CS3281 / CS5281

Process Termination and Signals

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**Some lecture slides borrowed and adapted from CMU's "Computer Systems: A Programmer's Perspective"*

Review

- System calls for process creation, program loading, and process reaping:
    - fork(): creates an (almost) identical copy of the calling process
    - exec(): loads a new program into the address space of the calling process
    - wait(): allows a parent process to reap a child process
- Typical sequence: fork() followed by exec()
    - fork() makes a new process
    - exec() blows away the address space of that new process

Process Termination

- When a process terminates, the kernel does not remove it from the system immediately
  - Minimal information is kept (in a terminated state) until the process is reaped by its parent
- A process can terminate in two ways
  - Normal termination:
    - This happens when you do something like exit(0) or return from main without calling exit(). (C library calls exit by default)
      - "Successful”: usually means the process returned 0
      - "Unsuccessful”: usually means the process didn’t return 0
  - Abnormal termination: the process was terminated by a <u>signal</u>
    - Example: a process dereferenced a null pointer, which cause the OS’s page fault handler to send it the SIGSEGV signal, whose default action is to terminate the process
  - Important: “normal” termination does not mean a program ran “successfully”! It mostly means that it didn’t get killed by a signal.

Typical Flow

- A parent process creates a child process via fork()
- The child process runs a new program via exec()
- The parent calls wait() to wait for the child program to terminate
- The parent uses the return information from wait() to determine whether the process exited normally or abnormally
  - If it exited normally, the exit status information can be obtained
  - If it exited abnormally, reason that killed it can be obtained

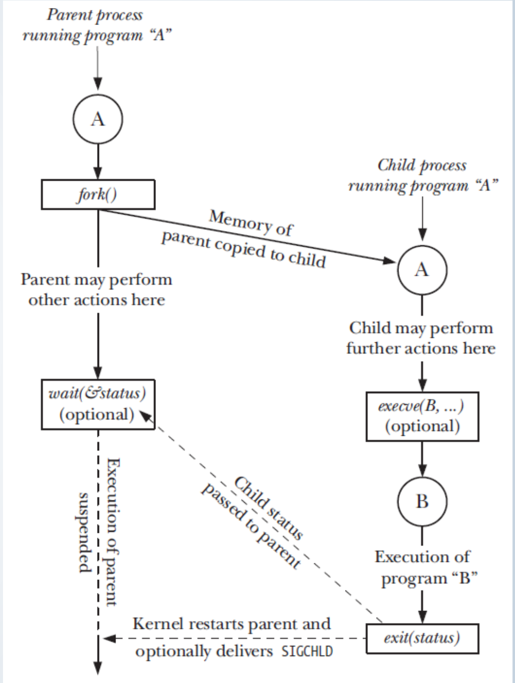

Parent process running program "A"
A
fork()
Memory of parent copied to child
Child process running program "A"
A
Parent may perform other actions here
Child may perform further actions here
wait(&status) (optional)
execve(B, ...) (optional)
Execution of parent suspended
Child status passed to parent
B
Execution of program "B"
Kernel restarts parent and optionally delivers SIGCHLD
exit(status)

Figure 24-1: Overview of the use of *fork()*, *exit()*, *wait()*, and *execve()*

wait() System Call

- The wait() system call is used by a parent to wait for its children to have a change in state
  - What is a change in state?
    - The child terminated
    - The child was stopped by a signal
    - The child was resumed by a signal
- If the child was terminated, performing wait() allows the system to release all resources associated with the child
    - Otherwise the child remains in the “zombie” state
      - Minimal information is kept around

waitpid(): Waiting for a Specific Process

- pid_t waitpid(pid_t pid, int &status, int options)
  - Suspends current process until specific process terminates
  - WIFEXITED: if the program terminated normally

```
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);
  }
}
```

Signals

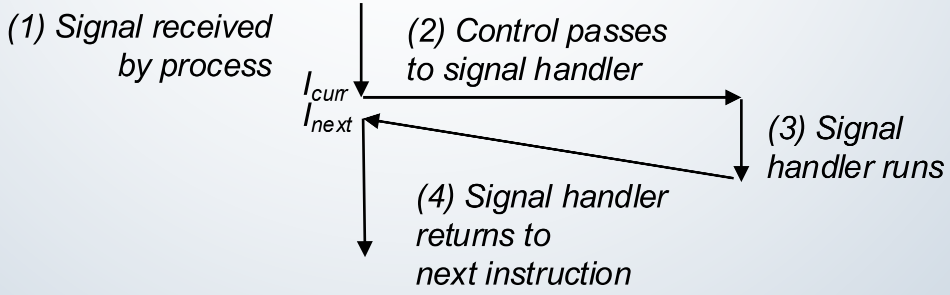
- Signals are a technique used to notify a process that some condition has occurred.
  - Also called software interrupts.
    - Example: if a process divides by zero, the signal whose name is SIGFPE (floating-point exception) is sent to the process.
- Processes can deal with signals in two ways:
  - Let the default action occur.
    - Ignore the signal
    - Terminate the process. It is the default action for most signals
  - Catch the signal. We do this by telling the kernel to call a function of ours whenever the signal occurs. We do this by registering a signal handler.

Transferring Signals

- The transfer of a signal to a destination process occurs in two distinct steps:
    - Sending (delivering) a signal.
        - The kernel delivers a signal to a destination process by updating some state in the context of the destination process. The signal is delivered for one of two reasons:
            - The kernel detected a system event (such as divide by zero)
            - A process invoked the kill function to send a signal to the destination process.
    - Receiving a signal.
        - The destination process receives a signal when it is forced by the kernel to react in some way to the delivery of the signal.
        - This reaction is one of the two choices described above (handle or let the default action occur).

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

Signals Example: Shell

- The simple shell waits for and reaps foreground jobs (A foreground job is visible on the screen. User can interact with foreground jobs).
- But what if we wanted to add 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
  - SIGCHLD signal in Linux
  - Shell doesn't ignore SIGCHLD. It receives it and runs the waitpid
  - By default, SIGCHLD is ignored in programs we write
    - But you can install a handler and do useful things with this!

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

Receiving Signals

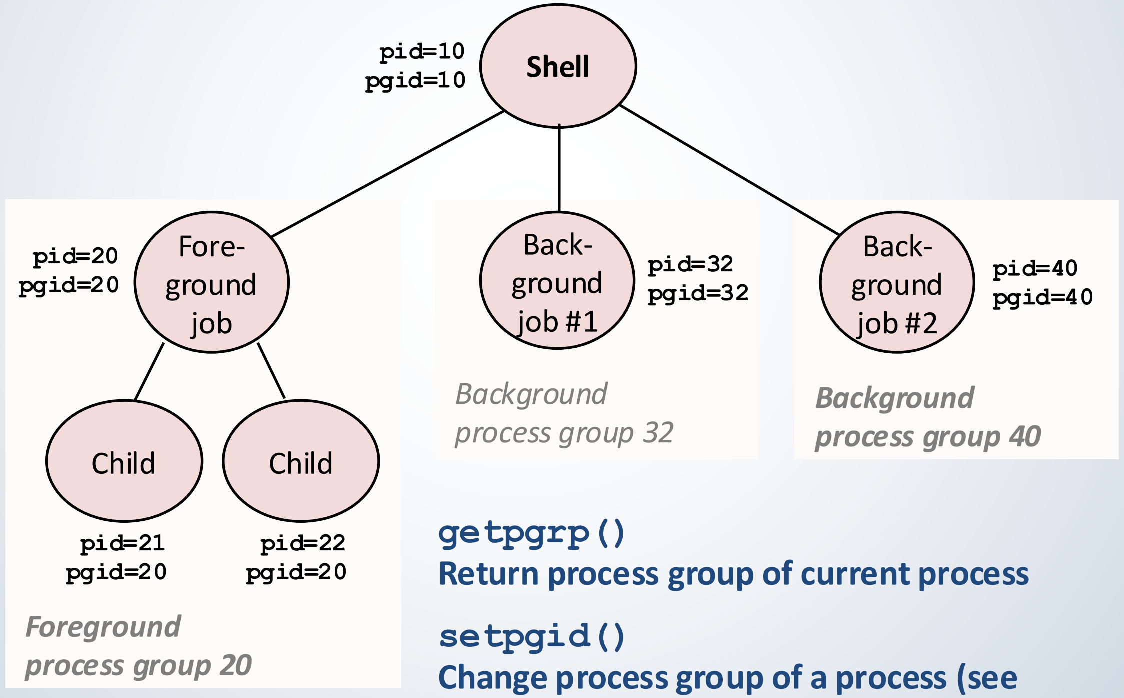
- Suppose kernel is returning from an exception handler and is ready to pass control to process p
- Kernel computes pnb = pending & ~blocked
  - The set of pending nonblocked signals for process p
- If (pnb == 0)
  - Pass control to next instruction in the logical flow for p
- Else
  - Pick some pending unblocked signal 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

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)

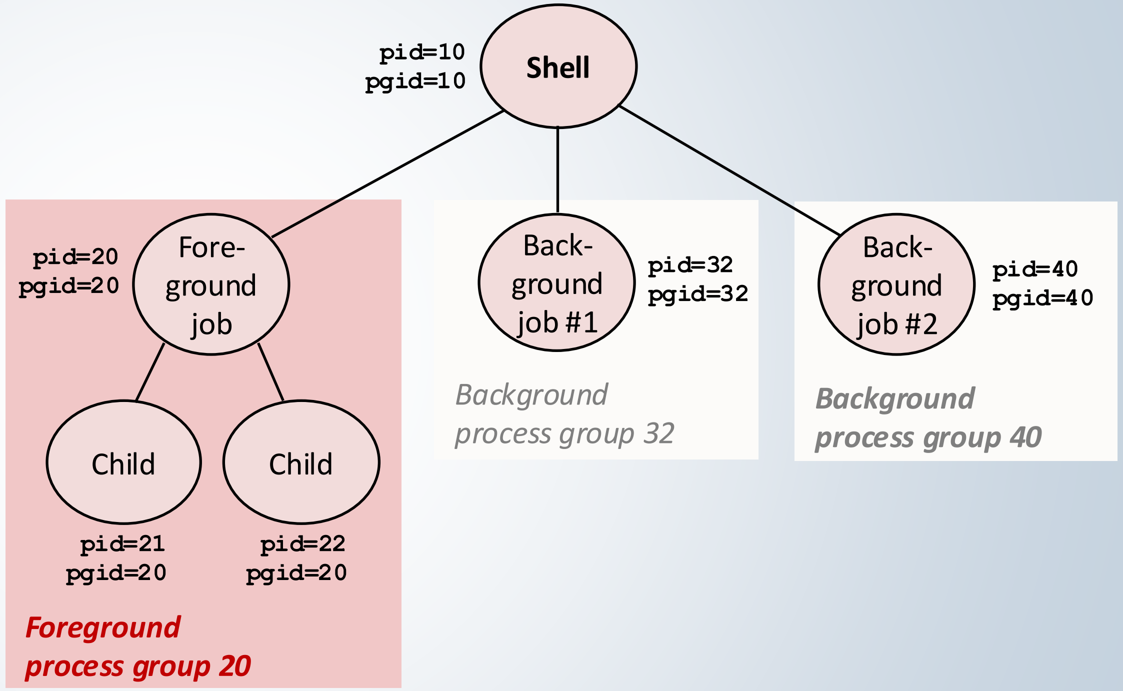
Sending Signals with “kill” Program

- `/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
24817 pts/2    00:00:02 forks
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);
    }
}
```

Default Actions

- Each signal type has one of three predefined *default actions*:
  - The process terminates
  - The process stops until restarted by a SIGCONT signal
  - The process ignores the signal

Installing Signal Handlers

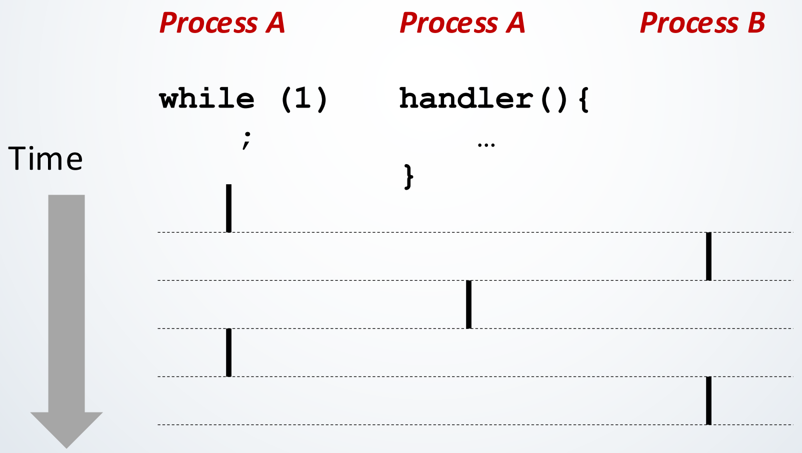
- The signal function modifies the default action associated with the receipt of signal signum:
  - typedef void (*sighandler_t)(int);
  - sighandler_t signal(int signum, sighandler_t handler)
- Different values for handler:
  - SIG_IGN: ignore signals of type signum
  - SIG_DFL: revert to the default 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
    - Passing the address of handler to the signal function is called "installing" the handler
    - Invoking a handler is called "catching" the signal
    - Executing handler is called "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

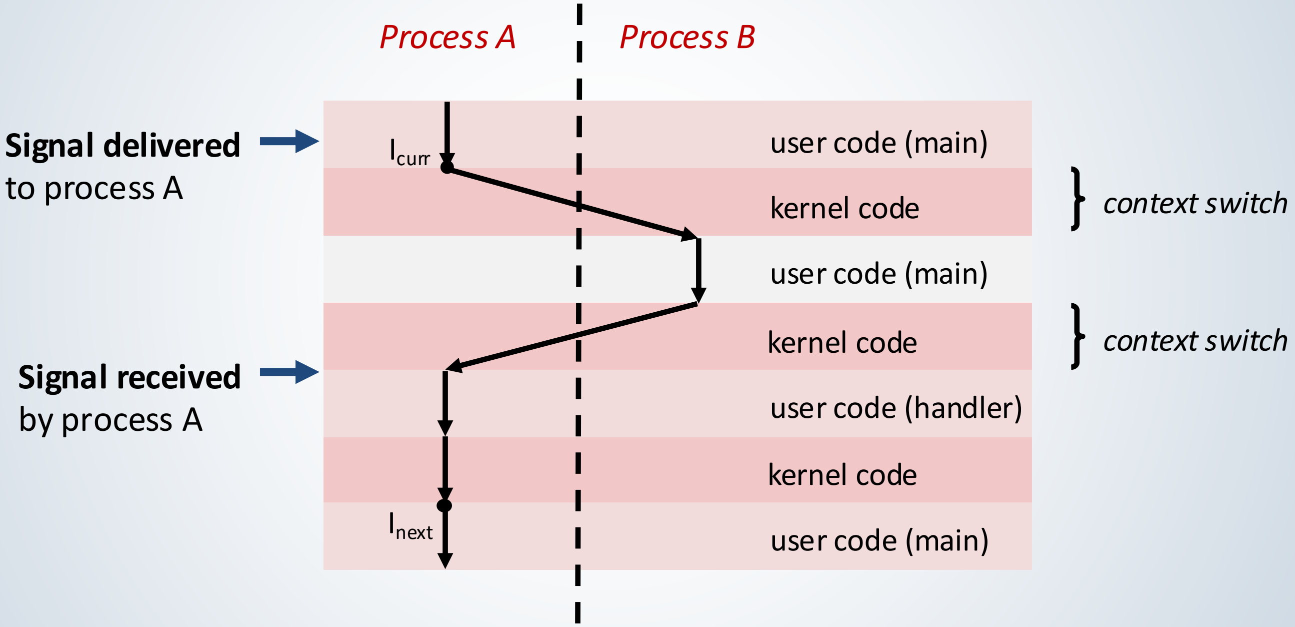
```
void sigint_handler(int sig) /* SIGINT handler */
{
    printf("So you think you can stop the bomb with ctrl-c, do you?\n");
    sleep(2);
    printf("Well...");
    fflush(stdout);
    sleep(1);
    printf("OK. :-)\n");
    exit(0);
}

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;
}
```

Signal Handlers as Concurrent Flows

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

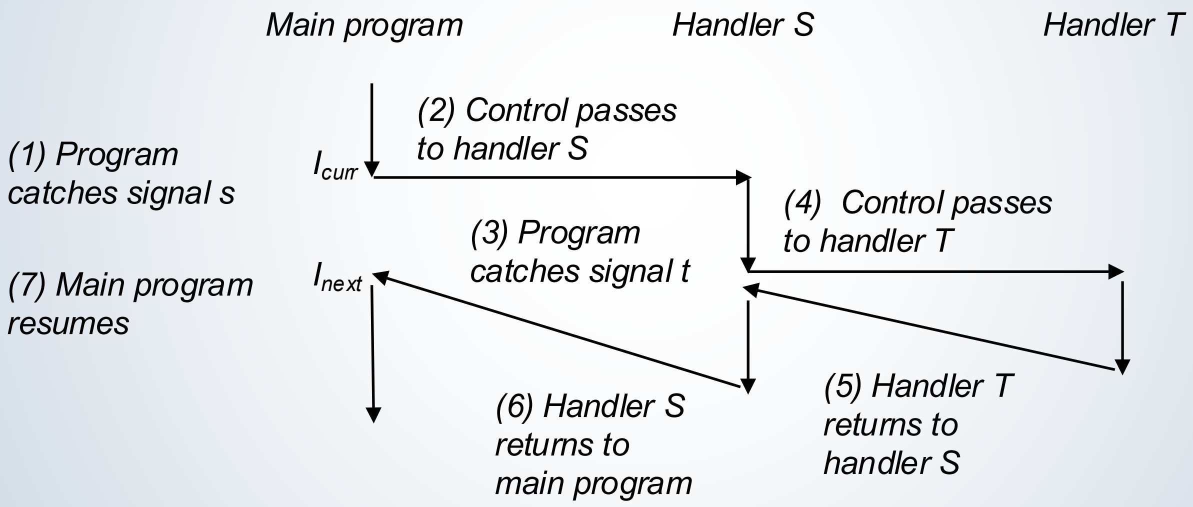


Signal Handlers as Concurrent Flows: Another View



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
(7) Main program resumes
I_{next}

Core Dumps

- The default action for some signals, like SIGABRT (abnormal termination) or SIGSEGV (invalid memory reference), is to terminate the process and generate a core dump.
- A core dump file contains an image of the virtual memory of the process, which can be loaded into a debugger to inspect the state of the process at the time that it terminated.