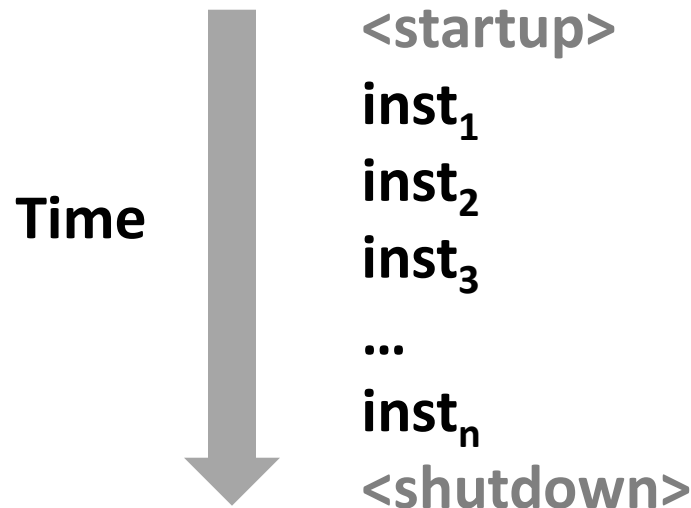


Control Flow

■ 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*)

Physical control flow



Altering the Control Flow

- **Up to now: two mechanisms for changing control flow:**

- Jumps and branches
- Call and return

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”**



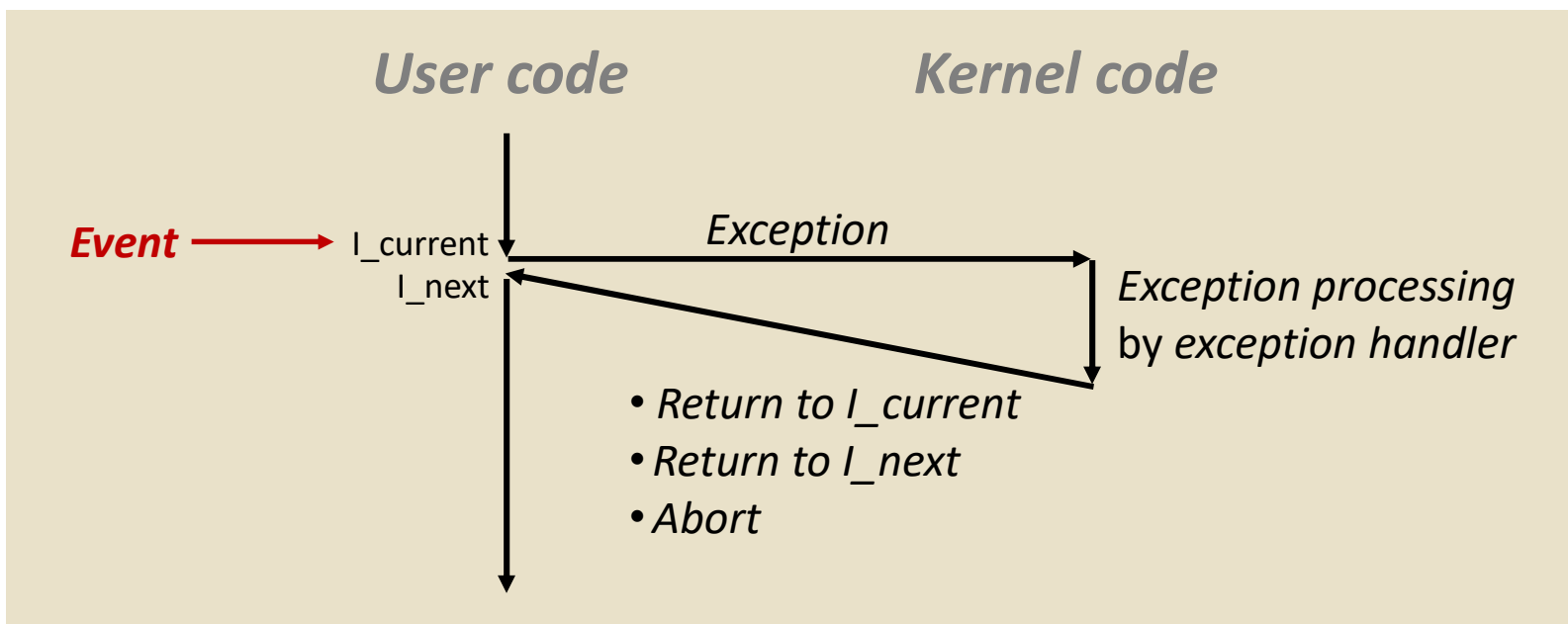
Exceptional Control Flow

- **Exists at all levels of a computer system**
- **Low level mechanisms**
 - 1. **Exceptions**
 - Change in control flow in response to a system event (i.e., change in system state)
 - Implemented using combination of hardware and OS software
- **Higher level mechanisms**
 - 2. **Process context switch**
 - Implemented by OS software and hardware timer
 - 3. **Signals**
 - Implemented by OS software
 - 4. **Nonlocal jumps**: `setjmp()` and `longjmp()`
 - Implemented by C runtime library

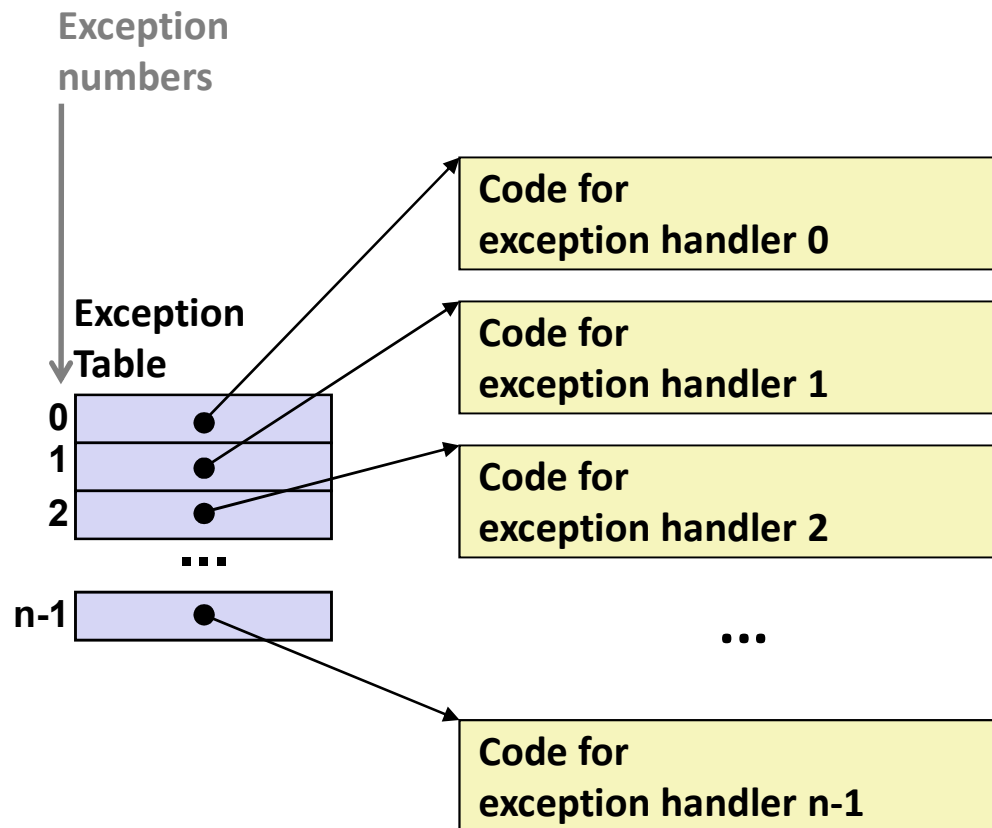


Exceptions

- An **exception** is a transfer of control to the OS *kernel* in response to some *event* (i.e., change in processor state)
 - Kernel is the memory-resident part of the OS
 - Examples of events: Divide by 0, arithmetic overflow, page fault, I/O request completes, typing Ctrl-C



Exception Tables



- 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



Asynchronous Exceptions (Interrupts)

- **Caused by events external to the processor**

- Indicated by setting the processor's *interrupt pin*
- Handler returns to “next” instruction

- **Examples:**

- Timer interrupt
 - Every few ms, an external timer chip triggers an interrupt
 - Used by the kernel to take back control from user programs
- I/O interrupt from external device
 - Hitting Ctrl-C at the keyboard
 - Arrival of a packet from a network
 - Arrival of data from a disk



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: illegal instruction, parity error, machine check
 - Aborts current program



System Calls

- Each x86-64 system call has a unique ID number
- Examples:

<i>Number</i>	<i>Name</i>	<i>Description</i>
0	read	Read file
1	write	Write file
2	open	Open file
3	close	Close file
4	stat	Get info about file
57	fork	Create process
59	execve	Execute a program
60	_exit	Terminate process
62	kill	Send signal to process



System Call Example: Opening File

- User calls: `open(filename, options)`
- Calls `__open` function, which invokes system call instruction `syscall`

```
0000000000e5d70 <__open>:
```

```
...
```

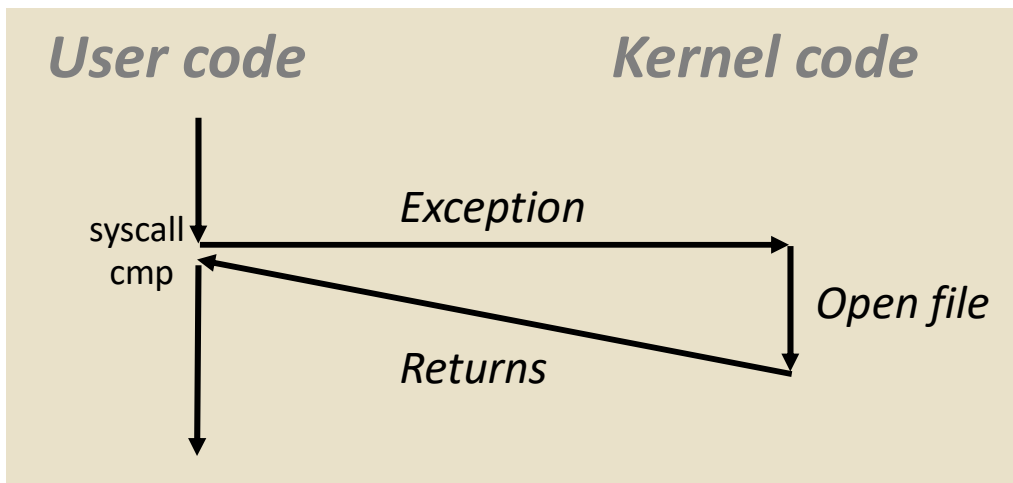
```
e5d79: b8 02 00 00 00    mov $0x2,%eax # open is syscall #2
```

```
e5d7e: 0f 05            syscall      # Return value in %rax
```

```
e5d80: 48 3d 01 f0 ff ff  cmp $0xfffffffffff001,%rax
```

```
...
```

```
e5dfa: c3              retq
```



- `%rax` contains syscall number
- Other arguments in `%rdi`, `%rsi`, `%rdx`, `%r10`, `%r8`, `%r9`
- Return value in `%rax`
- Negative value is an error corresponding to negative `errno`

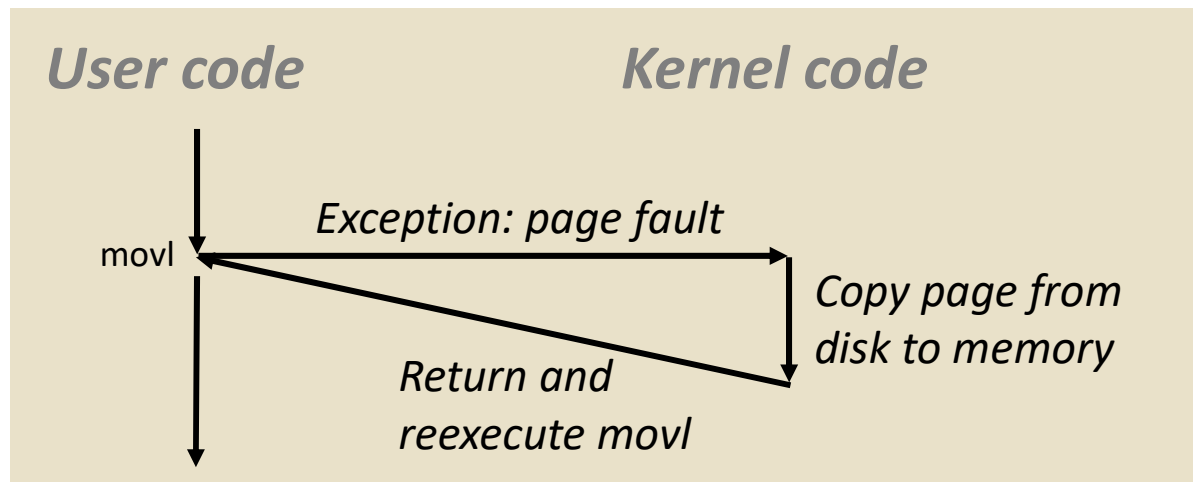


Fault Example: Page Fault

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

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

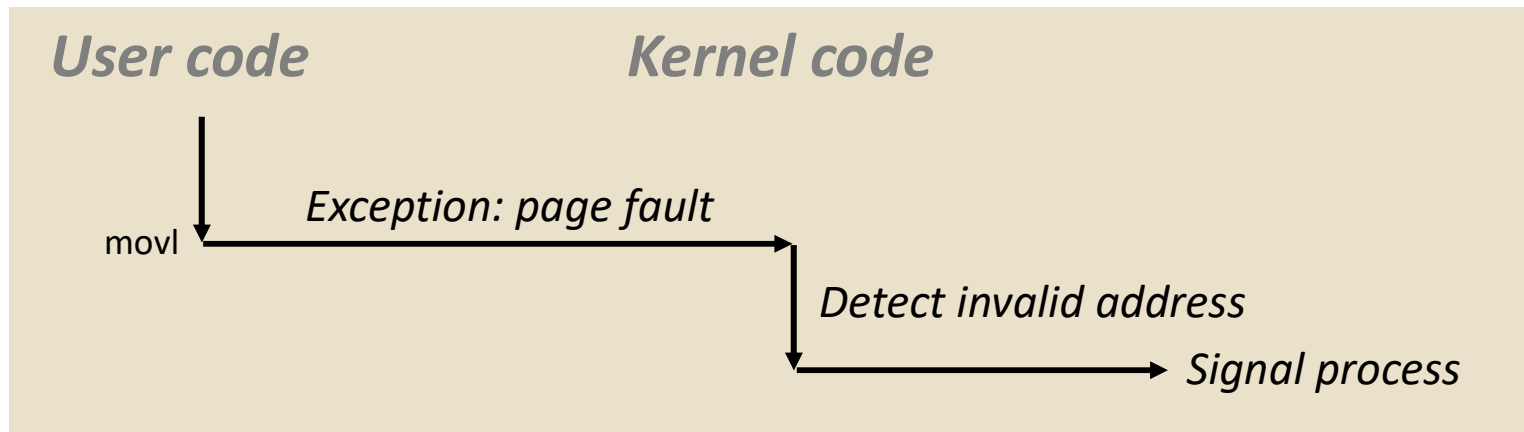
80483b7:	c7 05 10 9d 04 08 0d	movl	\$0xd,0x8049d10
----------	----------------------	------	-----------------



Fault Example: Invalid Memory Reference

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

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



- Sends **SIGSEGV** signal to user process
- User process exits with “segmentation fault”

