OS, Traps, Exceptions, System Calls, & Privileged Mode

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Outline for Today

• How do we protect processes from one another?
  • Skype should not crash Chrome.
    → Operating System

• How do we protect the operating system (OS) from other processes?
  • Chrome should not crash the computer!
    → Privileged Mode

• How does the CPU and OS (software) handle exceptional conditions?
  • Division by 0, Page Fault, Syscall, etc.
    → Traps, System calls, Exceptions, Interrupts
Operating System
Operating System

- Manages all of the software and hardware on the computer.
- Many processes running at the same time, requiring resources
  - CPU, Memory, Storage, etc.

- The Operating System multiplexes these resources amongst different processes, and isolates and protects processes from one another!
Operating System

- Operating System (OS) is a trusted mediator:
  - Safe control transfer between processes
  - Isolation (memory, registers) of processes
Which statement is FALSE?

A) OS is always in the Hard Disk.
B) OS is always in Memory.
C) All processes can access* OS code.
D) OS provides a consistent API to be used by other processes.
E) OS manages the CPU, Memory, Devices, and Storage.

*fetch/execute
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Privileged (Kernel) Mode
Privileged Mode

- Only privileged (and trusted!) processes can access & change important things.
  - Editing TLB, Page Tables, OS code, OS $sp, OS $fp...

- If an untrusted process could change the OS’ $sp, $fp, and $gp, OS would crash!
Privileged Mode

How can we get the privileged mode to work?

Attempt #1:

• Make privileged instructions and registers available only to “OS Code”!

  “OS Code” → resides in memory at preset virtual address
Privileged Mode

Would making privileged instructions and registers available only to “OS Code” work?

A) Will work great!
B) Will work, but performance will be slow!
C) Will not work because any process can jump into OS code
D) Will not work because process can access all registers
E) Whatever, I am bored!
Privileged Mode
How can we get the privileged mode to work?

Attempt #1:

• Make privileged instructions and registers available only to “OS Code”
  • “OS Code” → resides in memory at preset virtual address

Does not work:

• Process can still JAL into middle of OS functions
• Process can still access and change memory, page tables, ...
Privileged Mode

How can we get the privileged mode to work?

Attempt #2:

CPU Mode Bit in Privilege Level Status Register

Mode 0 = untrusted = user mode
  • “Privileged” instructions and registers are disabled by CPU

Mode 1 = trusted = kernel mode
  • All instructions and registers are enabled
Privileged Mode

How can we get the privileged mode to work?

Boot sequence:

• load first sector of disk (containing OS code) to predetermined address in memory
• Mode $\leftarrow 1$; PC $\leftarrow$ predetermined address

OS takes over...

• initializes devices, MMU, timers, etc.
• loads programs from disk, sets up page tables, etc.
• Mode $\leftarrow 0$; PC $\leftarrow$ program entry point
Privileged Mode – start here

If an untrusted process does not have privileges to use system resources, how can it

- Use the screen to print?
- Send message on the network?
- Allocate pages?
- Schedule processes?

System Calls
System Calls

System call: Not just a function call

• Don’t let process ram jump just anywhere in OS code
• OS can’t trust process’ registers (sp, fp, gp, etc.)

SYSCALL instruction: safe transfer of control to OS

• Mode ← 0; Cause ← syscall; PC ← exception vector

MIPS system call convention:

• Exception handler saves temp regs, saves ra, ...
• but: $v0 = system call number, which specifies the operation the application is requesting
printf() is a system call that is implemented in the user application's code. It is passed to the system call interface in privileged (kernel) mode. The implementation of printf() is found in the printf.c file. The diagram shows the memory map with the stack, dynamic data (heap), static data, and code (text) sections. The system reserved areas are located at the top and bottom of the memory map.
System Calls

System call examples:

putc(): Print character to screen
  • Need to multiplex screen between competing processes

send(): Send a packet on the network
  • Need to manipulate the internals of a device

sbrk(): Allocate a page
  • Needs to update page tables & MMU

sleep(): put current prog to sleep, wake other
  • Need to update page table base register
Invoking System Calls

```c
int getc() {
    asm("addiu $v0, $0, 4");
    asm("syscall");
}

char *gets(char *buf) {
    while (...) {
        buf[i] = getc();
    }
}
```
Libraries and Wrappers

Compilers do not emit SYSCALL instructions
  • Compiler doesn’t know OS interface

Libraries implement standard API from system API libc (standard C library):
  • getc() \rightarrow syscall
  • sbrk() \rightarrow syscall
  • write() \rightarrow syscall
  • gets() \rightarrow getc()
  • printf() \rightarrow write()
  • malloc() \rightarrow sbrk()
  • ...

Where does the OS live?

In its own address space?

• But then syscall would have to switch to a different address space

• Also harder to deal with syscall arguments passed as pointers

So in the same address space as process

• Use protection bits to prevent user code from writing kernel

• Higher part of virtual memory, lower part of physical memory
Typically all kernel text, most data

- At same virtual address in every address space
- Map kernel in contiguous physical memory when boot loader puts kernel into physical memory

The OS is omnipresent and steps in where necessary to aid application execution

- Typically resides in high memory

When an application needs to perform a privileged operation, it needs to invoke the OS
SYSCALL instruction

SYSCALL instruction does an atomic jump to a controlled location (i.e. MIPS 0x8000 0180)
  • Switches the sp to the kernel stack
  • Saves the old (user) SP value
  • Saves the old (user) PC value (= return address)
  • Saves the old privilege mode
  • Sets the new privilege mode to 1
  • Sets the new PC to the kernel syscall handler
SYSCALL instruction

Kernel system call handler carries out the desired system call

- Saves callee-save registers
- Examines the syscall number
- Checks arguments for sanity
- Performs operation
- Stores result in v0
- Restores callee-save registers
- Performs a “return from syscall” (ERET) instruction, which restores the privilege mode, SP and PC
Takeaway

• It is necessary to have a privileged (kernel) mode to enable the Operating System (OS):
  • provides isolation between processes
  • protects shared resources
  • provides safe control transfer
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• Privileged Mode

• How does the CPU and OS (software) handle exceptional conditions?
  • Division by 0, Page Fault, Syscall, etc.
  • Traps, System calls, Exceptions, Interrupts
Terminology

Trap: Any kind of a control transfer to the OS

Syscall: Synchronous and planned, process-to-kernel transfer
  • SYSCALL instruction in MIPS (various on x86)

Exception: Synchronous but unplanned, process-to-kernel transfer
  • exceptional events: div by zero, page fault, page protection err, ...

Interrupt: Asynchronous, device-initiated transfer
  • e.g. Network packet arrived, keyboard event, timer ticks
Exceptions

Exceptions are any unexpected change in control flow.

Interrupt -> cause of control flow change external
Exception -> cause of control flow change internal
  • Exception: Divide by 0, overflow
  • Exception: Bad memory address
  • Exception: Page fault
  • Interrupt: I/O interrupt (e.g. keyboard stroke)

We need both HW and SW to help resolve exceptions
  • Exceptions are at the hardware/software boundary
Hardware/Software Boundary

Hardware support for exceptions

• Exception program counter (EPC)
  – A 32-bit register to hold the addr of the affected instruction.
  – Syscall case: Address of SYSCALL

• Cause register
  – A register to hold the cause of the exception.
  – Syscall case: 8, Sys

• Special instructions to load TLB
  – Only do-able by kernel

Precise and imprecise exceptions

• In pipelined architecture
  – Have to correctly identify PC of exception
  – MIPS and modern processors support this
Exceptions

Code Stored in Memory (also, data and stack)

- System reserved
- Stack
- Dynamic data (heap)
- Static data
- Code (text)
- System reserved

$0$ (zero)
$1$ ($at$) register
$29$ ($sp$)
$31$ ($ra$)

PC

Inst

New pc

Instruction Fetch

IF/ID

Control

Detect hazard

Instruction Decode

ID/EX

Extend

Forward unit

EX/MEM

Memory

Write-back

EPC

Cause

System reserved

Stack

Memory

EPC

Stack, Data, Code Stored in Memory

$0$ (zero)

$1$ ($at$)

$29$ ($sp$)

$31$ ($ra$)
Hardware/Software Boundary

Precise exceptions: Hardware guarantees
(similar to a branch)
• Previous instructions complete
• Later instructions are flushed
• EPC and cause register are set
• Jump to prearranged address in OS
• When you come back, restart instruction

• Disable exceptions while responding to one
  – Otherwise can overwrite EPC and cause
Hardware/Software Boundary

What else requires both Hardware and Software?

A) Virtual to Physical Address Translation
B) Branching and Jumping
C) Clearing the contents of a register
D) Pipelining instructions in the CPU
E) What are we even talking about?
Hardware/Software Boundary

Virtual to physical address translation!

Hardware

• CPU has a concept of operating in physical or virtual mode.
• CPU helps manage the TLB.
• CPU raises page faults.
• CPU keeps Page Table Base Register (PTBR) and Process ID

Software

• OS manages Page Table storage
• OS handles Page Faults
• OS updates Dirty and Reference bits in the Page Tables
• OS keeps TLB valid on context switch:
  • Flush TLB when new process runs (x86)
  • Store process id (MIPS)
Summary

Trap
- Any kind of a control transfer to the OS

Syscall
- Synchronous, process-initiated control transfer from user to the OS to obtain service from the OS
  - e.g. SYSCALL

Exception
- Synchronous, process-initiated control transfer from user to the OS in response to an exceptional event
  - e.g. Divide by zero, TLB miss, Page fault

Interrupt
- Asynchronous, device-initiated control transfer from user to the OS
  - e.g. Network packet, I/O complete
What is the difference between traps, exceptions, interrupts, and system calls?
Interrupts & Exceptions

Hardware
• CPU saves PC of exception instruction (EPC)
• CPU Saves cause of the interrupt/privilege (Cause register)
• Switches the sp to the kernel stack
• Saves the old (user) SP value
• Saves the old (user) PC value
• Saves the old privilege mode
• Sets the new privilege mode to 1
• Sets the new PC to the kernel interrupt/exception handler
Interrupts & Exceptions

Software
Kernel interrupt/exception handler handles the event

• Saves all registers
• Examines the cause
• Performs operation required
• Restores all registers
• Performs a “return from interrupt” instruction, which restores the privilege mode, SP and PC
Example: Clock Interrupt

Example: Clock Interrupt*

- Every N cycles, CPU causes exception with Cause = CLOCK_TICK
- OS can select N to get e.g. 1000 TICKs per second

.ktext 0x8000 0180
# (step 1) save *everything* but $k0, $k1 to 0xB0000000
# (step 2) set up a usable OS context
# (step 3) examine Cause register, take action
if (Cause == PAGEFAULT) handle_pfault(BadVaddr)
else if (Cause == SYSCALL) dispatch_syscall($v0)
else if (Cause == CLOCK_TICK) schedule()
# (step 4) restore registers and return to where process left off

* not the CPU clock, but a programmable timer clock
struct regs context[];
int ptbr[];
schedule() {
    i = current_process;
    j = pick_some_process();
    if (i != j) {
        current_process = j;
        memcpy(context[i], 0xB0000000);
        memcpy(0xB0000000, context[j]);
        asm("mtc0 Context, ptbr[j] ");
    }
}
Syscall vs. Exception vs. Interrupt

Same mechanisms, but...

Syscall saves and restores much less state

Others save and restore full processor state

Interrupt arrival is unrelated to user code
Takeaway

- Traps are any transfer of control to the OS.
- *Exceptions are any unexpected change in control flow.*
- Precise exceptions are necessary to identify the exceptional instructions, cause of exception, and where to continue execution.
- We need help of both hardware and software (e.g. OS) to resolve exceptions.
Takeaway

To handle any exception or interrupt:

• OS analyzes the Cause register
• OS vectors into the appropriate exception handler.
• OS kernel handles the exception
• Returns control to the same process
  • Possibly kills the current process
  • Possibly schedules another process