Exceptional Control Flow: Signals and Nonlocal Jumps

CSE4100: Multicore Programming

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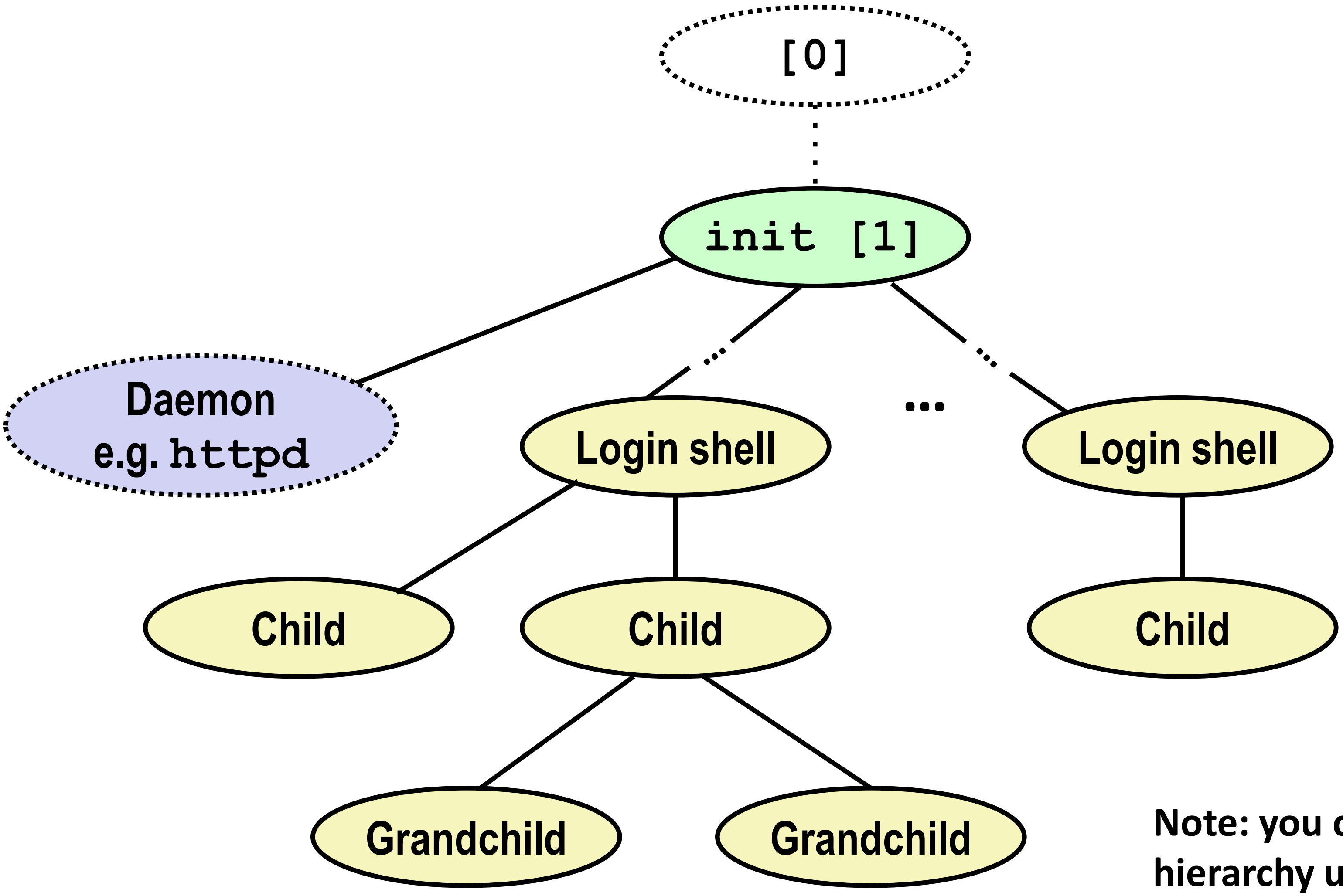
ECF Exists at All Levels of a System

- **Exceptions**
  - Hardware and operating system kernel software
- **Process Context Switch**
  - Hardware timer and kernel software
- **Signals**
  - Kernel software and application software
- **Nonlocal jumps**
  - Application code

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)
- **Simple shell**
  - Described in the textbook
  - Implementation of a very elementary shell
  - Purpose
    - Understand what happens when you type commands
    - Understand use and operation of process control operations

Simple Shell Implementation

- **Basic loop**
  - Read line from command line
  - Execute the requested operation
    - Built-in command (only one implemented is **`quit`**)
    - Load and execute program from file

```
int main(int argc, char** argv)
{
    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);          /* Check input ended in '&' */
    if (argv[0] == NULL) return;        /* Ignore empty lines */
    if (!builtin_command(argv)) {       /* If arg is a builtin command, run it here */
        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;
}

int builtin_command(char **argv)
{
    if (!strcmp(argv[0], "quit") exit(0);
    if (!strcmp(argv[0], ....) { .... }
}
```

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

- **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***

Signals

- **A *signal* is a small message that notifies a process that an event of some type has occurred in the system**
  - Similar to exceptions and interrupts
  - Sent from the kernel (sometimes at the request of another process) to a process
  - Signal type is identified by integer ID's (1-64): `kill -l` command
  - 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
8	**SIGFPE**	Terminate & dump core	Floating-point exception (divide by 0)
9	**SIGKILL**	Terminate	Kill program (cannot override or ignore)
11	**SIGSEGV**	Terminate & dump core	Segmentation violation
14	**SIGALRM**	Terminate	Timer signal
17	**SIGCHLD**	Ignore	Child stopped or terminated

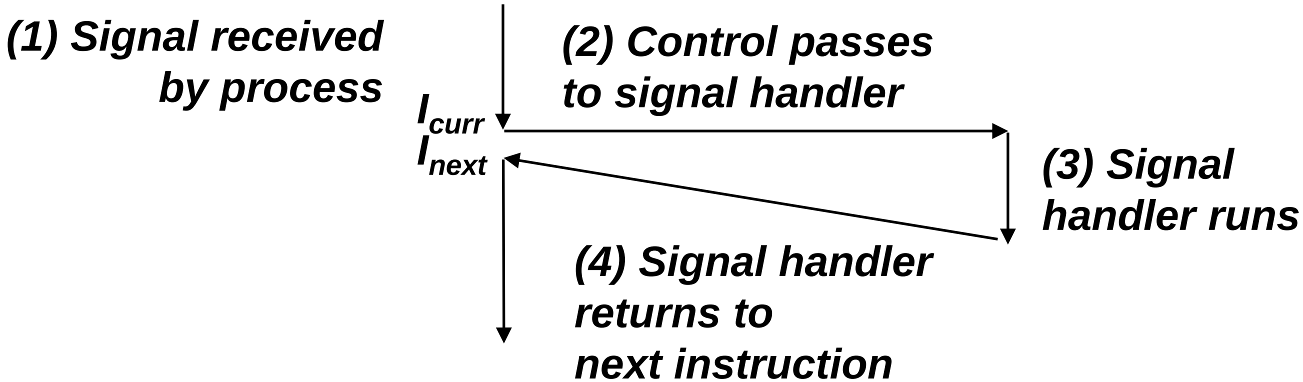
Signal Concepts: Sending a Signal

- **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
    - **`kill -9`** ***`pid`***: send a SIGKILL (#9) signal to a process with *pid*

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***
    - Similar to a hardware exception handler being called in response to an asynchronous interrupt:



Signal Concepts: Pending and Blocked Signals

- **A process can *block* the receipt of certain signals**
  - Blocked signals can be delivered, but will not be received until the signal is unblocked

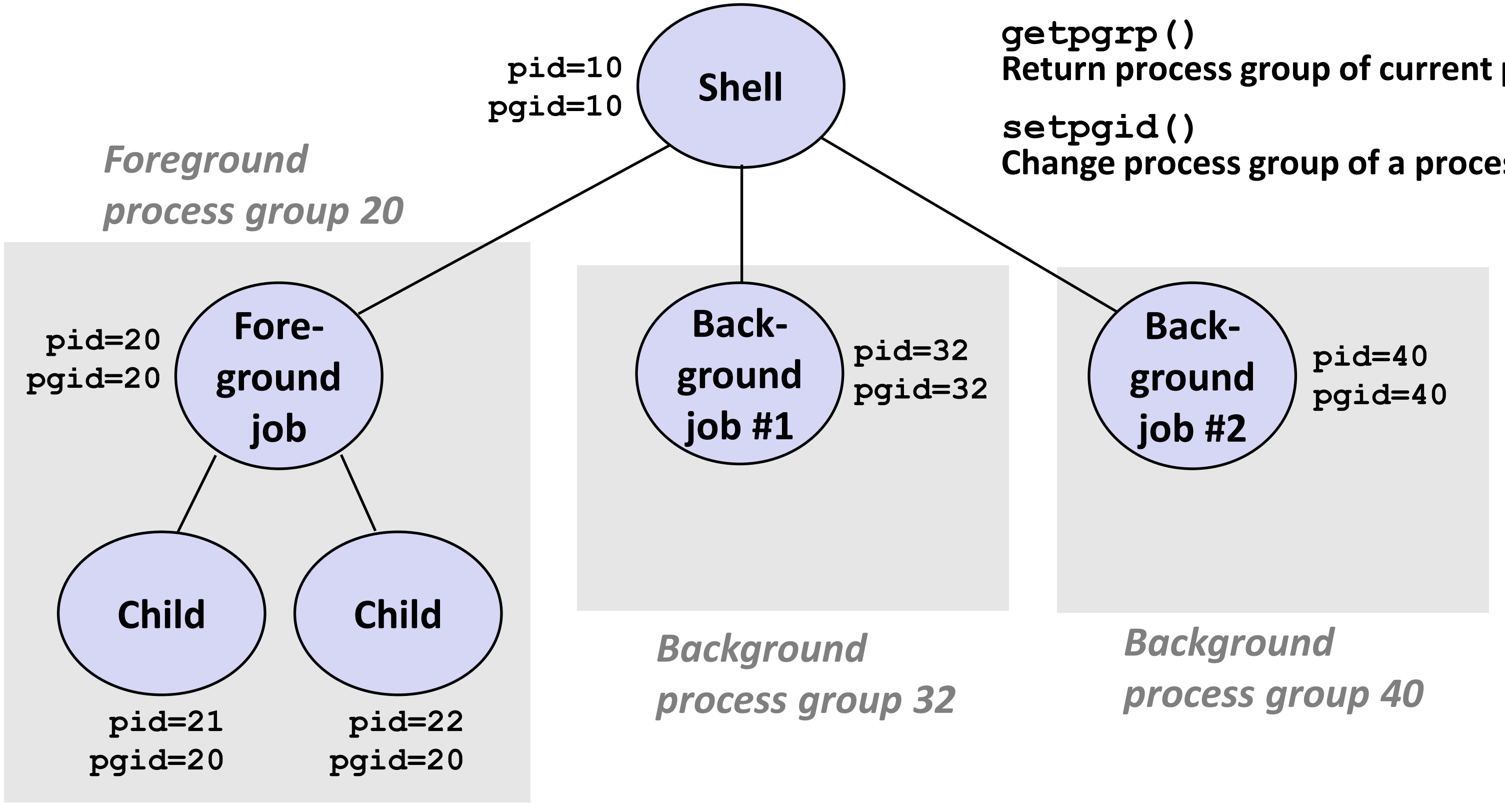
- **A signal is *pending* if sent but not yet received**
  - Most common reason for a signal to be pending is that the process has currently blocked the signal
  - Therefore, the blocked signals are also pending signals and they are delivered immediately upon unblock
  - There can be at most one pending signal of any particular type
    - A pending signal is received at most once
  - 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

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

- A *job* represents the processes created in a single command line
  - At most 1 foreground job and 0 or more background jobs
- The shell creates a separate process group for each job
  - 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 `/bin/kill` Program

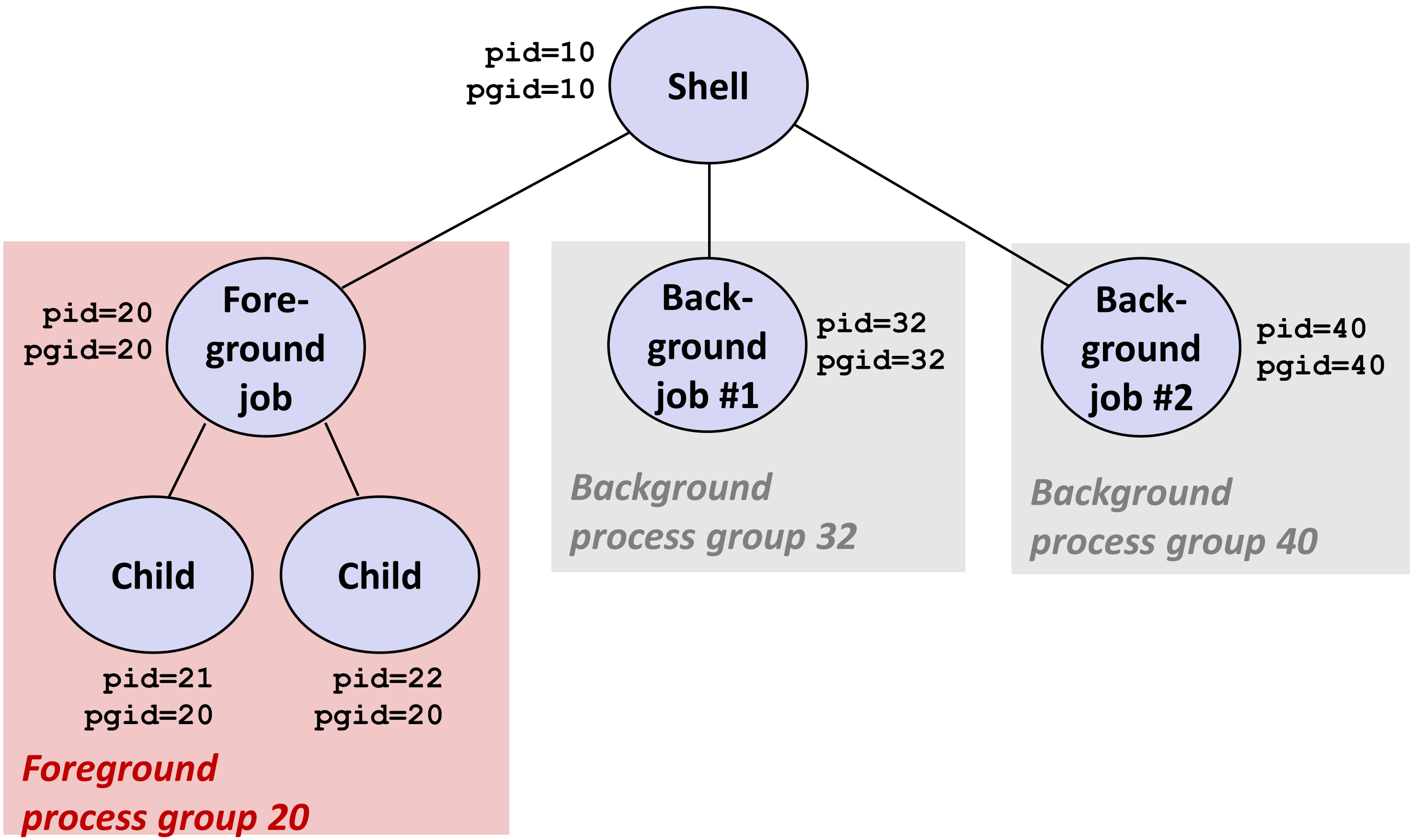
- `/bin/kill` program sends arbitrary signal to a process or process group

- 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
24817 pts/2    00:00:00 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 process 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

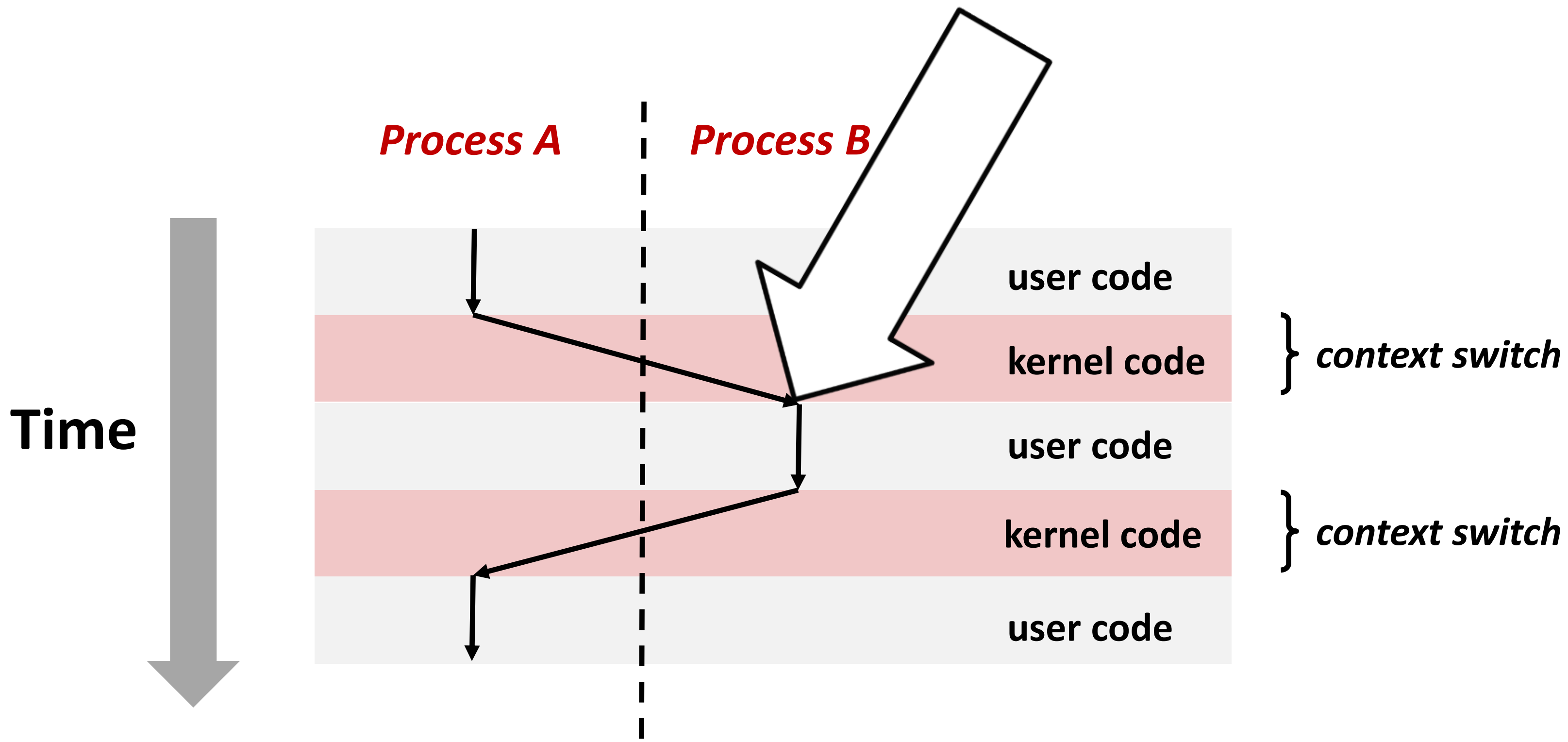
```
void fork12()
{
    pid_t pid[N];      N = 5
    int i;
    int child_status;

    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);
    }
}
```

```
➜  14-ecf-procs ./forks 12
Killing process 24526
Killing process 24527
Killing process 24528
Killing process 24529
Killing process 24530
Child 24527 terminated abnormally
Child 24530 terminated abnormally
Child 24529 terminated abnormally
Child 24528 terminated abnormally
Child 24526 terminated abnormally
➜  14-ecf-procs
```

forks.c

Receiving Signals

- **The kernel checks pending signals when switching a process *p* from kernel mode to user mode**
  - Returning from a system call or an exception handler
  - Completing a context switch to *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 non-blocked 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 (suspends) until restarted by a SIGCONT signal
  - The process ignores the signal

- **You can override the default signal handler with your own signal handler using *signal* or *sigaction* functions**
  - The SIGKILL and SIGSTOP signals cannot be caught or ignored

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

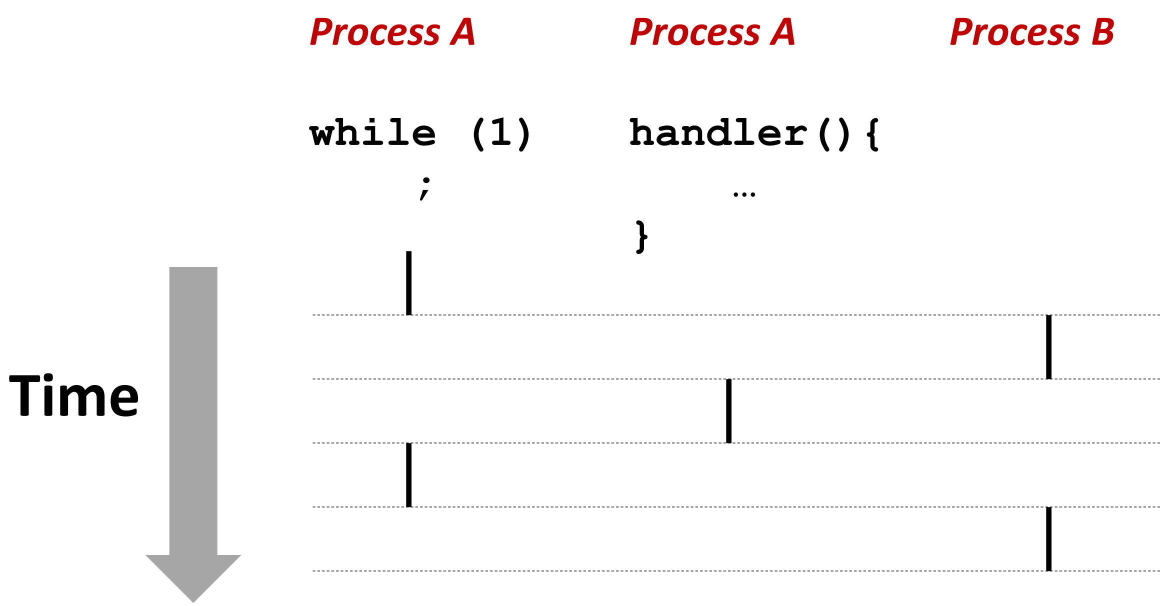
```c
void sigint_handler(int sig) /* SIGINT handler */
{
    printf("So you think you can stop the bomb with ctrl-c, do you?\n");
    sleep(2);
    printf("Well...");
    fflush(stdout);
    sleep(1);
    printf("OK. :-)\n");
    exit(0);
}

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;
}
```

```
➜  ecf-signals ./sigint
^CSo you think you can stop the bomb with ctrl-c, do you?
Well...OK. :-)
➜  ecf-signals
```

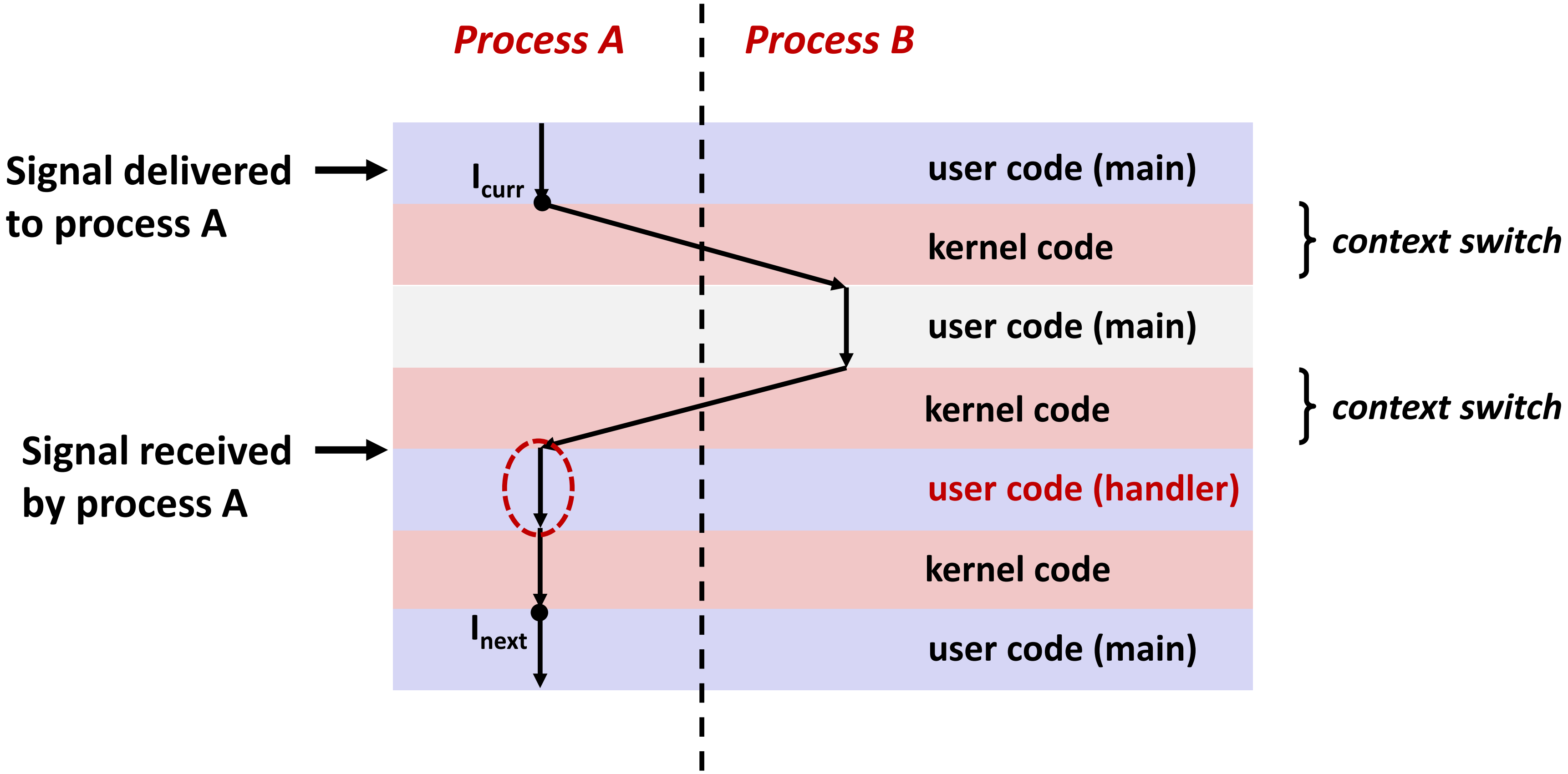
sigint.c

Signals Handlers as Concurrent Flows

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

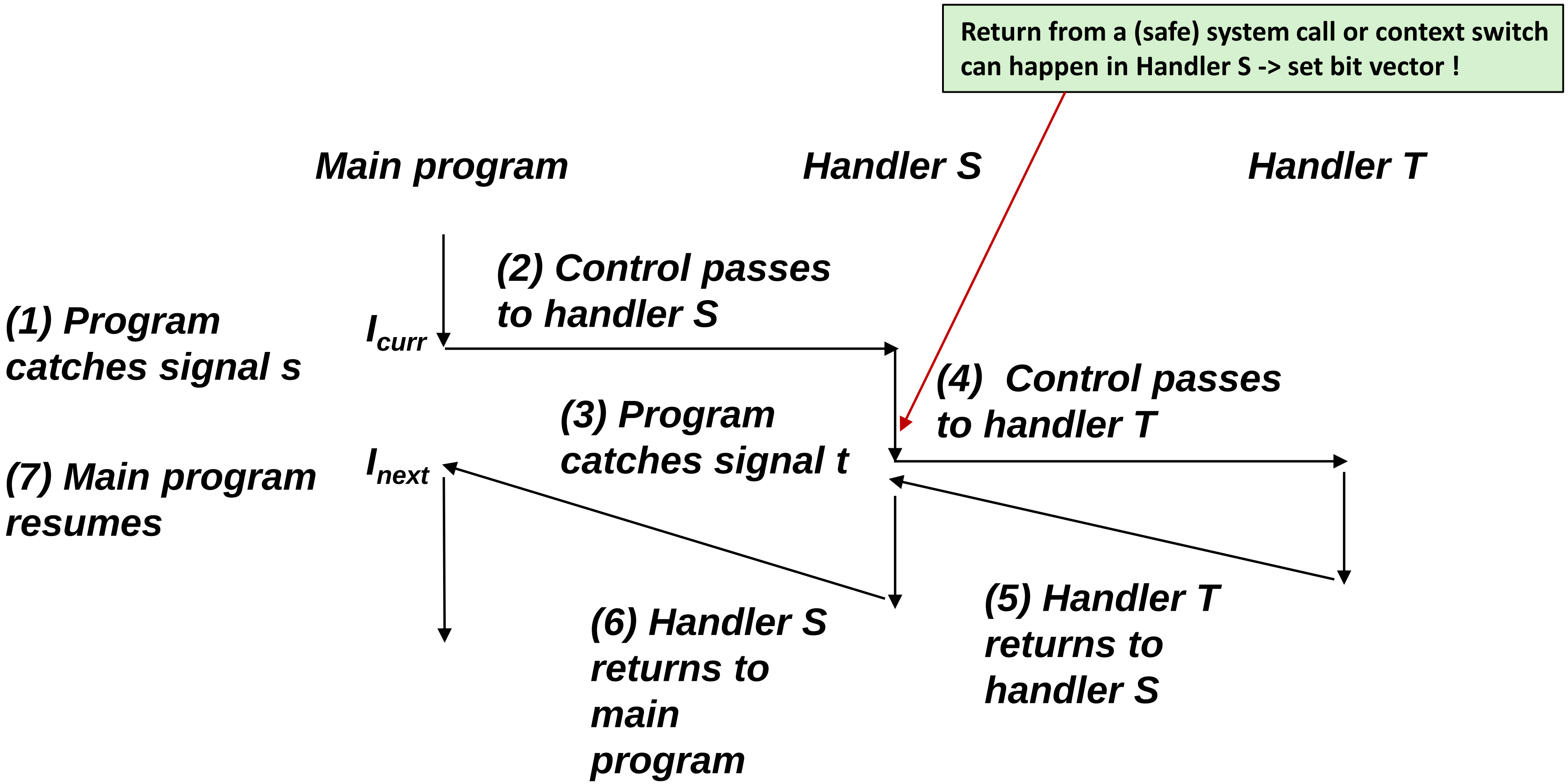


Another View of Signal Handlers as Concurrent Flows



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 this semester**

- **For now, here are some guidelines to help you avoid trouble**

6 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**
  - Function is *async-signal-safe* if
    - either reentrant -> use only variables (i.e., use local stack)
    - or non-interruptible by signals
  - POSIX guarantees 117 functions to be async-signal-safe
    - 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);
}
```

```
ssize_t sio_puts(char s[]) /* Put string */
{
    return write(STDOUT_FILENO, s, sio_strlen(s));
}
```

```
void sio_error(char s[]) /* Put error message and exit */
{
    sio_puts(s);
    _exit(1);
}
```

sigintsafe.c

6 Guidelines for Writing Safe Handlers (Cont)

- **G2: Save and restore `errno` on entry and exit**
  - So that other handlers don't overwrite your value of **`errno`**

```
void handler(int sig)
{
   int olderrno = errno;
   ....
   errno = olderrno;
}
```

- **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

> 1. What happens if compiler stores *flag* variable in a register to optimize speed?
> 2. *Volatile* keyword requests compilers to generate codes such that they always access memory!

```
void handler(int sig)
{
   ....
   flag = 1;
}
```

```
volatile int flag = 0;
int main()
{
   ....
   while ( ! flag ) ;
}
```

- **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

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 */
      ;
}
```

What if N > 2?

forks.c

```
ecf-signals> ./forks 14
Handler reaped child 23240
Handler reaped child 23241
... (hangs)
```

- **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 terminatingc**

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;
}
```

Wait() returns -1 with errno=ECHILD if the calling process does not have any unwaited children

```
ecf-signals> ./forks 15
Handler reaped child 23246
Handler reaped child 23247
Handler reaped child 23248
Handler reaped child 23249
Handler reaped child 23250
ecf-signals>
```

Portable Signal Handling

- **Different Unix versions have different signal handling semantics**
  - Unlike Linux, some older Unix systems restore action to default after catching signal -> need to explicitly reinstall itself by calling **`signal`**
  - Some interrupted system calls (i.e., slow system call such as read) can return with errno == EINTR -> need to check the error and continue
  - Some systems don't block signals of the type being handled
- **Solution: use `signal` wrapper using `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 (race)* 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);
}
```

What happens if child terminates before parent is able to run?

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 if exists */
        Sigprocmask(SIG_SETMASK, &prev_all, NULL);
    }
    if (errno != ECHILD)
        Sio_error("waitpid error");
    errno = olderrno;
}
```

procmask1.c

Oops! Nothing to delete!

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();

   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 for another fork from child */
         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);
}
```

Wait until parent finishes *addjob(pid)* – Block SIGCHLD handler

Unblock because child can fork another child

procmask2.c

Explicitly Waiting for Signals

- **Sometimes a main program needs to explicitly wait for a certain handler to run**
  - When a Linux shell creates a foreground job, it must wait for the job to terminate and be reaped by the SIGCHLD handler before accepting the next user command (i.e., child reaping is done at the SIGCHLD handler)
- **Handlers for program explicitly waiting for SIGCHLD to arrive**

```
volatile sig_atomic_t pid;      /* pid is initialized to 0 in main and updated in the SIGCHLD handler */
                                /* Declare pid as a global (atomic) variable for this */
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) exit(0);                   /* Child */
            pid = 0;                                    /* Parent */
            Sigprocmask(SIG_SETMASK, &prev, NULL);      /* Unblock SIGCHLD */

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

This spin loop is wasteful of CPU resources !

waitforsignal.c

Explicitly Waiting for Signals

- **Program is correct, but very wasteful**
  - Program in busy-wait loop

```
while (!pid)
    ;
```

- **Possible race condition**
  - Between checking pid and starting **`pause`**, might receive SIGCHLD signal
  - The **`pause`** will sleep forever !

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

- **Safe, but slow**
  - Will take up to one second to respond

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

- **Solution: `sigsuspend`**

Waiting for Signals with `sigsuspend`

- **`int sigsuspend(const sigset_t *mask)`**
  - Temporarily replaces the current blocked set with mask
  - Suspend the process until the receipt of a signal
    - If the action is to terminate, the calling process terminates
    - If the action is to run a handler, **`sigsuspend`** returns after the handler returns
  - Restore the blocked set to its state when **`sigsuspend`** was called
- **Equivalent to atomic (uninterruptable) version of:**

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

  - This eliminates the potential race where a signal is received after the call to **`sigprocmask`** and before the call to **`pause`**

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) exit(0);                  /* Child */

        /* 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);
}
```

Restore to initial state (SIGCHLD unblocked)

```
sigprocmask(SIG_BLOCK, &prev, &mask1);
pause();
sigprocmask(SIG_SETMASK, &mask1, NULL);
```

Restore to previous state (SIGCHLD blocked)

Between checking pid and starting pause, SIGCHLD signal cannot happen because SIGCHLD is blocked -> no race condition !

sigsuspend.c

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 sequence
  - Useful for error recovery and signal handling

- **`int setjmp(jmp_buf env)`**
  - Saves the current *calling environment* in the **`env`** buffer for a subsequent **`longjmp`** and returns 0
  - The *calling environment* includes the ***program counter***, ***stack pointer***, and ***general-purpose registers***
  - The return value should not be assigned to a variable; can be safely used as a test in a switch or conditional statement
  - Must be called before **`longjmp`**

- **`void longjmp(jmp_buf env, int retval)`**
  - Restore the *calling environment* from the **`env`** buffer and jump to the location remembered by the **`env`** buffer
  - The return value is nonzero **`retval`** instead of 0
  - Must be called after **`setjmp`**

setjmp/longjmp Example

```
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);
}
```

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

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

- **Can cause memory leak**
  - Intermediate functions allocate data structures that need to be deallocated
- **Works within stack discipline**
  - Can only long jump to the location that has been called but not yet completed

setjmp/longjmp Example in Signal

siglongjmp and sigsetjmp are functions for signal handling similar to setjmp and longjmp

Save the current signal mask

```
#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

```
ecf-signals> ./restart
starting
processing...
processing...
processing...
restarting        Ctrl-c
processing...
processing...
restarting        Ctrl-c
processing...
processing...
processing...
```

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