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

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

- **[0]**
- **init [1]**
- **Daemon** e.g. `httpd`
- **Login shell**
- **Child**
  - **Child**
  - **Grandchild**
  - **Grandchild**

### The `ps` command

#### Unix `ps aux -w --forest` (output edited to fit slide)

<table>
<thead>
<tr>
<th>USER</th>
<th>PID</th>
<th>TTY</th>
<th>STAT</th>
<th>COMMAND</th>
</tr>
</thead>
<tbody>
<tr>
<td>root</td>
<td>2</td>
<td>?</td>
<td>SW</td>
<td>[keventd]</td>
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<td>SW</td>
<td>[kswapd]</td>
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<td>[mdrecoveryd]</td>
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<td>S</td>
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<td>S</td>
<td>sshd</td>
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<td>/usr/bin/sh</td>
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### The `ps` Command (cont.)

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<th>STAT</th>
<th>COMMAND</th>
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<td>SW</td>
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<td>/usr/local/libexec/kde</td>
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<td>root</td>
<td>1020</td>
<td>tty1</td>
<td>S</td>
<td>/usr/local/libexec/kde</td>
</tr>
</tbody>
</table>

### 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

CPU

0xffffffff
0x00000000

BIOS ROM

0x00007c00
0x00000000

BIOS verifies MBR and jumps to 0x00007c00

LILO (or GRUB) is loaded from first sector of active partition

CPU executes LILO

The Linux kernel is loaded and begins initialization
Unix Startup: Step 2

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

/etc/inittab
init [1]
Daemons e.g. ftpd, httpd
getty

Unix Startup: Step 3

The getty process execs a login program

init [1]
login

Unix Startup: Step 4

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

Shell Programs

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

- sh – Original Unix Bourne Shell
- csh – BSD Unix C Shell, tcsh – Enhanced C Shell
- bash – 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

```c
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);
            }
        }
        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.

<table>
<thead>
<tr>
<th>ID</th>
<th>Name</th>
<th>Default Action</th>
<th>Corresponding Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>SIGINT</td>
<td>Terminate</td>
<td>Interrupt from keyboard (ctl-c)</td>
</tr>
<tr>
<td>9</td>
<td>SIGKILL</td>
<td>Terminate</td>
<td>Kill program (cannot override or ignore)</td>
</tr>
<tr>
<td>11</td>
<td>SIGSEGV</td>
<td>Terminate &amp; Dump</td>
<td>Segmentation violation</td>
</tr>
<tr>
<td>14</td>
<td>SIGALRM</td>
<td>Terminate</td>
<td>Timer signal</td>
</tr>
<tr>
<td>17</td>
<td>SIGCHLD</td>
<td>Ignore</td>
<td>Child stopped or terminated</td>
</tr>
</tbody>
</table>
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.

getpgrp() – Return process group of current process
setpgid() – Change process group of a process
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.

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

linux> ps
  PID  TTY          TIME CMD
  24788 pts/2    00:00:00 tcsh
  24818 pts/2    00:00:02 forks
  24819 pts/2    00:00:02 forks

linux> kill -9 -24817

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

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

```
Foreground

<table>
<thead>
<tr>
<th>Shell</th>
<th>Background job #1</th>
<th>Background job #2</th>
<th>Background process group 32</th>
<th>Background process group 40</th>
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<tr>
<td>ppid=10</td>
<td>ppid=20</td>
<td>ppid=32</td>
<td>ppid=20</td>
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<td>Child</td>
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<td>ppid=22</td>
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<td>ppid=20</td>
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<tr>
<td>process group 20</td>
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<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

```

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  S  00:00 -tcsh
  28107 pts/8  T  01:00 .forks 17
  28108 pts/8  T  01:00 .forks 17
  28109 pts/8  R+ 00:00 ps w
  bluefish> fg
  <types forks 17
  <types ctrl-c>
  bluefish> ps w
  PID  TTY  STAT  TIME COMMAND
  27699 pts/8  S  00:00 -tcsh
  28110 pts/8  R+ 00:00 ps w
```

Sending Signals with `kill` Function

```c
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++)
        if ((pid[i] = fork()) == 0)
           printf("Killing process %d\n", pid[i]);
           kill(pid[i], SIGINT);
    /* Parent reaps terminated children */
    for (i = 0; i < N; i++)
       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 the kernel is returning from an exception handler and is ready to pass control to process $p$.

Kernel computes $\text{pnb} = \text{pending} \& \sim \text{blocked}$
- The set of pending nonblocked signals for process $p$

If ($\text{pnb} == 0$)
- Pass control to next instruction in the logical flow for $p$.

Else
- Choose least nonzero bit $k$ in $\text{pnb}$ and force process $p$ to receive signal $k$.
- The receipt of the signal triggers some action by $p$
- Repeat for all nonzero $k$ in $\text{pnb}$.
- 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 $\text{signum}$:
- $\text{signal_t *signal(int signum, handler_t *handler)}$

Different values for $\text{handler}$:
- SIG_IGN: ignore signals of type $\text{signum}$
- SIG_DFL: revert to the default action on receipt of signals of type $\text{signum}$.
- Otherwise, $\text{handler}$ is the address of a signal handler
  - Called when process receives signal of type $\text{signum}$
  - Referred to as “installing” the handler.
  - Executing handler is called “catching” or “handling” the signal.
  - When the handler executes its return statement, control passes back to instruction in the control flow of the process that was interrupted by receipt of the signal.

Signal Handling Example

```c
void 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);
    ...
}
```

Excerpt from the output:
```bash
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
```
Signals Handlers as Concurrent Flows

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

```
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 */
}
```

Signal Handler Funkiness

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

```
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);
    . . .
}
```

Another View of Signal Handlers as Concurrent Flows

```
Process A code
user code (main)
```

Signal delivered ➡️
```
 Process A code
user code (main)
```

Context switch ➡️
```
Process B code
user code (main)
```

Signal received ➡️
```
 Process A code
user code (main)
```

Context switch ➡️
```
Process B code
user code (main)
```

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 **EINTER** 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)

```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 ctl-c handler */
    while(1) { }
}
```

---

A Program That Reacts to Internally Generated Events

```c
#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); /* sends SIGALRM in 1 second */
    while (1) {
        /* handler returns here */
    }
}
```

---

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

```c
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**

```c
#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

```c
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

```c
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 \texttt{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...
restarting
processing...
processing...
restarting
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