CIS330, Week 9

Processes, Exceptional Control Flow

CSAPPe2, Chapter 8

Plan for Today

- Exceptional Control Flow
  - Exceptions
  - Process context switches
  - Creating and destroying processes

Control Flow

- Computers do Only One Thing
  - From startup to shutdown, a CPU simply reads and executes (interprets) a sequence of instructions, one at a time.
  - This sequence is the system's physical *control flow* (or *flow of control*).

Physical control flow

Time

<startup>
$inst_1$
$inst_2$
$inst_3$
…
$inst_n$
<shutdown>

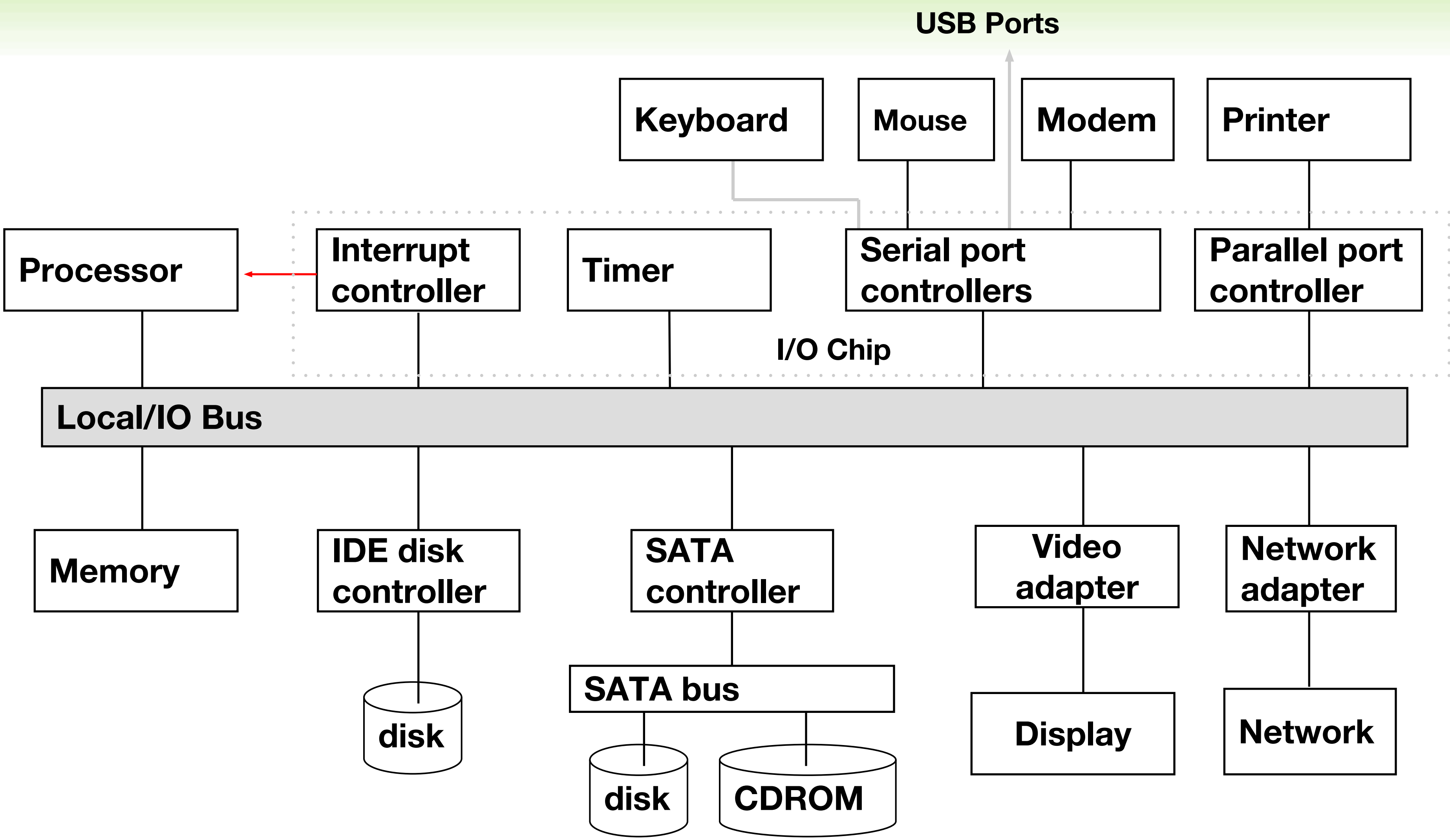
Altering the Control Flow

- Up to Now: two mechanisms for changing control flow:
  - Jumps and branches
  - Call and return using the stack discipline.
  - Both react to changes in program state.
- Insufficient for a useful system
  - Difficult for the CPU to react to changes in system state.
  - data arrives from a disk or a network adapter.
  - Instruction divides by zero
  - User hits **Ctrl-c** at the keyboard
  - System timer expires
- System needs mechanisms for “exceptional control flow”

Exceptional Control Flow

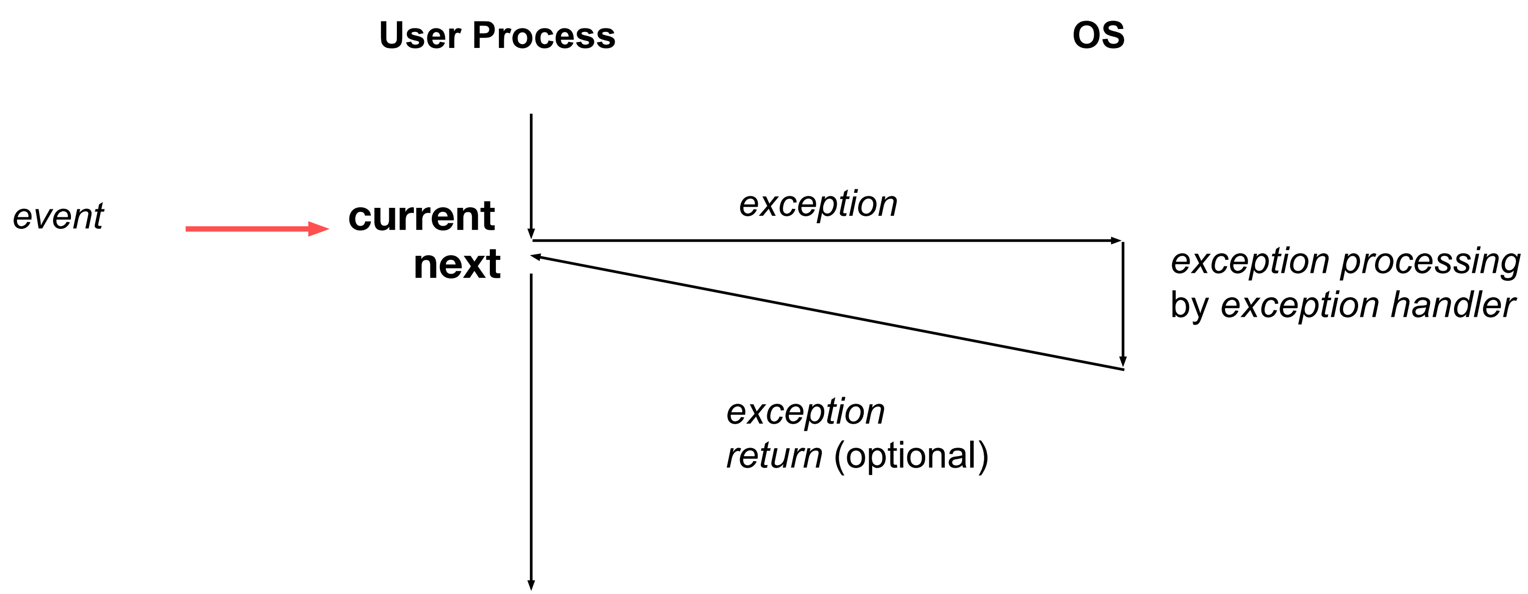
- Mechanisms for exceptional control flow exists at all levels of a computer system.
- Low level Mechanism
  - exceptions
  - change in control flow in response to a system event (i.e., change in system state)
  - Combination of hardware and OS software
- Higher Level Mechanisms
  - Process context switch
  - Signals
  - Nonlocal jumps (`setjmp/longjmp`)
  - Implemented by either:
  - OS software (context switch and signals).
  - C language runtime library: nonlocal jumps.

System context for exceptions

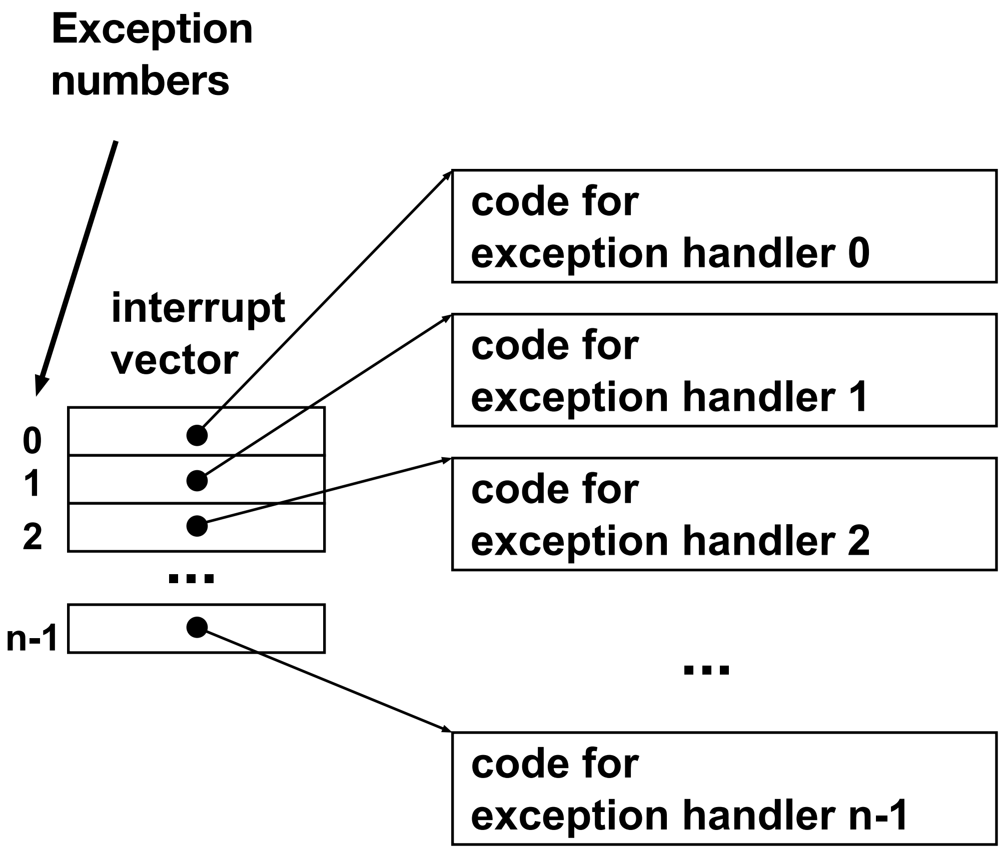


Exceptions

An *exception* is a transfer of control to the OS in response to some *event* (i.e., change in processor state)



Interrupt Vectors



- Each type of event has a unique exception number k
- Index into jump table (a.k.a., interrupt vector)
- Jump table entry k points to a function (exception handler).
- Handler k is called each time exception k occurs.

Asynchronous Exceptions (Interrupts)

- Caused by events external to the processor
  - Indicated by setting the processor's interrupt pin
  - handler returns to "next" instruction.

- Examples:
  - I/O interrupts
  - hitting ctl-c at the keyboard
  - arrival of a packet from a network
  - arrival of a data sector from a disk
  - Hard reset interrupt
  - hitting the reset button
  - Soft reset interrupt
  - hitting Ctrl-Alt-Delete on a PC

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: parity error, machine check.
  - Aborts current program

Precise vs. Imprecise Faults

- Precise Faults: the exception handler knows exactly which instruction caused the fault.
  - All prior instructions have completed and no subsequent instructions had any effect.

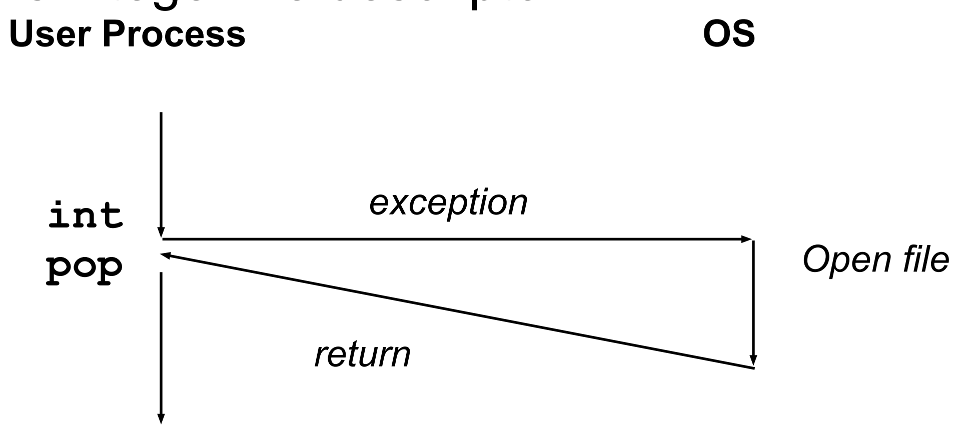
- Imprecise Faults: the CPU was working on multiple instructions concurrently and an ambiguity may exists as to which instruction caused the Fault.
  - For example, multiple FP instructions were in the pipe and one caused an exception.

Trap Example

- Opening a File
  - User calls **`open(filename, options)`**

```
0804d070 <__libc_open>:
 . . .
 804d082:   cd 80                       int     $0x80
 804d084:   5b                          pop     %ebx
 . . .
```

  - Function open executes system call instruction `int`
  - OS must find or create file, get it ready for reading or writing
  - Returns integer file descriptor



Fault Example #1

```
int a[1000];
main ()
{
    a[500] = 13;
}
```

Memory Reference

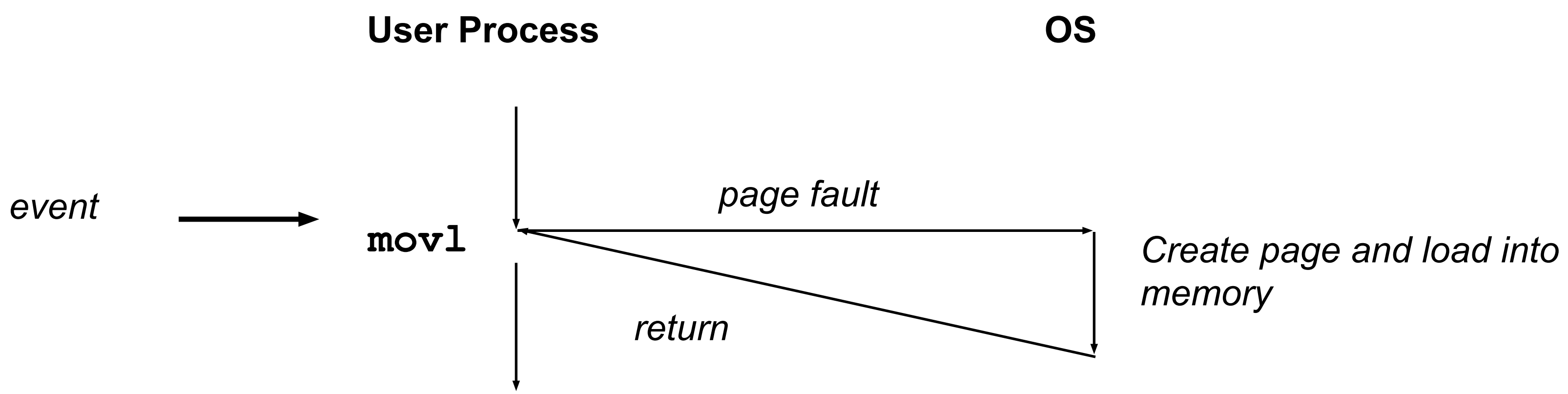
User writes to memory location

```
80483b7:   c7 05 10 9d 04 08 0d   movl   $0xd,0x8049d10
```

Page handler must load page into physical memory

Returns to faulting instruction

Successful on second try

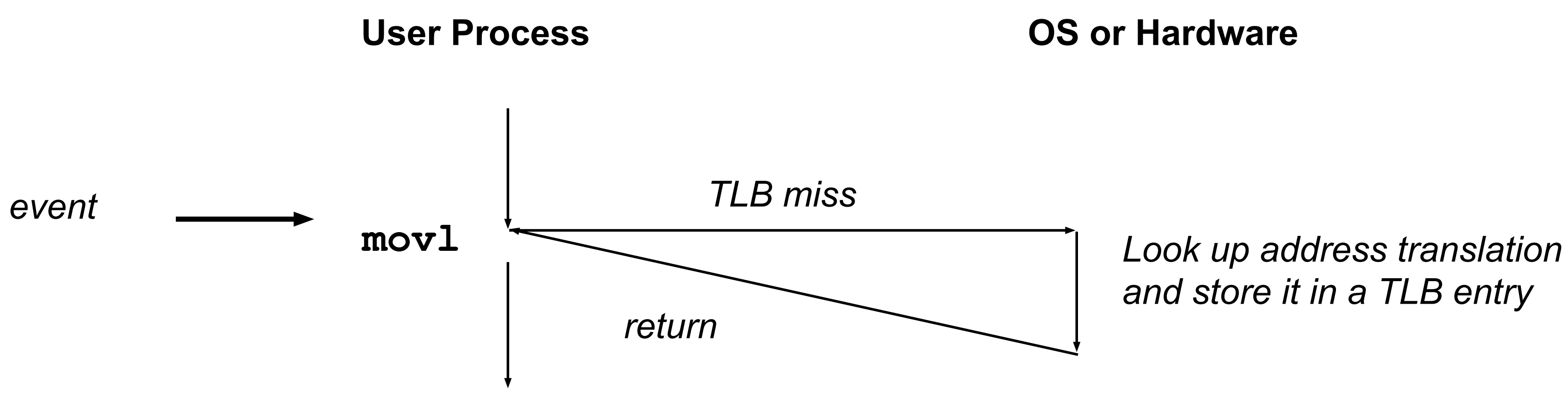


Fault Example #2

```
int a[1000];
main ()
{
    a[500] = 13;
}
```

Memory Reference with TLB miss

- User writes to memory location
- That portion (page) of user's memory is currently in physical memory, but the processor has forgotten how to translate the this virtual address to the physical address
- TLB must be reloaded with current translation
- Returns to faulting instruction
- Successful on second try



Fault Example

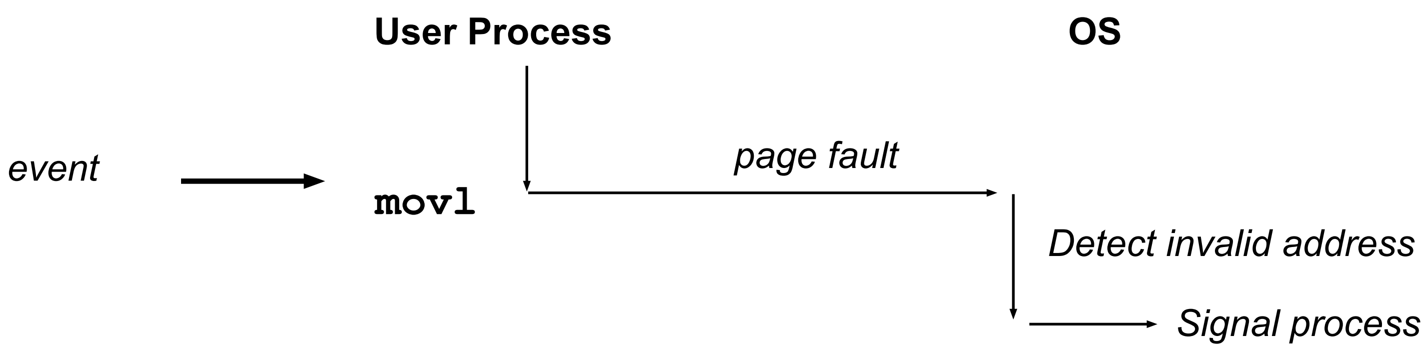
```
int a[1000];
main ()
{
    a[5000] = 13;
}
```

Memory Reference

- User writes to memory location
- Address is not valid

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

- Page handler detects invalid address (more on this next week)
- Sends `SIGSEG` signal to user process
- User process exits with “segmentation fault”

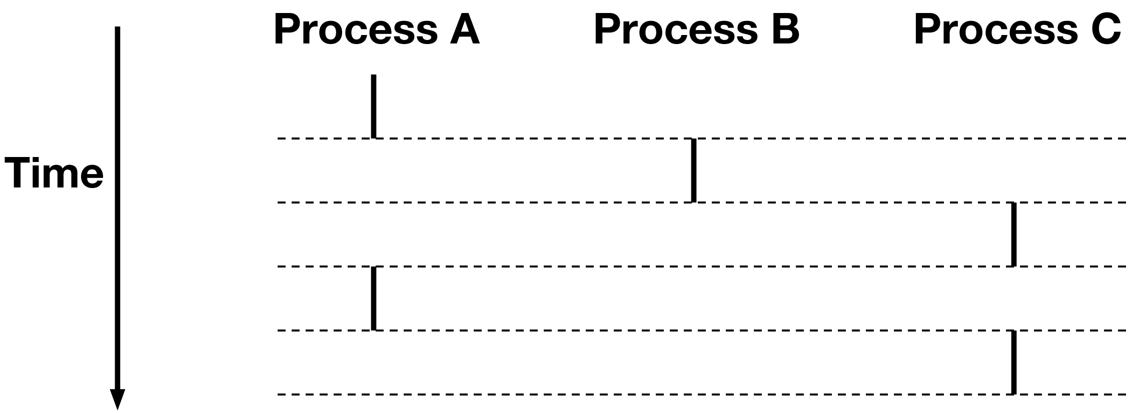


Processes

- 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
  - Private address space
  - Each program seems to have exclusive use of main memory
- How are these Illusions maintained?
  - Process executions interleaved (multitasking)
  - Address spaces managed by virtual memory system

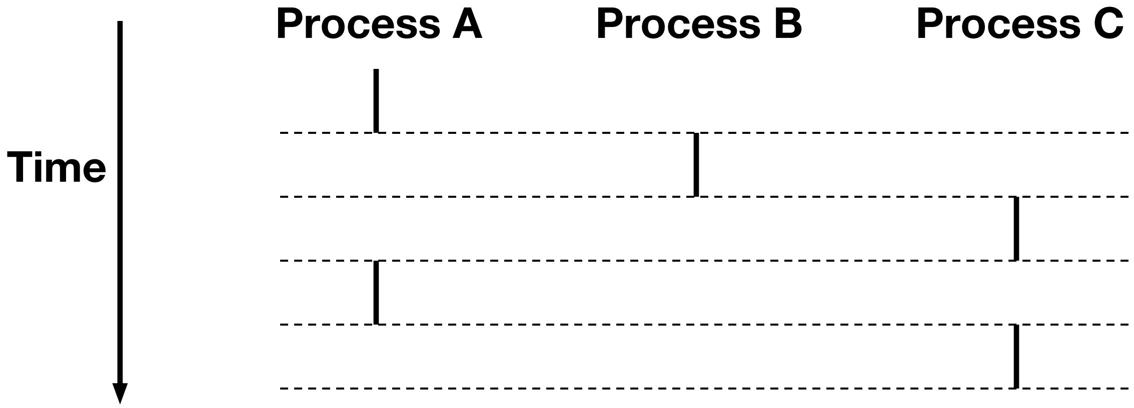
Logical Control Flows

- Each process has its own logical control flow



Concurrent Processes

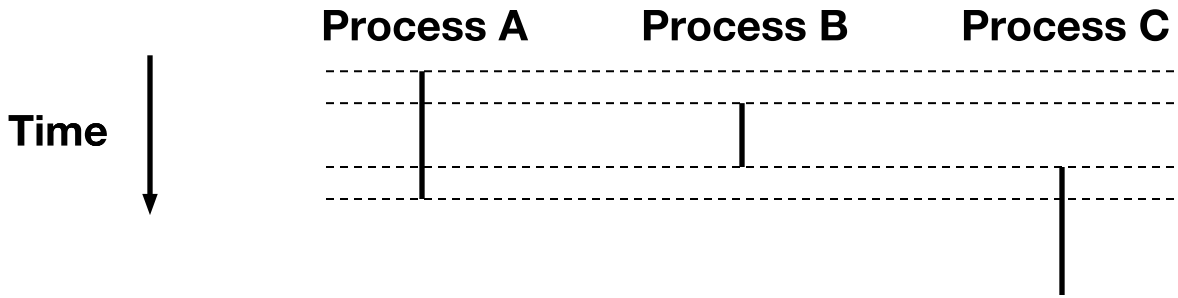
- Two processes *run concurrently* (*are concurrent)* if their flows overlap in time.
- Otherwise, they are *sequential.*
- Examples:
  - Concurrent: A & B, A & C
  - Sequential: B & C



User View of Concurrent Processes

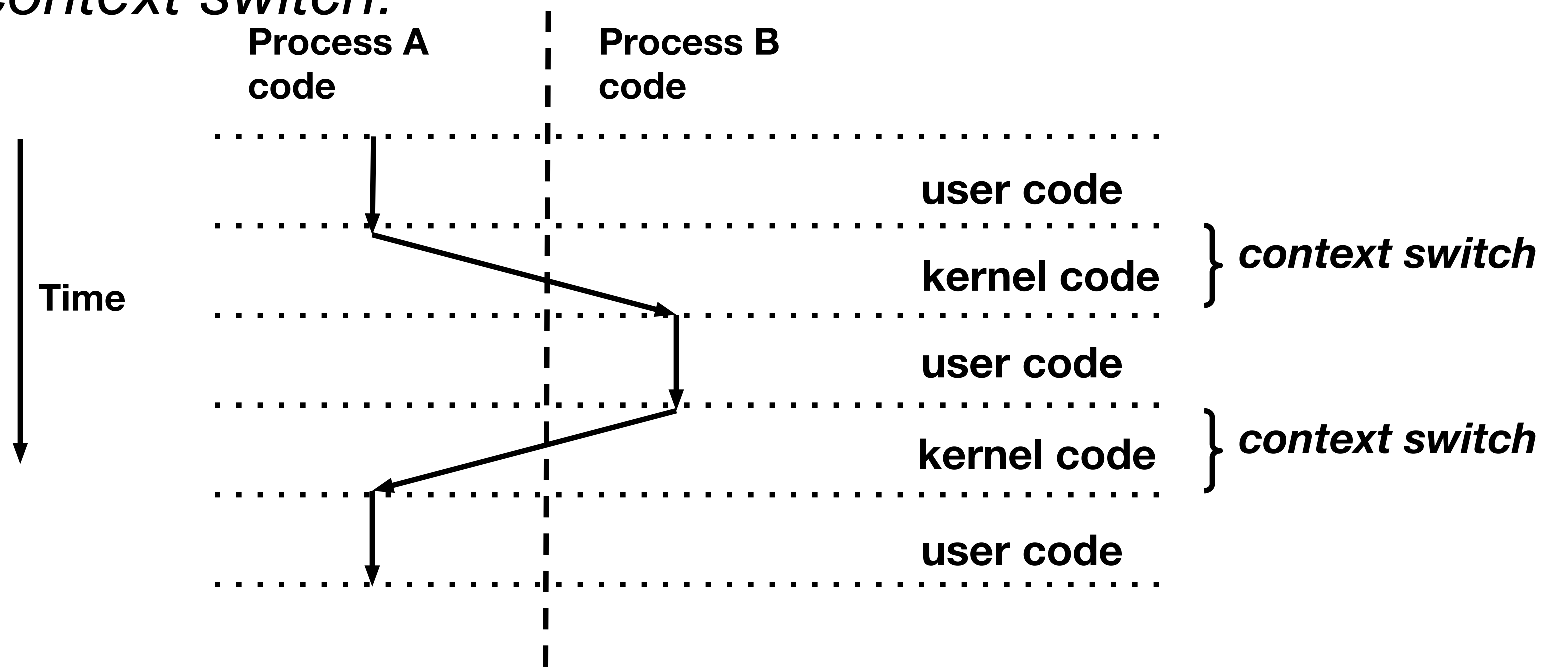
- Control flows for concurrent processes are disjoint in time.

- However, we can think of concurrent processes are running in parallel with each other.



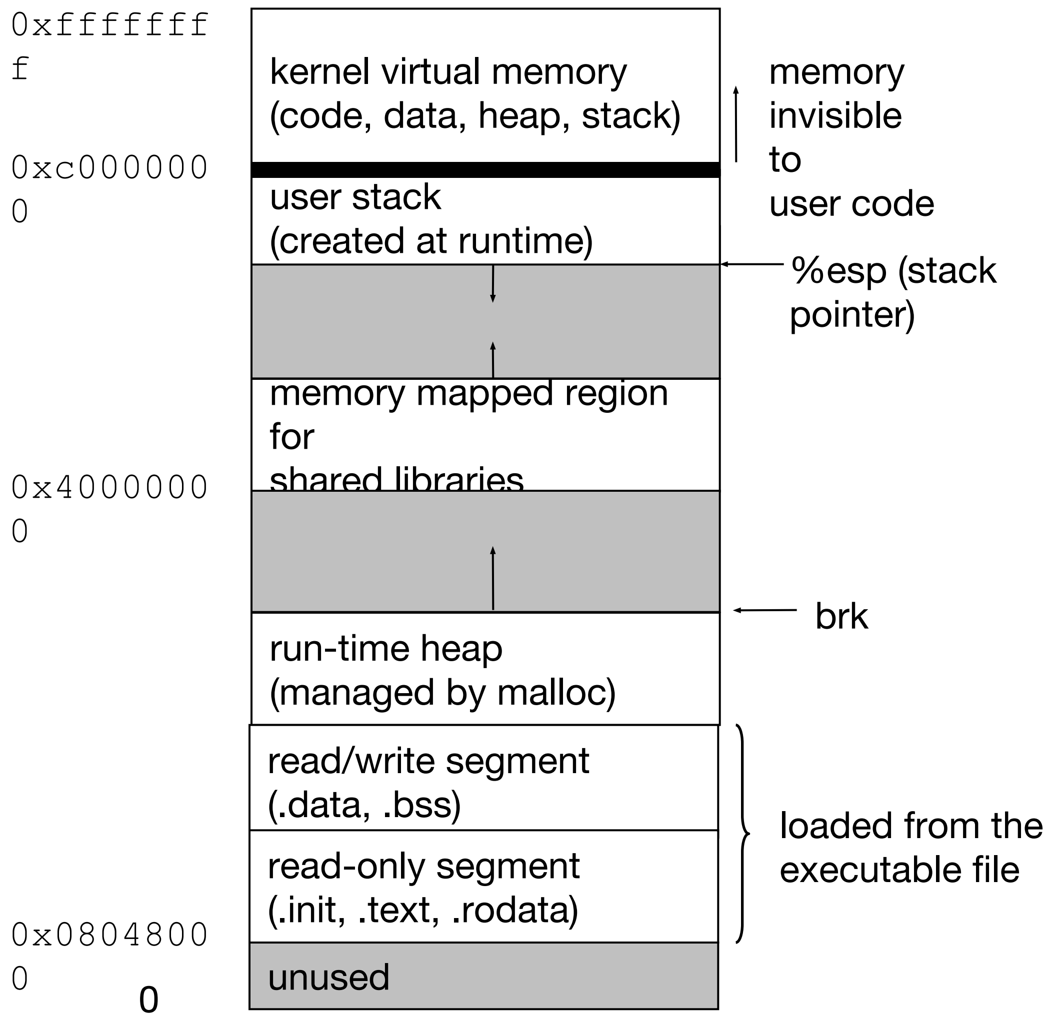
Context Switching

- Processes are managed by a shared chunk of OS code called the *kernel*
  - Important: the kernel is not a separate process, but rather runs as part of some user process
- Control flow passes from one process to another via a *context switch.*

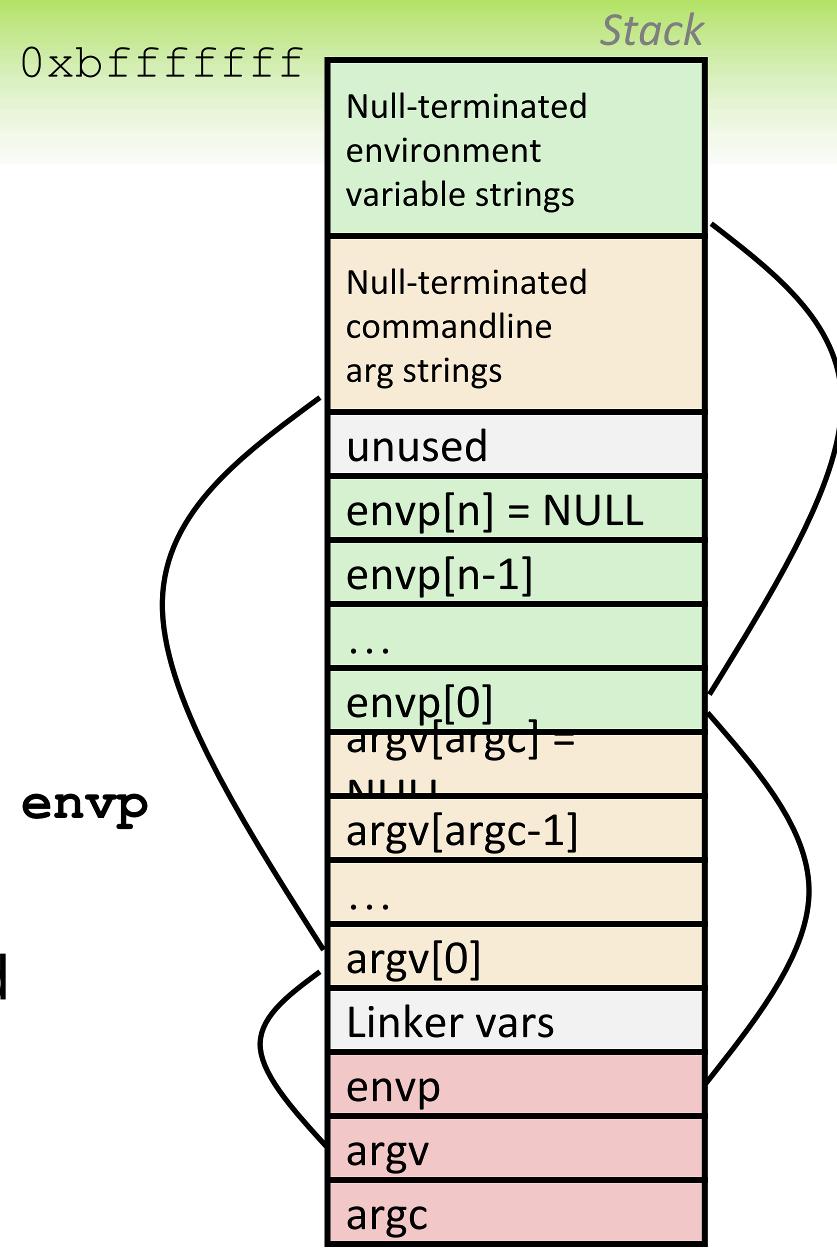


Private Address Spaces

Each process has its own private address space.



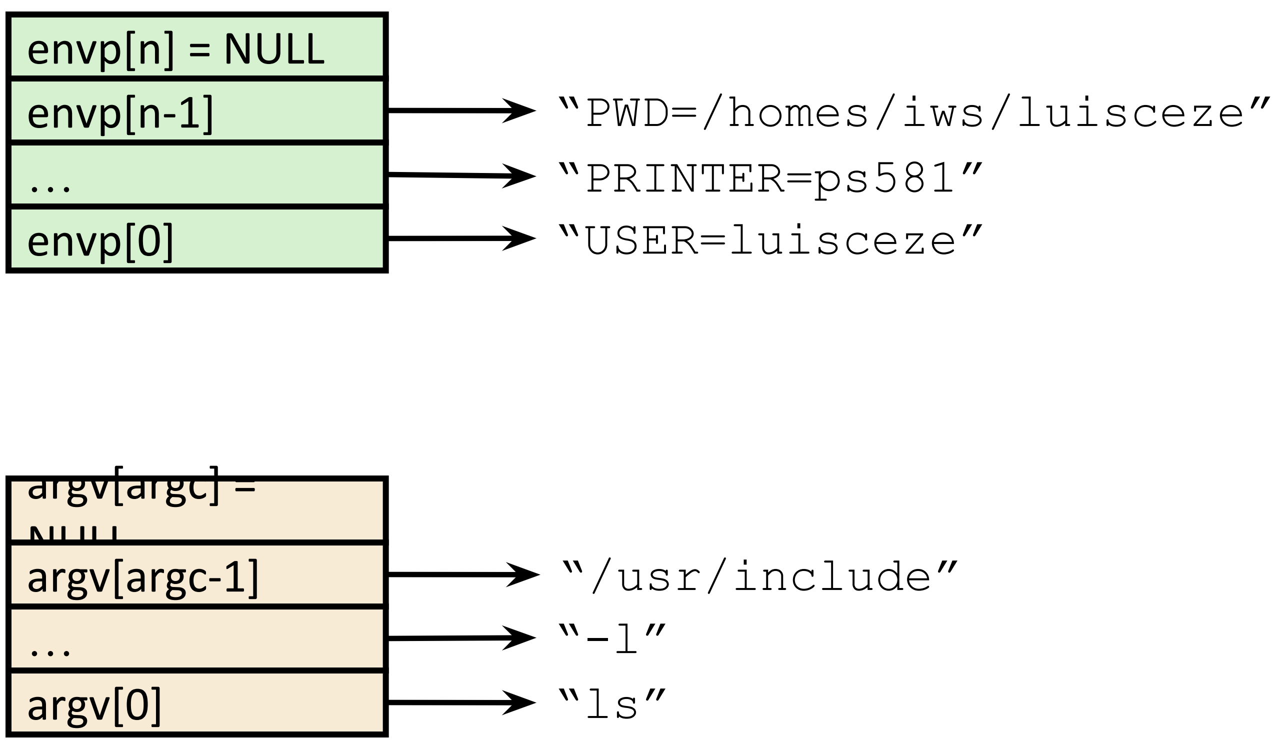
`execve`: Loading and Running Programs




```
int execve(
    char *filename,
    char *argv[],
    char *envp
 )
```

- Loads and runs
  - Executable **`filename`**
  - With argument list **`argv`**
  - And environment variable **`list envp`**
- Does not return (unless error)
- Overwrites process, keeps pid
- Environment variables:
  - “name=value” strings

execve: Example



Virtual Machines

- All current general purpose computers support multiple, concurrent *user-level* processes. Is it possible to run multiple kernels on the same machine?
- Yes: Virtual Machines (VM) were supported by IBM mainframes for over 30 years
- Intel's IA32 instruction set architecture is not virtualizable (neither are the Sparc, Mips, and PPC ISAs)
- With a lot of clever hacking, Vmware™ managed to virtualize the IA32 ISA in software
- User Mode Linux

`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*

Fork Example #1

- Key Points
  - Parent and child both run same code
    - Distinguish parent from child by return value from `fork`
  - Start with same state, but each has private copy
    - Including shared output file descriptor
    - Relative ordering of their print statements undefined

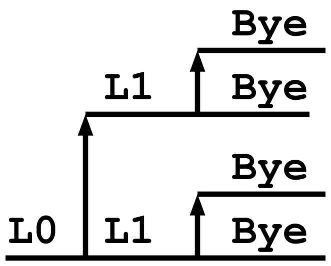
```
void fork1()
{
    int x = 1;
    pid_t pid = fork();
    if (pid == 0) {
        printf("Child has x = %d\n", ++x);
    } else {
        printf("Parent has x = %d\n", --x);
    }
    printf("Bye from process %d with x = %d\n", getpid(), x);
}
```

Fork Example #2

Key Points

Both parent and child can continue forking

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

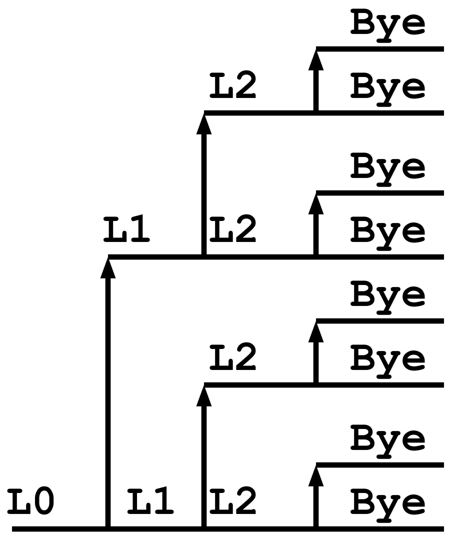


Fork Example #3

Key Points

- Both parent and child can continue forking

```
void fork3()
{
    printf("L0\n");
    fork();
    printf("L1\n");
    fork();
    printf("L2\n");
    fork();
    printf("Bye\n");
}
```

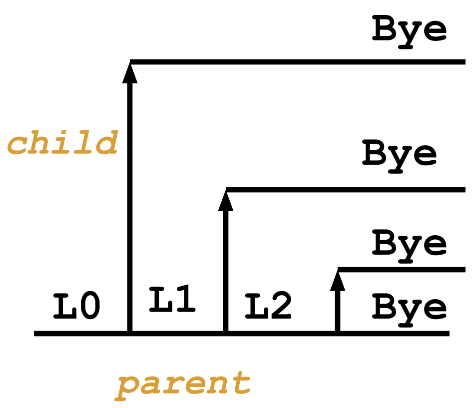


Fork Example #4

Key Points

Both parent and child can continue forking

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

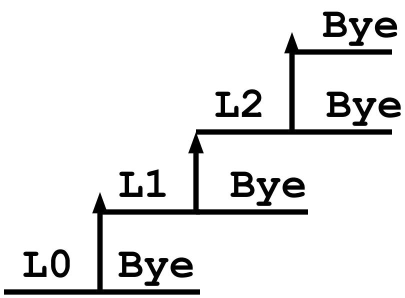


Fork Example #5

Key Points

- Both parent and child can continue forking

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



`exit`: Destroying Process

`void exit(int status)`

- exits a process
  - Normally return with status 0
- `atexit()` registers functions to be executed upon exit

```
void cleanup(void) {
   printf("cleaning up\n");
}

void fork6() {
   atexit(cleanup);
   fork();
   exit(0);
}
```

Zombies

- Idea
  - When process terminates, still consumes system resources
  - Various tables maintained by OS
  - Called a “zombie”
- Reaping
  - Performed by parent on terminated child
  - Parent is given exit status information
  - Kernel discards process
- What if Parent Doesn’t Reap?
  - If any parent terminates without reaping a child, then child will be reaped by `init` process
  - Only need explicit reaping for long-running processes
  - E.g., shells and servers

Zombie Example

- `ps` shows child process as "defunct"
- Killing parent allows child to be reaped

```
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
 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
```

```
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 */
    }
}
```

Nonterminating Child Example

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

```
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
```

```
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);
    }
}
```

`wait`: Synchronizing with children

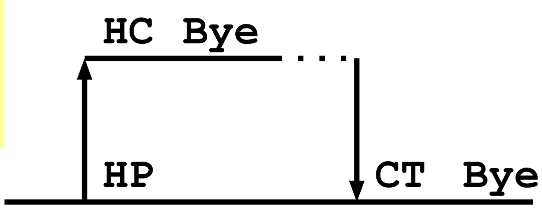
`int wait(int *child_status)`

- 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 object it points to will be set to a status indicating why the child process terminated

`wait`: Synchronizing with children

```
void fork9() {
   int child_status;

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



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

Waitpid()

`waitpid(pid, &status, options)`

- Can wait for specific process
- Various options

```
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 = 0; i < N; 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 terminated abnormally\n", wpid);
    }
```

Wait/Waitpid Example Outputs

Using **wait (fork10)**

```
Child 3565 terminated with exit status 103
Child 3564 terminated with exit status 102
Child 3563 terminated with exit status 101
Child 3562 terminated with exit status 100
Child 3566 terminated with exit status 104
```

Using **waitpid (fork11)**

```
Child 3568 terminated with exit status 100
Child 3569 terminated with exit status 101
Child 3570 terminated with exit status 102
Child 3571 terminated with exit status 103
Child 3572 terminated with exit status 104
```

`exec`: Running new programs

`int execl(char *path, char *arg0, char *arg1, …, 0)`

- loads and runs executable at `path` with args `arg0`, `arg1`, …
  - `path` is the complete path of an executable
  - `arg0` becomes the name of the process
    - typically `arg0` is either identical to `path`, or else it contains only the executable filename from `path`
  - "real" arguments to the executable start with `arg1`, etc.
  - list of args is terminated by a `(char *)0` argument
- returns `-1` if error, otherwise doesn't return!

```
main() {
   if (fork() == 0) {
      execl("/usr/bin/cp", "cp", "foo", "bar", 0);
   }
   wait(NULL);
   printf("copy completed\n");
   exit();
}
```

Summary

Exceptions

- Events that require non-standard 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, however,
- Each process appears to have total control of the processor + has a private memory space

Summary (cont'd)

- Spawning processes
  - Call to `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 `execl` (or variant)
  - One call, (normally) no return

Signals and Jumps

CSAPP2e, Chapter 8

Recall: Running a New Program

```
int execl(char *path,
          char *arg0, …, char *argn,
          char *null)
```

- Loads & runs executable:
  - `path` is the complete path of an executable
  - `arg0` becomes the name of the process
  - `arg0, …, argn` → `argv[0], …, argv[n]`
  - Argument list terminated by a `NULL` argument
- Returns -1 if error, otherwise doesn't return!

```
if (fork() == 0)
   execl("/usr/bin/cp", "cp", "foo", "bar", NULL);
else
   printf("hello from parent\n");
```

Interprocess Communication

- Synchronization allows very limited communication

- Pipes:
  - One-way communication stream that mimics a file in each process: one output, one input
  - See `man 7 pipe`
- Sockets:
  - A pair of communication streams that processes connect to
  - See `man 7 socket`

The World of Multitasking

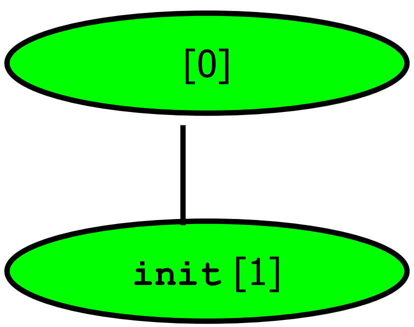
- System Runs Many Processes Concurrently
  - Process: executing program
    - State consists of memory image + register values + program counter
  - Continually switches from one process to another
    - Suspend process when it needs I/O resource or timer event occurs
    - Resume process when I/O available or given scheduling priority
  - Appears to user(s) as if all processes executing simultaneously
    - Even though most systems can only execute one process at a time
    - Except possibly with lower performance than if running alone

Programmer's Model of Multitasking

- Basic Functions
  - `fork()` spawns new process
    - Called once, returns twice
  - `exit()` terminates own process
    - Called once, never returns
    - Puts process into "zombie" status
  - `wait()` and `waitpid()` wait for and reap terminated children
  - `execl()` and `execve()` run a new program in an existing process
    - Called once, (normally) never returns
- Programming Challenge
  - Understanding the nonstandard semantics of the functions
  - Avoiding improper use of system resources
    - E.g., "Fork bombs" can disable a system

UNIX Startup: 1

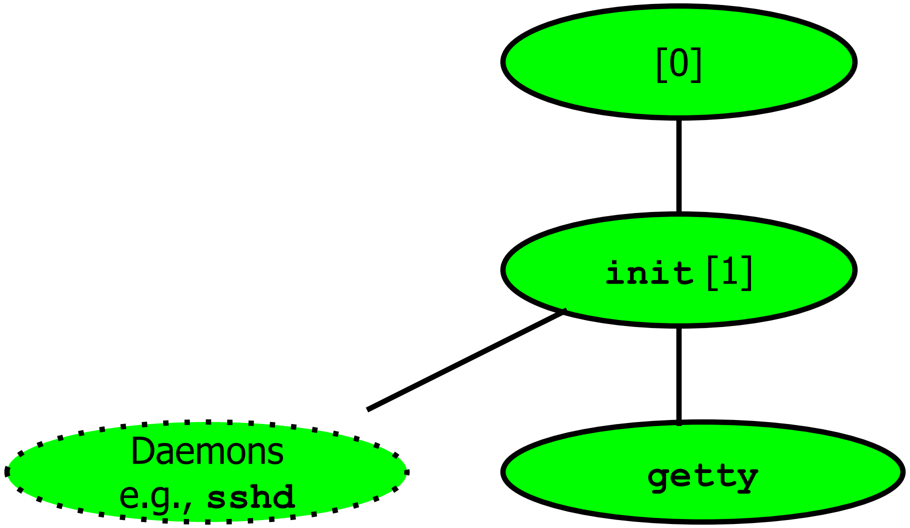
- Pushing reset button loads the PC with the address of a small bootstrap program
- Bootstrap program loads the boot block (disk block 0)
- Boot block program loads kernel from disk
- Boot block program passes control to kernel
- Kernel handcrafts the data structures for process 0



Process 0: handcrafted kernel process

Process 1: user mode process
`fork()` and **`exec(/sbin/init)`**

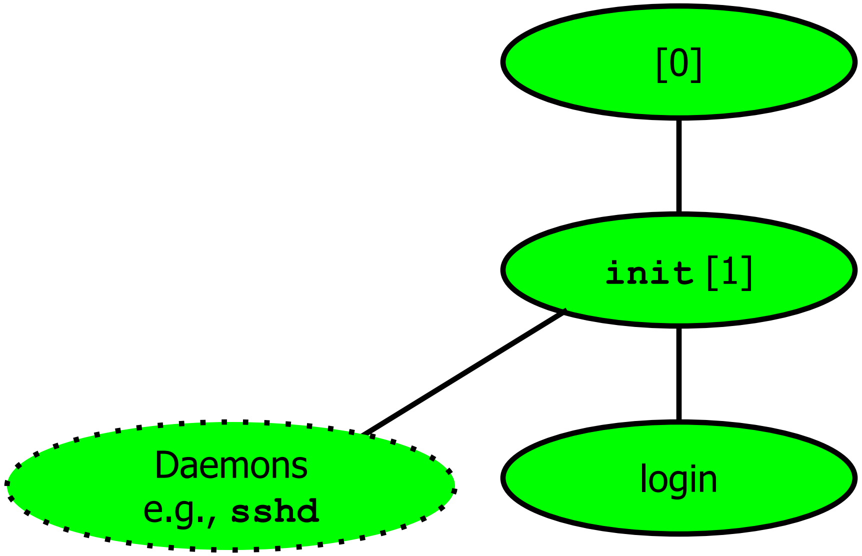
UNIX Startup: 2



`init` forks new processes as per the **`/etc/inittab`** file

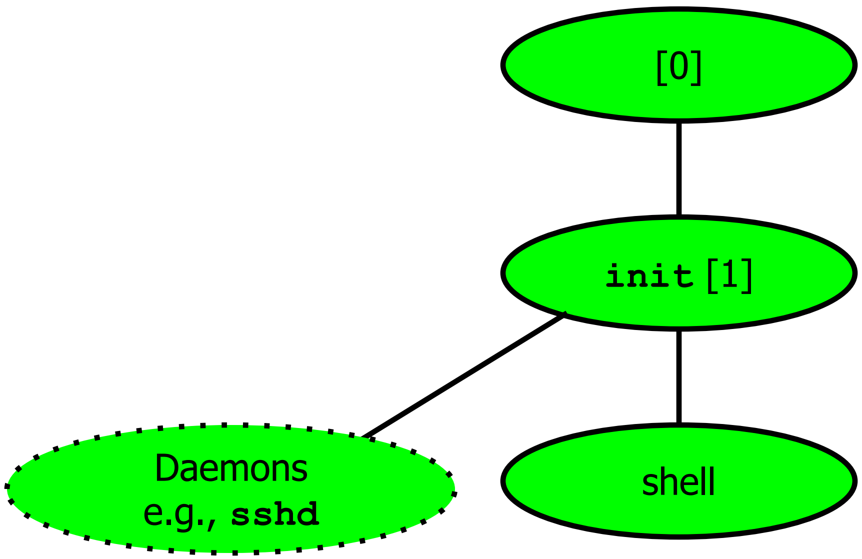
Forks **`getty`** (get tty or get terminal) for the console

UNIX Startup: 3



getty execs a login program

UNIX Startup: 4



login gets user's uid & password

- If OK, it execs appropriate shell
- If not OK, it execs **getty**

Shell Programs

- A shell is an application program that runs programs on behalf of user
  - sh – Original Unix Bourne Shell
  - csh – BSD Unix C Shell, tcsh – Enhanced C Shell
  - bash – Bourne-Again Shell
  - ksh – Korn Shell

Read-evaluate loop: an interpreter!

```
int main(void)
{
    char cmdline[MAXLINE];
    while (true) {
    /* read */
    printf("> ");
    Fgets(cmdline, MAXLINE, stdin);
    if (feof(stdin))
        exit(0);

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

Simple Shell `eval` Function

```
void eval(char *cmdline)
{
    char *argv[MAXARGS]; /* argv for execve() */
    bool  bg;            /* should the job run in bg or fg? */
    pid_t pid;           /* process id */
    int   status;        /* child status */

    bg = parseline(cmdline, argv);
    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);
        }
    }
    if (!bg) {   /* parent waits for fg job to terminate */
        if (waitpid(pid, &status, 0) < 0)
        unix_error("waitfg: waitpid error");
    }
    else         /* otherwise, don't wait for bg job */
        printf("%d %s", pid, cmdline);
    }
}
```

Problem with Simple Shell Example

- Correctly waits for & reaps foreground jobs

- But what about background jobs?
  - Will become zombies when they terminate
  - Will never be reaped because shell (typically) will not terminate
  - Creates a process leak that will eventually prevent the forking of new processes

- Solution: Reaping background jobs requires a mechanism 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
  - Kernel abstraction for exceptions and interrupts
  - Sent from the kernel (sometimes at the request of another process) to a process
  - Different signals are identified by small integer ID's
  - Typically, the only information in a signal is its ID and the fact that it arrived

ID	Name	Default Action	Corresponding Event
2	`SIGINT`	**Terminate**	**Keyboard interrupt (`ctrl-c`)**
9	`SIGKILL`	**Terminate**	**Kill program**
11	`SIGSEGV`	**Terminate & Dump**	**Segmentation violation**
14	`SIGALRM`	**Terminate**	**Timer signal**
18	`SIGCHLD`	**Ignore**	**Child stopped or terminated**

Signals: Sending

- OS kernel sends a signal to a destination process by updating some state in the context of the destination process
- Reasons:
  - OS detected an event
  - Another process used the kill system call to explicitly request the kernel to send a signal to the destination process

Signals: Receiving

- Destination process receives a signal when it is forced by the kernel to react in some way to the delivery of the signal

- Three ways to react:
  - Ignore the signal
  - Terminate the process (& optionally dump core)
  - Catch the signal with a user-level signal handler

Signals: Pending & Blocking

- Signal is pending if sent, but not yet received
  - At most one pending signal of any particular type
  - Important: Signals are not queued
    - If process has pending signal of type k, then process discards subsequent signals of type k
  - A pending signal is received at most once

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

Signals: Pending & Blocking

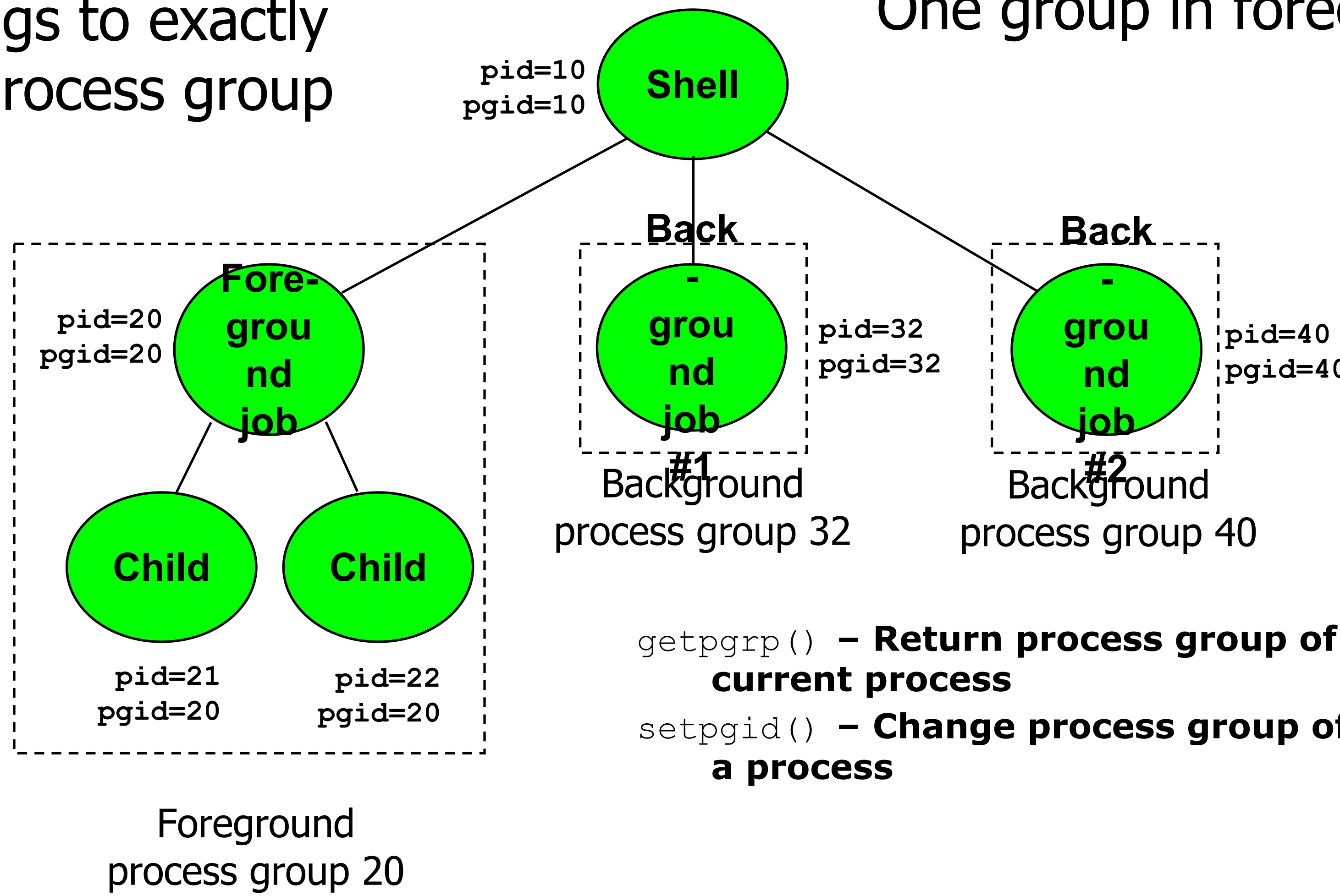
- Kernel maintains `pending` & `blocked` bit vectors in each process context

- `pending` – represents the set of pending signals
  - Signal type k delivered → kernel sets kth bit
  - Signal type k received → kernel clears kth bit
- `blocked` – represents the set of blocked signals
  - Application sets & clears bits via `sigprocmask()`

Process Groups

Each process belongs to exactly one process group

One group in foreground



`getpgrp()` **– Return process group of current process**

`setpgid()` **– Change process group of a process**

Sending Signals with `/bin/kill`

Sends arbitrary signal to a process or process group

`kill –9 11662`

Send SIGKILL to process 11662

`kill –9 –11661`

Send SIGKILL to every process in process group 11661

```
UNIX% fork2anddie
Child1: pid=11662 pgrp=11661
Child2: pid=11663 pgrp=11661

UNIX% ps x
   PID TTY      STAT TIME COMMAND
 11263 pts/7    Ss   0:00 -tcsh
 11662 pts/7    R    0:18 ./fork2anddie
 11663 pts/7    R    0:16 ./fork2anddie
 11664 pts/7    R+   0:00 ps x
UNIX% kill -9 -11661
UNIX% ps x
   PID TTY      STAT TIME COMMAND
 11263 pts/7    Ss   0:00 -tcsh
 11665 pts/7    R+   0:00 ps x
UNIX%
```

Sending Signals from the Keyboard

- Typing ctrl-c (ctrl-z) sends 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`

```
UNIX% ./fork1
Child: pid=24868 pgrp=24867
Parent: pid=24867 pgrp=24867
<typed ctrl-z>
Suspended
UNIX% ps x
  PID TTY      STAT   TIME COMMAND
24788 pts/2    Ss     0:00 -tcsh
24867 pts/2    T      0:01 fork1
24868 pts/2    T      0:01 fork1
24869 pts/2    R+     0:00 ps x
UNIX% fg
fork1
<typed ctrl-c>
UNIX% ps x
  PID TTY      STAT   TIME COMMAND
24788 pts/2    Ss     0:00 -tcsh
24870 pts/2    R+     0:00 ps x
```

S=Sleeping

R=Running or Runnable

T=Stopped

Z=Zombie

kill()

```
void kill_example(void)
{
    pid_t pid[N], wpid;
    int   child_status, i;
    for (i = 0; i < N; i++)
    if ((pid[i] = fork()) == 0)
        while (1); /* Child infinite loop */

    /* Parent terminates the child processes */
    for (i = 0; i < N; i++) {
    printf("Killing process %d\n", pid[i]);
    kill(pid[i], SIGINT);
    }

    /* Parent reaps terminated children */
    for (i = 0; i < N; i++) {
    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);
    }
}
```

Receiving Signals: How It Happens

- Suppose kernel is returning from an exception handler & 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 control 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 the logical control flow for p

Signals: Default Actions

- Each signal type has predefined *default action*

- One of:
  - Process terminates
  - Process terminates & dumps core
  - Process stops until restarted by a SIGCONT signal
  - Process ignores the signal

Signal Handlers

- `#include <signal.h>`
- `typedef void (*sighandler_t)(int);`
- `sighandler_t signal(int signum, sighandler_t handler);`
- Two args:
  - `signum` – Indicates which signal, e.g.,
    - SIGSEGV, SIGINT, ...
  - `handler` – Signal "disposition", one of
    - Pointer to a handler routine, whose int argument is the kind of signal raised
    - SIG_IGN – ignore the signal
    - SIG_DFL – use default handler
- Returns previous disposition for this signal
  - Details: `man signal` and `man 7 signal`

Signal Handlers: Example 1

```
#include <stdlib.h>
#include <stdio.h>
#include <signal.h>
#include <stdbool.h>

void sigint_handler(int sig) {
  printf("Control-C caught.\n");
  exit(0);
}

int main(void) {
  signal(SIGINT, sigint_handler);
  while (true) {
  }
}
```

Signal Handlers: Example 2

```
#include <stdio.h>
#include <signal.h>
#include <stdbool.h>

int ticks = 5;

void sigalrm_handler(int sig) {
  printf("tick\n");

  ticks -= 1;
  if (ticks > 0) {
    signal(SIGALRM,
           sigalrm_handler);
    alarm(1);
  } else {
    printf("*BOOM!*\n");
    exit(0);
  }
}
```

```
int main(void) {
  signal(SIGALRM,
         sigalrm_handler);
  alarm(1); /* send SIGALRM in
               1 second */

  while (true) {
    /* handler returns here */
  }
}
```

`signal` **resets handler to default action each time handler runs,** `sigset`**,** `sigaction` **do not**

```
UNIX% ./alrm
tick
tick
tick
tick
tick
*BOOM!*
UNIX%
```

Signal Handlers (POSIX)

- OS may allow more detailed control:

```
int sigaction(int sig,
              const struct sigaction *act,
              struct sigaction *oact);
```

- `struct sigaction` includes a handler:

```
void sa_handler(int sig);
```

- `Signal` from `csapp.c` is a clean wrapper around `sigaction`

Pending Signals Not Queued

```
int ccount = 0;

void child_handler(int sig)
{
    int   child_status;
    pid_t pid = wait(&child_status);
    ccount -= 1;
    printf("Received signal %d from process %d\n", sig, pid);
}

void example(void)
{
    pid_t pid[N];
    int   child_status, i;
    ccount = N;
    Signal(SIGCHLD, child_handler);
    for (i = 0; i < N; i+=1)
     if ((pid[i] = fork()) == 0) {
         /* Child: Exit */
         exit(0);
     }
    while (ccount > 0)
     pause();/* Suspend until signal occurs */
}
```

For each signal type, single bit indicates whether a signal is pending

Will probably lose some signals: `ccount` **never reaches 0**

Living With Non-Queuing Signals

Must check for all terminated jobs: typically loop with `wait`

```
void child_handler2(int sig)
{
    int   child_status;
    pid_t pid;
    while ((pid = waitpid(-1, &child_status, WNOHANG)) > 0) {
    ccount -= 1;
    printf("Received signal %d from process %d\n", sig, pid);
    }
}

void example(void)
{
    . . .
    Signal(SIGCHLD, child_handler2);
    . . .
}
```

More Signal Handler Funkiness

- Consider signal arrival during long system calls, e.g., `read`
- Signal handler interrupts `read()` call
  - Some flavors of Unix (e.g., Solaris):
    - `read()` fails with `errno==EINTER`
    - Application program may restart the slow system call
  - Some flavors of Unix (e.g., Linux):
    - Upon return from signal handler, `read()` restarted automatically
- Subtle differences like these complicate writing portable code with signals
  - `Signal` wrapper in `csapp.c` helps, uses `sigaction` to restart system calls automatically

Signal Handlers (POSIX)

- Handler can get extra information in `siginfo_t` when using `sigaction` to set handlers

  E.g., for SIGSEGV:

  - Whether virtual address didn’t map to any physical address, or whether the address was being accessed in a way not permitted (e.g., writing to read-only space)
  - Address of faulty reference

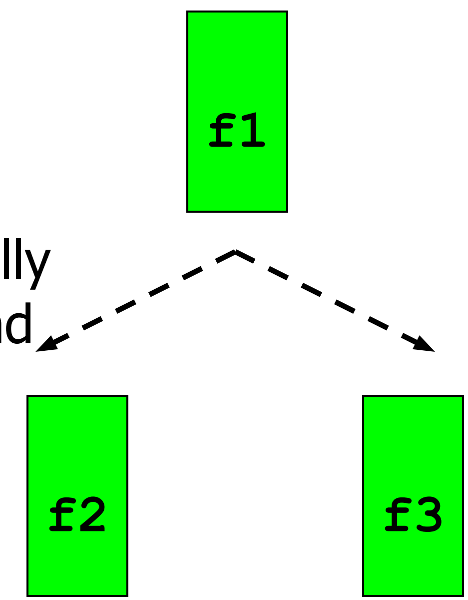
  Details: `man siginfo`

```
static void segv_handler(int sig, siginfo_t *sip, ucontext_t *uap)
{
    fprintf(stderr, "Segmentation fault caught!\n");
    fprintf(stderr, "Caused by access of invalid address %p.\n",
                    sip->si_addr);
    exit(1);
}
```

Other Types of Exceptional Control Flow

- Non-local Jumps
  - C mechanism to transfer control to any program point higher in the current stack

`f1` eventually calls `f2` and `f3`.



When can non-local jumps be used:

- **Yes: f2 to f1**
- **Yes: f3 to f1**

- **No: f1 to either f2 or f3**
- **No: f2 to f3, or vice versa**

Non-local Jumps

- `setjmp()`
  - Identify the current program point as a place to jump to
- `longjmp()`
  - Jump to a point previously identified by `setjmp()`

Non-local Jumps: setjmp()

- `int setjmp(jmp_buf env)`
  - Identifies the current program point with the name `env`
    - `jmp_buf` is a pointer to a kind of structure
    - Stores the current register context, stack pointer, and PC in `jmp_buf`
  - Returns 0

Non-local Jumps: longjmp()

- `void longjmp(jmp_buf env, int val)`
  - Causes another return from the `setjmp()` named by `env`
    - This time, `setjmp()` returns `val`
      - (Except, returns 1 if val==0)
    - Restores register context from jump buffer `env`
    - Sets function's return value register (SPARC: %o0) to `val`
    - Jumps to the old PC value stored in jump buffer `env`
  - `longjmp()` doesn't return!

Non-local Jumps

- From the UNIX `man` pages:

```
WARNINGS
     If longjmp() or siglongjmp() are called even though env  was
     never  primed  by a call to setjmp() or sigsetjmp(), or when
     the last  such  call  was  in  a  function  that  has  since
     returned, absolute chaos is guaranteed.
```

Non-local Jumps: Example 1

```
#include <setjmp.h>

jmp_buf  buf;

int main(void)
{
   if (setjmp(buf) == 0)
       printf("First time through.\n");
   else
       printf("Back in main() again.\n");

   f1();
}
```

```
f1()
{
   …
   f2();
   …
}

f2()
{
   …
   longjmp(buf, 1);
   …
}
```

Non-local Jumps: Example 2

```
#include <stdio.h>
#include <signal.h>
#include <setjmp.h>

sigjmp_buf buf;

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

int main(void)
{
  Signal(SIGINT, handler);

  if (sigsetjmp(buf, 1) == 0)
    printf("starting\n");
  else
    printf("restarting\n");
  …
```

```
  …
  while(1) {
    sleep(5);
    printf("  waiting...\n");
  }
}
```

```
> a.out
starting

waiting...          <—— Control-c

waiting...
restarting

waiting...          <—— Control-c

waiting...          <—— Control-c

waiting...
restarting
```

Application-level Exceptions

- Similar to non-local jumps
  - Transfer control to other program points outside current block
  - More abstract – generally “safe” in some sense
  - Specific to application language

Summary: Exceptions & Processes

- Exceptions
  - Events that require nonstandard control flow
  - Generated externally (interrupts) or internally (traps & faults)

- Processes
  - At any given time, system has multiple active processes
  - Only one can execute at a time, though
  - Each process appears to have total control of processor & private memory space

Summary: Processes

- Spawning
  - `fork` – one call, two returns
- Terminating
  - `exit` – one call, no return
- Reaping
  - `wait` or `waitpid`
- Replacing Program Executed
  - `execl` (or variant) – one call, (normally) no return

Summary: Signals & Jumps

- Signals – process-level exception handling
  - Can generate from user programs
  - Can define effect by declaring signal handler
  - Some caveats
    - Very high overhead
      - >10,000 clock cycles
      - Only use for exceptional conditions
    - Don't have queues
      - Just one bit for each pending signal type
- Non-local jumps – exceptional control flow within process
  - Within constraints of stack discipline