Shell and Exceptional Control Flows

Kai Shen

1

The World of Multiprogramming or Multitasking

- System runs many processes concurrently
- Process: executing program
  - State includes memory image + register values + program counter
- Regularly 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

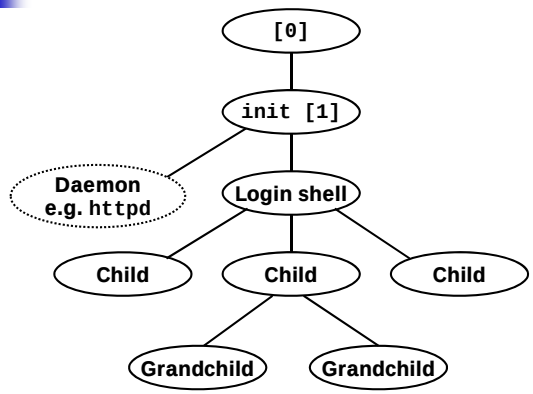
2

Management of Concurrent Processes

- 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
  - **`execve`** runs new program in existing process
    - Called once, (normally) never returns
- Programming challenge
  - Avoiding improper use of system resources (e.g. "Fork bombs" can disable a system)

3

Unix Process Hierarchy



4

Shell Programs

- A *shell* is a program that allows users run/control programs.
  - **sh** Original Unix shell (Stephen Bourne, AT&T Bell Labs, 1977)
  - **csh** BSD Unix C shell (**tcsh**: enhanced **csh** at CMU and elsewhere)
  - **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

5

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);
    }
}
```

6

What Is a "Background Job"?

- Users generally run one command at a time
  - Type command, read output, type another command
- Some programs run "for a long time"
  - Example: "delete this file in two hours"

```
unix> sleep 7200; rm /tmp/junk  # shell stuck for 2 hours
```

- A "background" job is a process we don't want to wait for

```
unix> (sleep 7200 ; rm /tmp/junk) &
[1] 907
unix> # ready for next command
```

7

Problem with Simple Shell Example

```
        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);
```

- Our 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
  - Will create a memory leak that could run the kernel out of memory
  - Modern Unix: once you exceed your process quota, your shell can't run any new commands for you: fork() returns -1

8

Exceptional Control Flow

- Problem
  - The shell doesn't know when a background job will finish
  - By nature, it could happen at any time
  - The shell's regular control flow can't reap exited background processes in a timely fashion
  - Regular control flow is "wait until running job completes, then reap it"
- Solution: Exceptional control flow
  - The kernel will interrupt regular processing to alert us when a background process completes
  - In Unix, the alert mechanism is called a ***signal***

9

Signals

- A *signal* is a small message that notifies a process that an event of some type has occurred in the system
  - akin to interrupts
  - sent from the kernel (sometimes at the request of another process) to a process
  - signal type is identified by small integer ID's (1-30)

ID	Name	Default Action	Corresponding Event
2	SIGINT	Terminate	Interrupt (e.g., ctl-c from keyboard)
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

10

Sending a Signal

- When is a signal sent?
  - A system event such as divide-by-zero (SIGFPE), segmentation violation (SIGSEGV), 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
- The operating system sends/delivers a signal

11

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

12

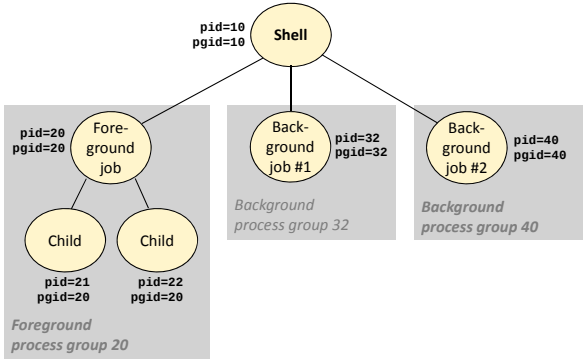
Pending and Blocked Signals

- A signal is *pending* if sent but not yet received
  - There can be at most one pending signal of any particular type
  - Important: Signals are not queued
    - If a process has a pending signal of type k, then subsequent signals of type k that are sent to that process are discarded
- A process can *block* the receipt of certain signals
  - Blocked signals can be delivered, but will not be received until the signal is unblocked

13

Process Groups

- Every process belongs to exactly one process group



14

Sending Signals with `kill`

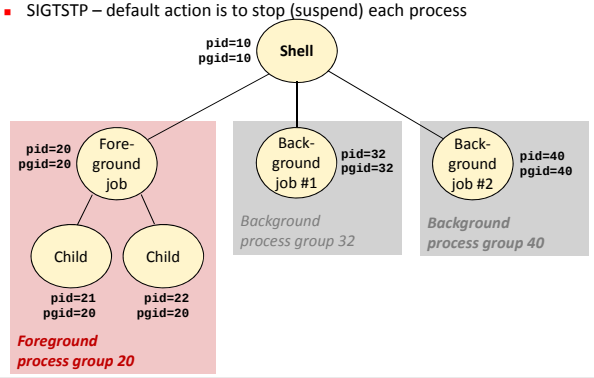
- `kill` program sends arbitrary signal to a process or process group
- Examples
  - `/bin/kill -9 24818`
    Send SIGKILL to process 24818
  - `/bin/kill -9 -24817`
    Send SIGKILL to every process in process group 24817

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

linux> ps
  PID TTY          TIME CMD
24788 pts/2    00:00:00 tcsh
24818 pts/2    00:00:02 forks
24819 pts/2    00:00:02 forks
24820 pts/2    00:00:00 ps
linux> /bin/kill -9 -24817
linux> ps
  PID TTY          TIME CMD
24788 pts/2    00:00:00 tcsh
24823 pts/2    00:00:00 ps
linux>
```

15

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



16

Sending Signals with `kill` Function

```
void fork_example()
{
    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);
    }
}
```

17

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

18

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

19

Signal Handling Example

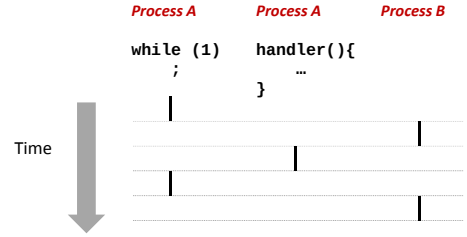
```
void int_handler(int sig) {
    safe_printf("Process %d received signal %d\n", getpid(), sig);
    exit(0);
}

void fork_example() {
    pid_t pid[N];
    int i, child_status;
    signal(SIGINT, int_handler);
    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0
            while(1); /* child inf
        }
    for (i = 0; i < N; i++) {
        printf("Killing process %d
        kill(pid[i], SIGINT);
    }
    for (i = 0; i < N; i++) {
        pid_t wpid = wait(&child_s
        if (WIFEXITED(child_status
            printf("Child %d termi
                   wpid, WEXITSTAT
        else
            printf("Child %d termi
    }
}
```

```
linux> ./forks
Killing process 25417
Killing process 25418
Killing process 25419
Killing process 25420
Killing process 25421
Process 25417 received signal 2
Process 25418 received signal 2
Process 25420 received signal 2
Process 25421 received signal 2
Process 25419 received signal 2
Child 25417 terminated with exit status 0
Child 25418 terminated with exit status 0
Child 25420 terminated with exit status 0
Child 25419 terminated with exit status 0
Child 25421 terminated with exit status 0
linux>
```

20

Signals Handlers as Concurrent Flows

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



- Are they really concurrent?
  - Where is the stack for signal handler?
  - Signal is “asynchronous”.
- You can have a dedicated signal handling stack.

21

Nonqueuing Signals

```
int ccount = 0;
void child_handler(int sig)
{
    int child_status;
    pid_t pid = wait(&child_status);
    ccount--;
    sleep(2);
}

void fork_example()
{
    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

22

More Signal Handler Funkiness

- 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

23

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");

  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> ./internal
BEEP
BEEP
BEEP
BEEP
BEEP
BOOM!
linux>
```

24

Asynchronous Signal Safety

- Function is *async-signal-safe* if
  - either reentrant (all variables stored on stack frame)
  - or non-interruptible by signals.
- Posix guarantees 117 functions to be async-signal-safe
  - **write** is on the list, **printf** is not
- One solution: async-signal-safe wrapper for **printf**:

```
void safe_printf(const char *format, ...) {
    char buf[MAXS];
    va_list args;

    va_start(args, format);                    /* reentrant */
    vsnprintf(buf, sizeof(buf), format, args); /* reentrant */
    va_end(args);                              /* reentrant */
    write(1, buf, strlen(buf));                /* async-signal-safe */
}
```

25

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

26

setjmp/longjmp (cont)

- **void longjmp(jmp_buf j, int i)**
  - Meaning:
    - return from the **setjmp** remembered by jump buffer **j** again ...
    - ... this time returning **i** instead of 0
  - Called after **setjmp**
  - Called once, but never returns
- **longjmp** Implementation:
  - Restore register context (stack pointer, base pointer, PC value) from jump buffer **j**
  - Set **%eax** (the return value) to **i**
  - Jump to the location indicated by the PC stored in jump buf **j**

27

setjmp/longjmp Example

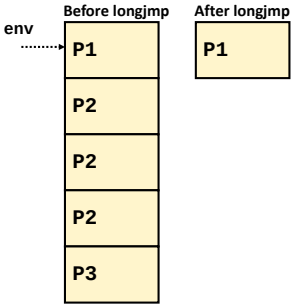
```
#include <setjmp.h>
jmp_buf buf;

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)
}
```

28

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);
}
```

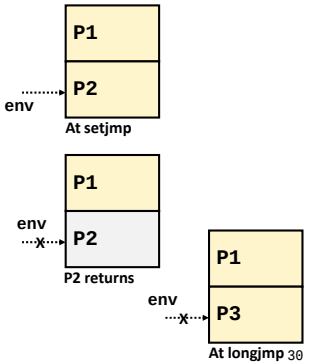


29

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);
}
```



30

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");
  }
}
```

restart.c

```
greatwhite> ./restart
starting
processing...
processing...
processing...
restarting
processing...        <-- Ctrl-c
processing...
restarting
processing...        <-- Ctrl-c
processing...
processing...
```

31

Summary

- Signals provide process-level exception handling
  - Can generate from user programs
  - Can define effect by declaring signal handler
- Some caveats
  - Far higher overhead than function call
  - 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

32

Disclaimer

These slides were adapted from the CMU course slides provided along with the textbook of “Computer Systems: A programmer’s Perspective” by Bryant and O’Hallaron. The slides are intended for the sole purpose of teaching the computer organization course at the University of Rochester.

33