

Traps, Exceptions, System Calls, & Privileged Mode

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CS 3410, Spring 2013

Computer Science

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P&H Chapter 4.9, pages 509–515, appendix B.7

Goals for Today

Hardware/Software boundary

- Traps, Exceptions, System Calls, & Privileged Mode
- Operating System

Hardware/Software Boundary

Virtual to physical address translation is assisted by hardware

Need *both* hardware and software support

Software

- Page table storage, fault detection and updating
 - Page faults result in interrupts that are then handled by the OS
 - Must update appropriately Dirty and Reference bits (e.g., ~LRU) in the Page Tables

Hardware/Software Boundary

OS has to keep TLB valid

Keep TLB valid on context switch

- Flush TLB when new process runs (x86)
- Store process id (MIPs)

Also, store pids with cache to avoid flushing cache on context switches

Hardware support

- Page table register
- Process id register

Hardware/Software Boundary

Hardware support for exceptions

- Exception program counter
- Cause register
- 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

Hardware/Software Boundary

Precise exceptions: Hardware guarantees

- 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

Attempt #2 is broken

Drawbacks:

- Any program can muck with TLB, PageTables, OS code...
- A program can intercept exceptions of other programs
- OS can crash if program messes up \$sp, \$fp, \$gp, ...

Wrong: Make these instructions and registers available only to “OS Code”

- “OS Code” == any code above 0x80000000
- Program can still JAL into middle of OS functions
- Program can still muck with OS memory, pagetables, ...

Privileged Mode
aka Kernel Mode

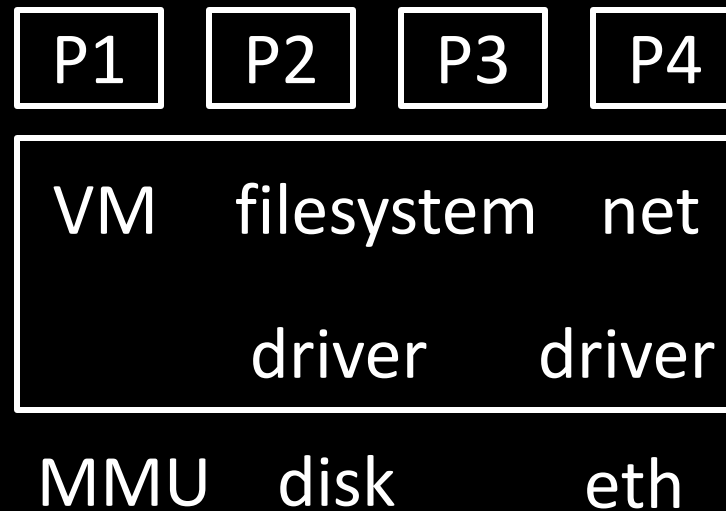
Operating System

Some things not available to untrusted programs:

- Exception registers, HALT instruction, MMU instructions, talk to I/O devices, OS memory, ...

Need trusted mediator: **Operating System (OS)**

- *Safe control transfer*
- *Data isolation*



Privilege Mode

CPU Mode Bit / Privilege Level Status Register

Mode 0 = untrusted = **user domain**

- “Privileged” instructions and registers are disabled by CPU

Mode 1 = trusted = **kernel domain**

- All instructions and registers are enabled

Boot sequence:

- load first sector of disk (containing OS code) to well known address in memory
- Mode \leftarrow 1; PC \leftarrow well known address

OS takes over...

- initialize devices, MMU, timers, etc.
- loads programs from disk, sets up pagetables, etc.
- Mode \leftarrow 0; PC \leftarrow program entry point

(note: x86 has 4 levels x 3 dimensions, but only virtual machines uses any the middle)

Terminology

Trap: Any kind of a control transfer to the OS

Syscall: Synchronous (planned), program-to-kernel transfer

- SYSCALL instruction in MIPS (various on x86)

Exception: Synchronous, program-to-kernel transfer

- exceptional events: div by zero, page fault, page protection err,
...

Interrupt: Aysnchronous, device-initiated transfer

- e.g. Network packet arrived, keyboard event, timer ticks

* real mechanisms, but nobody agrees on these terms

Sample System Calls

System call examples:

`putc()`: Print character to screen

- Need to multiplex screen between competing programs

`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

System Calls

System call: Not just a function call

- Don't let program jump just anywhere in OS code
- OS can't trust program's registers (sp, fp, gp, etc.)

SYSCALL instruction: safe transfer of control to OS

- $\text{Mode} \leftarrow 0$; $\text{Cause} \leftarrow \text{syscall}$; $\text{PC} \leftarrow \text{exception vector}$

MIPS system call convention:

- user program mostly normal (save temps, save ra, ...)
- but: $\$v0$ = system call number, which specifies the operation the application is requesting

Invoking System Calls

```
int getc() {  
    asm("addiu $2, $0, 4");  
    asm("syscall");  
}
```

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

Libraries and Wrappers

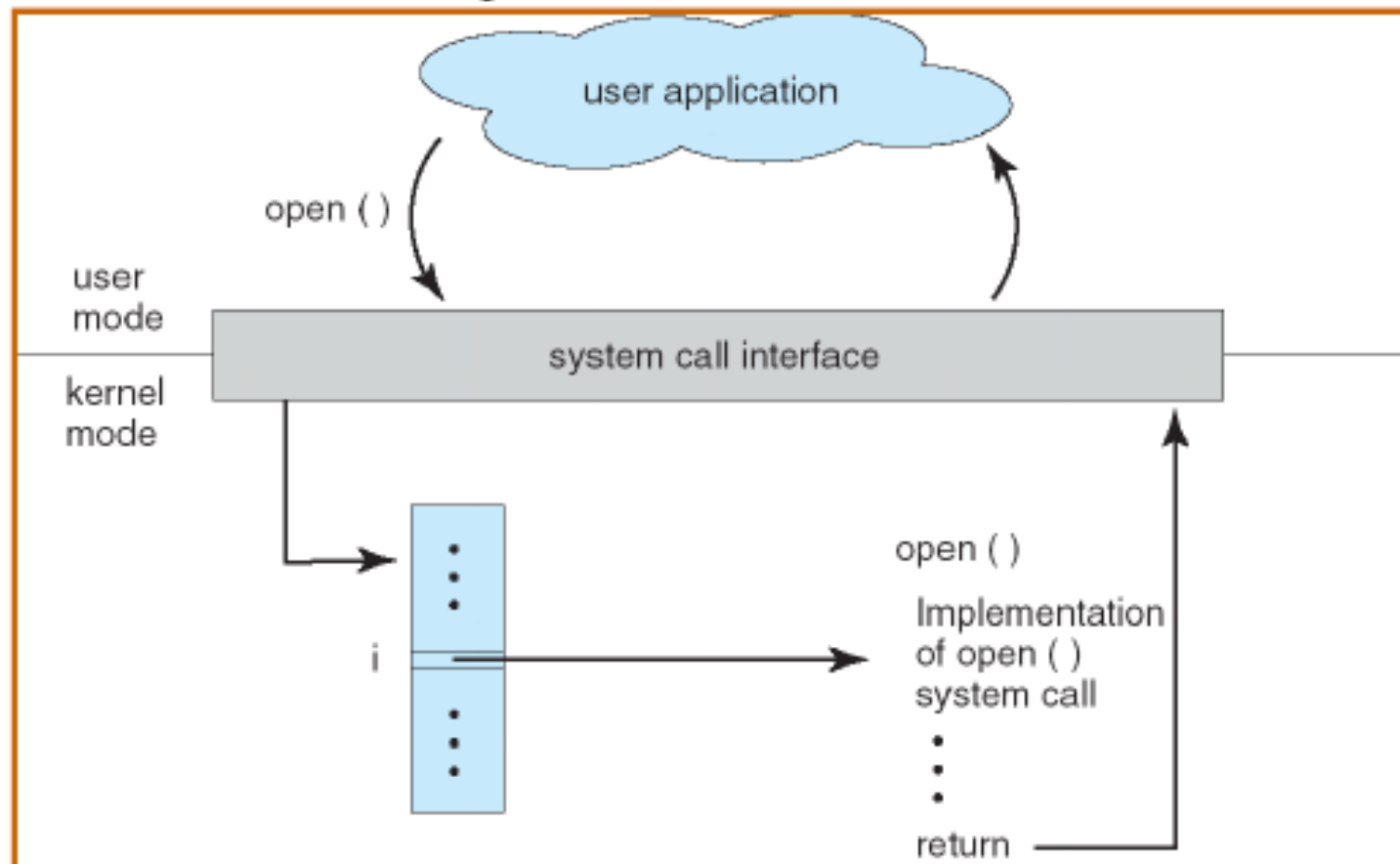
Compilers do not emit SYSCALL instructions

- Compiler doesn't know OS interface

Libraries implement standard API from system API

libc (standard C library):

- `getc()` → `syscall`
- `sbrk()` → `syscall`
- `write()` → `syscall`
- `gets()` → `getc()`
- `printf()` → `write()`
- `malloc()` → `sbrk()`
- ...



Where does 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 VM, lower part of physical memory

Full System Layout

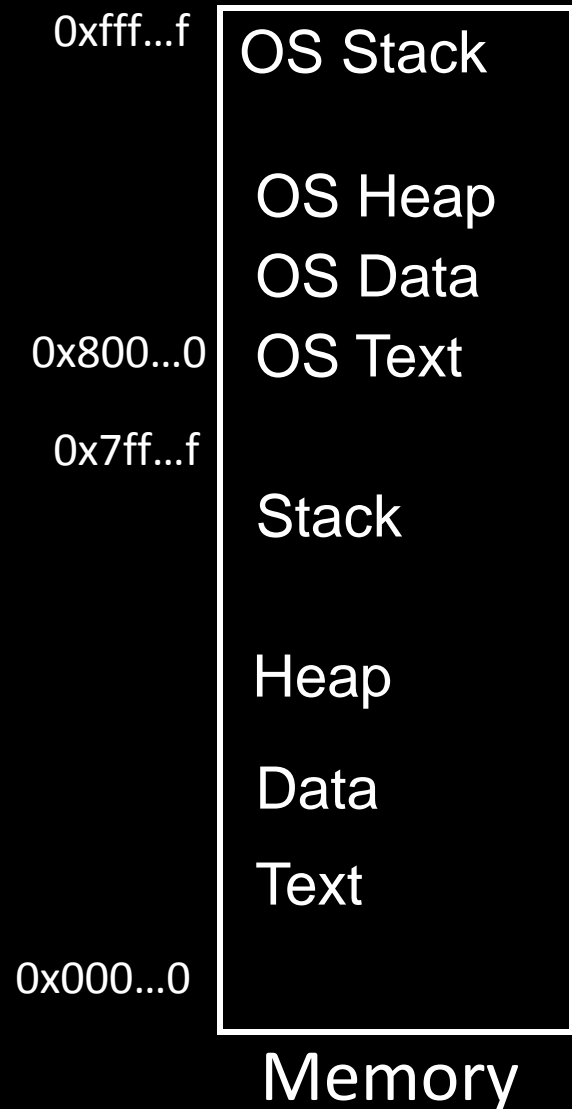
Typically all kernel text, most data

- At same VA 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

- 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**” instruction, which restores the privilege mode, SP and PC

Interrupts

Recap: Traps

- Map kernel into every process using *supervisor* PTEs
- Switch to **kernel mode** on trap, **user mode** on return

Syscall: Synchronous, program-to-kernel transfer

- user does caller-saves, invokes kernel via syscall
- kernel handles request, puts result in v0, and returns

Exception: Synchronous, program-to-kernel transfer

- user div/load/store/... faults, CPU invokes kernel
- kernel saves everything, handles fault, restores, and returns

Interrupt: Aysnchronous, device-initiated transfer

- e.g. Network packet arrived, keyboard event, timer ticks
- kernel saves everything, handles event, restores, and returns

Exceptions

System calls are control transfers to the OS, performed under the control of the user program

Sometimes, need to transfer control to the OS at a time when the user program least expects it

- Division by zero,
- Alert from power supply that electricity is going out
- Alert from network device that a packet just arrived
- Clock notifying the processor that clock just ticked

Some of these causes for interruption of execution have nothing to do with the user application

Need a (slightly) different mechanism, that allows resuming the user application

Interrupts & Exceptions

On an interrupt or exception

- Switches the sp to the kernel stack
- Saves the old (user) SP value
- Saves the old (user) PC value
- Saves the old privilege mode
- Saves cause of the interrupt/privilege
- Sets the new privilege mode to 1
- Sets the new PC to the kernel interrupt/exception handler

Interrupts & Exceptions

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 0x80000180
```

```
# (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 == PAGE_FAULT) handle_pfault(BadVaddr)
```

```
else if (Cause == SYSCALL) dispatch_syscall($v0)
```

```
else if (Cause == CLOCK_TICK) schedule()
```

```
# (step 4) restore registers and return to where program left off
```

* not the CPU clock, but a programmable timer clock

Scheduler

```
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. Interrupt

Syscall vs. Exceptions vs. Interrupts

Same mechanisms, but...

Syscall saves and restores much less state

Others save and restore full processor state

Interrupt arrival is unrelated to user code

Summary

Trap

- Any kind of a control transfer to the OS

Syscall

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

Exception

- Synchronous, program-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

Administrivia

Next four weeks

- Week 11 (Apr 8): Lab3 due and Project3/HW4 handout
- Week 12 (Apr 15): Project3 design doc due and HW4 due
- Week 13 (Apr 22): Project3 due and Prelim3
- Week 14 (Apr 29): Project4 handout

Final Project for class

- Week 15 (May 6): Project4 design doc due
- Week 16 (May 13): Project4 due

Administrivia

Lab3 is *due this week*, Thursday, April 11th

Project3 available now

- Design Doc *due next week*, Monday, April 15th
- Schedule a Design Doc review Mtg now, by this Friday, April 12th
- Whole project due Monday, April 22nd
- **Competition/Games night Friday, April 26th, 5-7pm**

Homework4 is available now

- *Due next week*, Wednesday, April 17th
- Question1 on Virtual Memory is pre-lab question for in-class Lab4
- Work **alone**

Prelim3 is in two and a half weeks, Thursday, April 25th

- Time and Location: 7:30pm in Phillips 101 and Upson B17
- Old prelims are online in CMS