Exceptional Control Flow

Alan L. Cox

alc@cs.rice.edu

Some slides adapted from CMU 15.213 slides

Processor Control Flow

Processor executes sequence of instructions

- **From start-up to shutdown**
- **Called system's physical *control flow***
- **One instruction at a time (or the illusion of it)**

We have seen two "normal" ways to alter control flow:

- **Conditional & unconditional branches**
- **Calls & returns**

Exceptional Control Flow

Hardware:

- Exceptions (= interrupts)

System software:

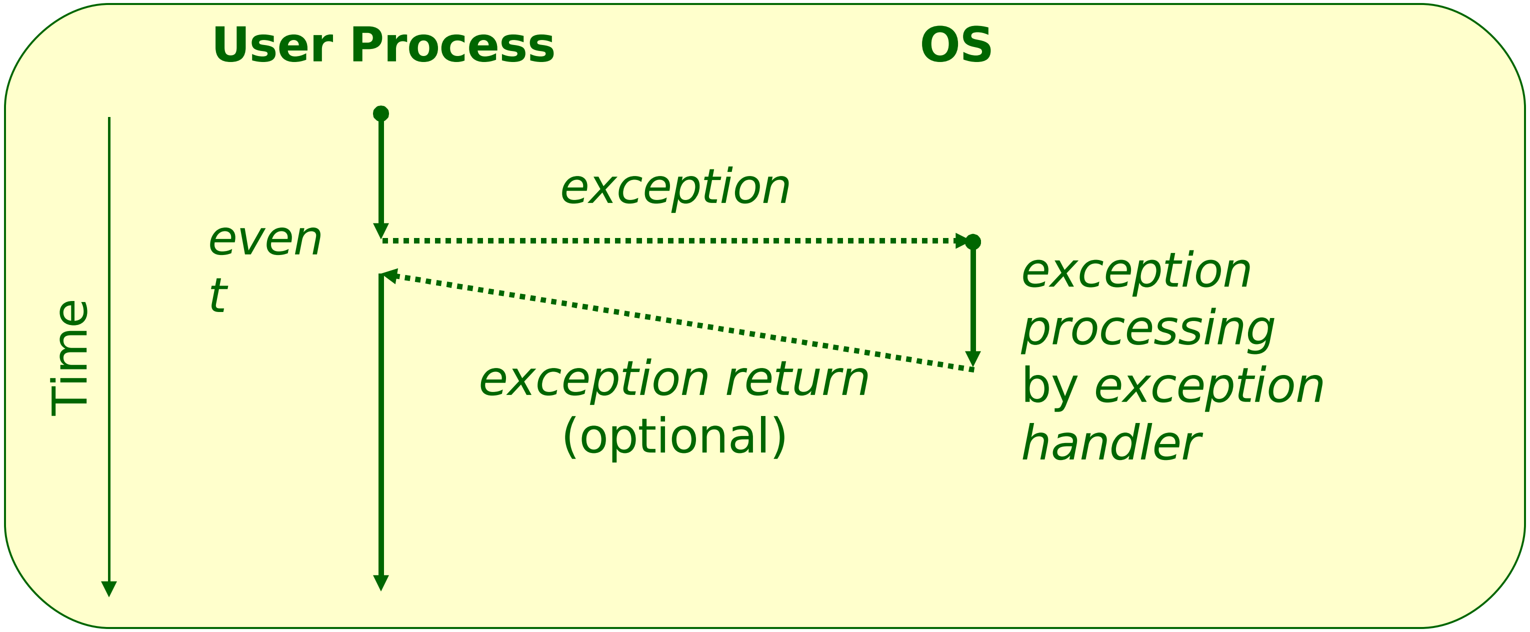
- Signals
- Thread context switch
- Process context switch

Application software (varies by language):

- Non-local jumps
- Exceptions – same name, similar idea
- ...

Hardware Exceptions

***Exception* = A transfer of control to the OS in response to some *event* (i.e., a change in processor state)**



Some Exceptions

Divide by zero

Page fault

Memory access violations

Breakpoints

System calls

Interrupts from I/O devices

etc.

Exception Table (Interrupt Vector)

How to find appropriate handler?

Exception numbers	Interrupt vector
0	Address of handler 0
1	Address of handler 1
2	Address of handler 2
...	...
n-1	Address of handler n-1

- Each event type has an exception number $k \in 0 \ldots n-1$
- Interrupt vector (a jump table) entry k points to an exception handler
- Handler k is called each time exception k occurs

Initialized by OS at boot time

Exception Classes

Asynchronous (not caused by an instruction)

- **Interrupt**
  - Signal from an I/O device (i.e. ctrl-c, network packet)
  - Always return to the next instruction

Synchronous (caused by an instruction)

- **Trap**
  - Intentional exception (i.e. system call)
  - Always return to the next instruction
- **Fault**
  - Potentially recoverable error (i.e. protection fault)
  - Might return to the current instruction (if problem is fixed) to allow it to re-execute
- **Abort**
  - Non-recoverable error (i.e. machine check error)
  - Terminates the application

Processes

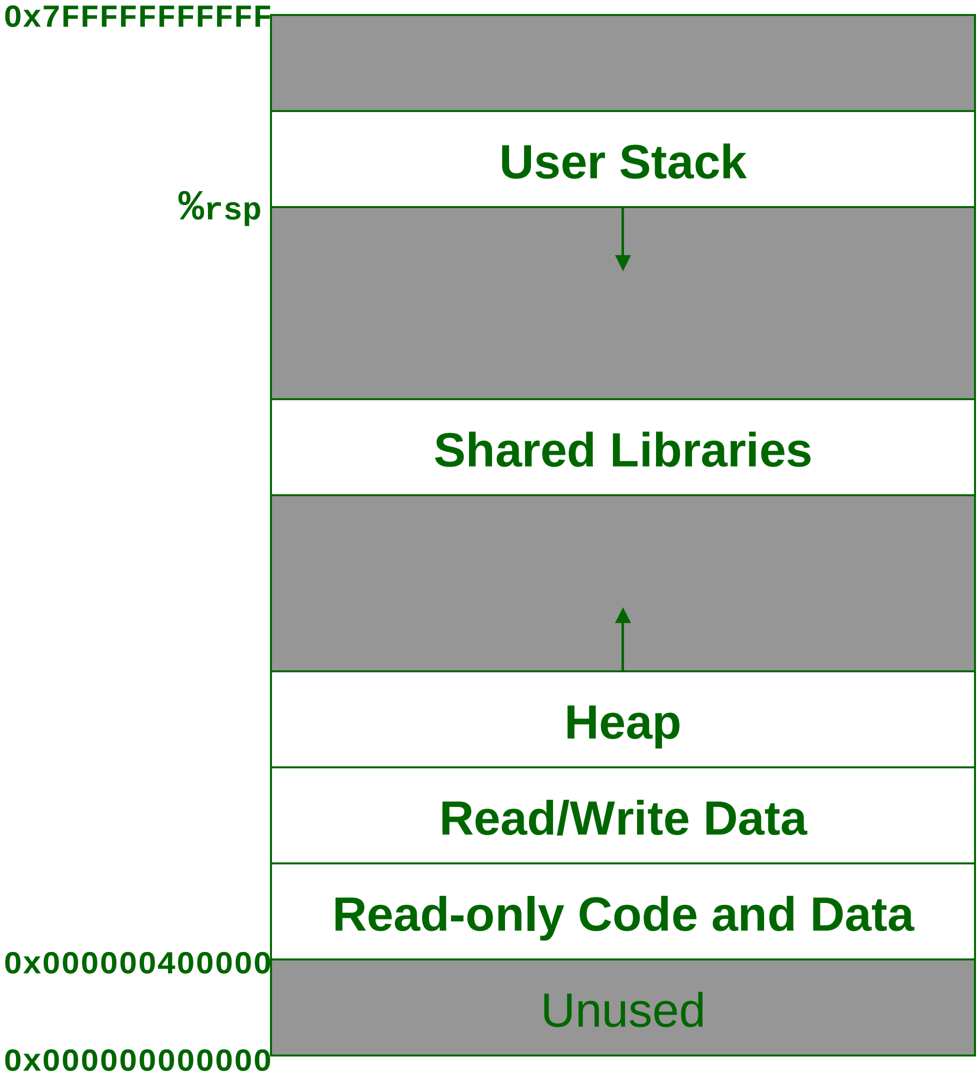
A *process* is an instance of a running program

Each program in the system runs in the context of a process

- Appears to be the only program running on the system
- Appears to have exclusive use of both the processor and the memory
- Appears to execute instructions of the program one after the other without interruption
- Program’s instructions and data appear to be the only objects in the system’s memory

Exceptions help make this possible!

Process Address Space



Every program believes it has exclusive use of the system's address space

Process address space is private

- Can not be read/written by any other process
- I.e., address 0x400000 is different for every process

User and Kernel Mode

Process isolation

- Hardware restricts the instructions an application can execute

Mode bit: user vs. kernel mode

- In kernel mode, everything is accessible
- In user mode, cannot execute privileged instructions
  - Halt the processor
  - Change the mode bit
  - Initiate I/O
  - Access data outside process address space
  - etc.

Exceptions switch from user to kernel mode

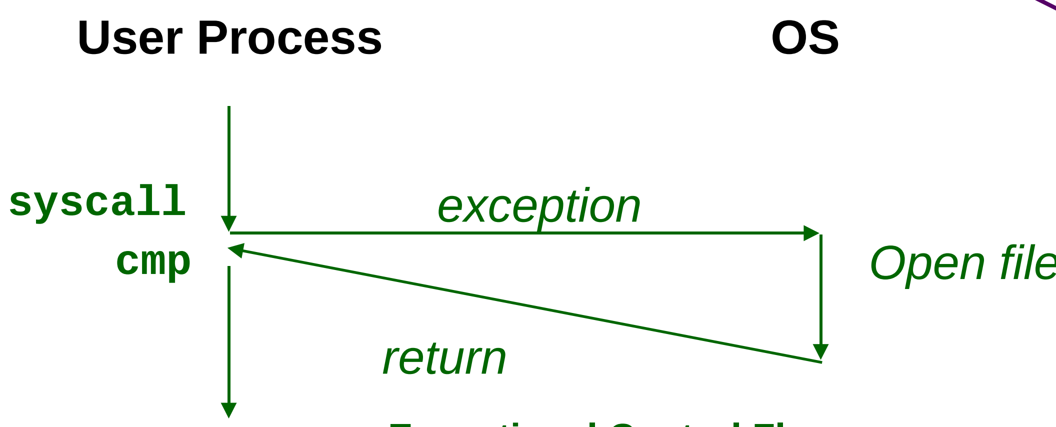
Trap Example

Opening a File

- **User calls `open(filename, options)`**
- **Function `open` executes `syscall` instruction**
- **OS must find or create file**
- **Returns integer file descriptor**

```
0000000000000000 <__libc_open>:
…
   9:   b8 02 00 00 00       mov  $0x2,%eax
   e:   0f 05                syscall
  10:   48 3d 01 f0 ff ff    cmp  $0xfffffffffffff001,%rax
```

`%eax` used to store system call number (`/usr/include/sys/syscall.h`)



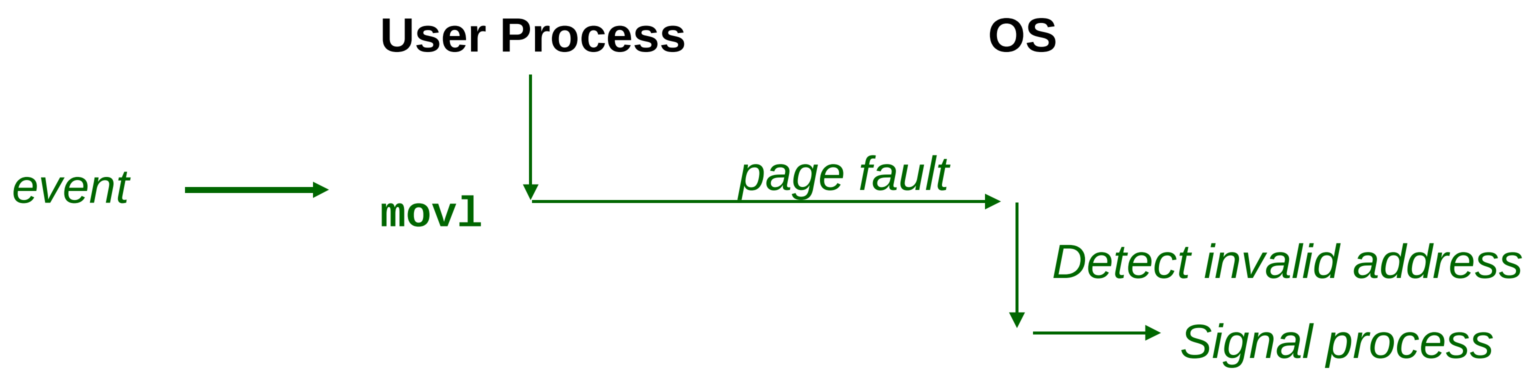
Fault Example #1

```
int a[1000];
int main(void) {
    a[5000] = 23;
    return (0);
}
```

Memory Reference

- User writes to memory location
- Address is not valid
- Page handler detects invalid address
- Send SIGSEGV signal to user process
- User process exits with “segmentation fault”

```
0x400448 <main>:        movl   $0x17,0x2051ee(%rip)        # 0x605640
```



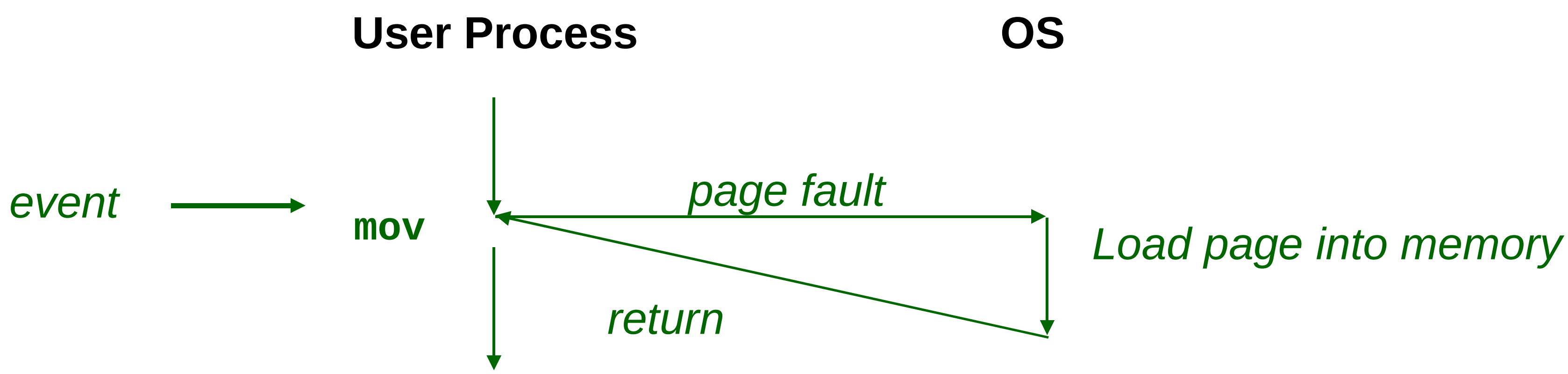
Fault Example #2

```
int a[1000] = {
    0, 1, 2, … };
int main(void) {
    printf(“%d\n”,
        a[500]);
    return (0);
}
```

Memory Reference

- User reads from memory location
- That portion of user’s memory is currently on disk
- Page handler must load page into physical memory
- Returns to faulting instruction
- Successful on second try

```
0x40049c <main+4>:      mov    0x200bae(%rip),%esi        # 0x601050 <a+2000>
```



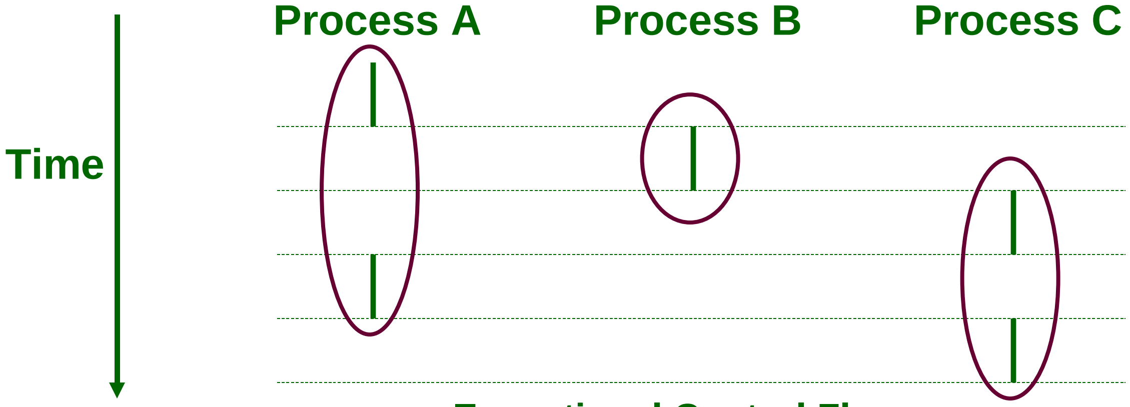
Logical Control Flow

Processes must share the processor with other processes as well as the OS

- **Logical control flow is the illusion that each process has exclusive use of the processor**

Processes take turns using the processor

- **Processes are periodically preempted to allow other processes to run**
- **Only evidence that a process is preempted is if you are precisely measuring time**



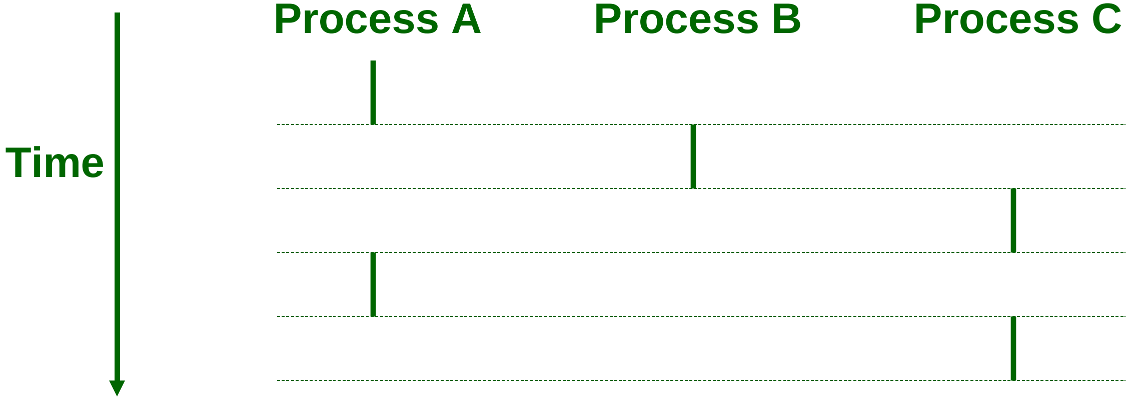
Concurrent Processes

Two processes run concurrently (are concurrent) if their flows overlap in time

Otherwise, they are sequential

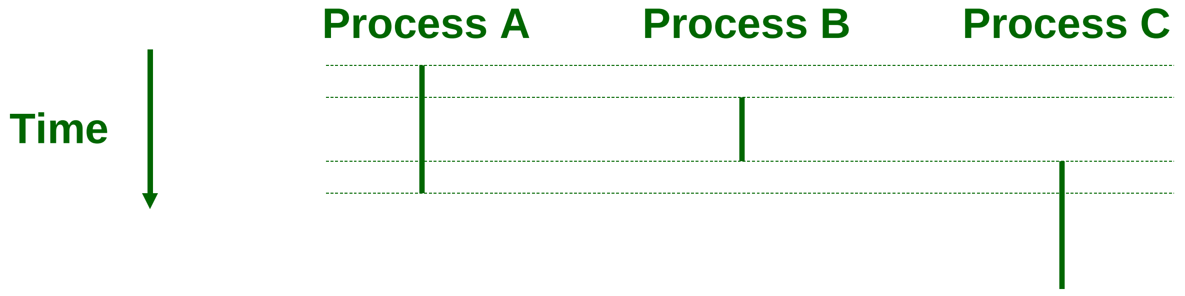
Examples:

- **Concurrent: A & B, A & C**
- **Sequential: B & C**



User View of Concurrent Processes

- Control flows for concurrent processes are physically disjoint in time
- However, we can think of concurrent processes are running in parallel with each other

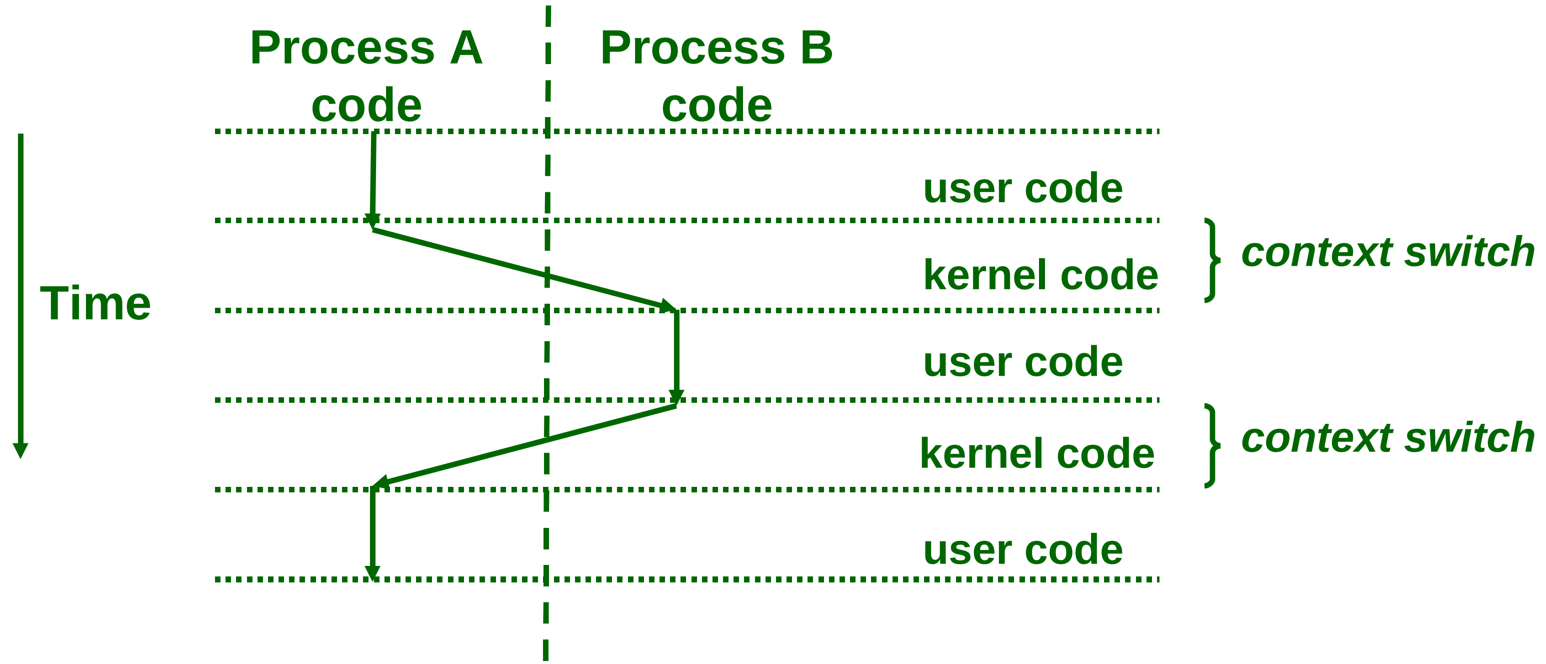


Context Switching

Processes are managed by OS 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



Creating a Process

`int fork(void)`

- Creates new *child process* identical to calling *parent process*
- Returns 0 to the child process
- Returns child's `pid` to the parent process
- Returns -1 to the parent process upon error (no child is created)

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

Interesting & confusing – called once, but returns twice!

Process IDs

Each process is assigned a unique process ID (PID)

- **Positive, non-zero identifier**
- **Used by many functions to indicate a particular process**
- **Visible with `ps` command**

Obtaining process IDs

- **PID of calling process:**

```
pid_t getpid(void);
```

- **PID of parent process:**

```
pid_t getppid(void);
```

Fork Example 1

```
void
fork1(void)
{
  pid_t pid;
  int x = 1;

  if (fork() == 0) {
    x++;
    pid = getpid();
    printf("Child (%d) has x = %d\n",
           (int)pid, x);
  } else {
    x--;
    pid = getpid();
    printf("Parent (%d) has x = %d\n",
           (int)pid, x);
  }
  printf("Process %d exiting.\n",
         (int)pid);
  exit(0);
}
```

```
UNIX% ./fork1
Parent (26152) has x = 0
Child (26153) has x = 2
Process 26153 exiting.
Process 26152 exiting.
```

Call once, return twice

- Parent/child run same code
- Different return values

Concurrent execution

- Parent/child different processes which run concurrently

Duplicate, but separate address spaces

- Child copies parents address space at time of fork call

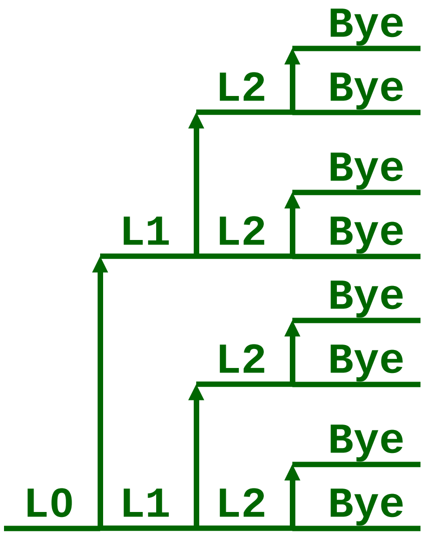
Shared files

- Child inherits all of the parent's open files

Fork Example 2

Both parent & child can continue forking

```
void fork2(void)
{
    printf("L0\n");
    fork();
    printf("L1\n");
    fork();
    printf("L2\n");
    fork();
    printf("Bye\n");
}
```

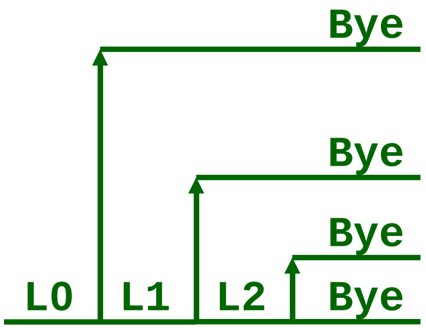


? What happens? ?

Fork Example 3

Both parent & child can continue forking

```
void fork3(void)
{
    printf("L0\n");
    if (fork() != 0) {
       printf("L1\n");
       if (fork() != 0) {
           printf("L2\n");
           fork();
       }
    }
    printf("Bye\n");
}
```



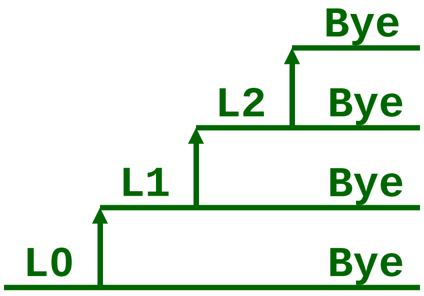
? What happens? ?

Fork Example 4

Both parent & child can continue forking

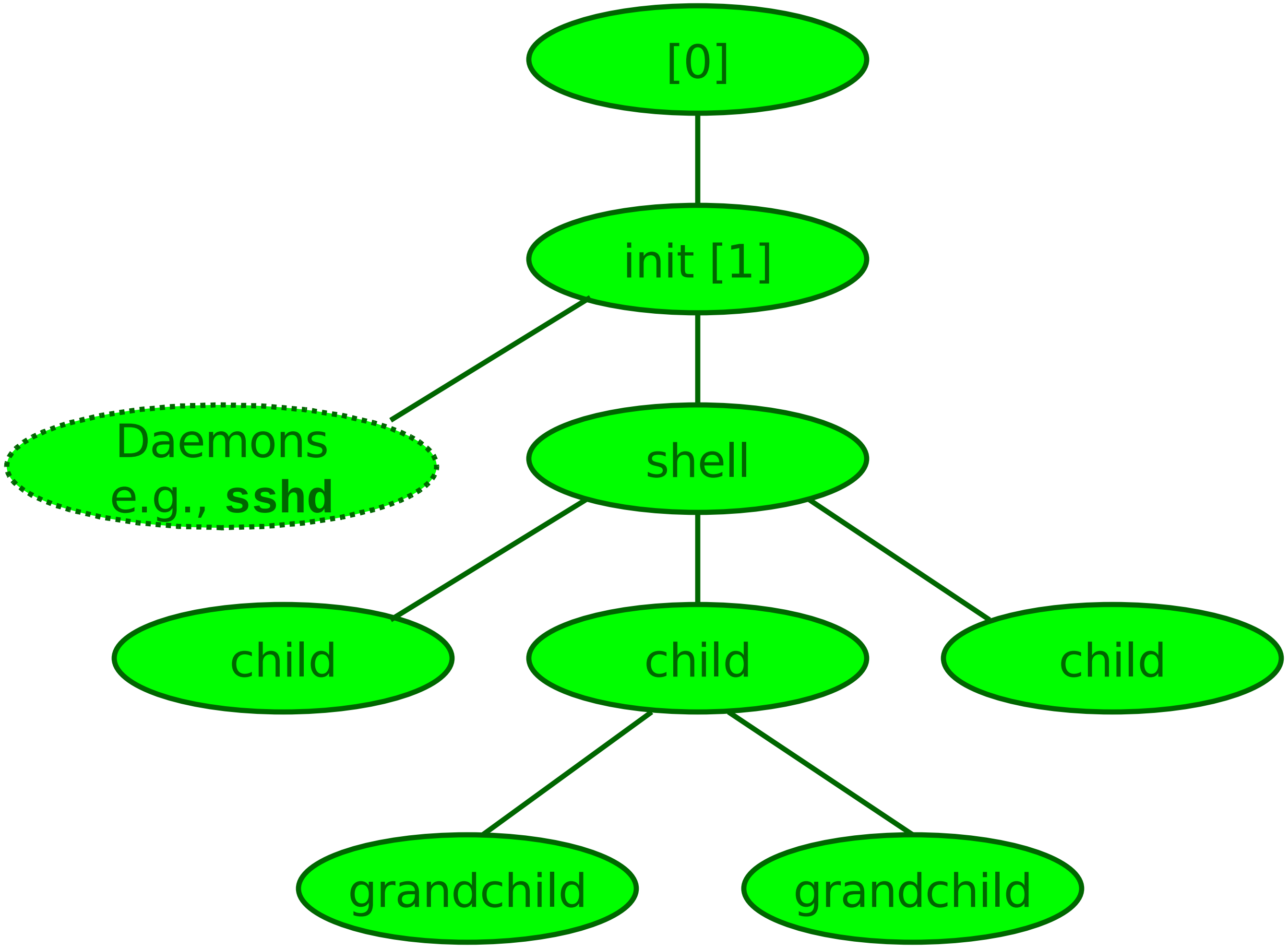
```
void fork4(void)
{
    printf("L0\n");
    if (fork() == 0) {
       printf("L1\n");
       if (fork() == 0) {
           printf("L2\n");
           fork();
       }
    }
    printf("Bye\n");
}
```

Changed != to ==



? What happens? ?

Processes Form a Tree



Destroying a Process

`void exit(int status)`

- **Exits current process**
- **Does not kill child processes**
- `atexit()` **registers functions to be executed upon exit**

```
void cleanup(void) {
   printf("cleaning up\n");
}
int main(void) {
   atexit(cleanup);
   if (fork() == 0)
      printf("hello from child\n");
   else
      printf("hello from parent\n");
   exit(0);
}
```

Process States

Running

- The process is either executing or waiting to execute (because another process is using the processor)

Stopped

- The process is suspended and will not be scheduled
- May later be resumed
- Process is suspended/resumed via signals (more later)

Terminated

- The process is stopped permanently
- Terminated via signal, return from `main()`, or call to `exit()`

Zombie Processes

When process terminates, still consumes system resources

- Various tables maintained by OS
- Called a zombie – half alive & half dead

Reaping

- Performed by parent on terminated child
- Parent is given exit status information
- Kernel discards process

What if Parent Doesn’t Reap?

- When parent terminates, its children reaped by init process – part of OS
- Only need explicit reaping of children for long-running processes
  - E.g., shells, servers

Zombie Example

- ps shows child process as “defunct”
- Killing parent allows child to be reaped

```
Z: zombie
S: sleeping
R: running/runnable
T: stopped
```

```
UNIX% ./example &
[1] 11299
Running Parent, PID = 11299
Terminating Child, PID = 11300
UNIX% ps x
   PID TTY      STAT  TIME COMMAND
 11263 pts/7    Ss    0:00 -tcsh
 11299 pts/7    R     0:07 ./example
 11300 pts/7    Z     0:00 […] <defunct>
 11307 pts/7    R+    0:00 ps x
UNIX% kill 11299
[1]    Terminated
UNIX% ps x
   PID TTY      STAT  TIME COMMAND
 11263 pts/7    Ss    0:00 -tcsh
 11314 pts/7    R+    0:00 ps x
```

```
void example(void)
{
    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 child explicitly, or it will keep running indefinitely**

```
UNIX% ./example
Terminating Parent, PID = 11396
Running Child, PID = 11397
UNIX% ps x
   PID TTY       STAT TIME COMMAND
 11263 pts/7     Ss   0:00 -tcsh
 11397 pts/7     R    0:01 ./example
 11398 pts/7     R+   0:00 ps x
UNIX% kill 11397
UNIX% ps x
   PID TTY       STAT TIME COMMAND
 11263 pts/7     Ss   0:00 -tcsh
 11399 pts/7     R+   0:00 ps x
```

```
void example(void)
{
    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);
    }
}
```

Synchronizing Processes

`int wait(int *child_status)`

- Suspends current process until any child terminates
- Return value is the `pid` of the terminated child
- If `child_status != NULL`, then the object it points to will be set to a status indicating why the child terminated

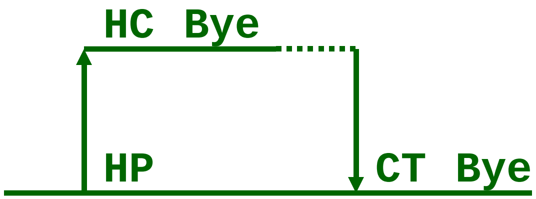
Process can only synchronize with its own children using wait!

- Other synchronization functions exist

Synchronizing Processes

```
int main(void) {
   int child_status;

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



`wait()` Example

If multiple children completed, will take in arbitrary order

Macros to get info about exit status

```
void example(void)
{
    pid_t pid[N], wpid;
    int   child_status, i;
    for (i = 0; i < N; i++)
       if ((pid[i] = fork()) == 0)
           exit(100 + i); /* Child */
    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);
    }
}
```

waitpid()

waitpid(pid, &status, options)

Waits for specific process

```
void example(void)
{
    pid_t pid[N], wpid;
    int   child_status, i;
    for (i = 0; i < N; i++)
       if ((pid[i] = fork()) == 0)
           exit(100 + i); /* Child */
    for (i = 0; i < N; i++) {
       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`

```
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`

```
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
```

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` $\rightarrow$ `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

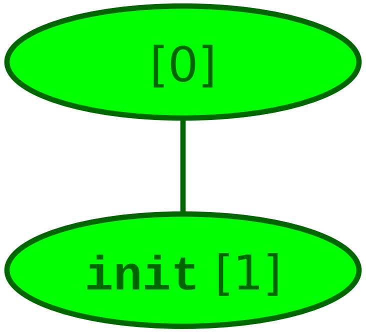
Pushing reset button loads the PC with the address of a small bootstrap program

Bootstrap program loads the boot block (disk block 0)

Boot block program loads kernel from disk

Boot block program passes control to kernel

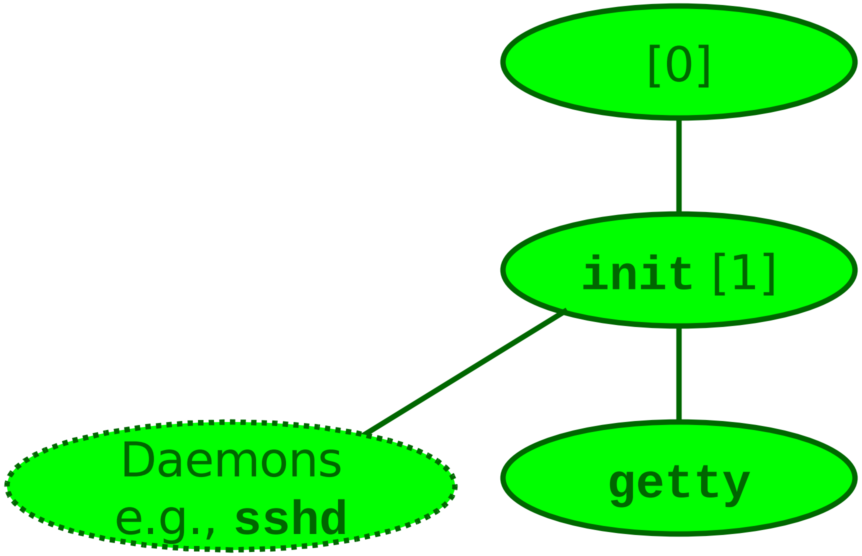
Kernel handcrafts the data structures for process 0



Process 0: handcrafted kernel process

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

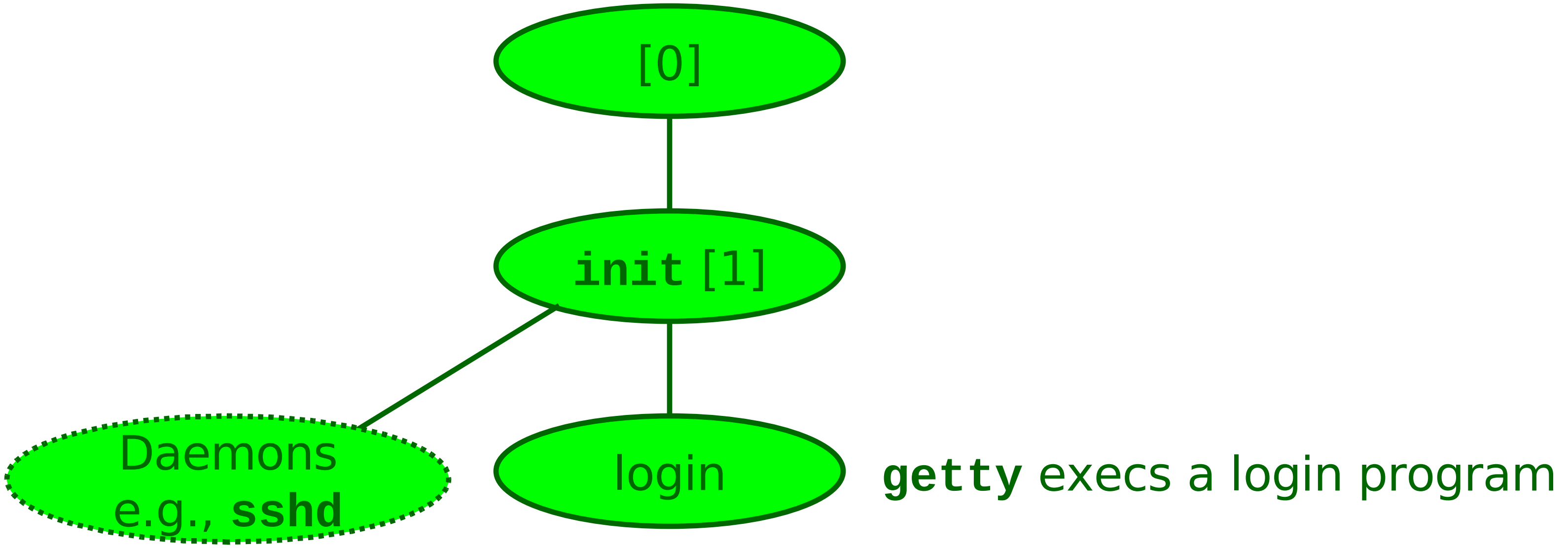
UNIX Startup: 2



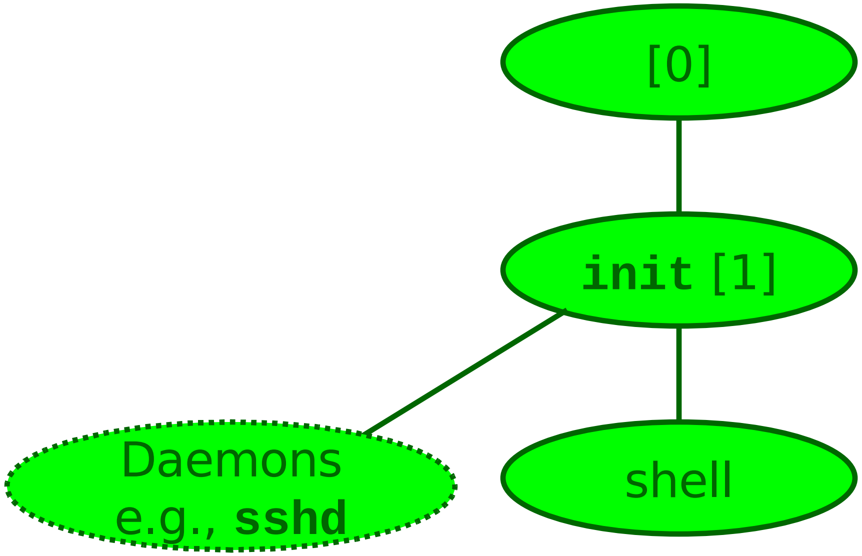
init forks new processes as per the **/etc/inittab** file

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

UNIX Startup: 3



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**

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

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

Read-evaluate loop:
an interpreter!

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**

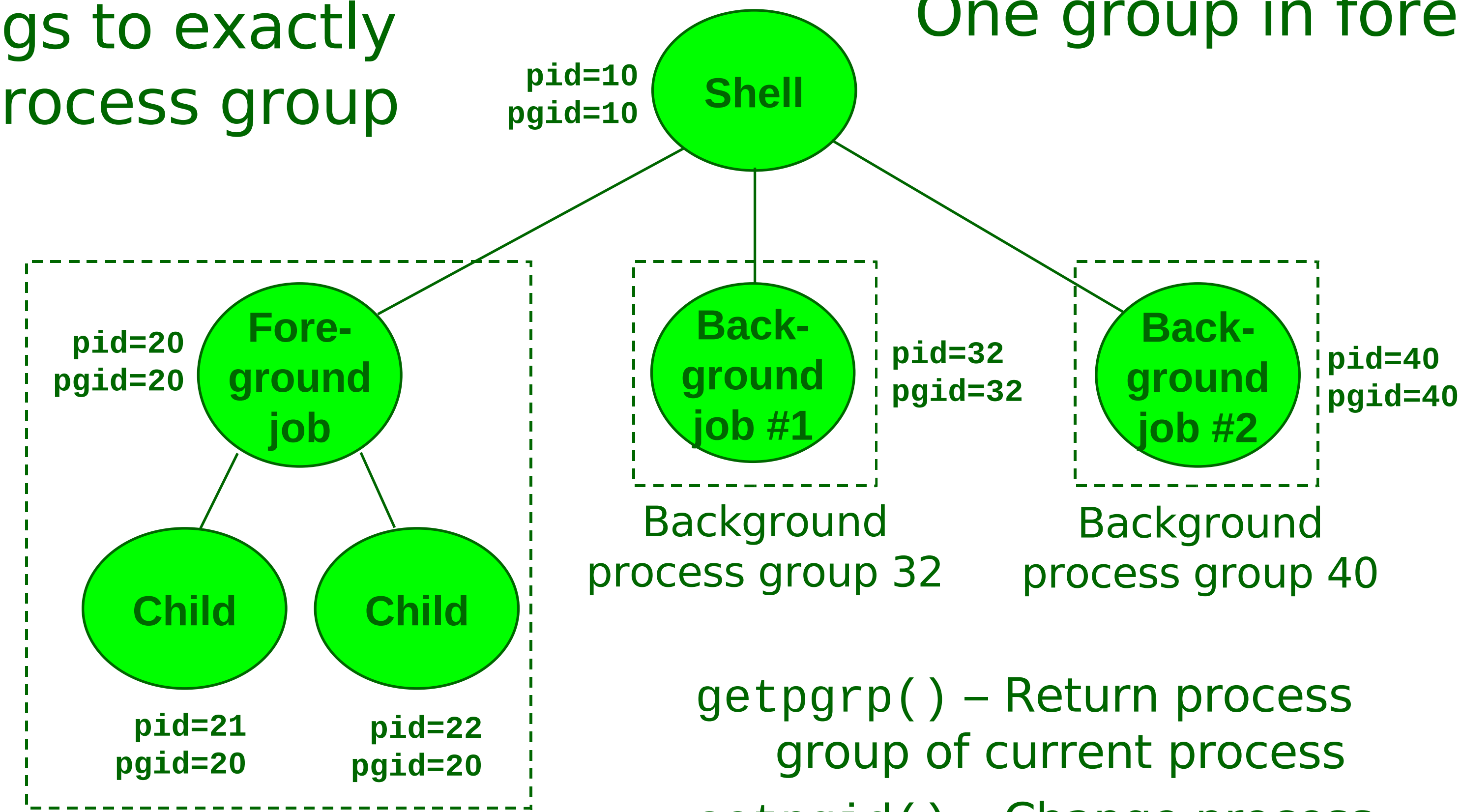
`blocked` – represents the set of blocked signals

- **Application sets & clears bits via `sigprocmask()`**

Process Groups

Each process belongs to exactly one process group

One group in foreground



Foreground process group 20

`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

```c
#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);
  }
}
```

```c
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**

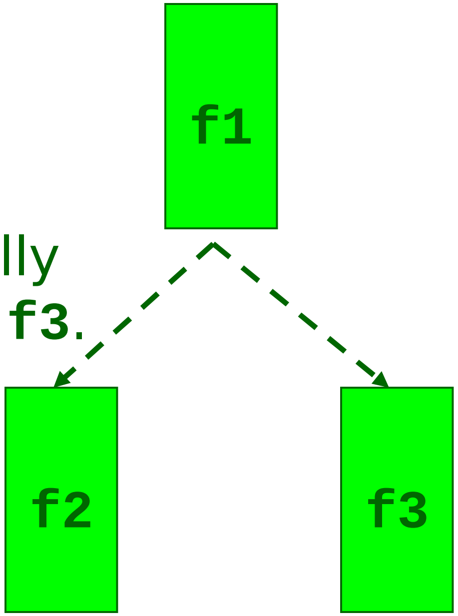
Details: `man siginfo`

```
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...
  waiting...          Control-c
restarting
  waiting...
  waiting...
  waiting...
restarting            Control-c
  waiting...
restarting            Control-c
  waiting...
  waiting...
```

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

Outside the scope of this course

- COMP 314, 311: Java exceptions
- COMP 311: Scheme continuations

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

Next Time

Measuring Time