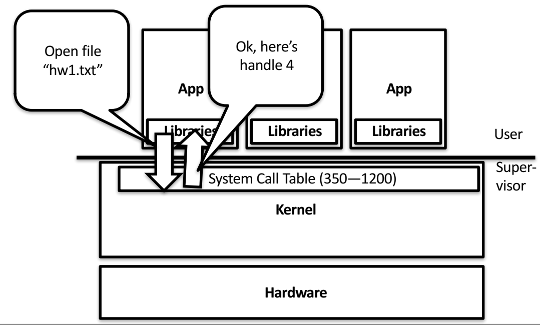
Interrupts and System Calls

Don Porter

First lecture…



Today's goal: Key OS building block

- Understand how system calls work
  - As well as how exceptions (e.g., divide by zero) work
- Understand the hardware tools available for irregular control flow.
  - I.e., things other than a branch in a running program
- Building blocks for context switching, device management, etc.

Background: Control Flow

pc

```
// x = 2, y = true
if (y) {
    2 /= x;
    printf(x);
} //...
```

```
void printf(va_args)
{
    //...
}
```

Regular control flow: branches and calls (logically follows source code)

Background: Control Flow

pc

```
// x = 0, y = true
if (y) {
    2 /= x;
    printf(x);
} //...
```

Divide by zero! Program can't make progress!

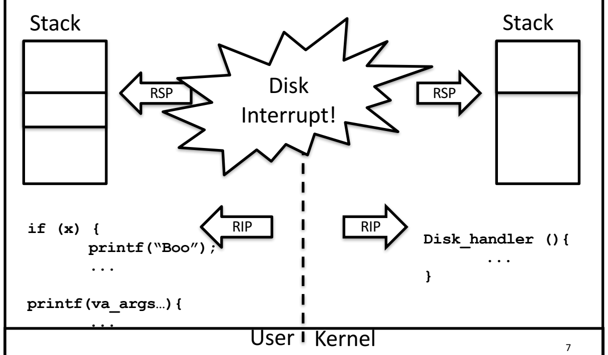
```
void handle_divzero(){
    x = 2;
}
```

Irregular control flow: exceptions, system calls, etc.

Two types of interrupts

- Synchronous: will happen every time an instruction executes (with a given program state)
  - Divide by zero
  - System call
  - Bad pointer dereference
- Asynchronous: caused by an external event
  - Usually device I/O
  - Timer ticks (well, clocks can be considered a device)

Asynchronous Interrupt Example



Intel nomenclature

- Interrupt – only refers to asynchronous interrupts
- Exception – synchronous control transfer

- Note: from the programmer's perspective, these are handled with the same abstractions

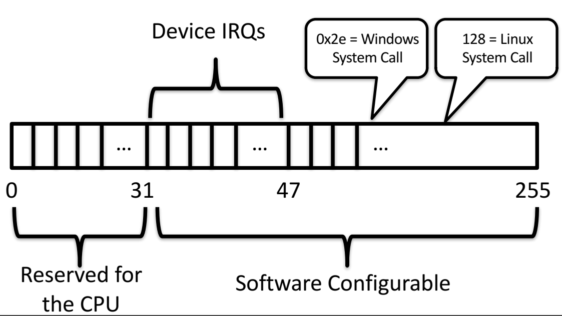
Lecture outline

- Overview
- How interrupts work in hardware
- How interrupt handlers work in software
- How system calls work
- New system call hardware on x86

Interrupt overview

- Each interrupt or exception includes a number indicating its type
- E.g., 14 is a page fault, 3 is a debug breakpoint
- This number is the index into an interrupt table

x86 interrupt table



x86 interrupt overview

- Each type of interrupt is assigned an index from 0—255.
- 0—31 are for processor interrupts; generally fixed by Intel
  - E.g., 14 is always for page faults
- 32—255 are software configured
  - 32—47 are for device interrupts (IRQs) in JOS
    - Most device's IRQ line can be configured
    - Look up APICs for more info (Ch 4 of Bovet and Cesati)
  - 0x80 issues system call in Linux (more on this later)

Software interrupts

- The `int <num>` instruction allows software to raise an interrupt
  - 0x80 is just a Linux convention. JOS uses 0x30
- There are a lot of spare indices
  - You could have multiple system call tables for different purposes or types of processes!
    - Windows does: one for the kernel and one for win32k

Software interrupts, cont

- OS sets ring level required to raise an interrupt
  - Generally, user programs can't issue an `int 14` (page fault) manually
  - An unauthorized `int` instruction causes a general protection fault
    - Interrupt 13

What happens (high level):

- Control jumps to the kernel
  - At a prescribed address (the interrupt handler)
- The register state of the program is dumped on the kernel's stack
  - Sometimes, extra info is loaded into CPU registers
  - E.g., page faults store the address that caused the fault in the `cr2` register
- Kernel code runs and handles the interrupt
- When handler completes, resume program (see `iret` instr.)

Important digression: Register state

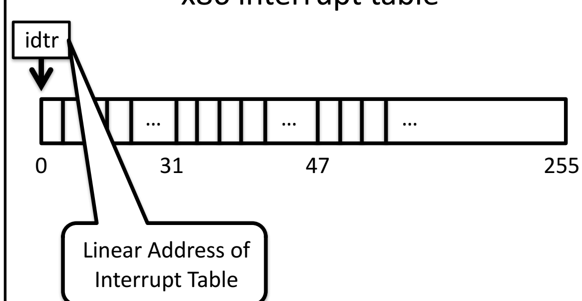
- Really, really, really big idea:
  - The state of a program's execution is succinctly and completely represented by CPU register state
- Pause a program: dump the registers in memory
- Resume a program: slurp the registers back into CPU

Be sure to appreciate the power of this idea

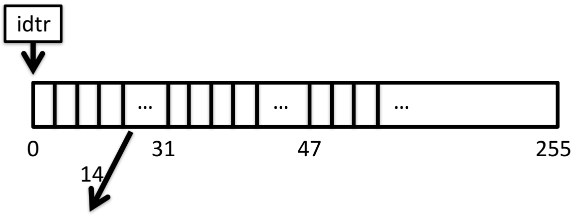
How is this configured?

- Kernel creates an array of Interrupt descriptors in memory, called Interrupt Descriptor Table, or IDT
  - Can be anywhere in memory
  - Pointed to by special register (`idtr`)
    - c.f., segment registers and `gdtr` and `ldtr`
- Entry 0 configures interrupt 0, and so on

x86 interrupt table



x86 interrupt table




```
Code Segment: Kernel Code
Segment Offset: &page_fault_handler //linear addr
Ring: 0 // kernel
Present: 1
Gate Type: Exception
```


Summary

- Most interrupt handling hardware state set during boot
- Each interrupt has an IDT entry specifying:
  - What code to execute, privilege level to raise the interrupt

Lecture outline

- Overview
- How interrupts work in hardware
- **How interrupt handlers work in software**
- How system calls work
- New system call hardware on x86

High-level goal

- Respond to some event, return control to the appropriate process
- What to do on:
  - Network packet arrives
  - Disk read completion
  - Divide by zero
  - System call

Interrupt Handlers

- Just plain old kernel code
  - Sort of like exception handlers in Java
  - But separated from the control flow of the program
- The IDT stores a pointer to the right handler routine

Lecture outline

- Overview
- How interrupts work in hardware
- How interrupt handlers work in software
- **How system calls work**
- New system call hardware on x86

What is a system call?

- A function provided to applications by the OS kernel
  - Generally to use a hardware abstraction (file, socket)
  - Or OS-provided software abstraction (IPC, scheduling)
- Why not put these directly in the application?
  - Protection of the OS/hardware from buggy/malicious programs
  - Applications are not allowed to directly interact with hardware, or access kernel data structures

System call "interrupt"

- Originally, system calls issued using `int` instruction
- Dispatch routine was just an interrupt handler
- Like interrupts, system calls are arranged in a table
  - See arch/x86/kernel/syscall_table*.S in Linux source
- Program selects the one it wants by placing index in `eax` register
  - Arguments go in the other registers by calling convention
  - Return value goes in `eax`

How many system calls?

- Linux exports about 350 system calls
- Windows exports about 400 system calls for core APIs, and another 800 for GUI methods

But why use interrupts?

- Also protection
- Forces applications to call well-defined "public" functions
  - Rather than calling arbitrary internal kernel functions
- Example:

```
public foo() {
        if (!permission_ok()) return –EP
        return _foo(); // no permission
}
```

Calling _foo() directly would circumvent permission check

Summary

- System calls are the "public" OS APIs
- Kernel leverages interrupts to restrict applications to specific functions
- Lab 1 hint: How to issue a Linux system call?
  - **`int $0x80`**, with system call number in **`eax`** register

Lecture outline

- Overview
- How interrupts work in hardware
- How interrupt handlers work in software
- How system calls work
- **New system call hardware on x86**

Around P4 era…

- Processors got very deeply pipelined
  - Pipeline stalls/flushes became very expensive
  - Cache misses can cause pipeline stalls
- System calls took twice as long from P3 to P4
  - Why?
  - IDT entry may not be in the cache
  - Different permissions constrain instruction reordering

Idea

- What if we cache the IDT entry for a system call in a special CPU register?
  - No more cache misses for the IDT!
  - Maybe we can also do more optimizations
- Assumption: system calls are frequent enough to be worth the transistor budget to implement this
  - What else could you do with extra transistors that helps performance?

AMD: syscall/sysret

- These instructions use MSRs (machine specific registers) to store:
  - Syscall entry point and code segment
  - Kernel stack
- A drop-in replacement for `int 0x80`
- Everyone loved it and adopted it wholesale
  - Even Intel!

Aftermath

- Getpid() on my desktop machine (recent AMD 6-core):
  - Int 80: 371 cycles
  - Syscall: 231 cycles
- So system calls are definitely faster as a result!

Summary

- Interrupt handlers are specified in the IDT
- Understand how system calls are executed
  - Why interrupts?
  - Why special system call instructions?