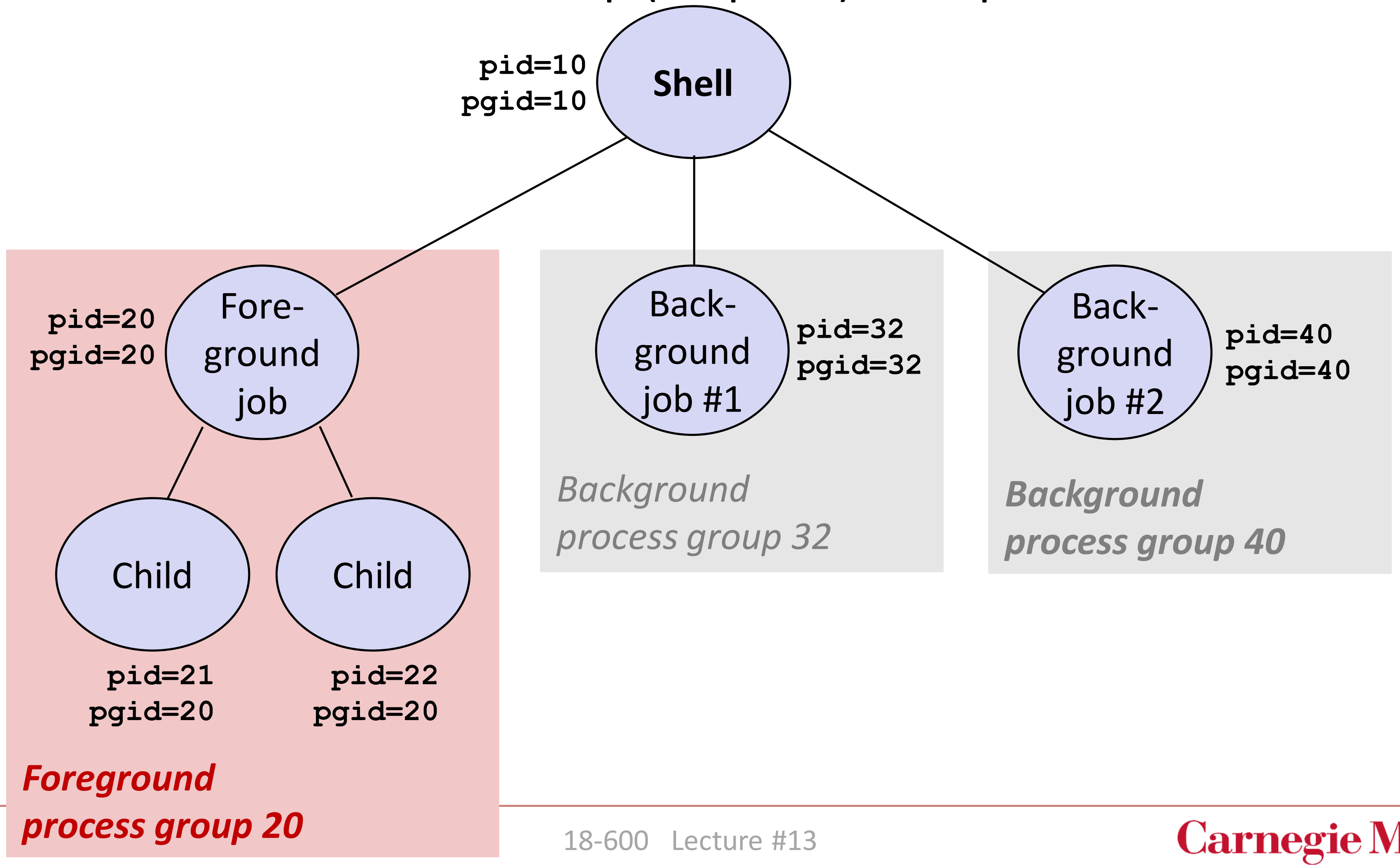
Sending Signals with `/bin/kill` Program

- `/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) causes the kernel to send 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

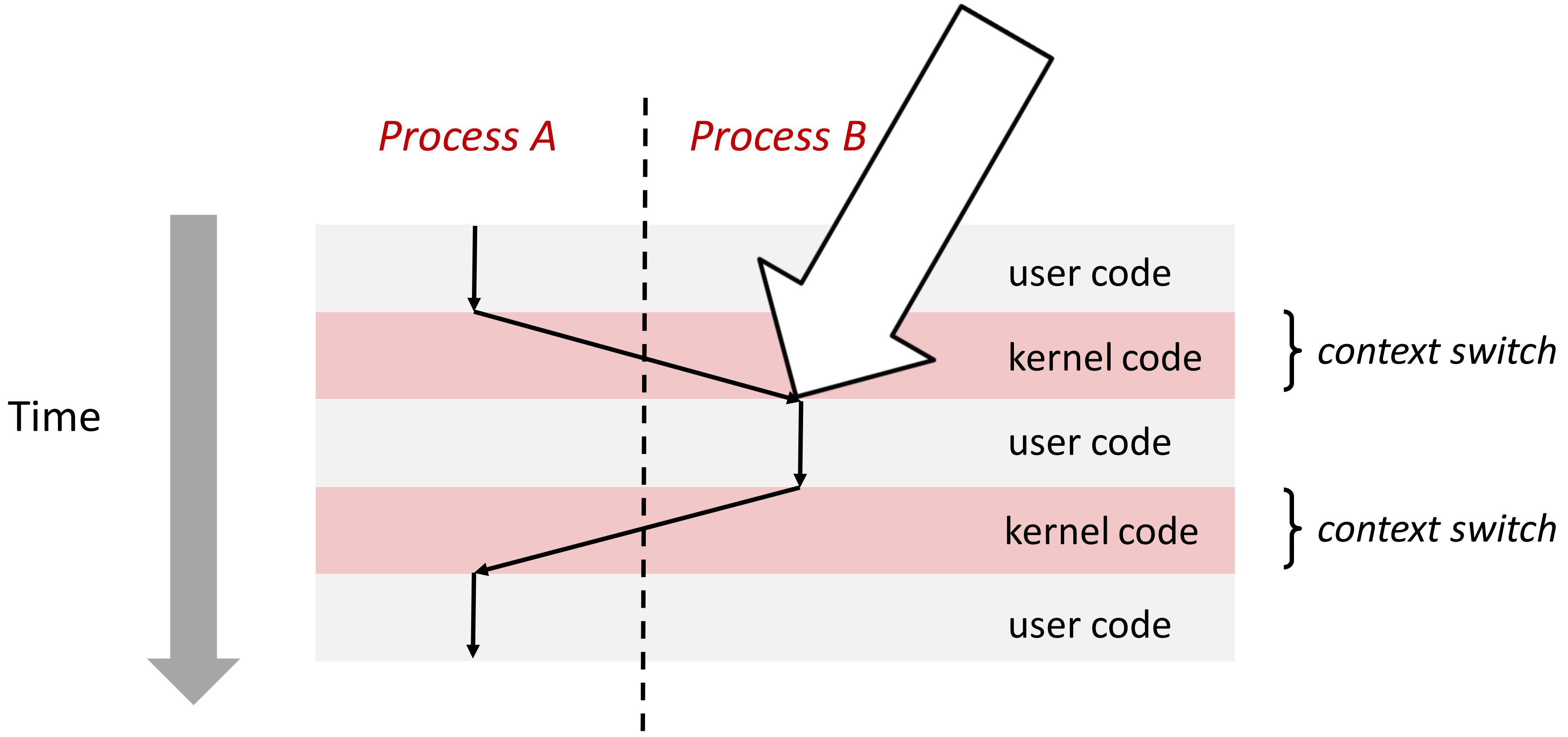
Sending Signals with `kill` Function

```
void fork12()
{
    pid_t pid[N];
    int i;
    int child_status;

    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0) {
            /* Child: Infinite Loop */
            while(1)
                ;
        }

    for (i = 0; i < N; i++) {
        printf("Killing process %d\n", pid[i]);
        kill(pid[i], SIGINT);
    }

    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);
    }
}
```

forks.c

Receiving Signals

- **Suppose kernel is returning from an exception handler and is ready to pass control to process *p***



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 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 user-level ***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

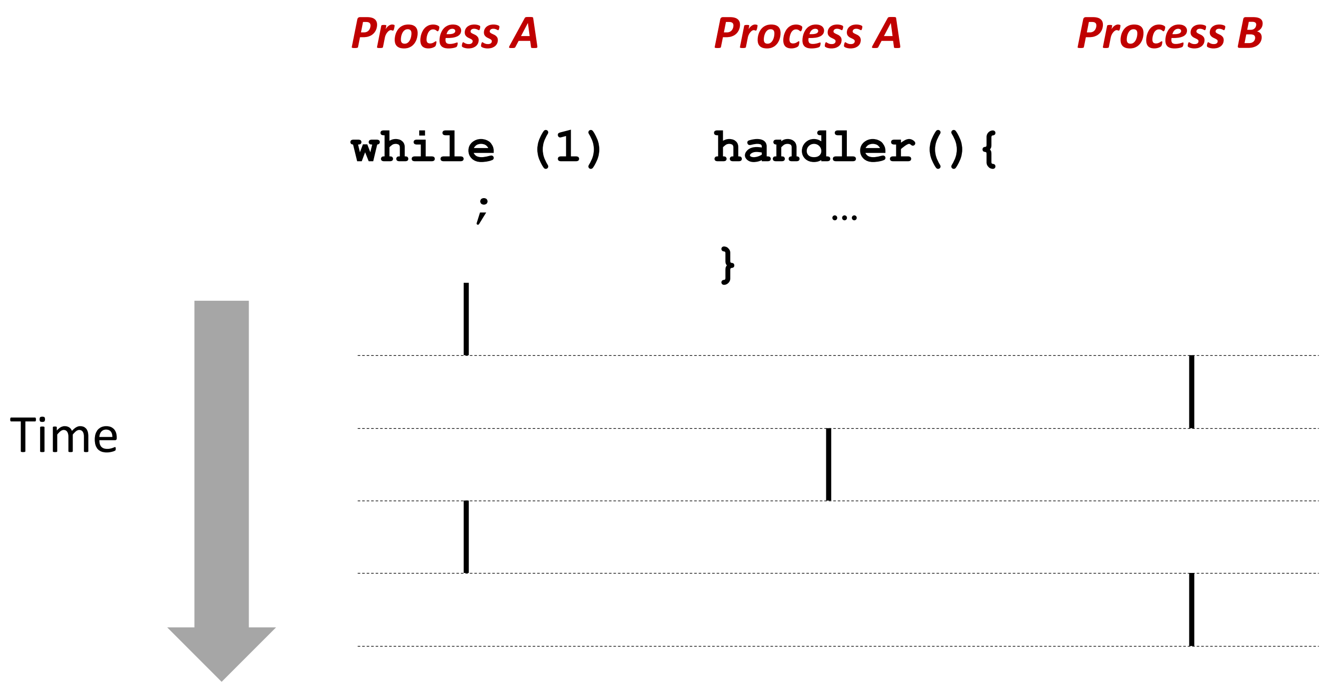
Signal Handling Example

```
void sigint_handler(int sig) /* SIGINT handler */
{
    printf("So you think you can stop the bomb with ctrl-c, do you?\n");
    sleep(2);
    printf("Well...");
    fflush(stdout);
    sleep(1);
    printf("OK. :-)\n");
    exit(0);
}

int main()
{
    /* Install the SIGINT handler */
    if (signal(SIGINT, sigint_handler) == SIG_ERR)
        unix_error("signal error");

    /* Wait for the receipt of a signal */
    pause();

    return 0;
}
```

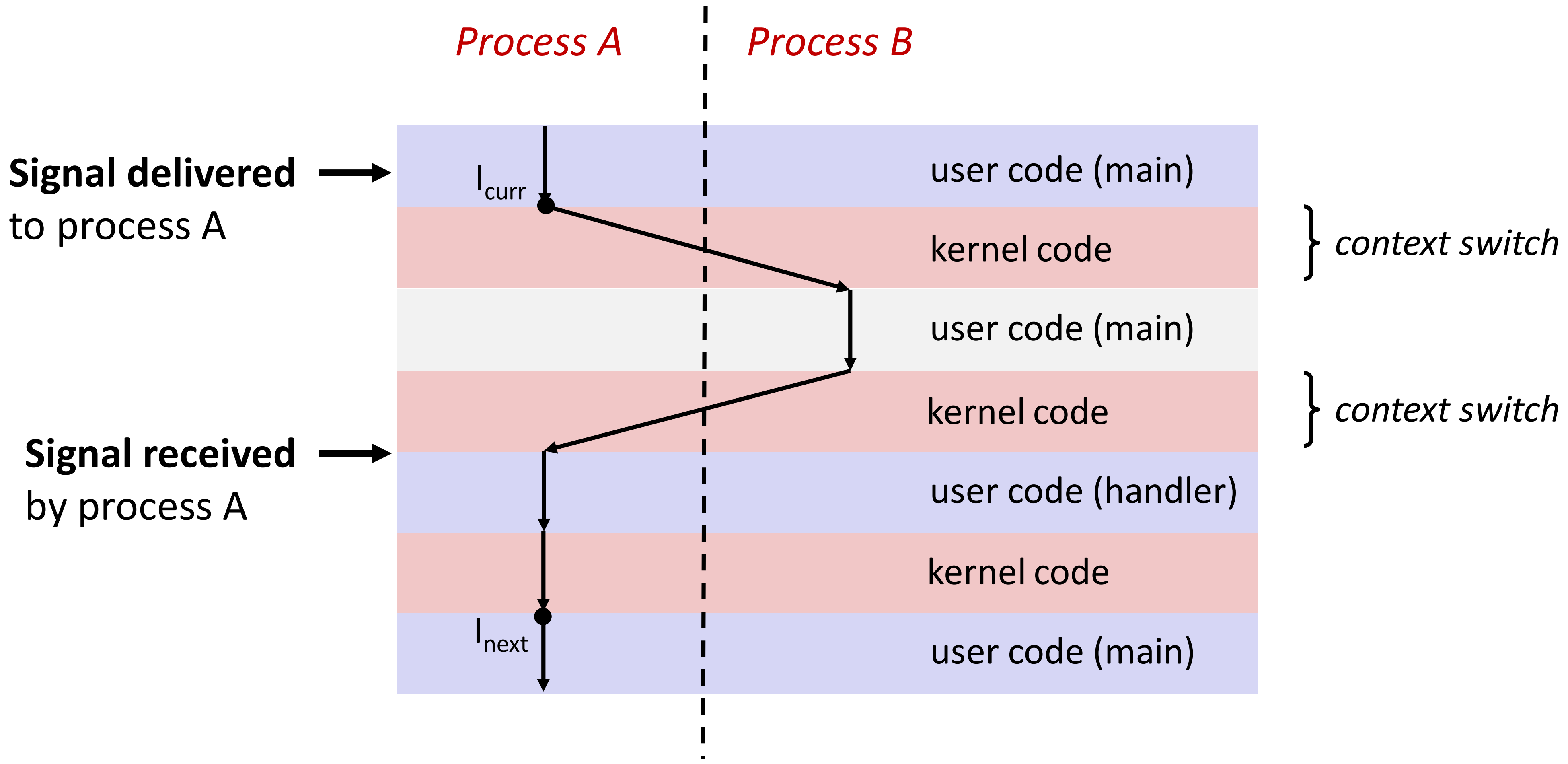
sigint.c

Signals Handlers as Concurrent Flows

- **A signal handler is a separate logical flow (not process) that runs concurrently with the main program**

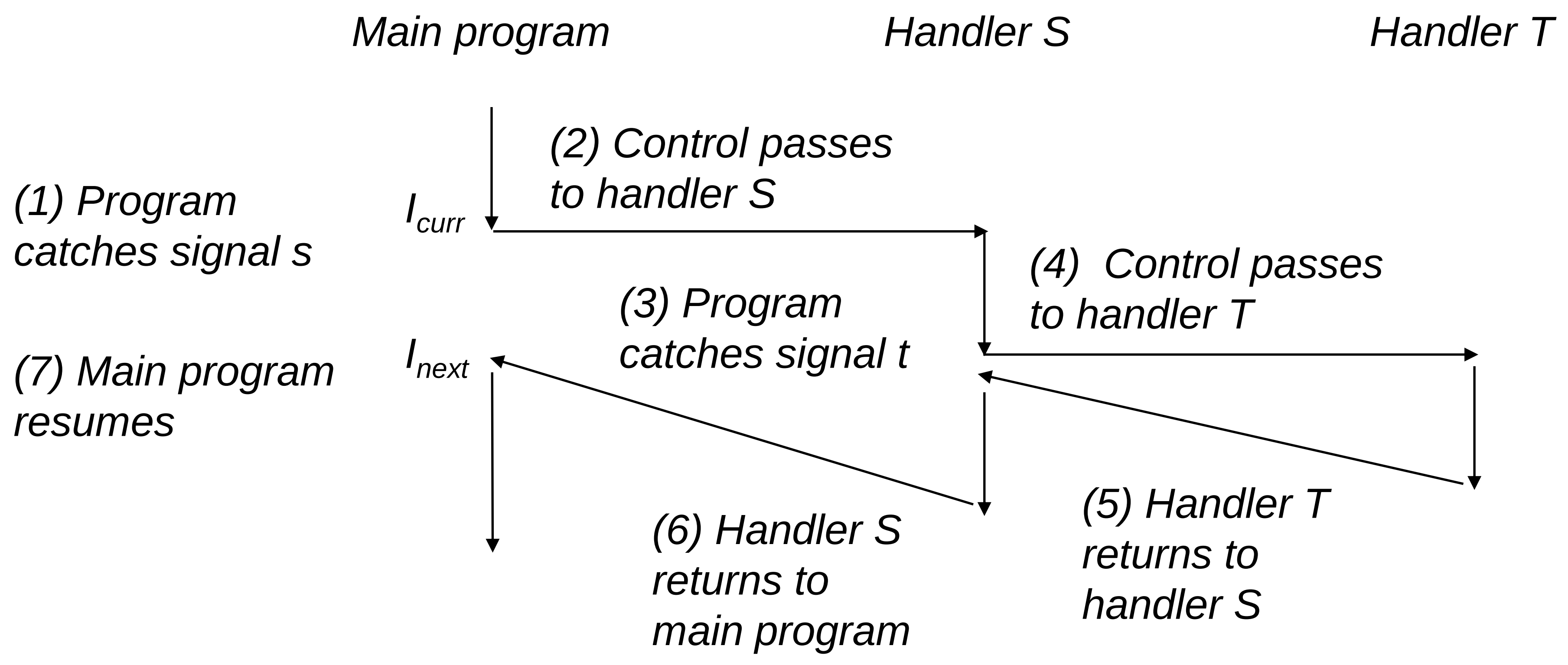


Another View of Signal Handlers as Concurrent Flows



Nested Signal Handlers

- **Handlers can be interrupted by other handlers**


Main program
Handler S
Handler T
(1) Program catches signal s
I_{curr}
(2) Control passes to handler S
(3) Program catches signal t
(4) Control passes to handler T
(5) Handler T returns to handler S
(6) Handler S returns to main program
I_{next}
(7) Main program resumes

Blocking and Unblocking Signals

- **Implicit blocking mechanism**
  - Kernel blocks any pending signals of type currently being handled.
  - E.g., A SIGINT handler can't be interrupted by another SIGINT

- **Explicit blocking and unblocking mechanism**
  - `sigprocmask` function

- **Supporting functions**
  - `sigemptyset` – Create empty set
  - `sigfillset` – Add every signal number to set
  - `sigaddset` – Add signal number to set
  - `sigdelset` – Delete signal number from set

Temporarily Blocking Signals

```
sigset_t mask, prev_mask;

Sigemptyset(&mask);
Sigaddset(&mask, SIGINT);

/* Block SIGINT and save previous blocked set */
Sigprocmask(SIG_BLOCK, &mask, &prev_mask);
  ⋮
  /* Code region that will not be interrupted by SIGINT */
  ⋮
/* Restore previous blocked set, unblocking SIGINT */
Sigprocmask(SIG_SETMASK, &prev_mask, NULL);
```

Safe Signal Handling

- **Handlers are tricky because they are concurrent with main program and share the same global data structures.**
  - Shared data structures can become corrupted.
- **We'll explore concurrency issues later in the term.**
- **For now here are some guidelines to help you avoid trouble.**

Guidelines for Writing Safe Handlers

- **G0: Keep your handlers as simple as possible**
  - e.g., Set a global flag and return
- **G1: Call only async-signal-safe functions in your handlers**
  - `printf`, `sprintf`, `malloc`, and `exit` are not safe!
- **G2: Save and restore `errno` on entry and exit**
  - So that other handlers don't overwrite your value of `errno`
- **G3: Protect accesses to shared data structures by temporarily blocking all signals.**
  - To prevent possible corruption
- **G4: Declare global variables as `volatile`**
  - To prevent compiler from storing them in a register
- **G5: Declare global flags as `volatile sig_atomic_t`**
  - *flag*: variable that is only read or written (e.g. flag = 1, not flag++)
  - Flag declared this way does not need to be protected like other globals

Async-Signal-Safety

- **Function is *async-signal-safe* if either reentrant (e.g., all variables stored on stack frame, CS:APP3e 12.7.2) or non-interruptible by signals.**
- **Posix guarantees 117 functions to be async-signal-safe**
  - Source: "`man 7 signal`"
  - Popular functions on the list:
    - `_exit, write, wait, waitpid, sleep, kill`
  - Popular functions that are **not** on the list:
    - `printf`, `sprintf`, `malloc, exit`
    - Unfortunate fact: `write` is the only async-signal-safe output function

Safely Generating Formatted Output

- **Use the reentrant SIO (Safe I/O library) from `csapp.c` in your handlers.**
  - `ssize_t sio_puts(char s[]) /* Put string */`
  - `ssize_t sio_putl(long v)   /* Put long */`
  - `void sio_error(char s[])   /* Put msg & exit */`

```
void sigint_handler(int sig) /* Safe SIGINT handler */
{
   Sio_puts("So you think you can stop the bomb with ctrl-c, do you?\n");
   sleep(2);
   Sio_puts("Well...");
   sleep(1);
   Sio_puts("OK. :-)\n");
   _exit(0);
}
```

sigintsafe.c

Correct Signal Handling

```
int ccount = 0;
void child_handler(int sig) {
   int olderrno = errno;
   pid_t pid;
   if ((pid = wait(NULL)) < 0)
      Sio_error("wait error");
   ccount--;
   Sio_puts("Handler reaped child ");
   Sio_putl((long)pid);
   Sio_puts(" \n");
   sleep(1);
   errno = olderrno;
}

void fork14() {
   pid_t pid[N];
   int i;
   ccount = N;
   Signal(SIGCHLD, child_handler);

   for (i = 0; i < N; i++) {
      if ((pid[i] = Fork()) == 0) {
         Sleep(1);
         exit(0);  /* Child exits */
      }
   }
   while (ccount > 0) /* Parent spins */
      ;
}
```

forks.c

- **Pending signals are not queued**
  - For each signal type, one bit indicates whether or not signal is pending…
  - …thus at most one pending signal of any particular type.
- **You can't use signals to count events, such as children terminating.**

```
whaleshark> ./forks 14
Handler reaped child 23240
Handler reaped child 23241
```

Correct Signal Handling

- **Must wait for all terminated child processes**
  - Put `wait` in a loop to reap all terminated children

```
void child_handler2(int sig)
{
    int olderrno = errno;
    pid_t pid;
    while ((pid = wait(NULL)) > 0) {
        ccount--;
        Sio_puts("Handler reaped child ");
        Sio_putl((long)pid);
        Sio_puts(" \n");
    }
    if (errno != ECHILD)
        Sio_error("wait error");
    errno = olderrno;
}
```

```
whaleshark> ./forks 15
Handler reaped child 23246
Handler reaped child 23247
Handler reaped child 23248
Handler reaped child 23249
Handler reaped child 23250
whaleshark>
```

Portable Signal Handling

- **Ugh! Different versions of Unix can have different signal handling semantics**
  - Some older systems restore action to default after catching signal
  - Some interrupted system calls can return with errno == EINTR
  - Some systems don't block signals of the type being handled
- **Solution: `sigaction`**

```
handler_t *Signal(int signum, handler_t *handler)
{
   struct sigaction action, old_action;

   action.sa_handler = handler;
   sigemptyset(&action.sa_mask); /* Block sigs of type being handled */
   action.sa_flags = SA_RESTART; /* Restart syscalls if possible */

   if (sigaction(signum, &action, &old_action) < 0)
      unix_error("Signal error");
   return (old_action.sa_handler);
}
```

csapp.c

Synchronizing Flows to Avoid Races

- **Simple shell with a subtle synchronization error because it assumes parent runs before child.**

```
int main(int argc, char **argv)
{
    int pid;
    sigset_t mask_all, prev_all;

    Sigfillset(&mask_all);
    Signal(SIGCHLD, handler);
    initjobs(); /* Initialize the job list */

    while (1) {
        if ((pid = Fork()) == 0) { /* Child */
            Execve("/bin/date", argv, NULL);
        }
        Sigprocmask(SIG_BLOCK, &mask_all, &prev_all); /* Parent */
        addjob(pid);  /* Add the child to the job list */
        Sigprocmask(SIG_SETMASK, &prev_all, NULL);
    }
    exit(0);
}
```

procmask1.c

Synchronizing Flows to Avoid Races

- **SIGCHLD handler for a simple shell**

```
void handler(int sig)
{
   int olderrno = errno;
   sigset_t mask_all, prev_all;
   pid_t pid;

   Sigfillset(&mask_all);
   while ((pid = waitpid(-1, NULL, 0)) > 0) { /* Reap child */
      Sigprocmask(SIG_BLOCK, &mask_all, &prev_all);
      deletejob(pid); /* Delete the child from the job list */
      Sigprocmask(SIG_SETMASK, &prev_all, NULL);
   }
   if (errno != ECHILD)
      Sio_error("waitpid error");
   errno = olderrno;
}
```

procmask1.c

Corrected Shell Program without Race

```
int main(int argc, char **argv)
{
   int pid;
   sigset_t mask_all, mask_one, prev_one;

   Sigfillset(&mask_all);
   Sigemptyset(&mask_one);
   Sigaddset(&mask_one, SIGCHLD);
   Signal(SIGCHLD, handler);
   initjobs(); /* Initialize the job list */

   while (1) {
      Sigprocmask(SIG_BLOCK, &mask_one, &prev_one); /* Block SIGCHLD */
      if ((pid = Fork()) == 0) { /* Child process */
         Sigprocmask(SIG_SETMASK, &prev_one, NULL); /* Unblock SIGCHLD */
         Execve("/bin/date", argv, NULL);
      }
      Sigprocmask(SIG_BLOCK, &mask_all, NULL); /* Parent process */
             addjob(pid);  /* Add the child to the job list */
      Sigprocmask(SIG_SETMASK, &prev_one, NULL);  /* Unblock SIGCHLD */
   }
   exit(0);
}
```

procmask2.c

Explicitly Waiting for Signals

- **Handlers for program explicitly waiting for SIGCHLD to arrive.**

```
volatile sig_atomic_t pid;

void sigchld_handler(int s)
{
    int olderrno = errno;
    pid = Waitpid(-1, NULL, 0); /* Main is waiting for nonzero pid */
    errno = olderrno;
}

void sigint_handler(int s)
{
}
```

waitforsignal.c

Explicitly Waiting for Signals

```
int main(int argc, char **argv) {
   sigset_t mask, prev;
   Signal(SIGCHLD, sigchld_handler);
   Signal(SIGINT, sigint_handler);
   Sigemptyset(&mask);
   Sigaddset(&mask, SIGCHLD);

   while (1) {
              Sigprocmask(SIG_BLOCK, &mask, &prev); /* Block SIGCHLD */
              if (Fork() == 0) /* Child */
         exit(0);
              /* Parent */
              pid = 0;
              Sigprocmask(SIG_SETMASK, &prev, NULL); /* Unblock SIGCHLD */

              /* Wait for SIGCHLD to be received (wasteful!) */
              while (!pid)
         ;
              /* Do some work after receiving SIGCHLD */
      printf(".");
   }
   exit(0);
}
```

Similar to a shell waiting for a foreground job to terminate.

waitforsignal.c

Explicitly Waiting for Signals

- **Program is correct, but very wasteful**
- **Other options:**

```
while (!pid)   /* Race! */
    pause();
```

```
while (!pid) /* Too slow! */
   sleep(1);
```

- **Solution: `sigsuspend`**

Waiting for Signals with **`sigsuspend`**

- **`int sigsuspend(const sigset_t *mask)`**

- **Equivalent to atomic (uninterruptable) version of:**

```
sigprocmask(SIG_BLOCK, &mask, &prev);
pause();
sigprocmask(SIG_SETMASK, &prev, NULL);
```

Waiting for Signals with **sigsuspend**

```
int main(int argc, char **argv) {
    sigset_t mask, prev;
    Signal(SIGCHLD, sigchld_handler);
    Signal(SIGINT, sigint_handler);
    Sigemptyset(&mask);
    Sigaddset(&mask, SIGCHLD);

    while (1) {
        Sigprocmask(SIG_BLOCK, &mask, &prev); /* Block SIGCHLD */
        if (Fork() == 0) /* Child */
            exit(0);

       /* Wait for SIGCHLD to be received */
        pid = 0;
        while (!pid)
            Sigsuspend(&prev);

       /* Optionally unblock SIGCHLD */
        Sigprocmask(SIG_SETMASK, &prev, NULL);
       /* Do some work after receiving SIGCHLD */
        printf(".");
    }
    exit(0);
}
```

sigsuspend.c

18-600 Foundations of Computer Systems

Lecture 13: "Exceptional Control Flow II: Signals and Nonlocal Jumps"

- Shells
- Signals
- **Nonlocal jumps**
  - Consult your textbook and additional slides

Summary

- **Signals provide process-level exception handling**
  - Can generate from user programs
  - Can define effect by declaring signal handler
  - Be very careful when writing signal handlers

- **Nonlocal jumps provide exceptional control flow within process**
  - Within constraints of stack discipline

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 (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

- **Goal: return directly to original caller from a deeply-nested function**

```
/* Deeply nested function foo */
void foo(void)
{
   if (error1)
            longjmp(buf, 1);
   bar();
}

void bar(void)
{
   if (error2)
      longjmp(buf, 2);
}
```

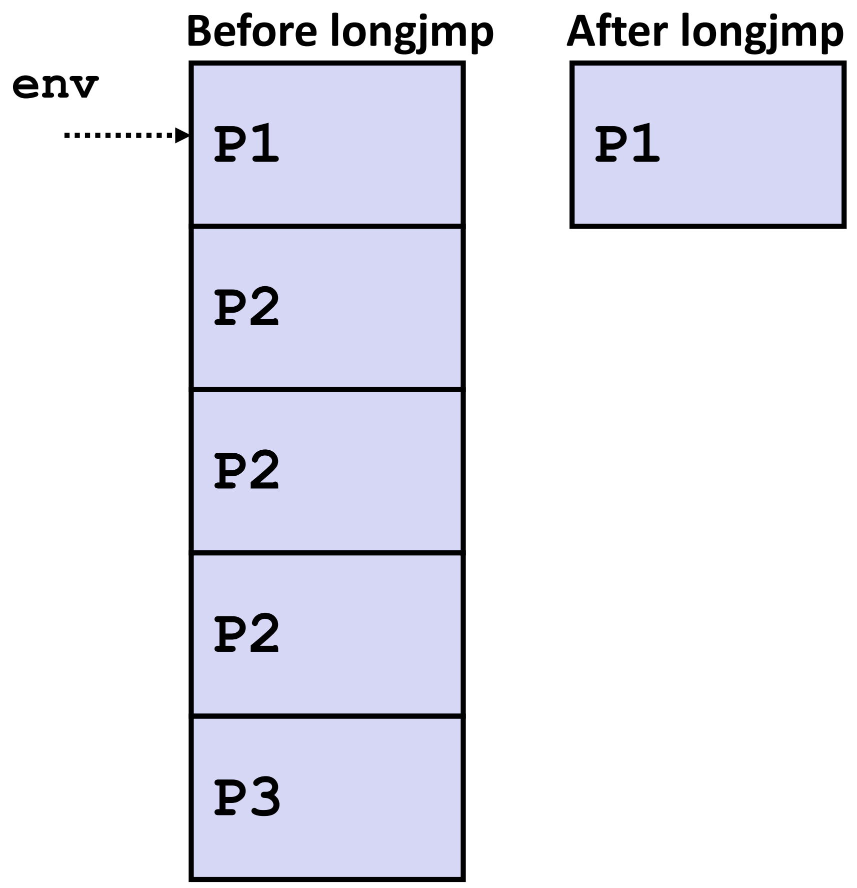
setjmp/longjmp Example (cont)

```
jmp_buf buf;

int error1 = 0;
int error2 = 1;

void foo(void), bar(void);

int main()
{
   switch(setjmp(buf)) {
   case 0:
      foo();
      break;
   case 1:
      printf("Detected an error1 condition in foo\n");
      break;
   case 2:
      printf("Detected an error2 condition in foo\n");
      break;
   default:
      printf("Unknown error condition in foo\n");
   }
   exit(0);
}
```

Limitations of Nonlocal Jumps

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

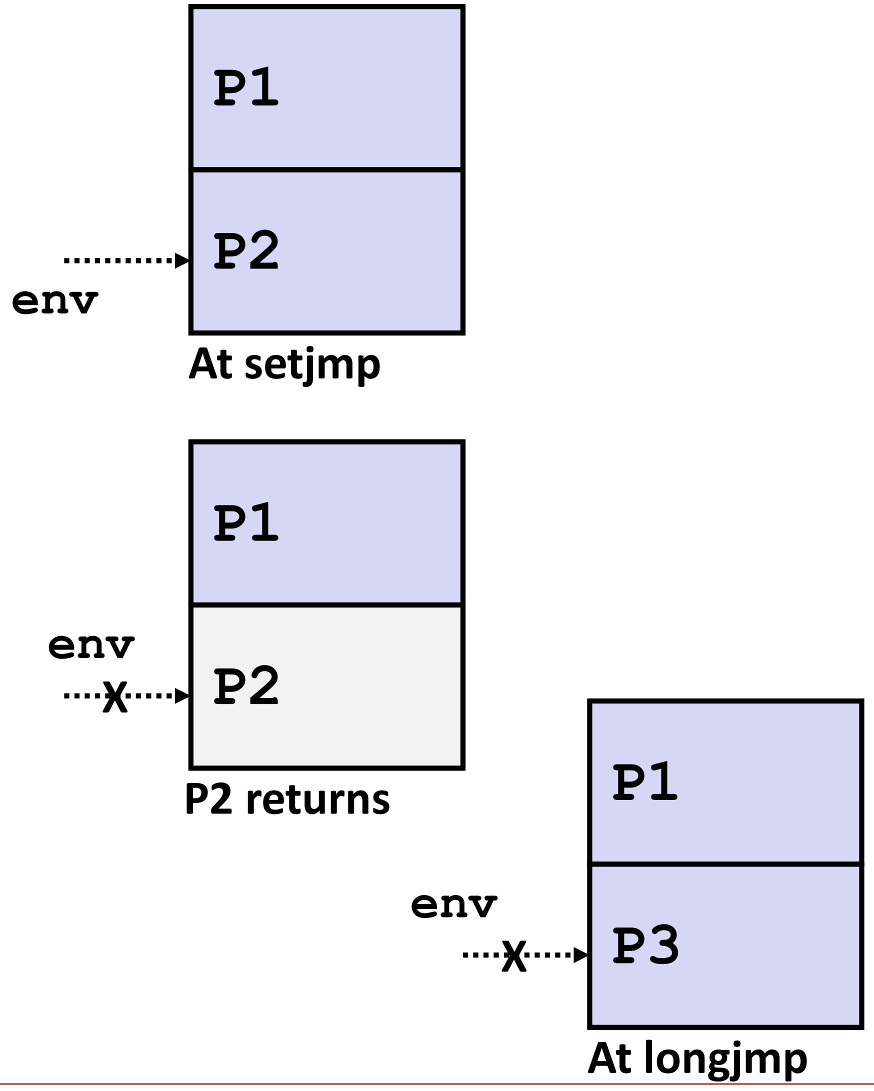
```
jmp_buf env;

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

```c
#include "csapp.h"

sigjmp_buf buf;

void handler(int sig)
{
    siglongjmp(buf, 1);
}

int main()
{
    if (!sigsetjmp(buf, 1)) {
        Signal(SIGINT, handler);
                Sio_puts("starting\n");
    }
    else
        Sio_puts("restarting\n");

    while(1) {
                Sleep(1);
                Sio_puts("processing...\n");
    }
    exit(0); /* Control never reaches here */
}
```

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

restart.c

18-600 Foundations of Computer Systems

Lecture 14: "System Level I/O"

October 16, 2017

Next Time …

- Required Reading Assignment:
  - **Chapter 10 of CS:APP (3rd edition) by Randy Bryant & Dave O'Hallaron.**

Electrical & Computer ENGINEERING