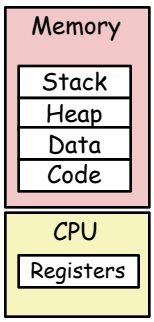
Processes & Signals

CS 475

This lecture is based on Chapter 8 of Computer Systems: A Programmer's Perspective (Bryant & O'Halloran), 3rd edition

Processes

- Definition: A *process* is an instance of a running program.
  - One of the most profound ideas in computer science
  - Not the same as "program" or "processor"
- Process provides each program with two key abstractions:
  - ***Logical control flow***
    - Each program seems to have exclusive use of the CPU
    - Provided by kernel mechanism called *context switching*
  - ***Private address space***
    - Each program seems to have exclusive use of main memory.
    - Provided by kernel mechanism called *virtual memory*



Creating processes

- UNIX
  - fork system call
  - Used in conjunction with exec system call

fork: Creating new processes

- `int fork(void)`
  - creates a new process (child process) that is identical to the calling process (parent process)
  - returns 0 to the child process
  - returns child's `pid` to the parent process

```
if (fork() == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

Fork is interesting (and often confusing) because it is called *once* but returns *twice*

System Call Error Handling

- On error, Linux system-level functions typically return -1 and set global variable `errno` to indicate cause.
- Hard and fast rule:
  - You must check the return status of every system-level function
  - Only exception is the handful of functions that return `void`
- Example:

```
if ((pid = fork()) < 0) {
    fprintf(stderr, "fork error: %s\n", strerror(errno));
    exit(0);
}
```

Error-reporting functions

- Can simplify somewhat using an *error-reporting function*:

```
void unix_error(char *msg) /* Unix-style error */
{
    fprintf(stderr, "%s: %s\n", msg, strerror(errno));
    exit(0);
}
```

```
if ((pid = fork()) < 0)
    unix_error("fork error");
```

Error-handling Wrappers

- We simplify the code we present to you even further by using Stevens-style error-handling wrappers:

```
pid_t Fork(void)
{
    pid_t pid;

    if ((pid = fork()) < 0)
        unix_error("Fork error");
    return pid;
}
```

```
pid = Fork();
```

Obtaining Process IDs

- `pid_t getpid(void)`
  - Returns PID of current process
- `pid_t getppid(void)`
  - Returns PID of parent process

Creating and Terminating Processes

From a programmer's perspective, we can think of a process as being in one of three states

- Running
  - Process is either executing, or waiting to be executed and will eventually be *scheduled* (i.e., chosen to execute) by the kernel
- Stopped
  - Process execution is *suspended* and will not be scheduled until further notice (next lecture when we study signals)
- Terminated
  - Process is stopped permanently

Terminating Processes

- Process becomes terminated for one of three reasons:
  - Receiving a signal whose default action is to terminate (next lecture)
  - Returning from the `main` routine
  - Calling the `exit` function
- `void exit(int status)`
  - Terminates with an *exit status* of `status`
  - Convention: normal return status is 0, nonzero on error
  - Another way to explicitly set the exit status is to return an integer value from the main routine
- `exit` is called once but never returns.

Creating Processes

- *Parent process* creates a new running *child process* by calling `fork`
- `int fork(void)`
  - Returns 0 to the child process, child's PID to parent process
  - Child is *almost* identical to parent:
    - Child get an identical (but separate) copy of the parent's virtual address space.
    - Child gets identical copies of the parent's open file descriptors
    - Child has a different PID than the parent
- `fork` is interesting (and often confusing) because it is called *once* but returns *twice*

`fork` Example

```
int main()
{
    pid_t pid;
    int x = 1;

    pid = Fork();
    if (pid == 0) {  /* Child */
        printf("child : x=%d\n", ++x);
    exit(0);
    }

    /* Parent */
    printf("parent: x=%d\n", --x);
    exit(0);
}
```

fork.c

```
linux> ./fork
parent: x=0
child : x=2
```

- **Call once, return twice**
- **Concurrent execution**
  - Can't predict execution order of parent and child
- **Duplicate but separate address space**
  - `x` has a value of 1 when fork returns in parent and child
  - Subsequent changes to `x` are independent
- **Shared open files**
  - `stdout` is the same in both parent and child

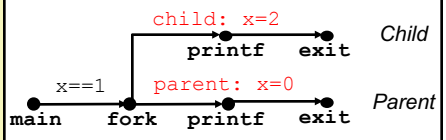
Modeling `fork` with Process Graphs

- A *process graph* is a useful tool for capturing the partial ordering of statements in a concurrent program:
  - Each vertex is the execution of a statement
  - a -> b means `a` happens before b
  - Edges can be labeled with current value of variables
  - `printf` vertices can be labeled with output
  - Each graph begins with a vertex with no inedges
- Any *topological sort* of the graph corresponds to a feasible total ordering.
  - Total ordering of vertices where all edges point from left to right

Process Graph Example

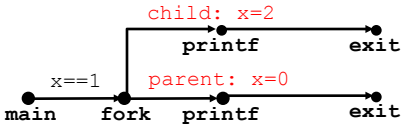
```c
int main()
{
    pid_t pid;
    int x = 1;

    pid = Fork();
    if (pid == 0) {  /* Child */
        printf("child : x=%d\n", ++x);
    exit(0);
    }

    /* Parent */
    printf("parent: x=%d\n", --x);
    exit(0);
}
```

fork.c

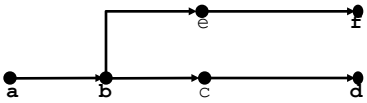


Interpreting Process Graphs

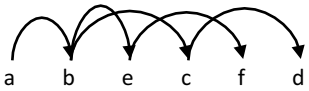
- Original graph:



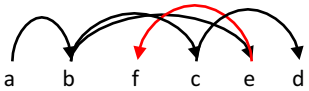
- Relabled graph:



Feasible total ordering:

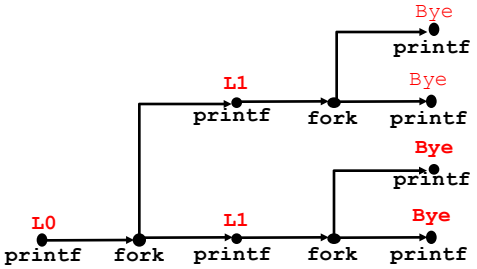


Infeasible total ordering:



fork Example: Two consecutive forks

```
void fork2()
{
    printf("L0\n");
    fork();
    printf("L1\n");
    fork();
    printf("Bye\n");
}
```
forks.c



Feasible output:

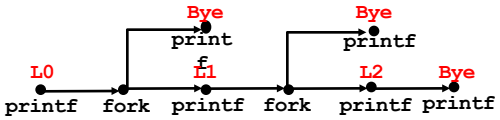
L0
L1
Bye
Bye
L1
Bye
Bye

Infeasible output:

L0
Bye
L1
Bye
L1
Bye
Bye

fork Example: Nested forks in parent

```
void fork4()
{
    printf("L0\n");
    if (fork() != 0) {
        printf("L1\n");
        if (fork() != 0) {
            printf("L2\n");
    }
    }
    printf("Bye\n");
}
```
forks.c

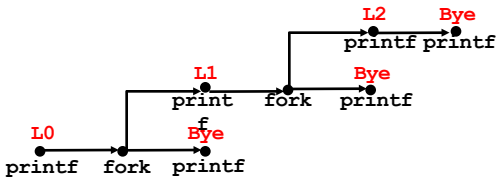


Feasible output:
L0
L1
Bye
Bye
L2
Bye

Infeasible output:
L0
Bye
L1
Bye
Bye
L2

fork Example: Nested forks in children

```
void fork5()
{
    printf("L0\n");
    if (fork() == 0) {
        printf("L1\n");
        if (fork() == 0) {
            printf("L2\n");
        }
    }
    printf("Bye\n");
}
```
forks.c



Feasible output:
L0
Bye
L1
L2
Bye
Bye

Infeasible output:
L0
Bye
L1
Bye
Bye
L2

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

```c
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
```

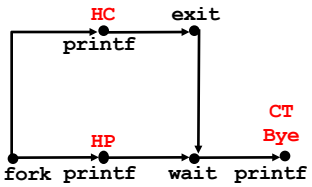
- Child process still active even though parent has terminated
- Must kill child explicitly, or else will keep running indefinitely

`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 (CS:APP) 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:
HC
HP
CT
Bye

Infeasible output:
HP
CT
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

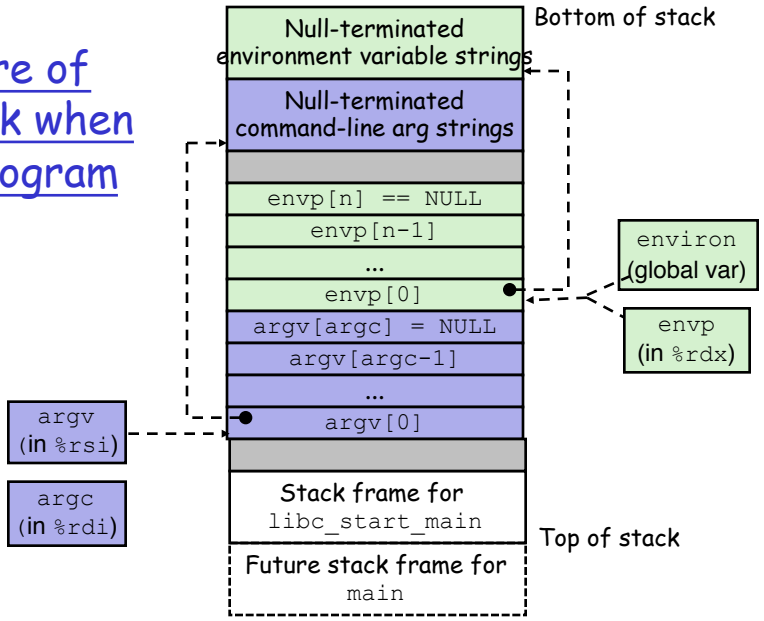
```c
void fork11() {
    pid_t pid[N];
    int i;
    int child_status;

    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

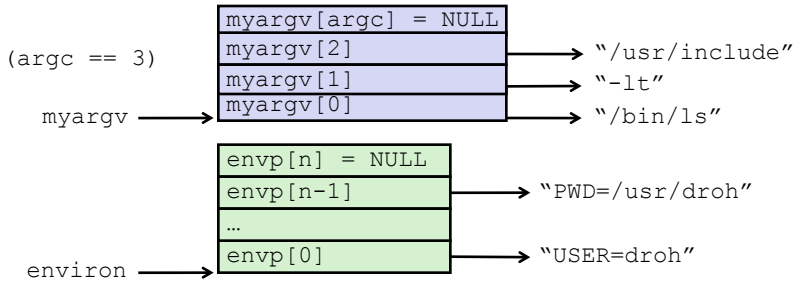
- `int execve(char *filename, char *argv[], char *envp[])`
- Loads and runs in the current process:
  - Executable file **`filename`**
    - Can be object file or script file beginning with `#!interpreter` (e.g., `#!/bin/bash`)
  - …with argument list **`argv`**
    - By convention **`argv[0]==filename`**
  - …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:**

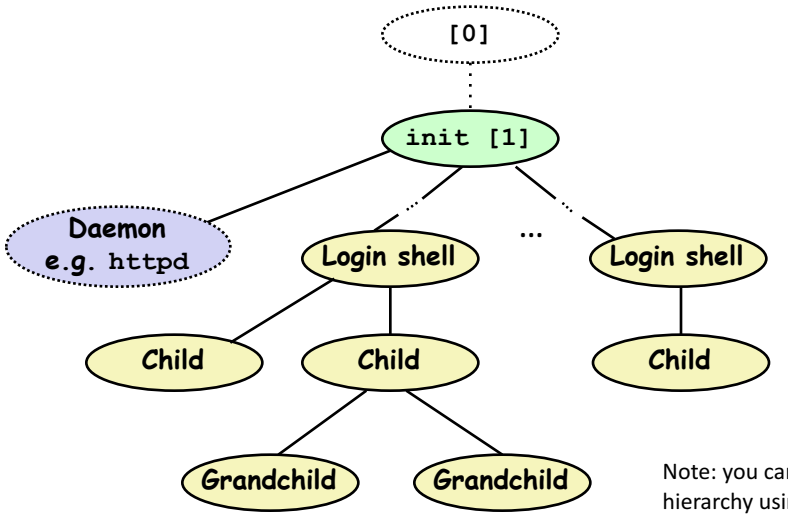



```
if ((pid = Fork()) == 0) {   /* Child runs program */
    if (execve(myargv[0], myargv, environ) < 0) {
        printf("%s: Command not found.\n", myargv[0]);
        exit(1);
    }
}
```

Summary

- Spawning processes
  - Call `fork`
  - One call, two returns
- Process completion
  - Call `exit`
  - One call, no return
- Reaping and waiting for processes
  - Call `wait` or `waitpid`
- Loading and running programs
  - Call `execve` (or variant)
  - One call, (normally) no return

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)

```c
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

```c
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

Signals to the Rescue!

- Solution: Signals
  - 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

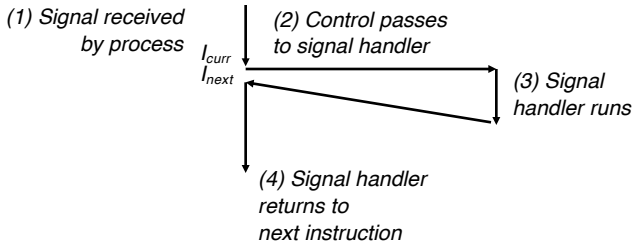
ID	Name	Default Action	Corresponding Event
2	SIGINT	Terminate	User typed ctrl-c
9	SIGKILL	Terminate	Kill program (cannot override or ignore)
11	SIGSEGV	Terminate	Segmentation violation
14	SIGALRM	Terminate	Timer signal
17	SIGCHLD	Ignore	Child stopped or terminated

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:



Signal Concepts: Pending and Blocked Signals

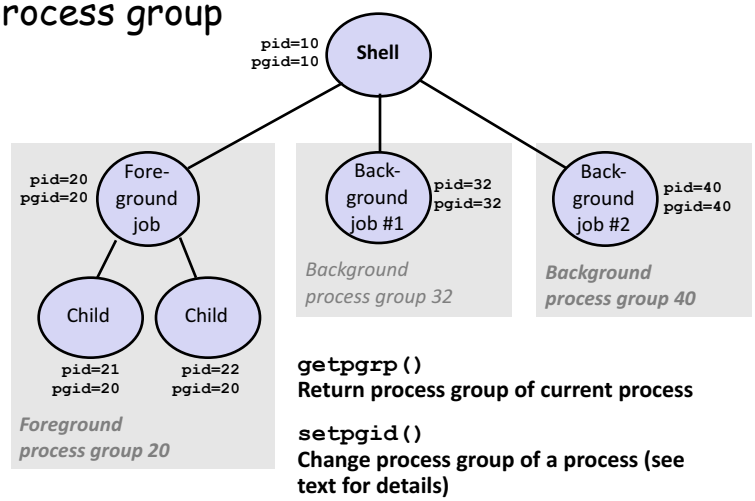
- A signal is *pending* if sent but not yet received
  - There can be at most one pending signal of any particular type
  - Important: Signals are not queued
    - If a process has a pending signal of type k, then subsequent signals of type k that are sent to that process are discarded
- A process can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

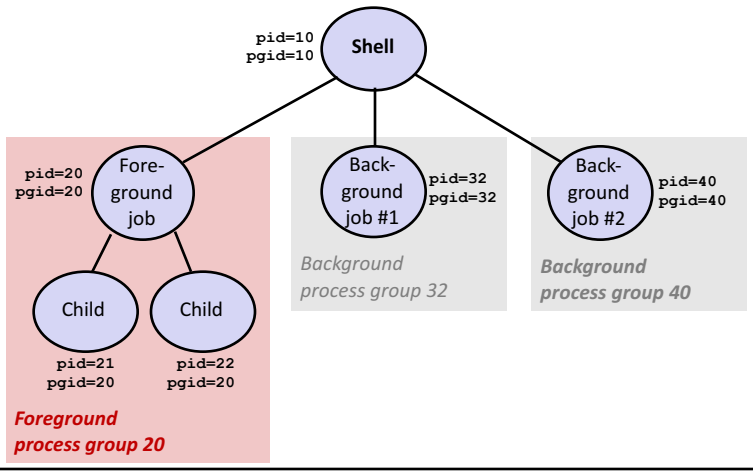
Sending Signals with `/bin/kill` Program

- `/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

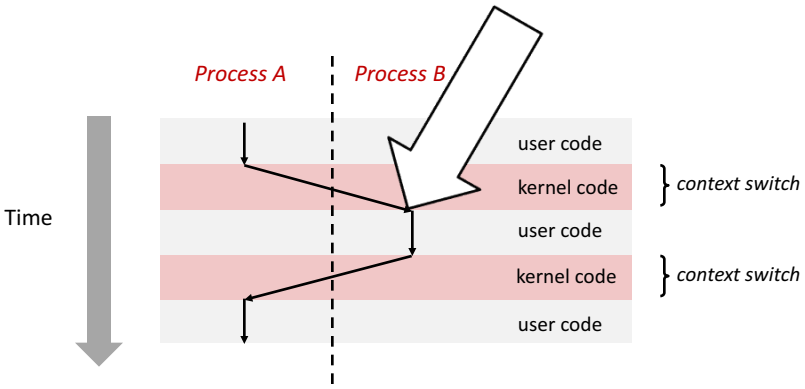
Sending Signals with `kill` Function

```c
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

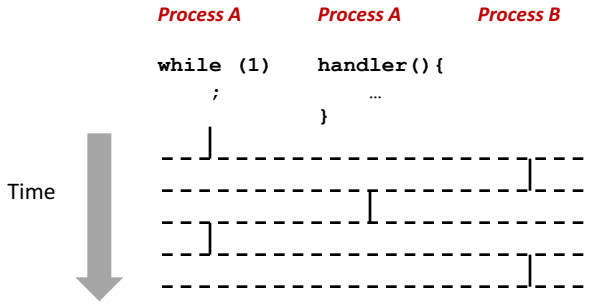
Signal Handling Example

```c
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;
}
```

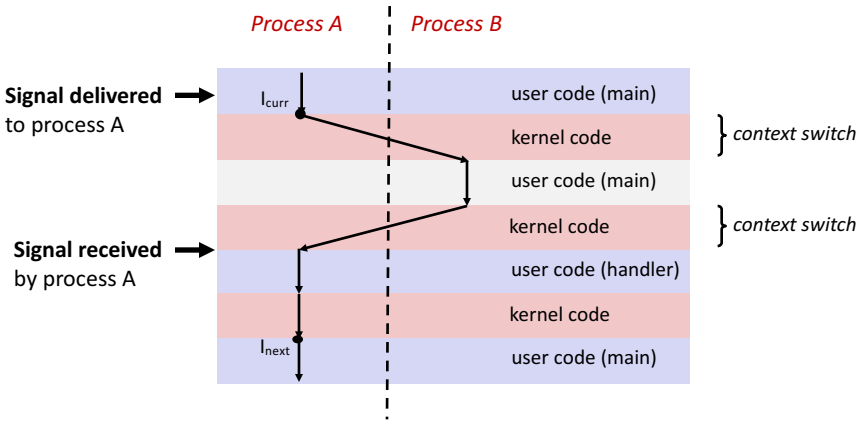
sigint.c

Signals Handlers as Concurrent Flows

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

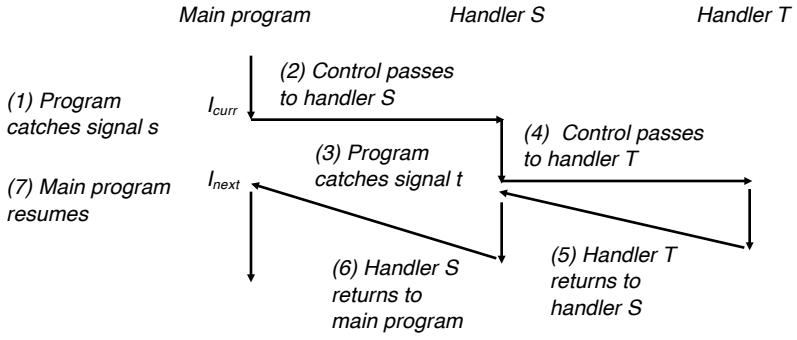


Another View of Signal Handlers as Concurrent Flows



Nested Signal Handlers

- Handlers can be interrupted by other handlers



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

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
```

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

- 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>
```

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

Additional slides

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

```c
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

```c
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

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

```
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);
}
```

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

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);
}
```

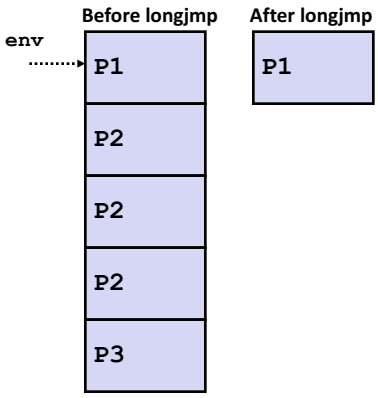
setjmp/longjmp Example (cont)

```
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

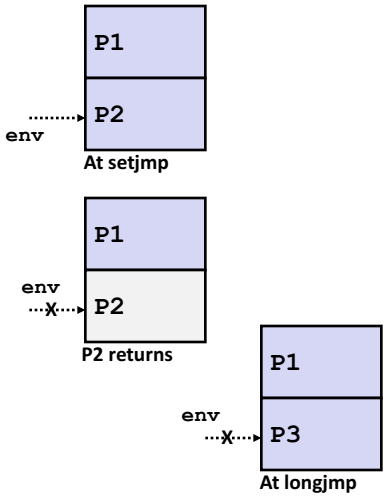
```
jmp_buf env;

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

```
#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 */
}
```

restart.c

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