

15-213

“The course that gives CMU its Zip!”

Exceptional Control Flow **Part II** **October 18, 2006**

Topics

- **Process Hierarchy**
- **Shells**
- **Signals**
- **Nonlocal jumps**

ECF Exists at All Levels of a System

Exceptions

- Hardware and operating system kernel software

Concurrent processes

- Hardware timer and kernel software

Signals

- Kernel software

Non-local jumps

- Application code

Previous Lecture

This Lecture

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

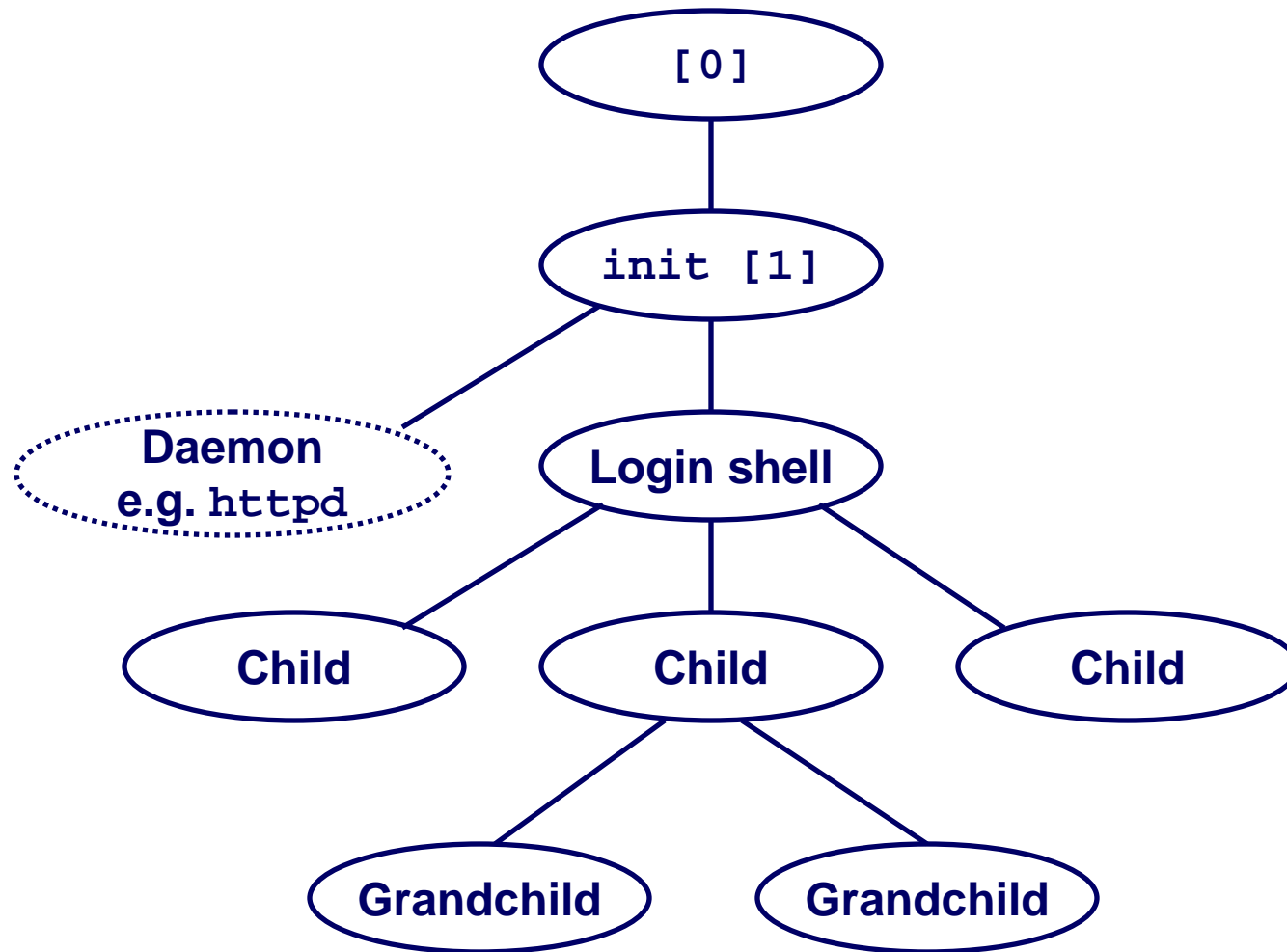
Basic Functions

- `fork()` spawns new process
 - Called once, returns twice
- `exit()` terminates own process
 - Called once, never returns
 - Puts it 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 Process Hierarchy



The ps command

```
Unix> ps aux -w --forest
```

(output edited to fit slide)

```
USER          PID  TTY          STAT COMMAND
root           1  ?           S    init [3]
root           2  ?           SW   [keventd]
root           3  ?           SWN  [ksoftirqd_CPU0]
root           4  ?           SW   [kswapd]
root           5  ?           SW   [bdflush]
root           6  ?           SW   [kupdated]
root           9  ?           SW<  [mdrecoveryd]
root          12  ?           SW   [scsi_eh_0]
root          397  ?           S    /sbin/pump -i eth0
root          484  ?           S<   /usr/local/sbin/afsd -nosettime
root          533  ?           S    syslogd -m 0
root          538  ?           S    klogd -2
rpc           563  ?           S    portmap
rpcuser       578  ?           S    rpc.statd
daemon        696  ?           S    /usr/sbin/atd
root          713  ?           S    /usr/local/etc/nanny -init /etc/nanny.conf
mmdf          721  ?           S    \_ /usr/local/etc/deliver -b -csmtpcmu
root          732  ?           S    \_ /usr/local/sbin/named -f
root          738  ?           S    \_ /usr/local/sbin/sshd -D
root          739  ?           S<L  \_ /usr/local/etc/ntpd -n
root          752  ?           S<L  |   \_ /usr/local/etc/ntpd -n
root          753  ?           S<L  |   \_ \_ /usr/local/etc/ntpd -n
root          744  ?           S    \_ /usr/local/sbin/zhm -n zephyr-1.srv.cm
root          774  ?           S    gpm -t ps/2 -m /dev/mouse
root          786  ?           S    crond
```

The ps Command (cont.)

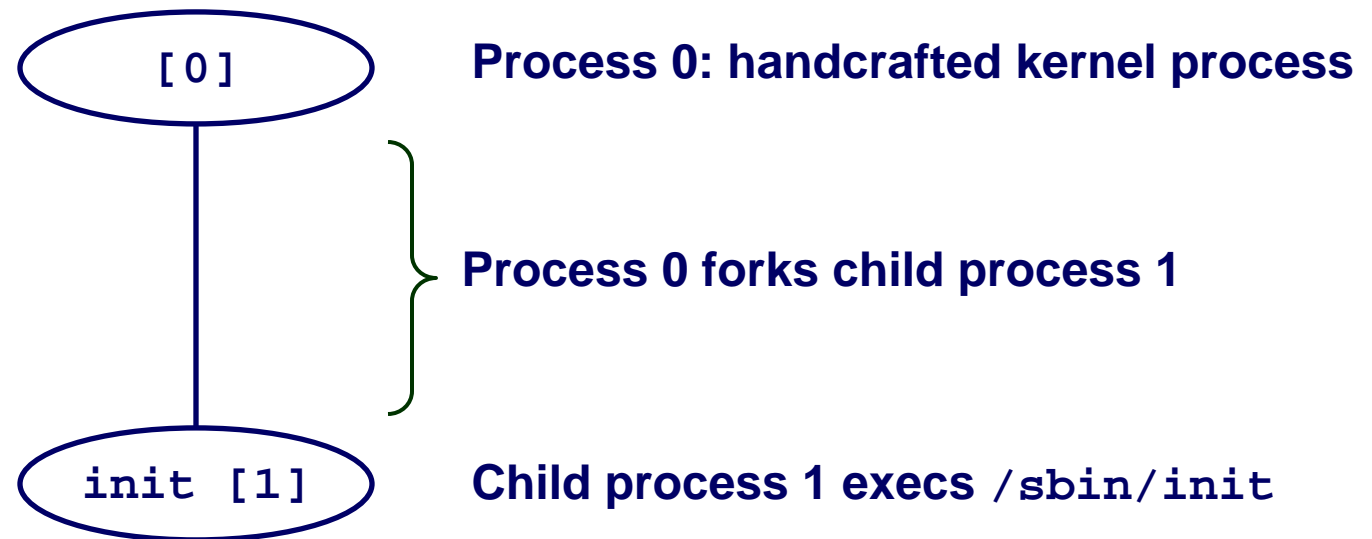
```

USER      PID  TTY      STAT  COMMAND
root      889  tty1     S      /bin/login -- agn
agn       900  tty1     S      \_ xinit -- :0
root      921  ?        SL     \_ /etc/X11/X -auth /usr1/agn/.Xauthority :0
agn       948  tty1     S      \_ /bin/sh /afs/cs.cmu.edu/user/agn/.xinitrc
agn       958  tty1     S      \_ xterm -geometry 80x45+1+1 -C -j -ls -n
agn       966  pts/0    S      \_ -tcsch
agn       1184 pts/0    S      \_ /usr/local/bin/wish8.0 -f /usr
agn       1212 pts/0    S      \_ /usr/local/bin/wish8.0 -f
agn       3346 pts/0    S      \_ aspell -a -S
agn       1191 pts/0    S      \_ /bin/sh /usr/local/libexec/moz
agn       1204 8 pts/0    S      \_ /usr/local/libexec/mozilla
agn       1207 8 pts/0    S      \_ /usr/local/libexec/moz
agn       1208 8 pts/0    S      \_ /usr/local/libexec
agn       1209 8 pts/0    S      \_ /usr/local/libexec
agn       17814 8 pts/0    S      \_ /usr/local/libexec
agn       2469 pts/0    S      \_ usr/local/lib/Acrobat
agn       2483 pts/0    S      \_ java_vm
agn       2484 pts/0    S      \_ java_vm
agn       2485 pts/0    S      \_ java_vm
agn       3042 pts/0    S      \_ java_vm
agn       959  tty1     S      \_ /bin/sh /usr/local/libexec/kde/bin/sta
agn       1020 tty1     S      \_ kwrapper ksmsserver

```

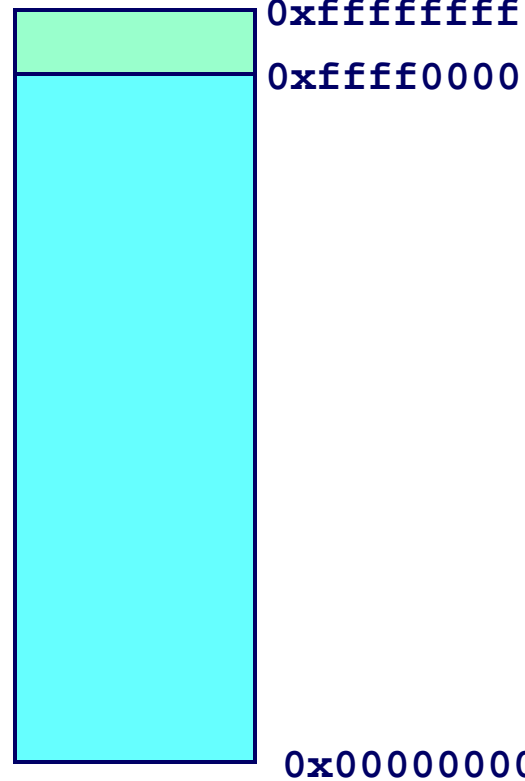
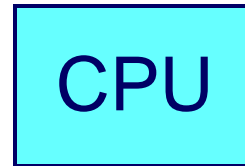
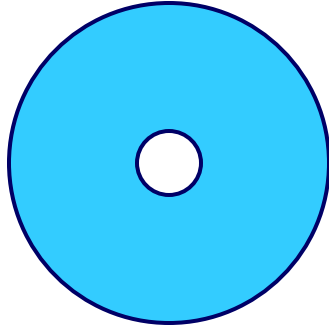
Unix Startup: Step 1

1. Pushing reset button loads the PC with the address of a small bootstrap program.
2. Bootstrap program loads the boot block (disk block 0).
3. Boot block program loads kernel binary (e.g., `/boot/vmlinux`)
4. Boot block program passes control to kernel.
5. Kernel handcrafts the data structures for process 0.



Some PC Start-up Details

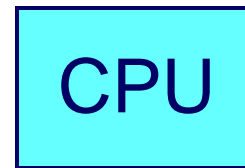
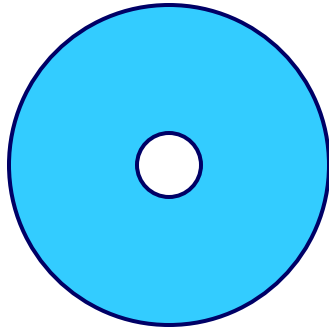
Boot Disk / CD / Floppy



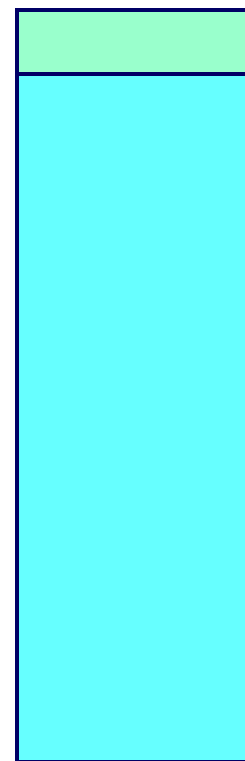
BIOS ROM

Some PC Start-up Details

Boot Disk / CD / Floppy



← Power on/Reset



0xffffffff

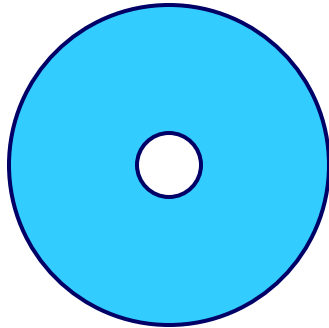
0xffff0000

BIOS ROM

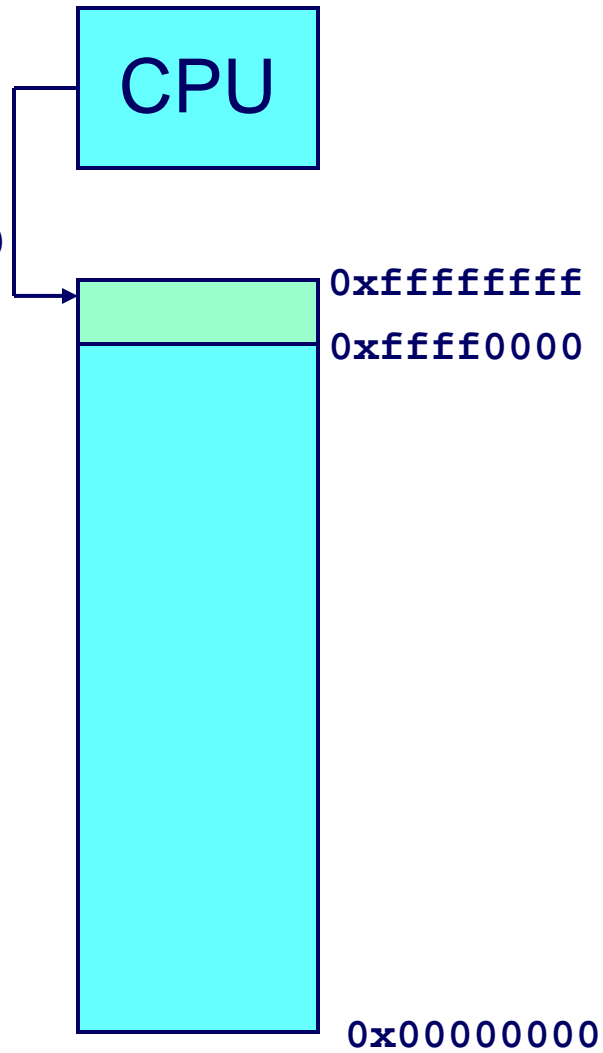
0x00000000

Some PC Start-up Details

Boot Disk / CD / Floppy



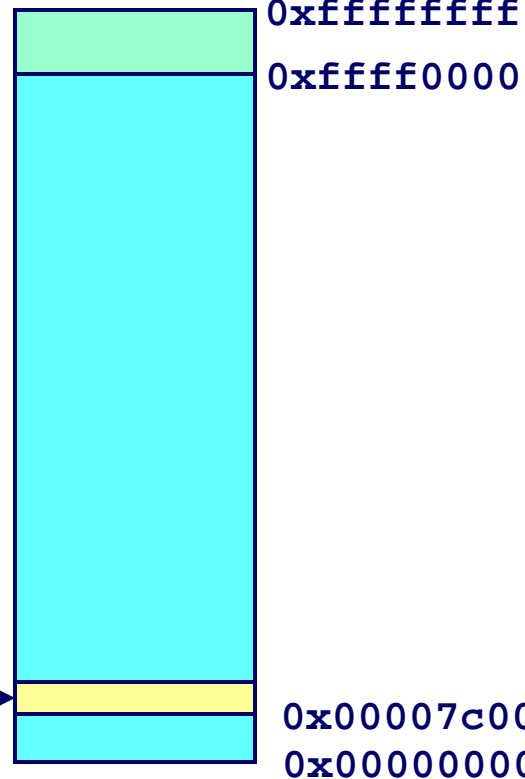
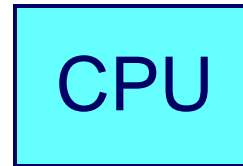
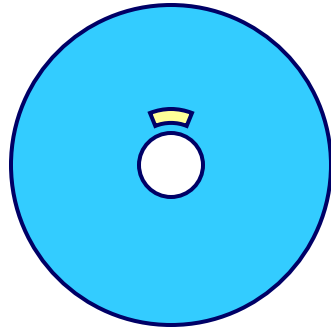
Start
Execution at
`0xfffffffff0`



BIOS ROM

Some PC Start-up Details

Boot Disk / CD / Floppy

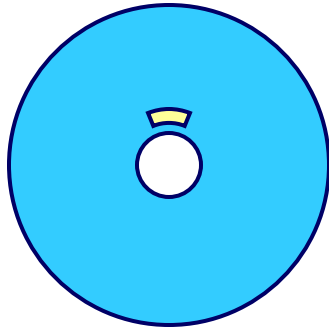


BIOS ROM

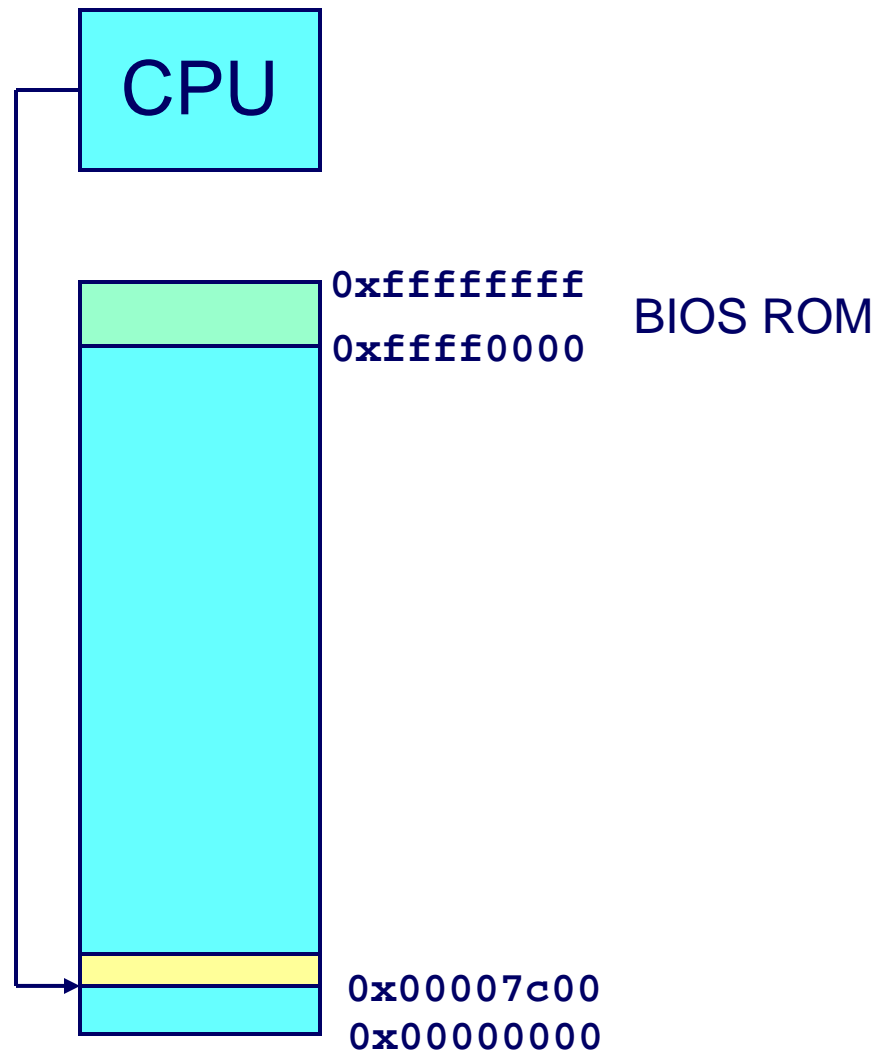
Copy
Master Boot Record
(MBR)
into memory

Some PC Start-up Details

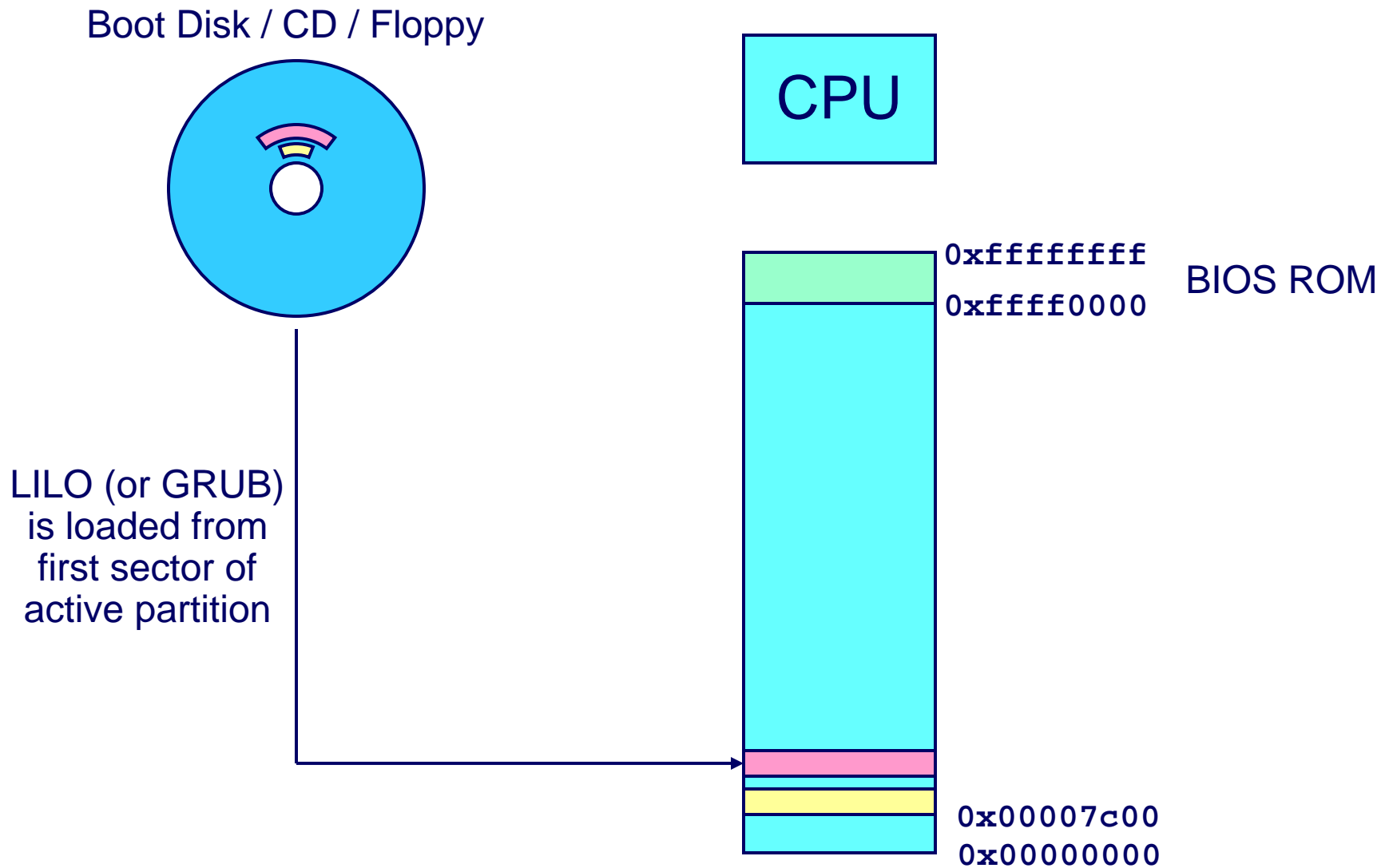
Boot Disk / CD / Floppy



BIOS verifies MBR
and jumps to
0x00007c00

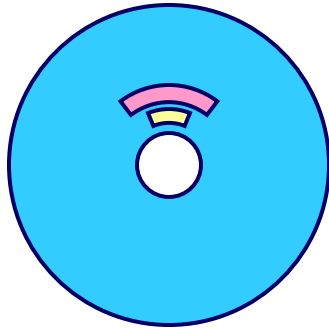


Some PC Start-up Details

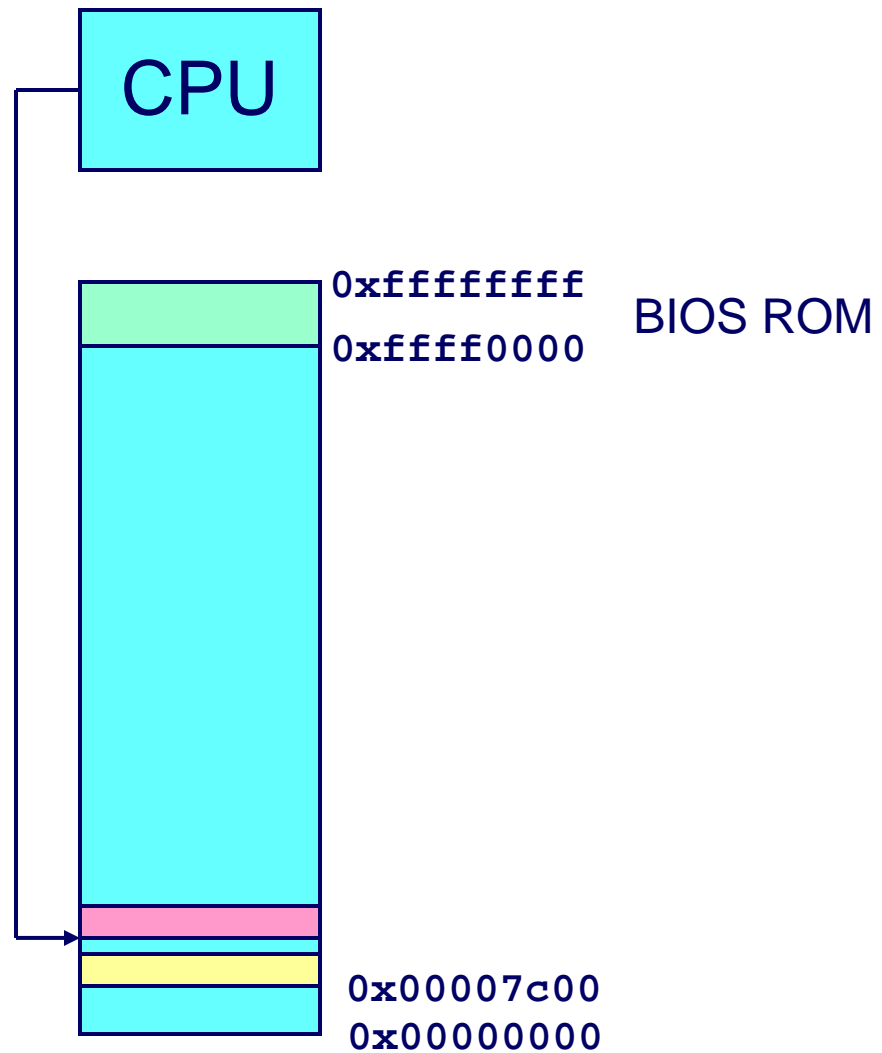


Some PC Start-up Details

Boot Disk / CD / Floppy

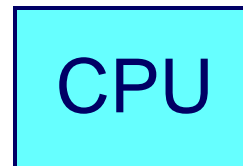
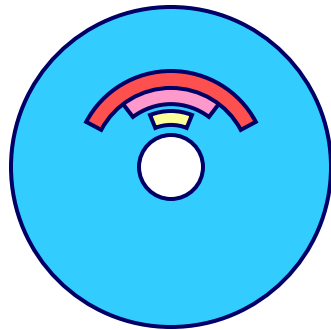


CPU executes LILO

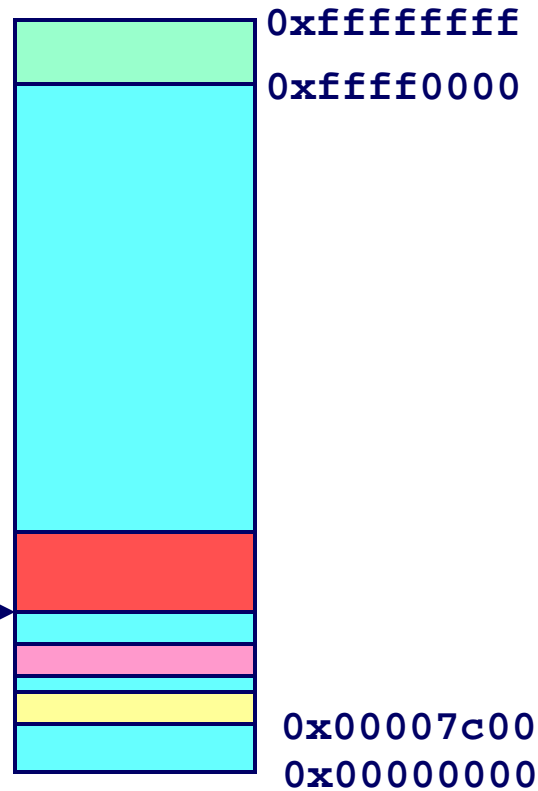


Some PC Start-up Details

Boot Disk / CD / Floppy



The Linux kernel is loaded and begins initialization



BIOS ROM

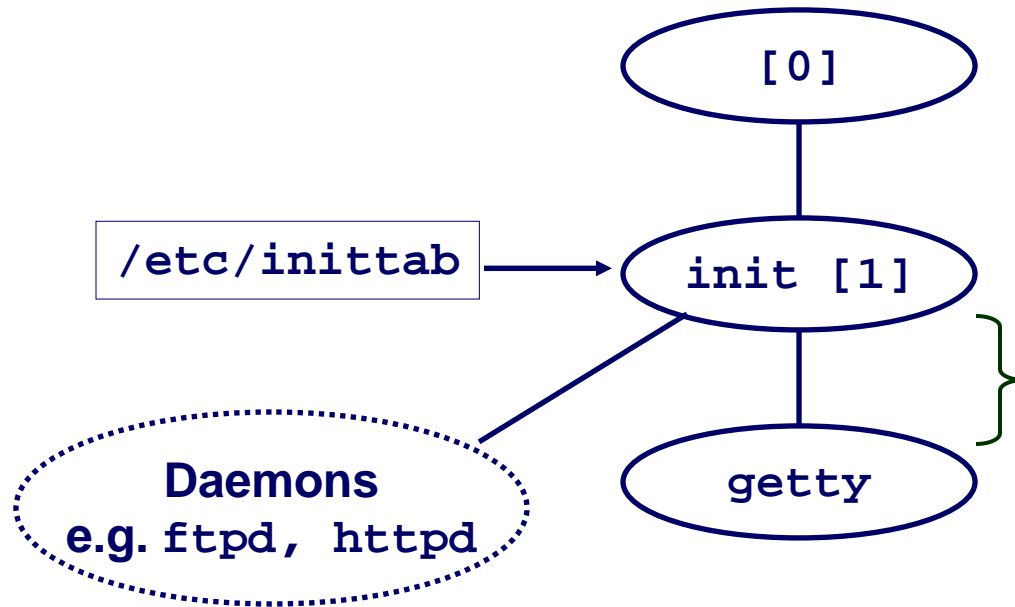
0xffffffff

0xffff0000

0x00007c00

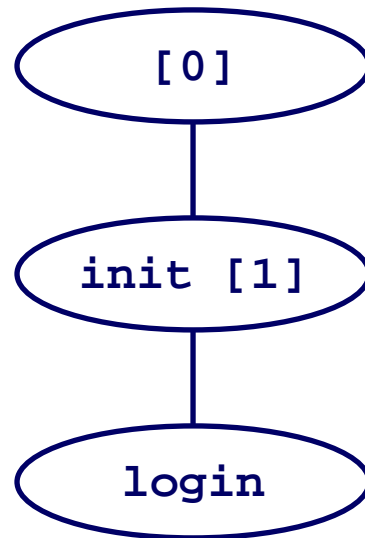
0x00000000

Unix Startup: Step 2



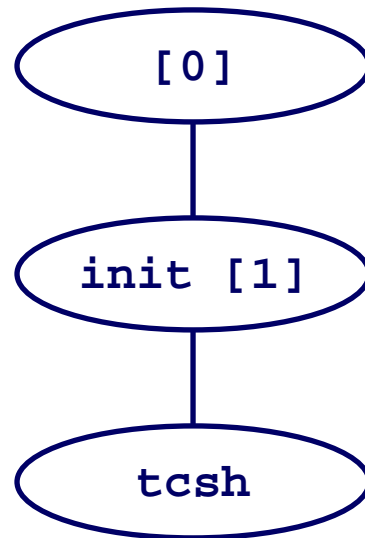
`init` forks and execs daemons per `/etc/inittab`, and forks and execs a `getty` program for the console

Unix Startup: Step 3



The `getty` process
execs a `login`
program

Unix Startup: Step 4



`login` reads `login-ID` and `passwd`.
if OK, it execs a *shell*.
if not OK, it execs another `getty`

In case of `login` on the console
`xinit` may be used instead of
a shell to start the window manger

Shell Programs

A **shell** is an application program that runs programs on behalf of the user.

- **sh** – Original Unix Bourne Shell
- **cs**h – BSD Unix C Shell, **tc**sh – Enhanced C Shell
- **ba**sh – Bourne-Again Shell

```
int main()
{
    char cmdline[MAXLINE];

    while (1) {
        /* read */
        printf("> ");
        Fgets(cmdline, MAXLINE, stdin);
        if (feof(stdin))
            exit(0);

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

Execution is a sequence of read/evaluate steps

Simple Shell eval Function

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

    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 */
            int status;
            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

Shell correctly waits for and reaps foreground jobs.

But what about background jobs?

- Will become zombies when they terminate.
- Will never be reaped because shell (typically) will not terminate.
- Creates a memory leak that will eventually crash the kernel when it runs out of memory.

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 (1-30)
- The only information in a signal is its ID and the fact that it arrived.

ID	Name	Default Action	Corresponding Event
2	SIGINT	Terminate	Interrupt from keyboard (ct1-c)
9	SIGKILL	Terminate	Kill program (cannot override or ignore)
11	SIGSEGV	Terminate & Dump	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.

Signal Concepts (continued)

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.
- Three 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 a *signal handler*.
 - » Akin to a hardware exception handler being called in response to an asynchronous interrupt.

Signal Concepts (continued)

A signal is **pending** if it has been 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.

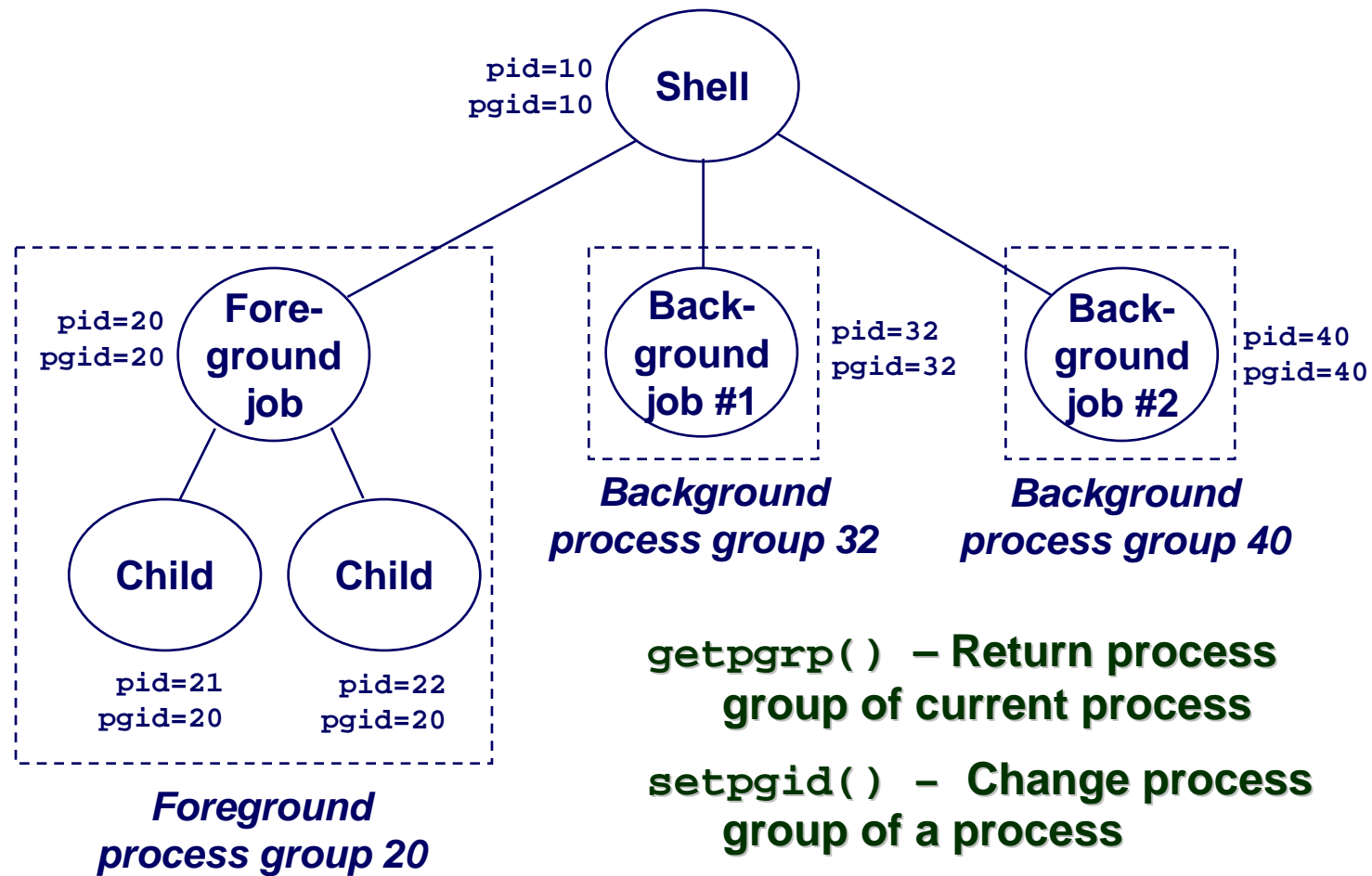
Signal Concepts

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` whenever a signal of type `k` is delivered.
 - Kernel clears bit `k` in `pending` whenever a signal of type `k` is received
- `blocked` – represents the set of blocked signals
 - Can be set and cleared by the application using the `sigprocmask` function.

Process Groups

Every process belongs to exactly one process group



Sending Signals with `kill` Program

`kill` program sends arbitrary signal to a process or process group

Examples

- `kill -9 24818`
 - Send SIGKILL to process 24818
- `kill -9 -24817`
 - Send SIGKILL to every process in process group 24817.

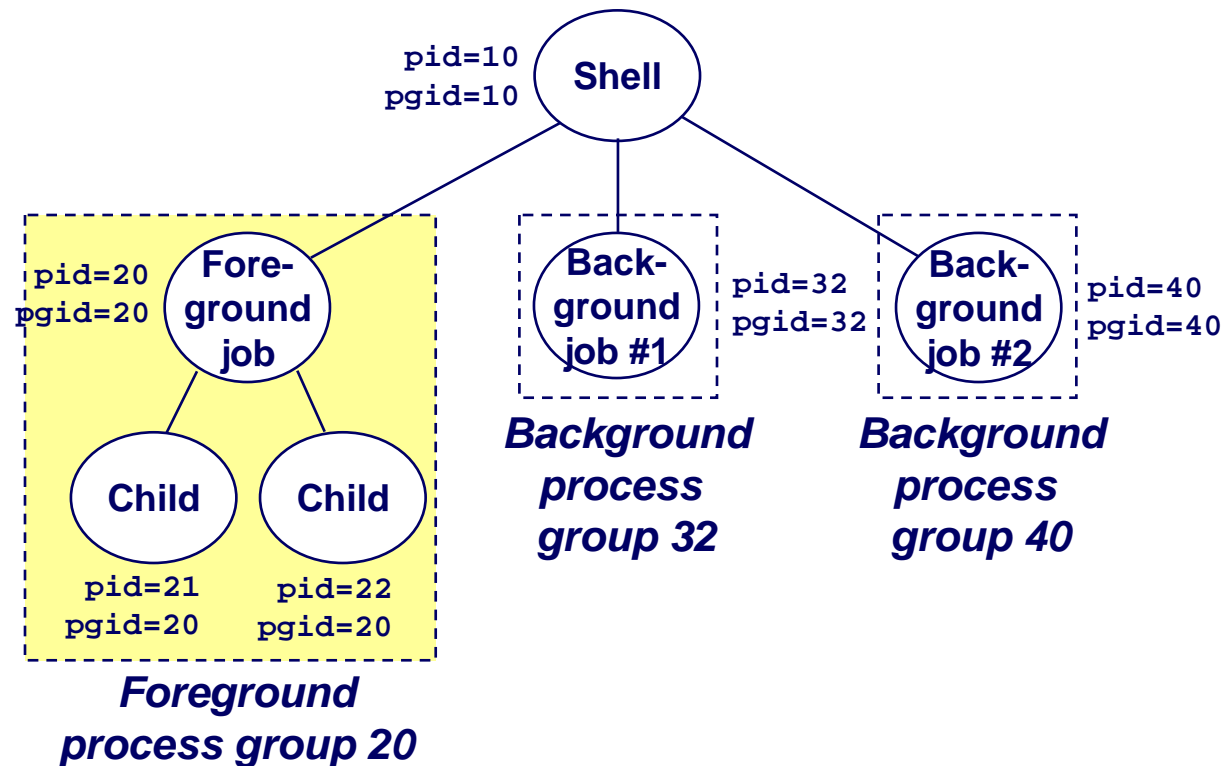
```
linux> ./forks 16
linux> Child1: pid=24818 pgrp=24817
Child2: pid=24819 pgrp=24817

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> kill -9 -24817
linux> ps
  PID TTY          TIME CMD
 24788 pts/2        00:00:00 tcsh
 24823 pts/2        00:00:00 ps
linux>
```

Sending Signals from the Keyboard

Typing ctrl-c (ctrl-z) sends a SIGINT (SIGTSTP) to every job in the foreground process group.

- SIGINT – default action is to terminate each process
- SIGTSTP – default action is to stop (suspend) each process



Example of `ctrl-c` and `ctrl-z`

```
bluefish> ./forks 17
Child: pid=28108 pgrp=28107
Parent: pid=28107 pgrp=28107
<types ctrl-z>
Suspended
bluefish> ps w
  PID TTY          STAT       TIME COMMAND
 27699 pts/8        Ss          0:00 -tcsh
 28107 pts/8        T           0:01 ./forks 17
 28108 pts/8        T           0:01 ./forks 17
 28109 pts/8        R+          0:00 ps w
bluefish> fg
./forks 17
<types ctrl-c>
bluefish> ps w
  PID TTY          STAT       TIME COMMAND
 27699 pts/8        Ss          0:00 -tcsh
 28110 pts/8        R+          0:00 ps w
```

STAT (process state)
Legend:

First letter:
S: sleeping
T: stopped
R: running

Second letter:
s: session leader
+: foreground proc group

See “man ps” for more
details

Sending Signals with `kill` Function

```
void fork12()
{
    pid_t pid[N];
    int i, child_status;
    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++) {
        pid_t wpid = wait(&child_status);
        if (WIFEXITED(child_status))
            printf("Child %d terminated with exit status %d\n",
                wpid, WEXITSTATUS(child_status));
        else
            printf("Child %d terminated abnormally\n", wpid);
    }
}
```


Receiving Signals

Suppose kernel is returning from an exception handler and is ready to pass control to process p .

Kernel computes $pnb = pending \ \& \ \sim blocked$

- 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 terminates and dumps core.
- The process stops until restarted by a SIGCONT signal.
- The process ignores the signal.

Installing Signal Handlers

The `signal` function modifies the default action associated with the receipt of signal `signum`:

■ `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 *signal handler*
 - Called when process receives signal of type `signum`
 - Referred to as “*installing*” the handler.
 - Executing handler is called “*catching*” or “*handling*” the signal.
 - When the handler executes its return statement, control passes back to instruction in the control flow of the process that was interrupted by receipt of the signal.

Signal Handling Example

```
void int_handler(int sig)
{
    printf("Process %d received signal %d\n",
           getpid(), sig);
    exit(0);
}
```

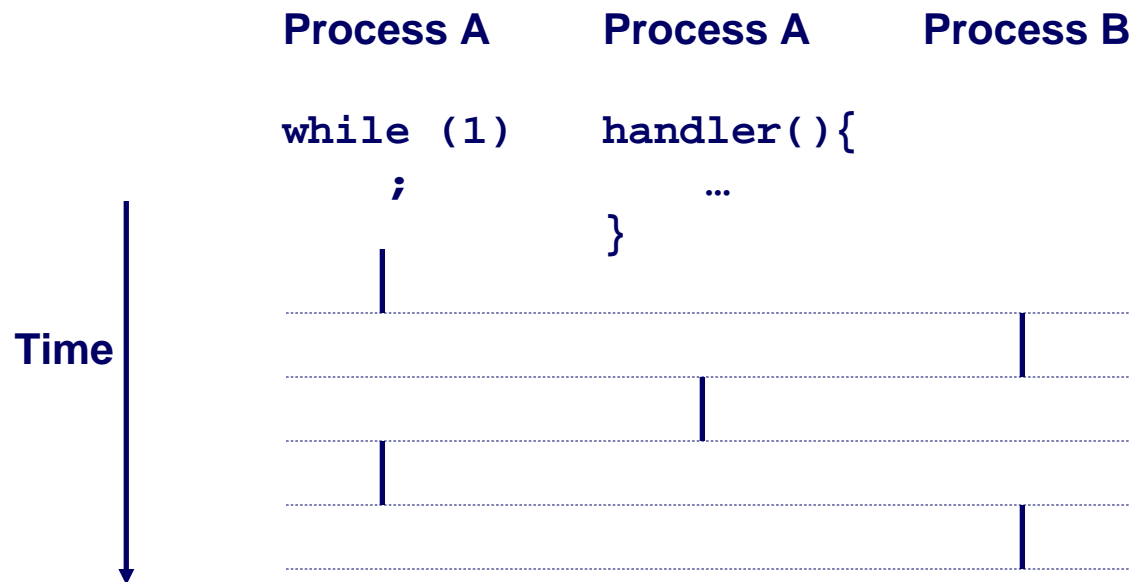
```
void fork13()
{
    pid_t pid[N];
    int i, child_status;
    signal(SIGINT, int_handler);

    . . .
}
```

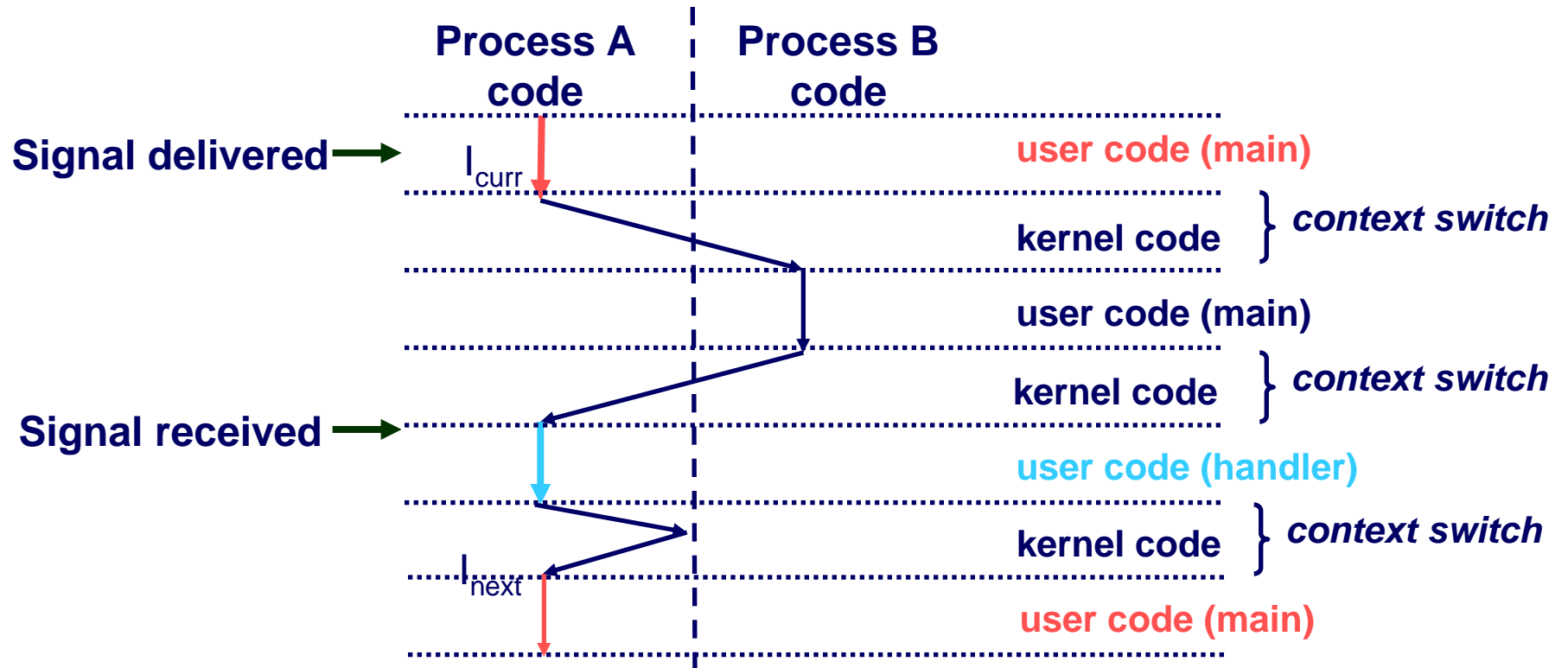
```
linux> ./forks 13
Killing process 24973
Killing process 24974
Killing process 24975
Killing process 24976
Killing process 24977
Process 24977 received signal 2
Child 24977 terminated with exit status 0
Process 24976 received signal 2
Child 24976 terminated with exit status 0
Process 24975 received signal 2
Child 24975 terminated with exit status 0
Process 24974 received signal 2
Child 24974 terminated with exit status 0
Process 24973 received signal 2
Child 24973 terminated with exit status 0
linux>
```

Signals Handlers as Concurrent Flows

A signal handler is a separate logical flow (thread) that runs concurrently with the main program.



Another View of Signal Handlers as Concurrent Flows



Signal Handler Funkiness

```
int ccount = 0;
void child_handler(int sig)
{
    int child_status;
    pid_t pid = wait(&child_status);
    ccount--;
    printf("Received signal %d from process %d\n",
          sig, pid);
}

void fork14()
{
    pid_t pid[N];
    int i, child_status;
    ccount = N;
    signal(SIGCHLD, child_handler);
    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0) {
            sleep(1); /* deschedule child */
            exit(0); /* Child: Exit */
        }
    while (ccount > 0)
        pause(); /* Suspend until signal occurs */
}
```

Pending signals are not queued

- For each signal type, just have single bit indicating whether or not signal is pending
- Even if multiple processes have sent this signal

Living With Nonqueuing 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--;
        printf("Received signal %d from process %d\n", sig, pid);
    }
}

void fork15()
{
    . . .
    signal(SIGCHLD, child_handler2);
    . . .
}
```


Signal Handler Funkiness (Cont.)

Signal arrival during long system calls (say a `read`)

- **Signal handler interrupts `read()` call**
 - Linux: upon return from signal handler, the `read()` call is restarted automatically
 - Some other flavors of Unix can cause the `read()` call to fail with an `EINTR` error number (`errno`)
in this case, the application program can restart the slow system call

Subtle differences like these complicate the writing of portable code that uses signals.

A Program That Reacts to Externally Generated Events (ctrl-c)

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

void handler(int sig) {
    printf("You think hitting ctrl-c will stop the bomb?\n");
    sleep(2);
    printf("Well...");
    fflush(stdout);
    sleep(1);
    printf("OK\n");
    exit(0);
}

main() {
    signal(SIGINT, handler); /* installs ctrl-c handler */
    while(1) {
    }
}
```

A Program That Reacts to Internally Generated Events

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

int beeps = 0;

/* SIGALRM handler */
void handler(int sig) {
    printf("BEEP\n");
    fflush(stdout);

    if (++beeps < 5)
        alarm(1);
    else {
        printf("BOOM!\n");
        exit(0);
    }
}
```

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

    while (1) {
        /* handler returns here */
    }
}
```

```
linux> a.out
BEEP
BEEP
BEEP
BEEP
BEEP
BOOM!
bass>
```

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 from jump buffer `j`
- Set `%eax` (the return value) to `i`
- Jump to the location indicated by the PC stored in jump buf `j`.

setjmp/longjmp Example

```
#include <setjmp.h>
jmp_buf buf;

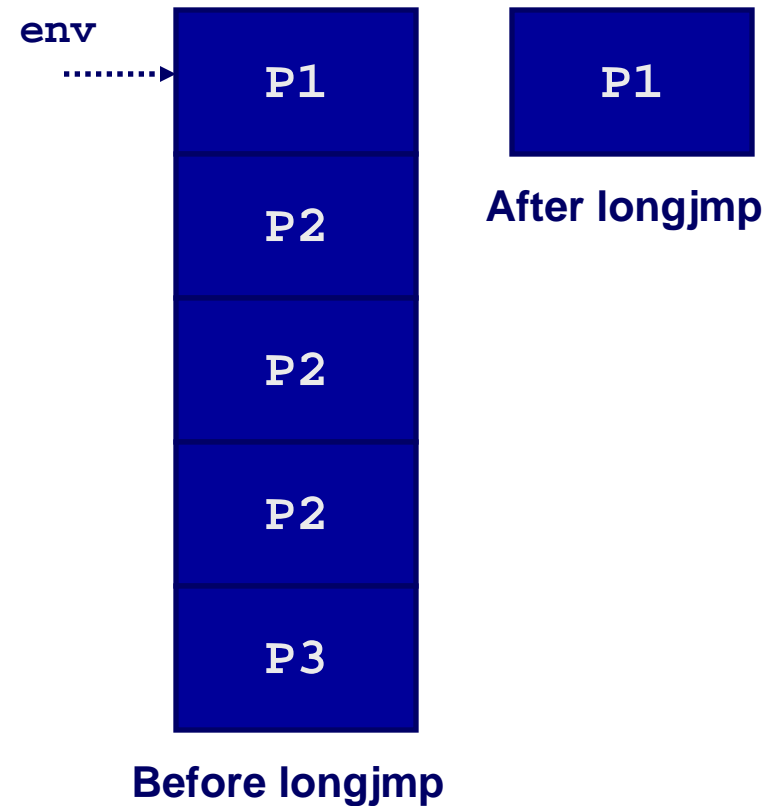
main() {
    if (setjmp(buf) != 0) {
        printf("back in main due to an error\n");
    } else {
        printf("first time through\n");
        p1(); /* p1 calls p2, which calls p3 */
    }
    ...
    p3() {
        <error checking code>
        if (error)
            longjmp(buf, 1)
    }
}
```

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);  
}
```



Limitations of Long Jumps (cont.)

Works within stack discipline

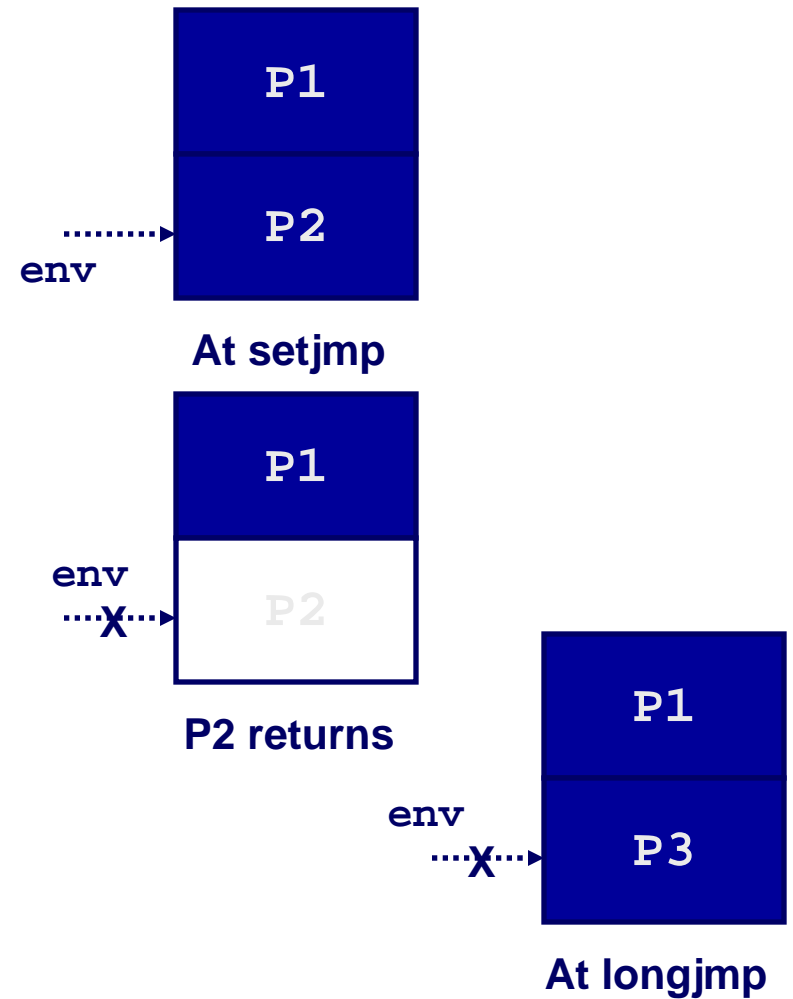
- Can only long jump to environment of function that has been called but not yet completed

```
jmp_buf env;

P1()
{
    P2(); P3();
}

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

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



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

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

sigjmp_buf buf;

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

main() {
    signal(SIGINT, handler);

    if (!sigsetjmp(buf, 1))
        printf("starting\n");
    else
        printf("restarting\n");
}
```

```
while(1) {
    sleep(1);
    printf("processing...\n");
}
}
```

```
bass> a.out
starting
processing...
processing...
restarting ← Ctrl-c
processing...
processing...
restarting ← Ctrl-c
processing...
```

Summary

Signals provide 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

Nonlocal jumps provide exceptional control flow within process

- Within constraints of stack discipline