CSE 451: Operating Systems
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Module 2
Architectural Support for Operating Systems

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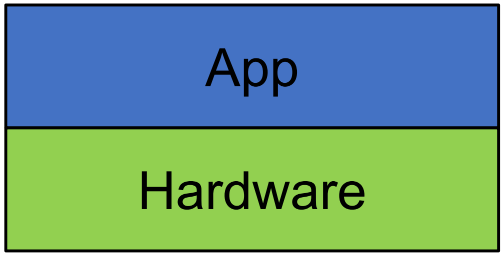
Lecture Questions

- What is the basic control flow of the system?
- Why do transitions from user code to the OS take place?
- Since they run on the same CPU, why can't applications do everything the OS can do?
- What happens on a transition from user code into the OS?
- On a transition from the OS to user code?
- What mechanisms does the hardware provide to help the OS keep control of the system?
- When the OS is running, what stack is it using (in xk)?
- How does xk use the segmented memory system provided by x86_64?
- How is memory protected?
- How are IO devices protected?

Low-level architecture affects the OS dramatically



Who's making sure the app behaves?

Who should get to define what "behaves" means?

(Hardware provides ***mechanism*** *and OS provides* ***policy.)***

Low-level architecture affects the OS dramatically

- The operating system supports sharing of hardware and protection of hardware
  - multiple applications can run concurrently, sharing resources
  - a buggy or malicious application can’t violate other applications or the system

- Those are high level goals
  - There are many mechanisms that can be used to achieve them

- The architecture determines which approaches are viable (reasonably efficient, or even possible)
  - includes instruction set (synchronization, I/O, …)
  - also hardware components like MMU or DMA controllers

Architectural features affecting OS's

- These hardware features were built primarily to support OS's:
  - timer (clock) operation
  - synchronization instructions (e.g., atomic test-and-set, mem fence)
  - memory protection
  - I/O control operations
  - interrupts and exceptions
  - protected modes of execution (kernel vs. user)
  - privileged instructions
  - system calls (and software interrupts)
  - virtualization architectures

The OS Needs To Be Special

- Only the OS should be able to:
  - directly access I/O devices (disks, network cards)
    - why?
  - manipulate memory state management
    - page table pointers, TLB loads, etc.
    - why?
  - manipulate special ‘mode bits’
    - interrupt priority level
    - why?
- But users can put any bit strings in memory they want
  - so they can execute any instructions that the OS uses to do those things
- So how can this work?

So How Can This Work?

- Some hardware resource must be available to the OS but not to applications
  - Could be instructions
  - Could be access to special registers and/or addresses
- Turns out it's both!

- The CPU hardware provides privileged instructions that "only the OS can execute"

- Some resources can be modified only by instructions that are privileged
  - E.g., information related to address translation

- The OS can use them to establish an execution environment that limits access (e.g., to memory)
  - The application cannot remove the restrictions because it must execute privileged instructions to do so

“… only the OS can execute”

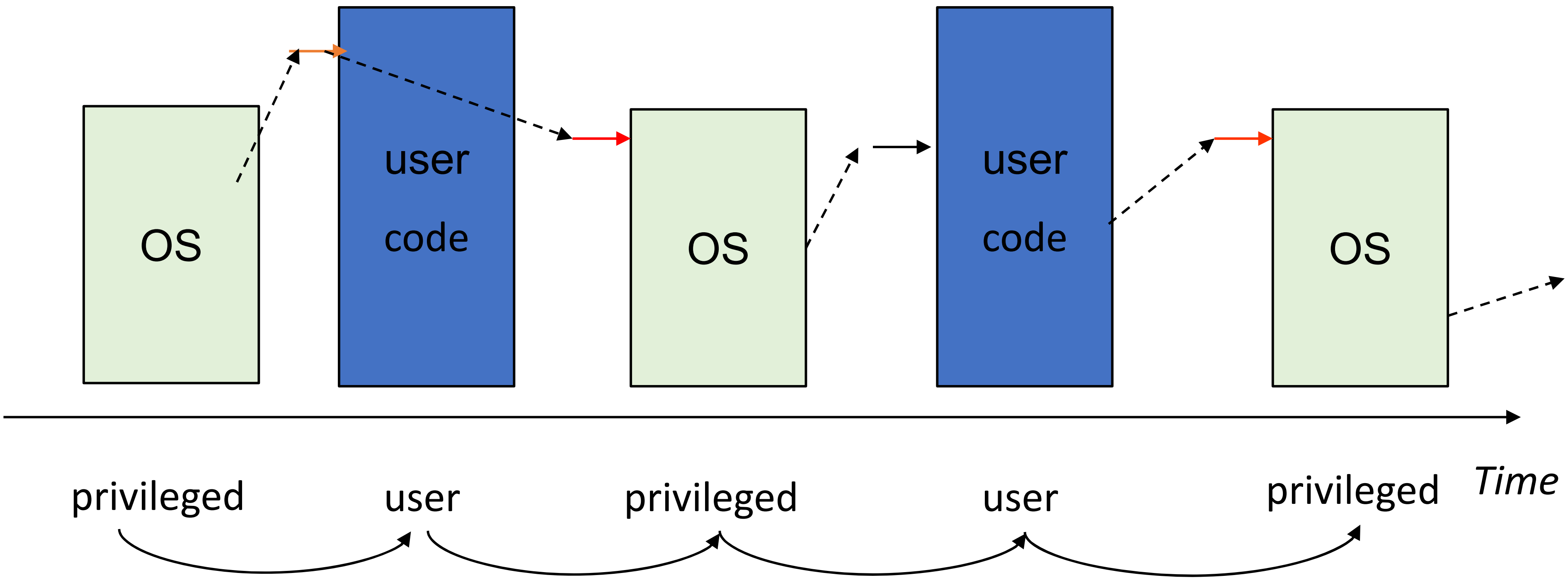
- This is a policy goal
  - What mechanism(s) can be used to achieve it?
- Q1 (Mechanism): How can the CPU hardware tell when the OS is running?
  - A0: How about instructions in some range of memory addresses are the OS and instructions at other addresses aren’t?
  - A1: It can’t. The OS is a concept, the hardware is a state machine. (So need a mechanism that code can use to say, “I’m the OS” (which is a policy decision).)
- Q2 (Policy): What should happen when something that isn’t the OS tries to execute a privileged instruction?
  - (Poor) A2: As a mechanism, the CPU could just consider it to be a NOP, say.
  - (Good) A2: Gee, what happens is really a policy decision. The OS should make it, not the hardware.

Mechanism: How Does CPU Decide Whether or Not to Execute a Privileged Instruction

- Privilege Level: There is at least one bit of data somewhere accessible to the CPU (e.g., in a special register)
  - When the bit == 1 we say we're executing in privileged mode, and the CPU is willing to execute privileged instructions
  - When the bit == 0 we say we're executing in unprivileged (or user) mode, and the CPU is unwilling to execute privileged instructions
  - *(Processors typically offer more than just two privilege levels, to support more sophisticated code structure in the OS.)*

- Exception Mechanism: What happens if the CPU hardware fetches a privileged instruction while in unprivileged mode?
  - The hardware invokes the OS, so that it can decide what to do
  - We'll see exactly how in just a bit

Making CPU Privilege Mode == Running OS

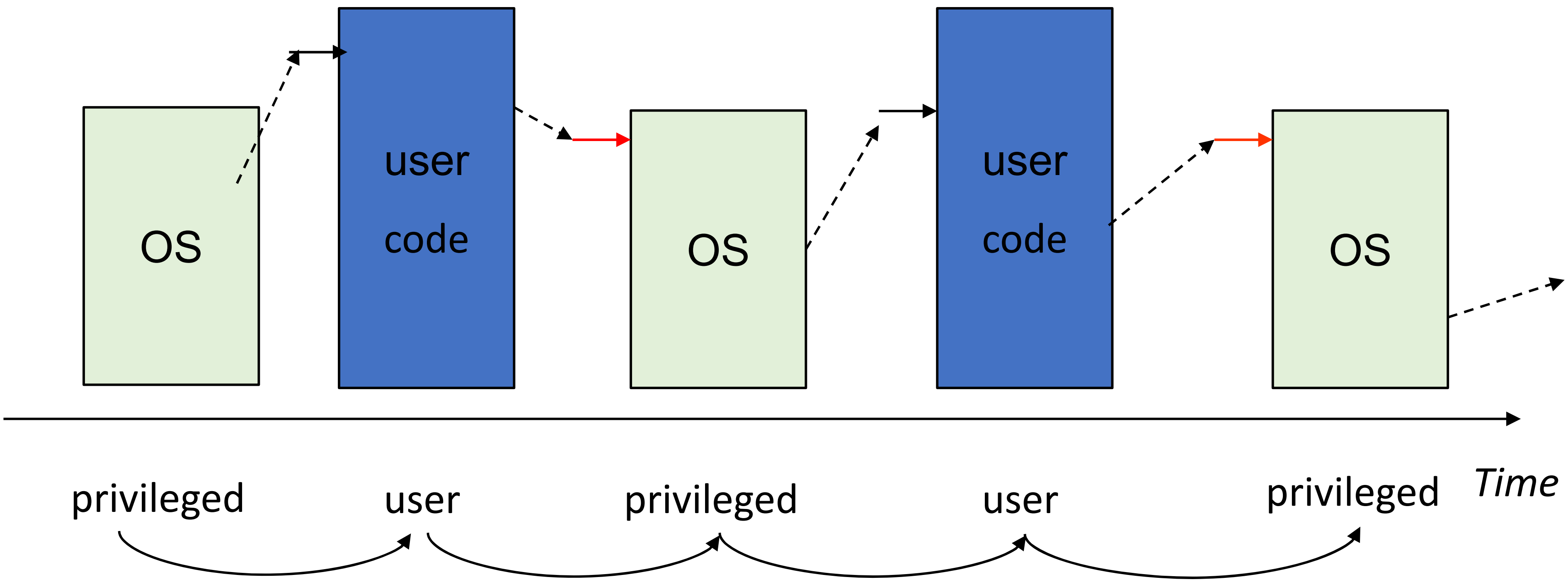


- OS runs first (boot)
  - CPU starts in privileged mode
- OS sets privilege mode to user before handing CPU over to user code
  - So far so good...
- Eventually we need to run the OS again...

Entering the OS: system calls

- Sometimes user code wants the OS to do something for it
  - E.g., read/write files, send/receive network data, start another program running, etc.
- In the abstract, it wants to do a procedure call, as though the OS were a library
  - Establish some arguments to be passed to the OS
  - Let the OS run for a bit and produce return values (and/or side effects)
  - Return to the application statement following the call to the OS procedure
  - Find the return values produced by the OS
- CPU is at user privilege while executing user code
- CPU needs to be in privileged mode while executing the OS
- So, how can the user cause the CPU to transition from unprivileged to privileged?

Making CPU Privilege Mode == Running OS



- Each transition from user level code to OS code transfers control to the same place (the orange arrow)
- The user level code passes as an argument a “syscall number” identifying which operation it is asking for (as well as any further arguments needed for that system call)
- The OS runs at privileged level starting with lines of code it decided upon
- User level code can’t both elevate CPU privilege level **and** define what instruction to execute next

System Calls

- User programs must cause execution of an OS method
  - OS defines a set of system calls
  - App code places a bunch of arguments to the call somewhere the OS can a find them
    - e.g., on the stack or in registers
  - One of the arguments "names" the system call that is being requested
    - usually a syscall number (whose meaning is defined by the OS)
    - *when app code wants to call a subroutine in that app, how does it "name" which one it wants?*
  - App executes a syscall instruction
    - Hardware: CPU privilege level is set to privileged **and** PC is set to the contents of a privileged register
      (after PC of the calling code is first saved)
    - during boot the OS set that register to point at the OS "trap handler" method
    - user code can't mess with it because modifying that register is a privileged operation

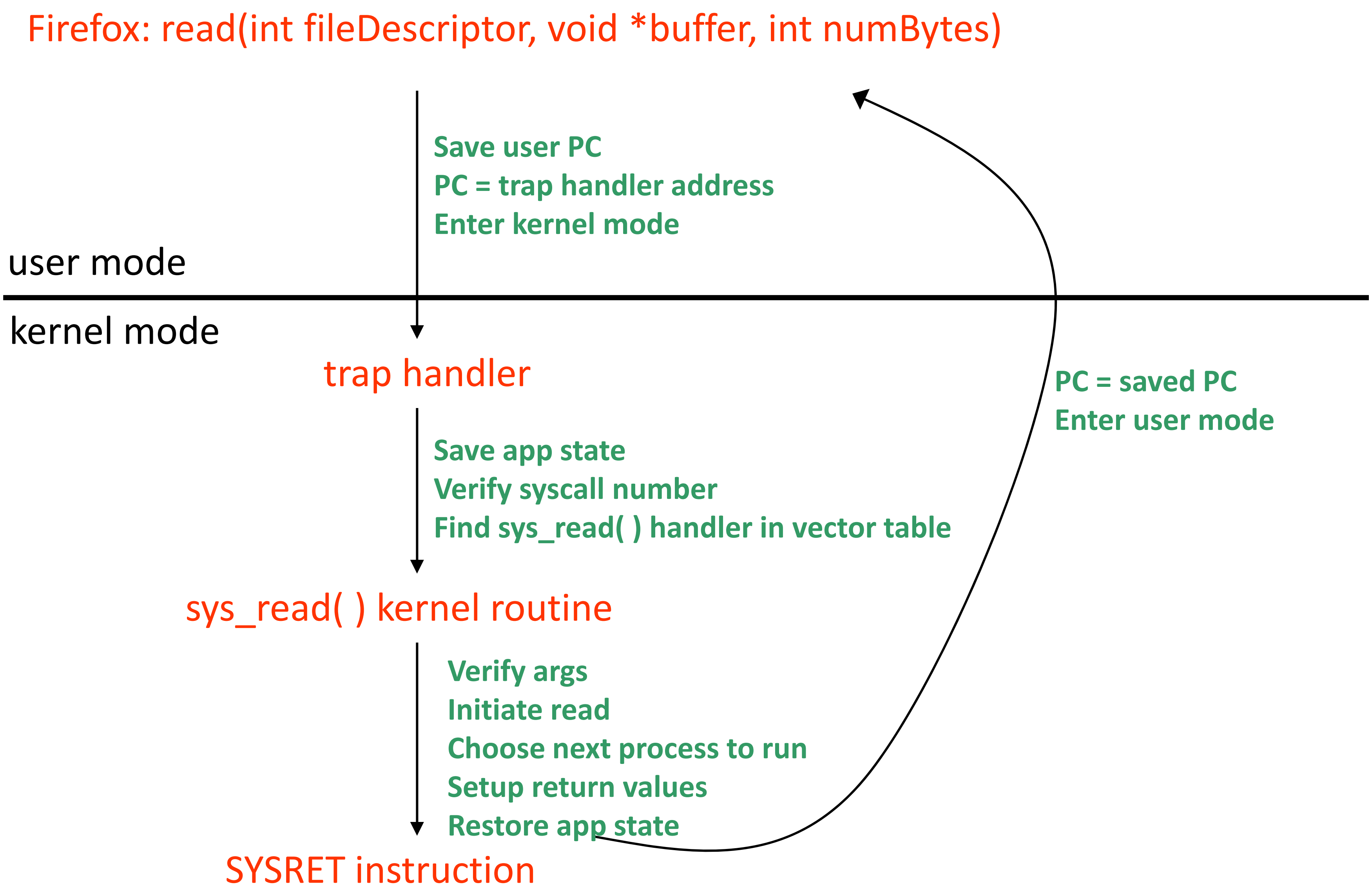
syscall/sysret instructions

- The syscall instruction atomically:
  - Sets the execution mode to privileged
  - Sets the PC to a handler address (that was established by the OS during boot)
  - Saves the current (user) PC
    - Why?
- The sysret instruction atomically:
  - Restores the previously saved user PC
  - Sets the execution mode to unprivileged

“Protected procedure call”

- Caller puts arguments in a place callee expects (registers or stack)
- Caller causes jump to OS by executing syscall instruction
  - **The OS determines what address to start executing at, not the caller**
  - One of the passed args is a syscall number, indicating which OS function to invoke
  - Some hardware state that can’t be saved if left to software (e.g., the user level PC of the instruction that follows the syscall instruction) is “pushed on the stack”
    - Which stack?
- Callee (OS) saves caller’s state (registers, other control state)
- OS function code runs
  - **OS must verify caller’s arguments** (e.g., pointers)
- OS (mostly) restores caller’s state
- OS returns by executing sysret instruction
  - Automatically sets execution mode to user and PC to return address previously saved on the stack

A kernel crossing illustrated



One More Issue: Stacks

- The kernel code is structured like user level code
  - It needs a stack
- The transition from user level to kernel level must involve a change in which stack is in use
  - A stack is just a region of memory used as the stack, so there can be any number of them in memory
- On some processors this transition is done in software
- On the x86 family it is done in hardware as part of the syscall instruction
  - On syscall, the user-level SP is saved to a temporary, the SP is set to an address determined by a privileged register previously initialized by the OS, and then the temporary is pushed onto that stack (along with the user-level PC)
  - On sysret, more or less the reverse is done

- Why can't the OS just use the user-level stack?

x86 Interrupt Stack (Mechanism)

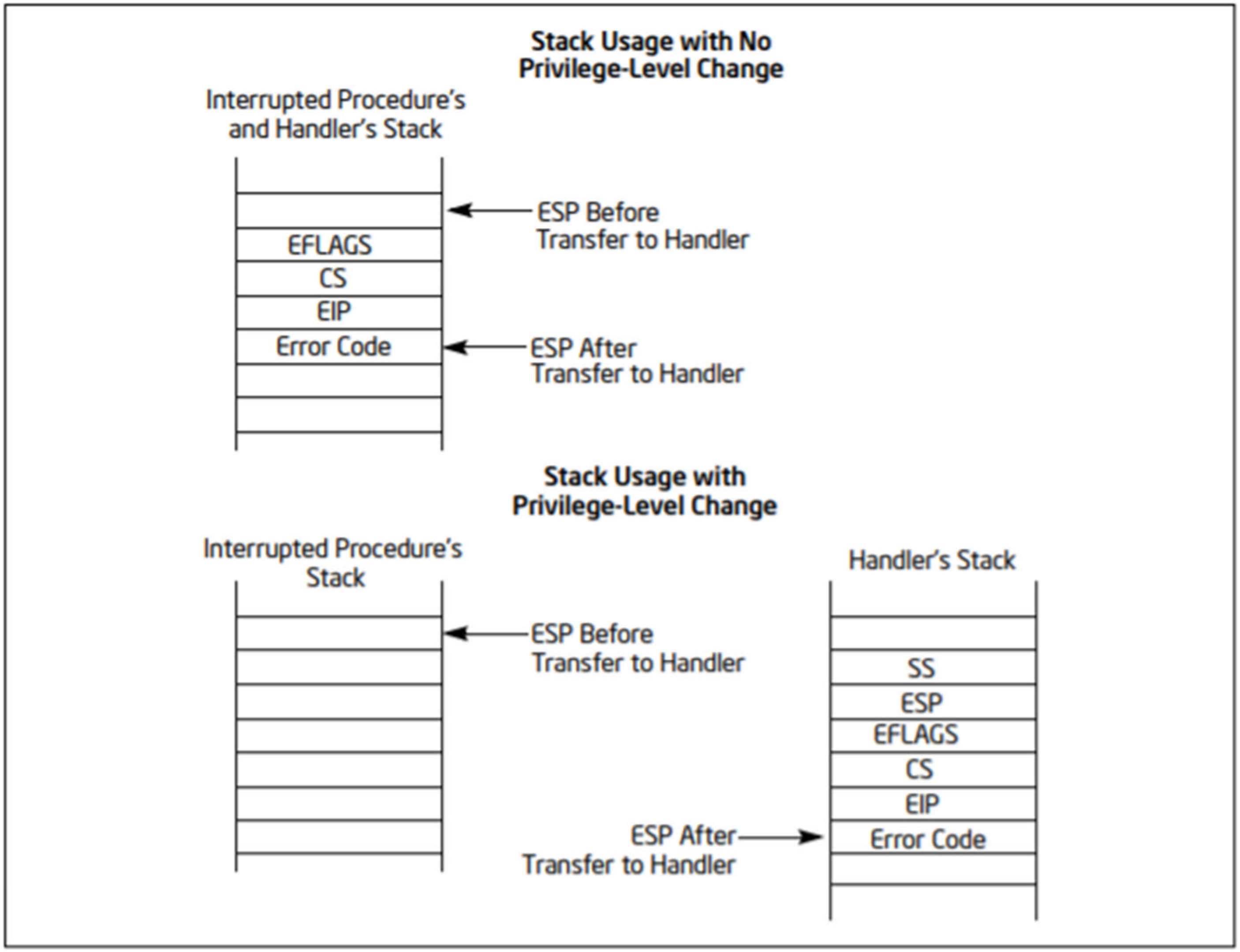


Figure 6-5. Stack Usage on Transfers to Interrupt and Exception Handling Routines

System call issues

- What would be wrong if a syscall worked like a regular subroutine call, with the caller specifying the next PC?
- What would happen if kernel didn’t save state?
- Why must the kernel verify arguments?
- How can you reference kernel objects as arguments to or results from system calls?
  - What does that question mean?!

Exception Handling and Protection

- *All* entries to the OS occur via the mechanism just described
  - Acquiring privileged mode and branching to the trap handler are inseparable
- Terminology:
  - **Interrupt**: asynchronous event; caused by an external device
  - **Exception**: synchronous event; unexpected problem with instruction
  - **Trap**: synchronous event; intended transition to OS due to an instruction
- Privileged instructions and resources are the basis for most everything: memory protection, protected I/O, limiting user resource consumption, …

Some Details

- The architecture defines the trap handling mechanism
- Exactly what's done in hardware and what in software differs across architectures
  - So, what I described isn't "the way it's done" it's more the idea of the way it's done
- For example, x86 trap handling doesn't have a register that gives the single entry point into the OS, it has something more complicated
  - You can think of it as a privileged register that points to an array of entry addresses
  - On trap/exception/interrupt, the hardware uses the trap/exception/hardware type (a number, called the "vector") to index the table and set the PC
- In general, x86 does a lot of complicated things in hardware, and RISC-like processors try to push as much as possible to software

x86 Interrupt/Trap Handling: Interrupt vectors

Vector	Mne-monic	Description	Type	Error Code	Source
0	#DE	Divide Error	Fault	No	DIV and IDIV instructions.
1	#DB	Debug Exception	Fault/ Trap	No	Instruction, data, and I/O breakpoints; single-step; and others.
2	—	NMI Interrupt	Interrupt	No	Nonmaskable external interrupt.
3	#BP	Breakpoint	Trap	No	INT 3 instruction.
4	#OF	Overflow	Trap	No	INTO instruction.
5	#BR	BOUND Range Exceeded	Fault	No	BOUND instruction.
6	#UD	Invalid Opcode (Undefined Opcode)	Fault	No	UD2 instruction or reserved opcode.[1]
7	#NM	Device Not Available (No Math Coprocessor)	Fault	No	Floating-point or WAIT/FWAIT instruction.
8	#DF	Double Fault	Abort	Yes (zero)	Any instruction that can generate an exception, an NMI, or an INTR.
9		Coprocessor Segment Overrun (reserved)	Fault	No	Floating-point instruction.[2]
10	#TS	Invalid TSS	Fault	Yes	Task switch or TSS access.
11	#NP	Segment Not Present	Fault	Yes	Loading segment registers or accessing system segments.
12	#SS	Stack-Segment Fault	Fault	Yes	Stack operations and SS register loads.
13	#GP	General Protection	Fault	Yes	Any memory reference and other protection checks.
14	#PF	Page Fault	Fault	Yes	Any memory reference.

x86 Interrupt/Trap Handling: Overview

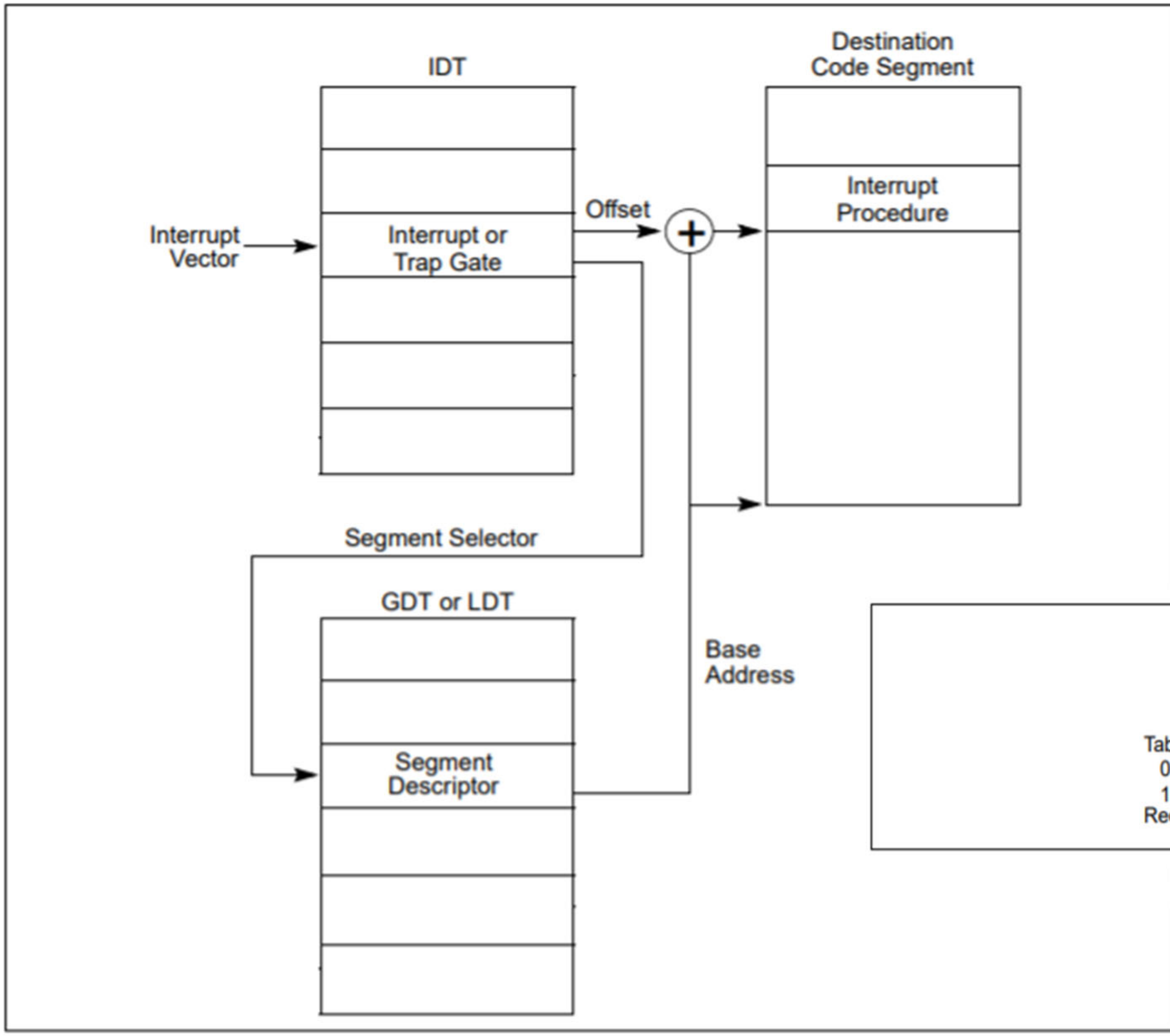


Figure 6-3. Interrupt Procedure Call

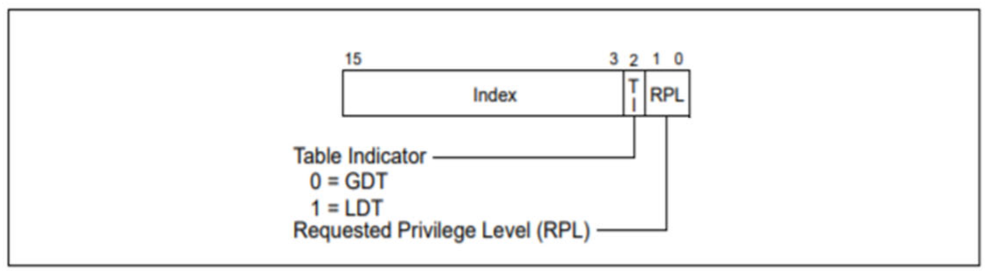


Figure 3-6. Segment Selector

x86 Interrupt/Trap Handling: Finding the IDT

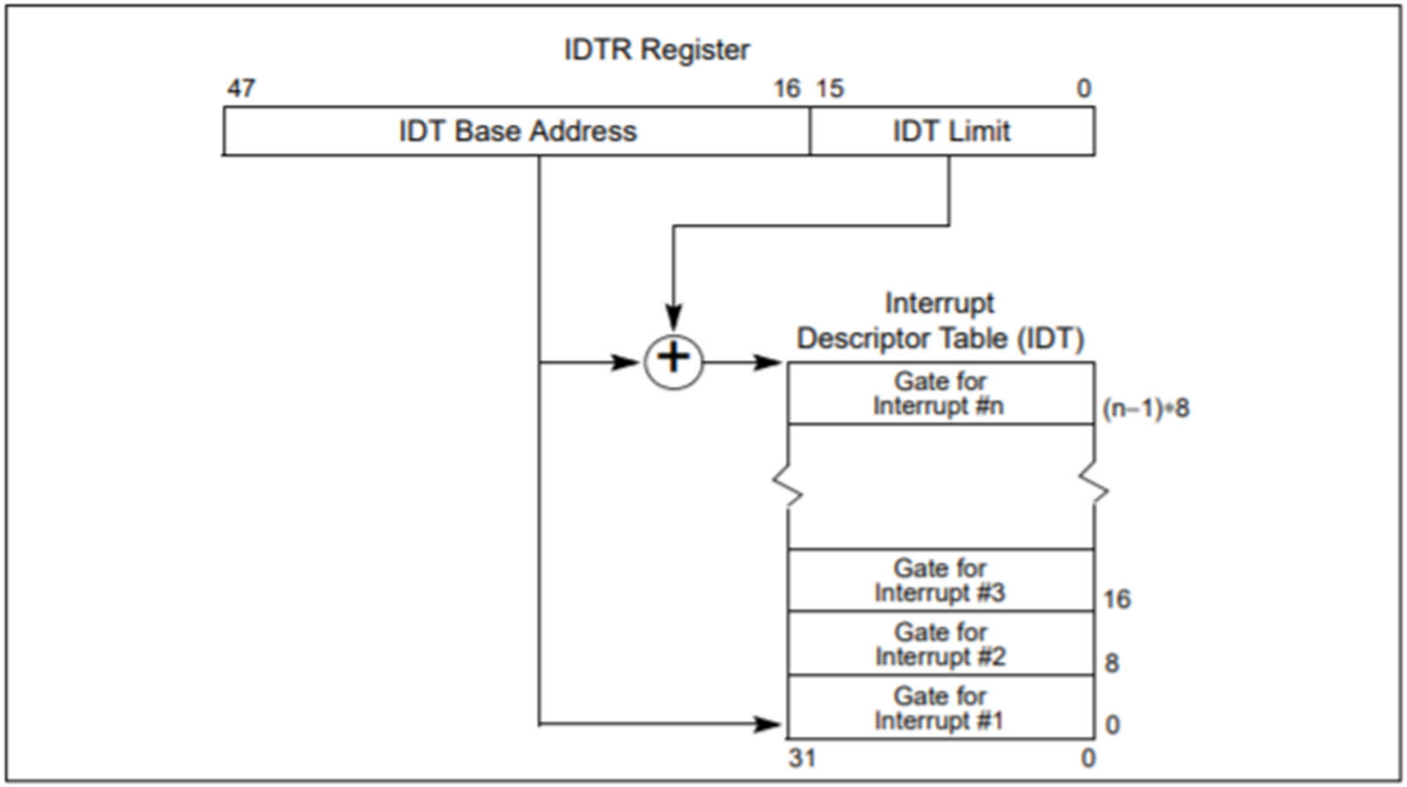


Figure 6-1. Relationship of the IDTR and IDT

x86 Interrupt/Trap Handling: IDT entries

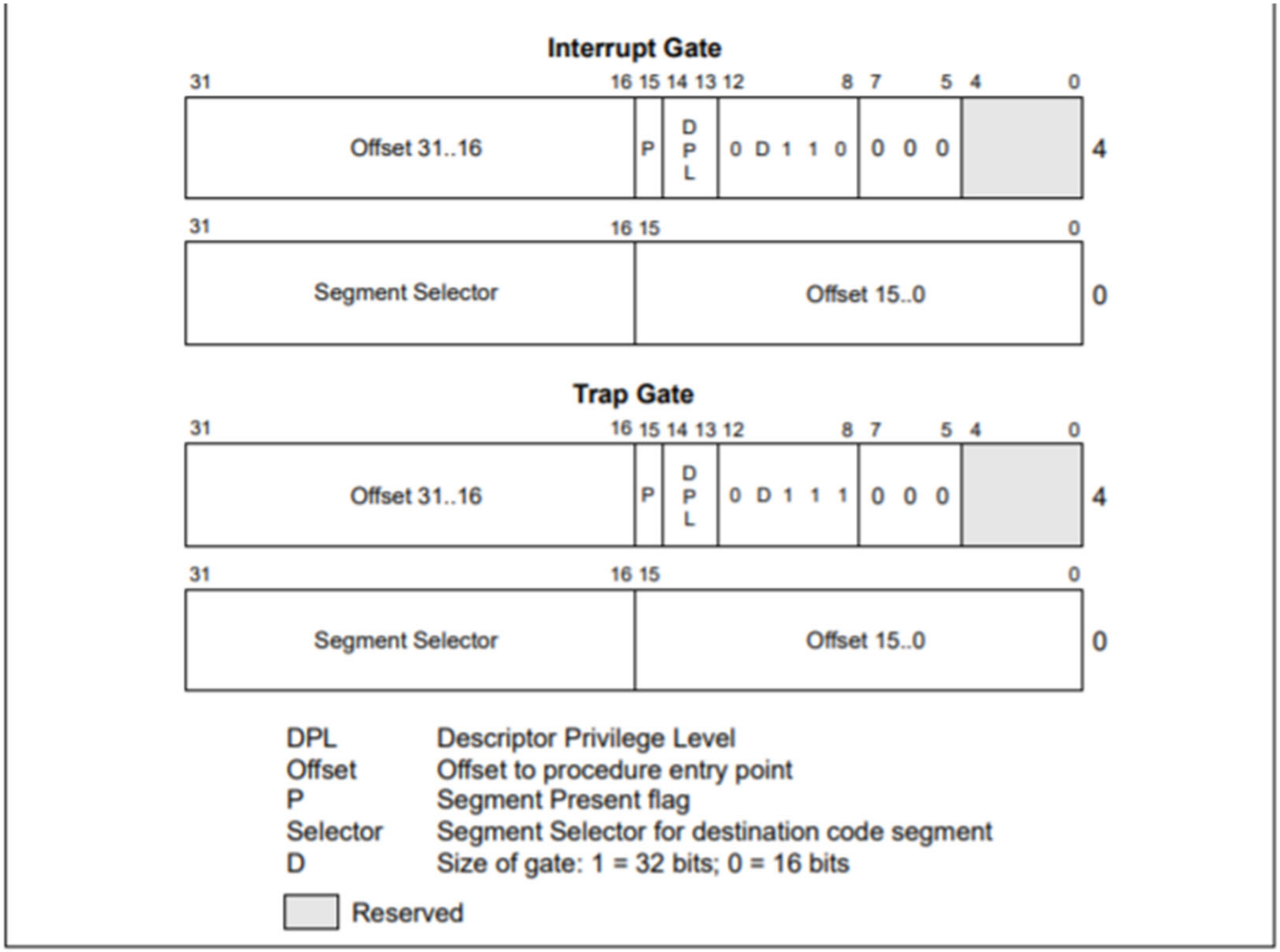
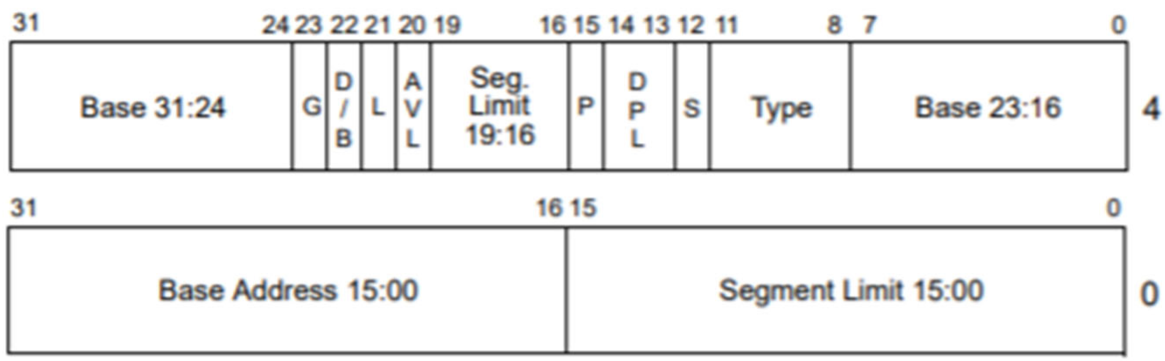


Figure 6-2. IDT Gate Descriptors

x86 Interrupt/Trap Handling: Segment Descriptors



L — 64-bit code segment (IA-32e mode only)
AVL — Available for use by system software
BASE — Segment base address
D/B — Default operation size (0 = 16-bit segment; 1 = 32-bit segment)
DPL — Descriptor privilege level
G — Granularity
LIMIT — Segment Limit
P — Segment present
S — Descriptor type (0 = system; 1 = code or data)
TYPE — Segment type

Figure 3-8. Segment Descriptor

x86 Interrupt/Trap Handling: Stacks

31	15	0	
I/O Map Base Address	Reserved	T	100
Reserved	LDT Segment Selector		96
Reserved	GS		92
Reserved	FS		88
Reserved	DS		84
Reserved	SS		80
Reserved	CS		76
Reserved	ES		72
EDI			68
ESI			64
EBP			60
ESP			56
EBX			52
EDX			48
ECX			44
EAX			40
EFLAGS			36
EIP			32
CR3 (PDBR)			28
Reserved	SS2		24
ESP2			20
Reserved	SS1		16
ESP1			12
Reserved	SS0		8
ESP0			4
Reserved	Previous Task Link		0

Reserved bits. Set to 0.

Figure 7-2. 32-Bit Task-State Segment (TSS)

Exception Summary

- Basically all protection provided by the OS relies in some way on the exception mechanism
  - Performance requires application code to run directly on the CPU and memory hardware
  - That leaves it to the hardware to intercept unsafe/illegal activity
  - Separation of policy and mechanism means that when the hardware notices something wrong, it should invoke OS code to decide what to do in response

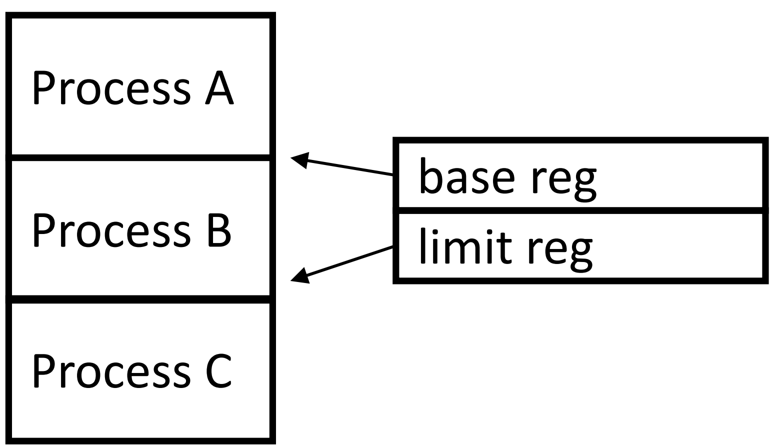
- The same mechanism is used whenever the hardware wants to "upcall" to the OS, even when nothing has gone wrong
  - Interrupts: some IO device wants attention
  - Traps: user level code wants to do a syscall

Exception Generalization

- To think about:
  - Let's move up a level, from hw/sw to os/user-level code.
  - Might there be situations in which it makes sense for the OS to provide mechanism and the application to provide policy?
    - The OS mechanism would be the detection of some event
    - The application policy would be the steps it wants to take in response to that event
    - What might be an example of an OS-level "event"?
  - What would the mechanism to "upcall" from OS to app need to do?
    - Invoke a handler method in the app, implying
    - Finding a thread of execution to execute the handler (a stack)
    - How would it know the location of the handler code?

Issue: Memory protection

- OS must protect user programs from each other
  - malice, bugs
- OS must also protect itself from user programs
  - integrity and security
  - what about protecting user programs from OS?
- Simplest scheme: base and limit registers
  - (Hey, segments!)
  - are these protected?



base and limit registers are loaded by OS before starting program

More sophisticated memory protection

- Paging, segmentation, virtual memory
  - page tables, page table pointers
  - translation lookaside buffers (TLBs)
  - page fault handling
  - isolation via naming
- Coming later in the course
  - also coming earlier in your course sequence!
  - so we won’t spend much time on these in 451

Issue: I/O control

- Issues:
  - how does the OS start an I/O?
    - special I/O instructions
    - memory-mapped I/O
      - special addresses, not special instructions
  - how does the OS notice when something interesting has happened (e.g., an I/O has finished or a network packet has arrived)?
    - polling
    - Interrupts
  - how does the OS exchange data with an I/O device?
    - Programmed I/O (PIO)
    - Direct Memory Access (DMA)

Asynchronous I/O

- what does the "asynchronous" part mean?
  - device performs an operation asynchronously to CPU
- Interrupts are the basis for asynchronous I/O
  - device sends an interrupt signal on bus when done
  - in memory, a vector table contains list of addresses of kernel routines to handle various interrupt types
    - who populates the vector table, and when?
  - CPU switches to address indicated by vector index specified by interrupt signal and the stack registered for that handler
- What's the advantage of asynchronous I/O?
  - Is this an advantage only to the OS? Is there a reason for an individual app to want to use asynchronous I/O? What would be required to allow it to do so?

Issue: Taking the CPU Back from Apps

- Q: How can the OS prevent runaway user programs from hogging the CPU (infinite loops?)
- A: Use a hardware timer that generates a periodic interrupt
  - before it transfers to a user program, the OS loads the timer with a time to interrupt
    - "quantum" – how big should it be set?
  - when timer fires, an interrupt transfers control back to OS
    - at which point OS must decide which program to schedule next
    - very interesting policy question: we'll dedicate a class to it
- Should access to the timer be privileged?

Issue: Synchronization

- Interrupts cause a wrinkle:
  - may occur any time, causing code to execute that interferes with code that was interrupted
  - OS must be able to synchronize concurrent processes
- Critical Sections (synchronization)
  - guarantee that short instruction sequences (e.g., read-modify-write) execute atomically
  - one method: turn off interrupts before the sequence, execute it, then re-enable interrupts
    - architecture must support disabling interrupts
      - Privileged???
    - does this method work?
  - another method: have special complex atomic instructions
    - read-modify-write
    - test-and-set
    - compare-and-swap
    - load-linked store-conditional

“Concurrent programming”

- Management of concurrency and asynchronous events is an important difference between “systems programming” and “traditional application programming”
  - “event-driven” application programming is a middle ground
  - And in a multi-core world, more and more apps have internal concurrency and more and more languages acknowledge and support it
  - And in a networked world more and more apps engage in asynchronous I/O (network communication)
- Arises from the architecture
  - Can be sugar-coated, but cannot be totally abstracted away

Some questions

- Why wouldn’t you want a user program to be able to access an I/O device (e.g., the disk) directly?
  - Why would you?!
- OK, so what keeps this from happening? What prevents user programs from directly accessing the disk?
- How then does a user program cause disk I/O to occur?

Some questions

- What prevents a user program from writing the memory of another user program?
  - Why might you want to allow it to?
- What prevents a user program from writing the memory of the operating system?
- What prevents a user program from over-writing its own instructions?
  - Why do you want to prevent that?
  - Why do you want to allow it?!
- Is there any reason to support preventing an application from over-writing any of its own data?
  - Is there a use for read-only data memory?
- What prevents a user program from doing a denial of service attack on the CPU simply by going into an infinite loop?

Lecture Question Answers

- What is the basic control flow of the system?
  - The CPU switches between running OS code and application code
- Why do transitions from user code to the OS take place?
  - Interrupts – some IO device (typically) needs attention
  - Exceptions – the CPU has detected something problematic in completing execution of an instruction
  - Trap – the purpose of the instruction being executed is to transition into the OS (syscall)
- Since they run on the same CPU, why can't applications do everything the OS can do?
  - The hardware has two or more privilege levels
  - Some instructions are privileged – require a sufficiently high privilege level – for the CPU to be willing to execute them
- What happens on a transition from user code into the OS?
  - Some registers that execution of the OS is about wipe out are saved by hardware, e.g., the user code PC at which the switch is occurring
  - The PC is set to the address previously set by the OS. The address is a safe entry point into the OS.
  - The privilege level of the CPU is elevated so that it can execute privileged instructions
  - The hw or sw saves all registers so that execution of the user code can eventually be resumed
- On a transition from the OS to user code?
  - The previously saved registers (including the PC) are restored on t he CPU
  - The privilege level is lowered to user level

Lecture Question Answers

- What mechanisms does the hardware provide to help the OS keep control of the system?
  - CPU privilege level + privileged instructions
  - memory access limitations, e.g., virtual memory
  - the exception mechanism – detecting when something that needs OS attention has happened and causing a switch into the OS
- When the OS is running, what stack is it using (in xk)?
  - A per-process kernel stack
- How does xk use the segmented memory system provided by x86_64?
  - It basically renders it moot by mapping every hardware segment to the full linear address space (i.e., base 0 and length 4GB)

Lecture Question Answers

- How is memory protected?
  - On modern system, virtual memory
  - The OS sets a privileged CPU register to point to address mapping structures for the address space the CPU should be using (e.g., when it dispatches a user process)
- How are IO devices protected?
  - Depending on the architecture or even system, it could be privileged instructions are required to communicate with the IO devices, or it could be that protected addresses must be read/written to communicate with them