Exceptional Control Flow

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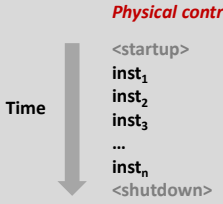
Your instructor: Stephen McCamant

Based on slides originally by:
Randy Bryant, Dave O'Hallaron, Antonia Zhai

Control Flow

- **Processors do only one thing:**
  - From startup to shutdown, a CPU simply reads and executes (interprets) a sequence of instructions, one at a time
  - This sequence is the CPU's *control flow* (or *flow of control*)



Altering the Control Flow

- **Up to now: two mechanisms for changing control flow:**
  - Jumps and branches
  - Call and return

  Both react to changes in ***program state***
- **Insufficient for a useful system:**
  Difficult to react to changes in *system state*
  - data arrives from a disk or a network adapter
  - instruction divides by zero
  - user hits Ctrl-C at the keyboard
  - System timer expires
- **System needs mechanisms for "exceptional control flow"**

Exceptional Control Flow

- **Exists at all levels of a computer system**
- **Low level mechanisms**
  - Exceptions
    - change in control flow in response to a system event (i.e., change in system state)
  - Combination of hardware and OS software
- **Higher level mechanisms**
  - Process context switch
  - Signals
  - Nonlocal jumps: setjmp()/longjmp()
  - Implemented by either:
    - OS software (context switch and signals)
    - C language runtime library (nonlocal jumps)

Today

- **Non-local Jumps**
- Hardware Exceptions

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 (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`**

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

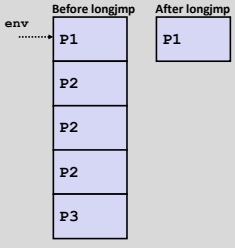
- **Works within stack discipline**
  - Can only long jump to environment of function that has been called but not yet completed

```
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.)

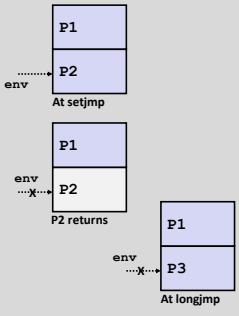
- **Works within stack discipline**
  - Can only long jump to environment of function that has been called but not yet completed

```
jmp_buf env;

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

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

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

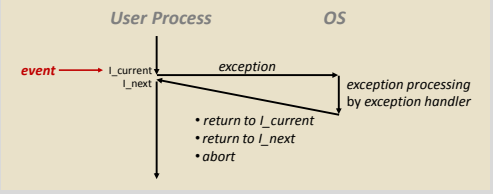


Today

- Non-local Jumps
- **Hardware Exceptions**

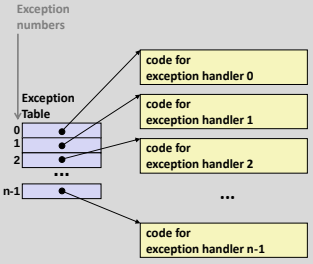
Exceptions

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



- **Examples:**
  div by 0, arithmetic overflow, page fault, I/O request completes, Ctrl-C

Interrupt Vectors



- Each type of event has a unique exception number k
- k = index into exception table (a.k.a. interrupt vector)
- Handler k is called each time exception k occurs

13

Asynchronous Exceptions (Interrupts)

- **Caused by events external to the processor**
  - Indicated by setting the processor's interrupt pin
  - Handler returns to "next" instruction
- **Examples:**
  - I/O interrupts
    - hitting Ctrl-C at the keyboard
    - arrival of a packet from a network
    - arrival of data from a disk
  - Hard reset interrupt
    - hitting the reset button
  - Soft reset interrupt
    - hitting Ctrl-Alt-Delete on a PC

14

Synchronous Exceptions

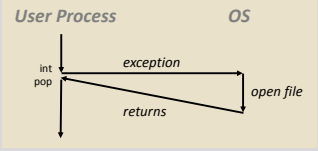
- **Caused by events that occur as a result of executing an instruction:**
  - ***Traps***
    - Intentional
    - Examples: ***system calls***, breakpoint traps, special instructions
    - Returns control to "next" instruction
  - ***Faults***
    - Unintentional but possibly recoverable
    - Examples: page faults (recoverable), protection faults (unrecoverable), floating point exceptions
    - Either re-executes faulting ("current") instruction or aborts
  - ***Aborts***
    - unintentional and unrecoverable
    - Examples: parity error, machine check
    - Aborts current program

15

Trap Example: Opening File

- User calls: `open(filename, options)`
- Function `open` executes system call instruction `int`

```
0804d070 <__libc_open>:
 . . .
 804d082:       cd 80                   int    $0x80
 804d084:       5b                      pop    %ebx
 . . .
```



- OS must find or create file, get it ready for reading or writing
- Returns integer file descriptor

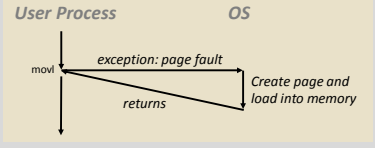
16

Fault Example: Page Fault

- User writes to memory location
- That portion (page) of user's memory is currently on disk

```
int a[1000];
main ()
{
    a[500] = 13;
}
```

```
80483b7:      c7 05 10 9d 04 08 0d   movl   $0xd,0x8049d10
```



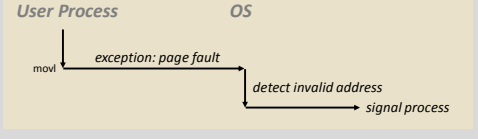
- Page handler must load page into physical memory
- Returns to faulting instruction
- Successful on second try

17

Fault Example: Invalid Memory Reference

```
int a[1000];
main ()
{
    a[5000] = 13;
}
```

```
80483b7:      c7 05 60 e3 04 08 0d   movl   $0xd,0x804e360
```



- Page handler detects invalid address
- Sends `SIGSEGV` signal to user process
- User process exits with "segmentation fault"

18

Exception Table IA32 (Excerpt)

Exception Number	*Description*	*Exception Class*
0	Divide error	Fault
13	General protection fault	Fault
14	Page fault	Fault
18	Machine check	Abort
32-127	OS-defined	Interrupt or trap
128 (0x80)	System call	Trap
129-255	OS-defined	Interrupt or trap

Check Table 6-1:
http://download.intel.com/design/processor/manuals/253665.pdf

19

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...
```

20

Summary

- **Nonlocal jumps provide exceptional control flow within process**
  - Within constraints of stack discipline
- **Exceptions**
  - Events that require nonstandard control flow
  - Generated externally (interrupts) or internally (traps and faults)

21