15-213

"The course that gives CMU its Zip!"

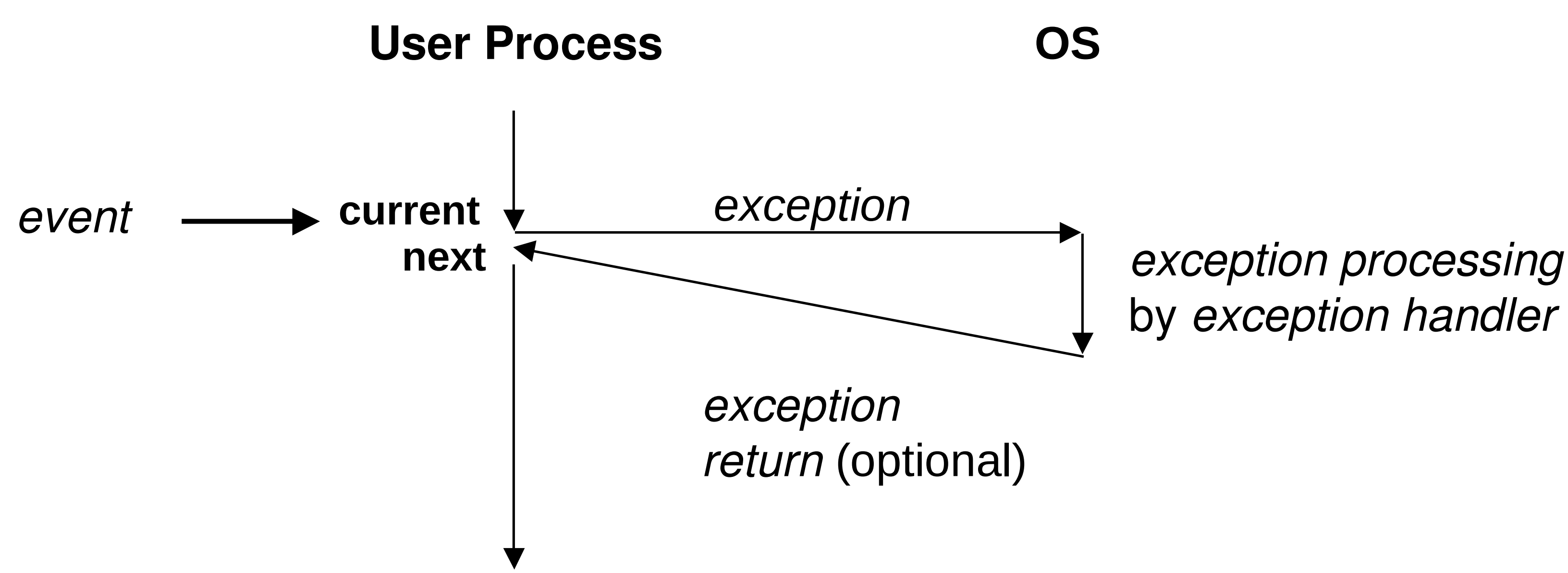
Exceptional Control Flow II
Oct 23, 2001

Topics

- Exceptions
- Process context switches

Exceptions

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



Role of Exceptions

Error Handling

- **Error conditions detected by hardware and/or OS**
  - Divide by zero
  - Invalid pointer reference

Getting Help from OS

- **Initiate I/O operation**
- **Fetch memory page from disk**

Process Management

- **Create illusion that running many programs and services simultaneously**

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()` replace state of existing process with that of newly started program**
  - Called once, never returns

Programming Challenge

- **Understanding the nonstandard semantics of the functions**
- **Avoiding improper use of system resources**
  - Fewer safeguards provided

Fork Example #4

Key Points

- **Both parent and child can continue forking**

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

Fork Example #5

Key Points

- Both parent and child can continue forking

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

Zombie Example

```
void fork7()
{
    if (fork() == 0) {
        /* Child */
        printf("Terminating Child, PID = %d\n",
               getpid());
        exit(0);
    } else {
        printf("Running Parent, PID = %d\n",
               getpid());
        while (1)
            ; /* Infinite loop */
    }
}
```

```
linux> ./forks 7 &
[1] 6639
Running Parent, PID = 6639
Terminating Child, PID = 6640
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6639 ttyp9    00:00:03 forks
 6640 ttyp9    00:00:00 forks <defunct>
 6641 ttyp9    00:00:00 ps
linux> kill 6639
[1]    Terminated
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6642 ttyp9    00:00:00 ps
```

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

Nonterminating Child Example

```
void fork8()
{
    if (fork() == 0) {
        /* Child */
        printf("Running Child, PID = %d\n",
               getpid());
        while (1)
            ; /* Infinite loop */
    } else {
        printf("Terminating Parent, PID = %d\n",
               getpid());
        exit(0);
    }
}
```

```
linux> ./forks 8
Terminating Parent, PID = 6675
Running Child, PID = 6676
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6676 ttyp9    00:00:06 forks
 6677 ttyp9    00:00:00 ps
linux> kill 6676
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6678 ttyp9    00:00:00 ps
```

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

Exec Example

Task

- **Sort a set of files**
- **E.g., `./sortfiles f1.txt f2.txt f3.txt`**
- **Perform concurrently**
  - Using Unix `sort` command
  - Commands of form

  `sort f1.txt -o f1.txt`

Steps

- **Invoke a process for each file**
- **Complete by waiting for all processes to complete**

```
#include <stdlib.h>
#include <stdio.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>

int main(int argc, char *argv[])
{
    int cnt = invoke(argc, argv);
    complete(cnt);
    return 0;
}
```

Exec Example (cont.)

- Use `fork` and `execl` to spawn set of sorting processes

```
int invoke(int argc, char *argv[])
{
    int i;
    for (i = 1; i < argc; i++) {
        /* Fork off a new process */
        if (fork() == 0) {
            /* Child: Invoke sort program */
            printf("Process %d sorting file %s\n", getpid(), argv[i]);
            if (execl("/bin/sort", "sort",
                      argv[i], "-o", argv[i], 0) < 0) {
                perror("sort");
                exit(1);
            }
            /* Never reach this point */
        }
    }
    return argc-1;
}
```

Exec Example (cont.)

- Use `wait` to wait for and reap terminating children

```
void complete(int cnt)
{
    int i, child_status;
    for (i = 0; i < cnt; i++) {
        pid_t wpid = wait(&child_status);
        if (WIFEXITED(child_status))
            printf("Process %d completed with status %d\n",
                   wpid, WEXITSTATUS(child_status));
        else
            printf("Process %d terminated abnormally\n", wpid);

    }
}
```

Signals

Signals

- **Software events generated by OS and processes**
  - an OS abstraction for exceptions and interrupts
- **Sent from the kernel or a process to other processes.**
- **Different signals are identified by small integer ID’s**
- **Only information in a signal is its ID and the fact that it arrived.**

Num.	Name	Default	Description
2	`SIGINT`	Terminate	Interrupt from keyboard (cntl-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

Sending Signals

Unix `kill` Program

- **Sends arbitrary signal to process**
- **e.g., `/bin/kill -s 9 pid`**
  - sends `SIGKILL` to specified process

Function `kill`

- **Send signal to another process**

`kill(pid, signal)`

```
linux> ./forks 8
Terminating Parent, PID = 6675
Running Child, PID = 6676
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6676 ttyp9    00:00:06 forks
 6677 ttyp9    00:00:00 ps
linux> /bin/kill -s 9 6676
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6678 ttyp9    00:00:00 ps
```

Kill Example

```
void fork12()
{
    pid_t pid[N];
    int i;
    int child_status;
    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0) {
            /* Child: Infinite Loop */
            while(1);
        }
    for (i = 0; i < N; i++) {
        printf("Killing process %d\n", pid[i]);
        kill(pid[i], SIGINT);
    }
    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);
    }
}
```

- **Use kill to forcibly terminate children**

Handling Signals

Every Signal Type has Default Behavior

- Typically terminate or ignore

Can Override by Declaring Special Signal Handler Function

- `signal(sig, handler)`
  - Indicates that signals of type `sig` should invoke function `handler`
  - Handler returns to point where exception occurred

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

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) {
            /* Child: Exit */
            exit(0);
        }
    while (ccount > 0)
        pause();/* Suspend until signal occurs */
}
```

Signals are not Queued

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

Living with Nonqueuing Signals

Must Check for All Possible Signal Sources

- Typically loop with `wait`

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

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

A program that reacts to externally generated events (ctrl-c)

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

static 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

```
#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 */
  }
}
```

```
bass> 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

`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
- **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)
}
```

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");
  }
}
```

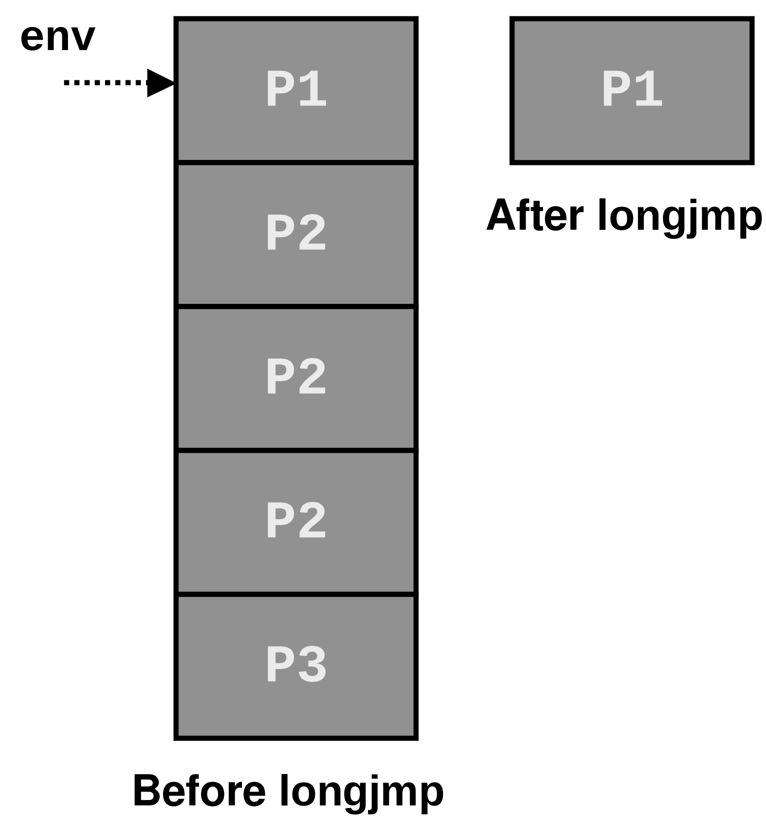
```
bass> a.out
starting
processing...
processing...
restarting       Ctrl-c
processing...
processing...
processing...
restarting       Ctrl-c
processing...
restarting       Ctrl-c
processing...
processing...
```

Limitations of Long 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);
}
```

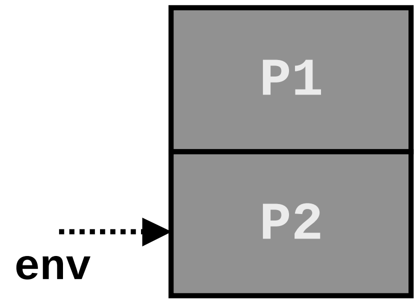


Limitations of Long Jumps (cont.)

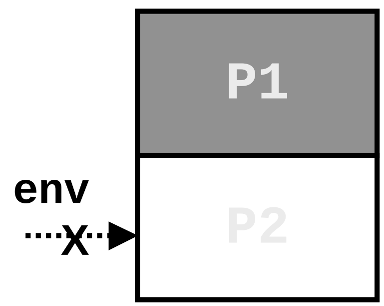
Works Within Stack Discipline

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

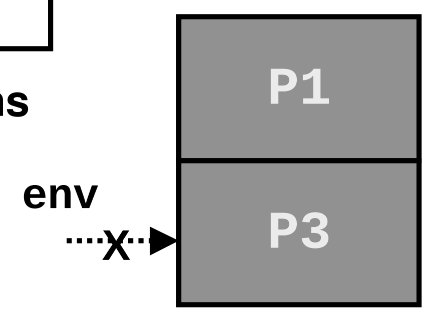
```
jmp_buf env;

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

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

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



At setjmp



P2 returns



At longjmp

Summary

Signals Provide Process-Level Exception Handling

- **Can generate with `kill`**
- **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 of status for each signal type

Long Jumps Provide Exceptional Control Flow Within Process

- **Within constraints of stack discipline**