Exceptions and Processes

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Review from last lecture

- Exceptions
  - Events that require nonstandard control flow
  - Generated externally (interrupts) or internally (traps and faults)
- Processes
  - At any given time, system has multiple active processes
  - Only one can execute at a time on any single core
  - Each process appears to have total control of processor + private memory space

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Asynchronous Exceptions (Interrupts)

- Caused by events external to the processor
  - Indicated by setting the processor's *interrupt pin*
  - Handler returns to "next" instruction
- Examples:
  - Timer interrupt
    - Every few ms, an external timer chip triggers an interrupt
    - Used by the kernel to take back control from user programs
  - I/O interrupt from external device
    - Hitting Ctrl-C at the keyboard
    - Arrival of a packet from a network
    - Arrival of data from a disk

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Synchronous Exceptions

- Caused by events that occur as a result of executing an instruction:
  - ***Traps***
    - Intentional
    - Examples: ***system calls***, breakpoint traps, special instructions
    - Returns control to "next" instruction
  - ***Faults***
    - Unintentional but possibly recoverable
    - Examples: page faults (recoverable), protection faults (unrecoverable), floating point exceptions
    - Either re-executes faulting ("current") instruction or aborts
  - ***Aborts***
    - Unintentional and unrecoverable
    - Examples: illegal instruction, parity error, machine check
    - Aborts current program

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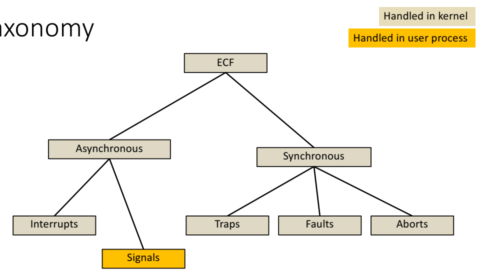
ECF Exists at All Levels of a System

- Exceptions
  - Hardware and operating system kernel software
- Process Context Switch
  - Hardware timer and kernel software
- Signals
  - Kernel software and application software

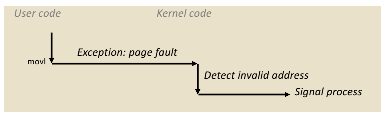
Taxonomy



Fault Example: Invalid Memory Reference

```
int a[1000];
main ()
{
    a[5000] = 13;
}
```

```
 80483b7:      c7 05 60 e3 04 08 0d   movl   $0xd,0x804e360
```



- Sends `SIGSEGV` signal to user process
- User process exits with “segmentation fault”

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

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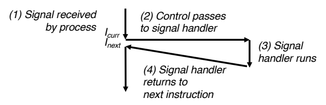
Signal Concepts: Receiving a Signal

- 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

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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

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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*.

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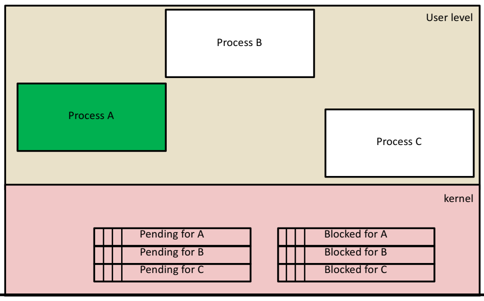
Signal Concepts: Sending a Signal



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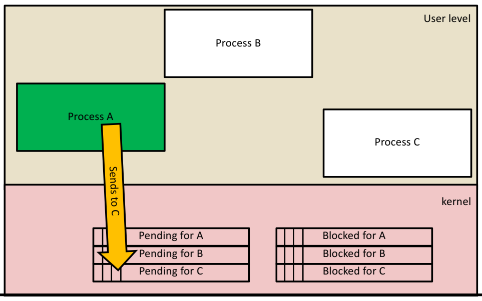
Signal Concepts: Sending a Signal



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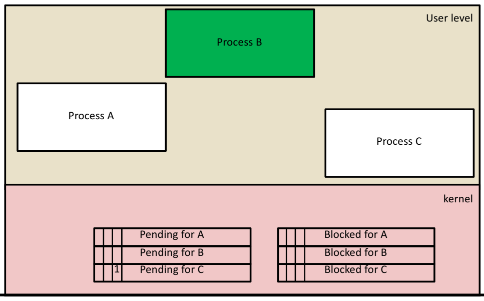
Signal Concepts: Sending a Signal



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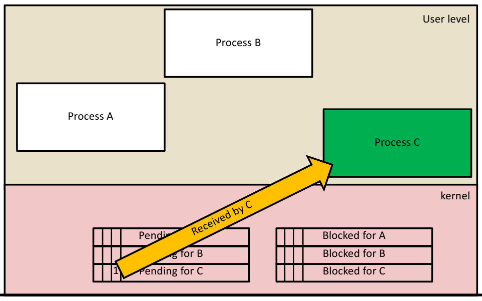
Signal Concepts: Sending a Signal



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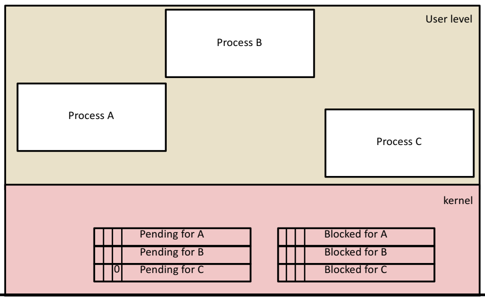
Signal Concepts: Sending a Signal



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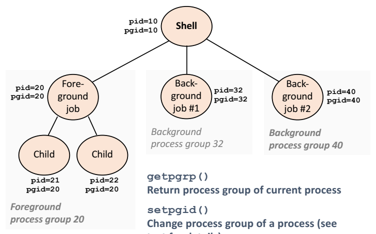
Sending Signals: Process Groups

- 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)

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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>
```

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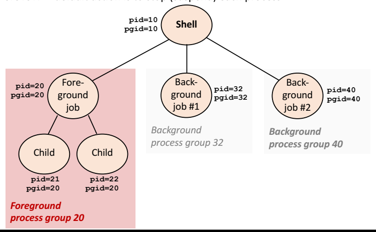
Sending Signals from the Keyboard

- 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



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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

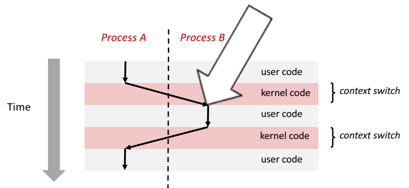
See "man ps" for more details

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);
    }

}                                                          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

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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

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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(int argc, char** argv)
{
    /* 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

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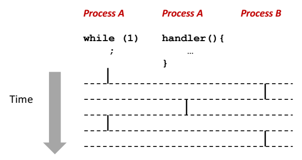
Signals Handlers as Concurrent Flows

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



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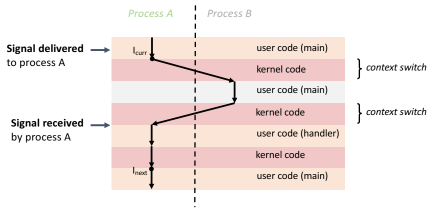
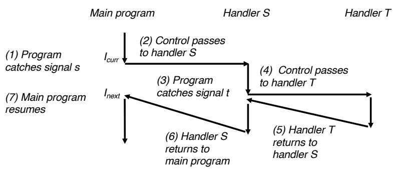
Another View of Signal Handlers as Concurrent Flows



Nested Signal Handlers

- Handlers can be interrupted by other handlers


Main program
Handler S
Handler T
(1) Program catches signal s
(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_{curr}
I_{next}

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

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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

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Async-Signal-Safety

- Function is *async-signal-safe* if either reentrant (e.g., all variables stored on stack frame) 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

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Safely Generating Formatted Output

- Use the reentrant SIO (Safe I/O library)
  - `ssize_t sio_puts(char s[]) /* Put string */`
  ```
  ssize_t sio_puts(char s[]) /* Put string */
  {
      return write(STDOUT_FILENO, s, sio_strlen(s));
  }
  ```

```
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

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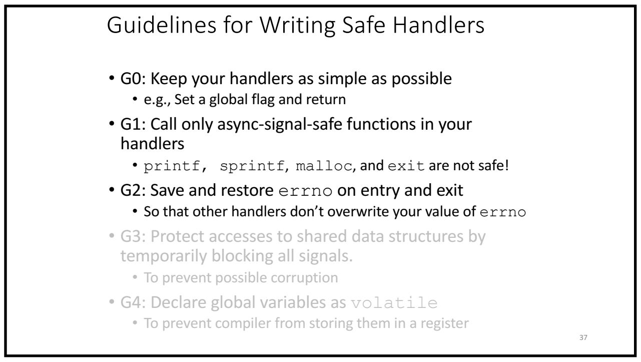

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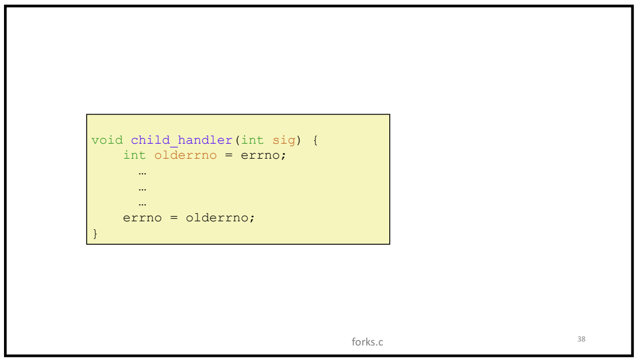

```
void child_handler(int sig) {
    int olderrno = errno;
      …
      …
      …
    errno = olderrno;
}
```

forks.c

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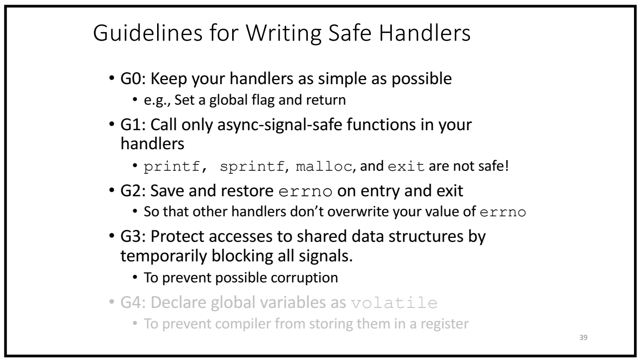

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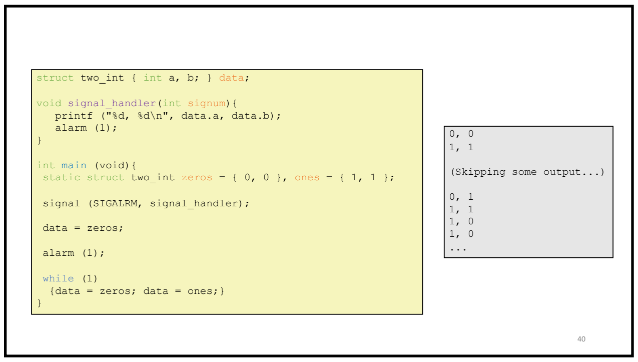

```
struct two_int { int a, b; } data;

void signal_handler(int signum){
   printf ("%d, %d\n", data.a, data.b);
   alarm (1);
}

int main (void){
 static struct two_int zeros = { 0, 0 }, ones = { 1, 1 };

 signal (SIGALRM, signal_handler);

 data = zeros;

 alarm (1);

 while (1)
  {data = zeros; data = ones;}
}
```

```
0, 0
1, 1

(Skipping some output...)

0, 1
1, 1
1, 0
1, 0
...
```

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Guidelines for Writing Safe Handlers

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Examples of Issues with Signals

- Pending signals are not queued
- Race condition

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Correct Signal Handling

```
volatile 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 */
        ;
}
```

This code is incorrect!

N == 5

forks.c

```
whaleshark> ./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 terminating.

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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");
    }
    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>
```

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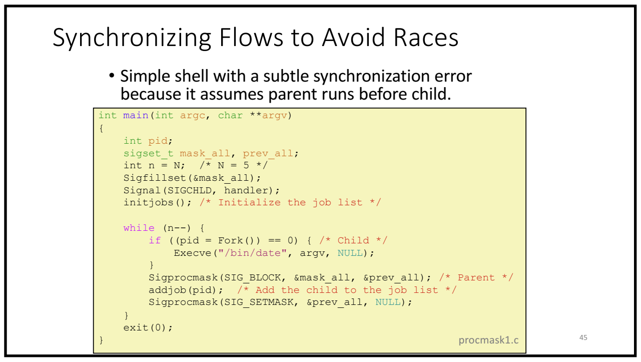

Synchronizing Flows to Avoid Races

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

```c
int main(int argc, char **argv)
{
    int pid;
    sigset_t mask_all, prev_all;
    int n = N;  /* N = 5 */
    Sigfillset(&mask_all);
    Signal(SIGCHLD, handler);
    initjobs(); /* Initialize the job list */

    while (n--) {
        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

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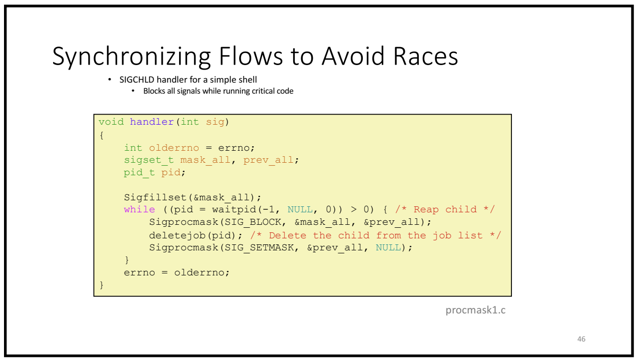

Synchronizing Flows to Avoid Races

- SIGCHLD handler for a simple shell
  - Blocks all signals while running critical code

```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);
    }
    errno = olderrno;
}
```

procmask1.c

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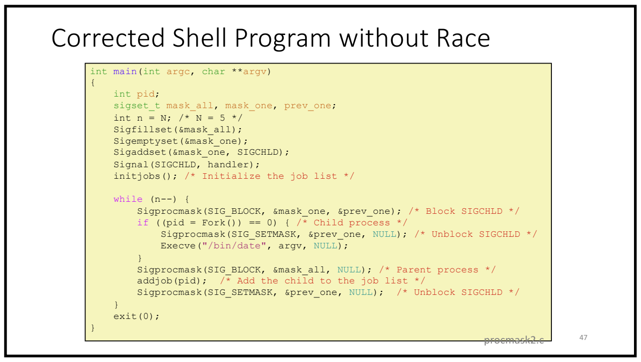

Corrected Shell Program without Race

```c
int main(int argc, char **argv)
{
    int pid;
    sigset_t mask_all, mask_one, prev_one;
    int n = N; /* N = 5 */
    Sigfillset(&mask_all);
    Sigemptyset(&mask_one);
    Sigaddset(&mask_one, SIGCHLD);
    Signal(SIGCHLD, handler);
    initjobs(); /* Initialize the job list */

    while (n--) {
        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

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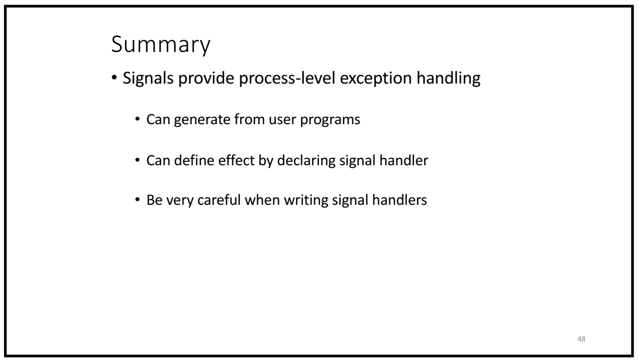

Summary

- 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

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Exceptions and Processes

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Additional slides

Portable Signal Handling

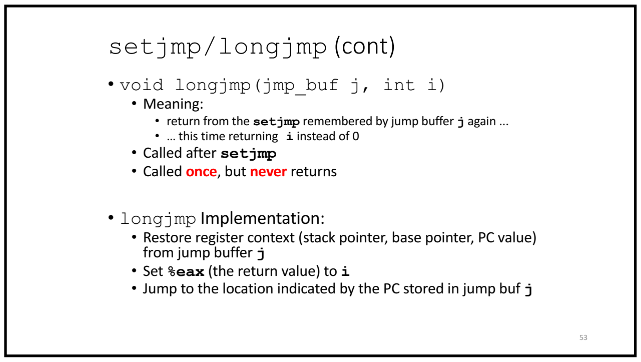
- Ugh! Different versions of Unix can have different signal handling semantics
  - Some older systems restore action to default after catching signal
  - Some interrupted system calls can return with errno == EINTR
  - Some systems don't block signals of the type being handled
- Solution: `sigaction`

```
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

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`**

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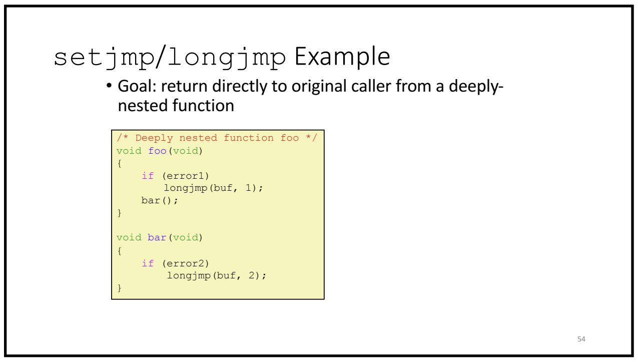

setjmp/longjmp Example

- 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);
}
```

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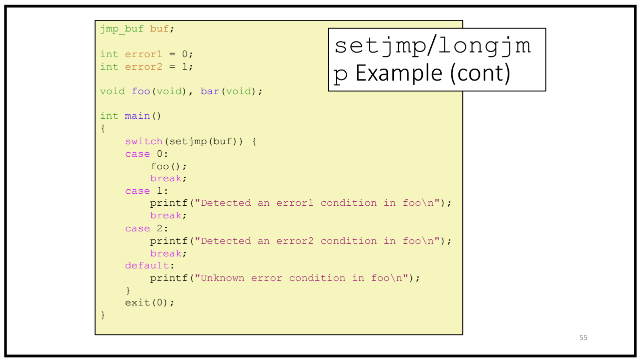

setjmp/longjmp Example (cont)

```
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);
}
```

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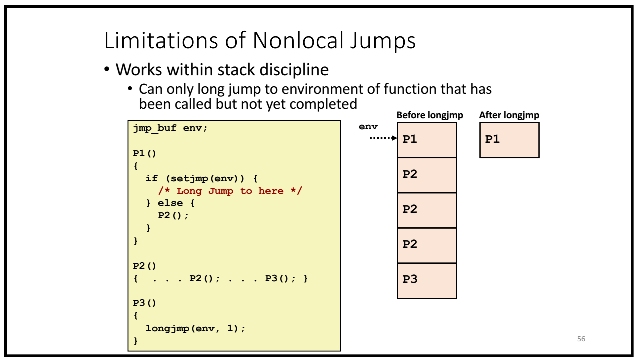


Limitations of Nonlocal Jumps

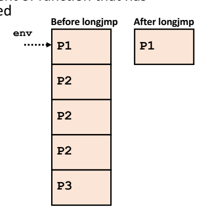
- Works within stack discipline
  - Can only long jump to environment of function that has been called but not yet completed

```
jmp_buf env;

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

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

P3()
{
  longjmp(env, 1);
}
```



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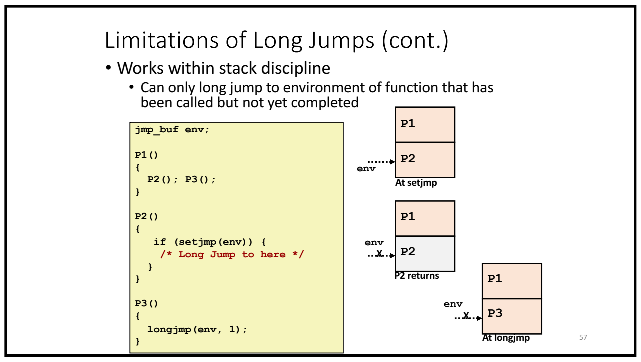

Limitations of Long Jumps (cont.)

- 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);
}
```

P1
P2
env
At setjmp
P1
env
X
P2
P2 returns
P1
env
X
P3
At longjmp

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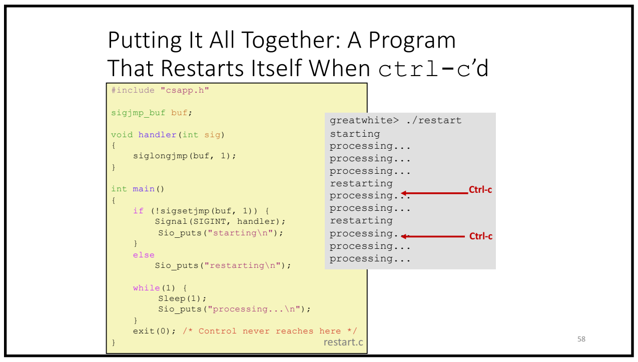

Putting It All Together: A Program That Restarts Itself When `ctrl-c`'d

```
#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...
processing...
restarting
processing...
processing...
processing...
```

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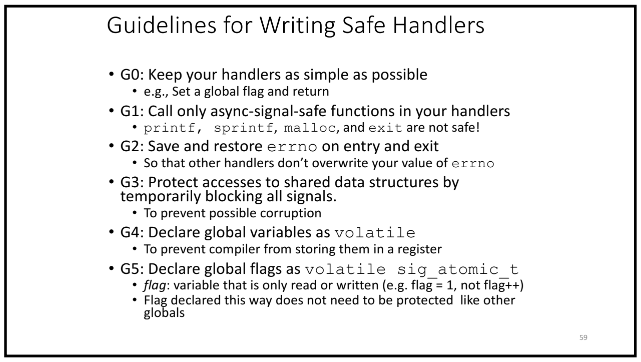

Guidelines for Writing Safe Handlers

- 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

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