CSE451 Operating Systems Winter 2009

Module 2
Architectural Support

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Today

- Quick look at hardware trends
- What special hardware support is there for an OS?

Even coarse architectural trends impact tremendously the design of systems

- Processing power
  - doubling every 18 months
  - 60% improvement each year
  - factor of 100 every decade

  - 1980: 1 MHz Apple II+ == $2,000
    - 1980 also 1 MIPS VAX-11/780 == $120,000
  - 2008: Intel Quad-Core 2.66GHz == $900
    er… make that $700

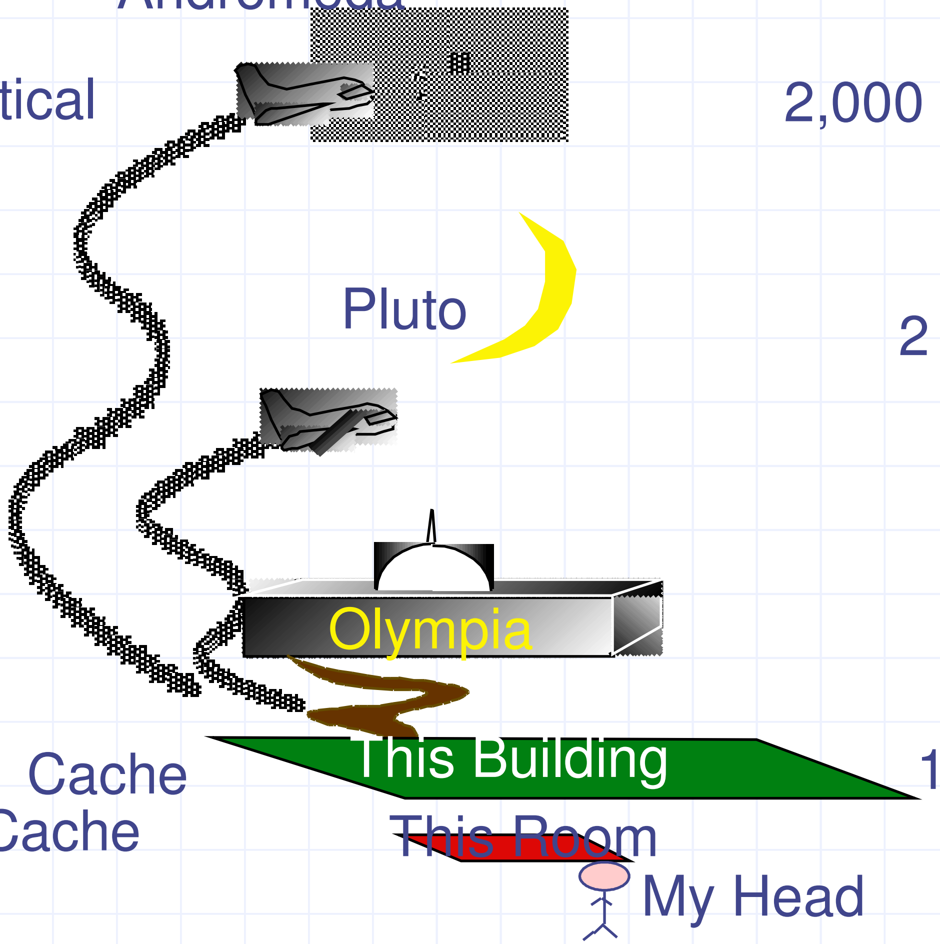
- Primary memory capacity
  - same story, same reason (Moore's Law)
    - 1972: 1MB = $1,000,000
    - 1982: 4 MB for DECSYSTEM 20 - $60,000
    - 2009: 2 GB for Dell Inspiron - $75

- Disk capacity, 1975-1989
  - doubled every 3+ years
  - 25% improvement each year
  - factor of 10 every decade
  - Still exponential, but far less rapid than processor performance
- Disk capacity since 1990
  - doubling every 12 months
  - 100% improvement each year
  - factor of 1000 every decade
  - 10x as fast as processor performance!
- Disk Performance has NOT kept up
  - Speed in 1983: 500KB/sec
  - Speed in 2009: ~40MB/sec (less than 90x!)

- Optical network bandwidth today
  - *Doubling every 9 months*
  - 150% improvement each year
  - Factor of 10,000 every decade
  - 10x as fast as disk capacity!
  - 100x as fast as processor performance!!

- What are some of the implications of these trends?
  - Just one example: We have always designed systems so that they “spend” processing power in order to save “scarce” storage and bandwidth!

Storage Latency: How Far Away is the Data?



10^9	Tape /Optical Robot	Andromeda	2,000 Years
10^6	Disk	Pluto	2 Years
100	Memory	Olympia	1.5 hr
10	On Board Cache	This Building	10 min
2	On Chip Cache	This Room	
1	Registers	My Head	1 min

Lower-level architecture affects the OS even more dramatically

- The operating system supports sharing and protection
  - multiple applications can run concurrently, sharing resources
  - a buggy or malicious application can't nail other applications or the system
- There are many approaches to achieving this
- 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 support can vastly simplify (or complicate!) OS tasks
  - e.g.: early PC operating systems (DOS, MacOS) lacked support for virtual memory, in part because at that time PCs lacked necessary hardware support
    - Apollo workstation used two CPUs as a bandaid for non-restartable instructions!
  - Until very recently, Intel-based PCs still lacked support for 64-bit addressing (which has been available for a decade on other platforms: MIPS, Alpha, IBM, etc…)
    - changing rapidly due to AMD’s 64-bit architecture

Architectural Features affecting OS's

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

Privileged Instructions

- some instructions are restricted to the OS
  - known as protected or privileged instructions
- e.g., only the OS can:
  - 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?
  - halt instruction
    - why?

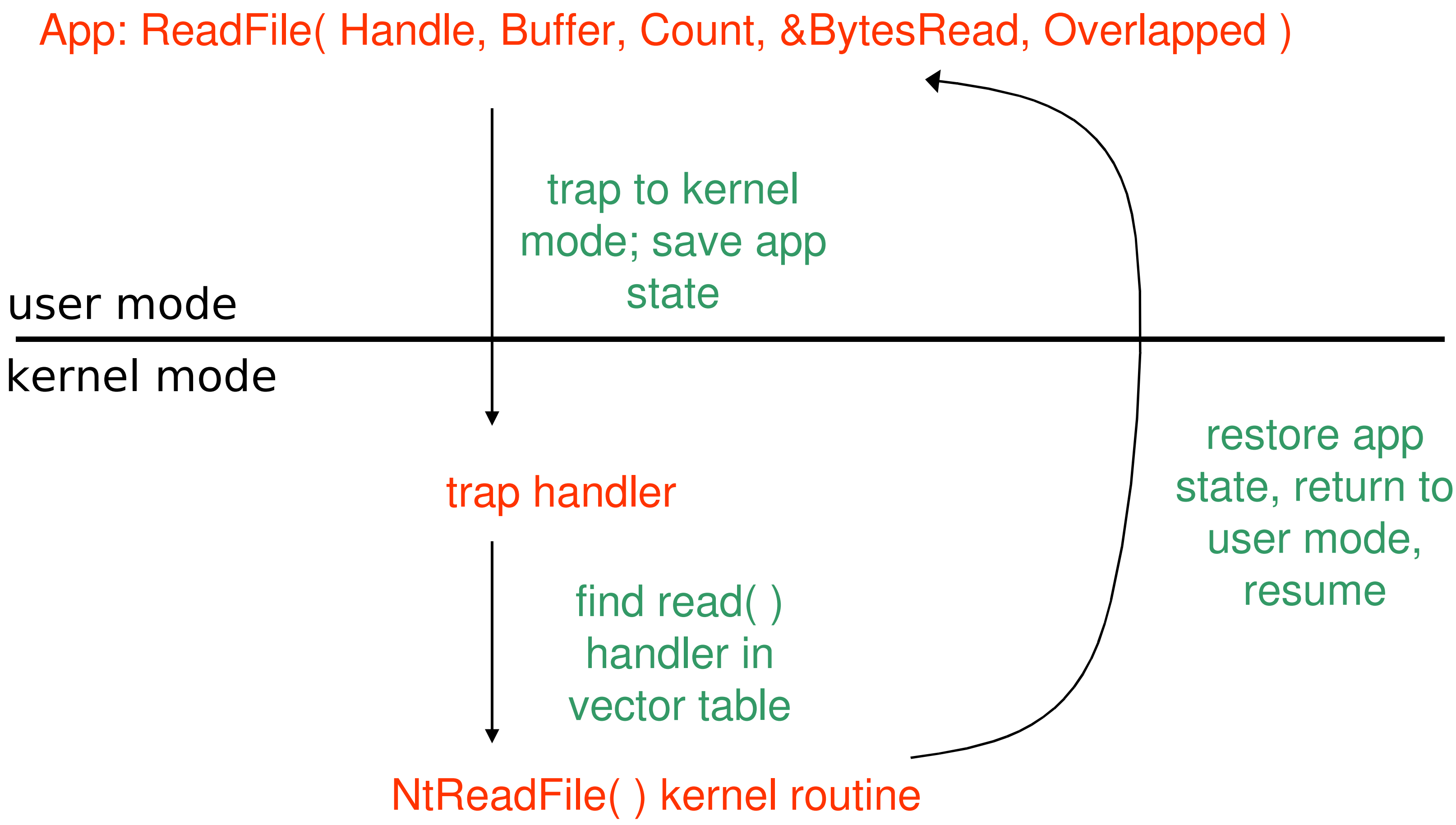
OS Protection

- So how does the processor know if a protected instruction should be executed?
  - the architecture must support at least two modes of operation: kernel mode and user mode
    - VAX, x86 support 4 protection modes
    - why more than 2?
  - mode is set by status bit in a protected processor register
    - user programs execute in user mode
    - OS executes in kernel mode (OS == kernel)
- Protected instructions can only be executed in the kernel mode
  - what happens if user mode executes a protected instruction?

Crossing Protection Boundaries

- So how do user programs do something privileged?
  - e.g., how can you write to a disk if you can't do I/O instructions?
- User programs must call an OS procedure
  - OS defines a sequence of system calls
  - how does the user-mode to kernel-mode transition happen?
- There must be a system call instruction, which:
  - causes an exception (throws a software interrupt), which vectors to a kernel handler
  - passes a parameter indicating which system call to invoke
  - saves caller's state (registers, mode bit) so they can be restored
  - OS must verify caller's parameters (e.g. pointers)
  - must be a way to return to user mode once done

A Kernel Crossing Illustrated

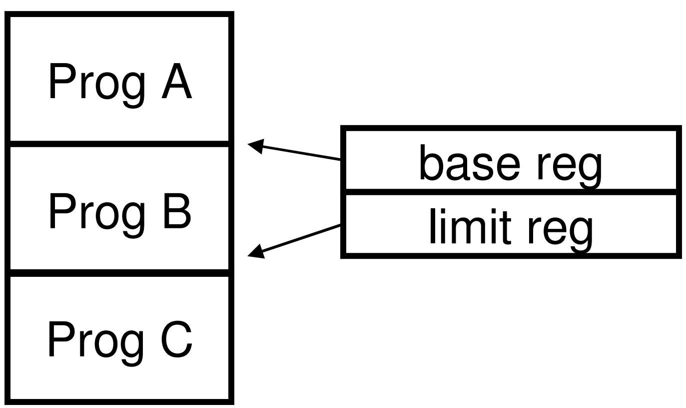


System Call Issues

- What would happen if kernel didn't save state?
- Why must the kernel verify arguments?
- How can you reference kernel objects as arguments or results to/from system calls?

Memory Protection

- OS must protect user programs from each other
  - maliciousness, ineptitude
- OS must also protect itself from user programs
  - integrity and security
  - what about protecting user programs from OS?
- Simplest scheme: base and limit registers
  - are these protected?



base and limit registers are loaded by OS before starting program

More sophisticated memory protection

- coming later in the course
- virtual memory
  - paging, segmentation
  - page tables, page table pointers
  - translation lookaside buffers (TLBs)
  - page fault handling

OS control flow

- after the OS has booted, all entry to the kernel happens as the result of an event
  - event immediately stops current execution
  - changes mode to kernel mode, event handler is called
- kernel defines handlers for each event type
  - specific types are defined by the architecture
    - e.g.: timer event, I/O interrupt, system call trap
  - when the processor receives an event of a given type, it
    - transfers control to handler within the OS
    - handler saves program state (PC, regs, etc.)
    - handler functionality is invoked
    - handler restores program state, returns to program

Interrupts and Exceptions

- Two main types of events: interrupts and exceptions
  - exceptions are caused by software executing instructions
    - e.g. the x86 ‘int’ instruction
    - e.g. a page fault, write to a read-only page
    - an expected exception is a “trap”, unexpected is a “fault”
  - interrupts are caused by hardware devices
    - e.g. device finishes I/O
    - e.g. timer fires

Exceptions

- Hardware must detect special conditions: page fault, write to a read-only page, overflow, trace trap, odd address trap, privileged instruction trap, syscall...
- Must transfer control to handler within the OS
- Hardware must save state on fault (PC, etc) so that the faulting process can be restarted afterwards
- Modern operating systems use VM traps for many functions: debugging, distributed VM, garbage collection, copy-on-write...
- Exceptions are a performance optimization, i.e., conditions could be detected by inserting extra instructions in the code (at high cost)

I/O Control

- Issues:
  - how does the kernel start an I/O?
    - special I/O instructions
    - memory-mapped I/O
  - how does the kernel notice an I/O has finished?
    - polling
    - interrupts
- Interrupts are basis for asynchronous I/O
  - device performs an operation asynchronously to CPU
  - 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 specified by interrupt signal

I/O Control (continued)

device interrupts

↓

CPU stops current operation, switches to kernel mode, and saves current PC and other state on kernel stack

↓

CPU fetches proper vector from vector table and branches to that address (to routine to handle interrupt)

↓

interrupt routine examines device database and performs action required by interrupt

↓

handler completes operation, restores saved (interrupted state) and returns to user mode (or calls scheduler to switch to another program)

Timers

- How can the OS prevent runaway user programs from hogging the CPU (infinite loops?)
  - 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 the timer be privileged?
  - for reading or for writing?

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
- 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
  - another method: have special complex atomic instructions
    - read-modify-write
    - test-and-set
    - load-linked store-conditional

“Concurrent programming”

- Management of concurrency and asynchronous events is biggest difference between “systems programming” and “traditional application programming”
  - modern “event-oriented” application programming is a middle ground
- Arises from the architecture
- Can be sugar-coated, but cannot be totally abstracted away
- Huge intellectual challenge
  - Unlike vulnerabilities due to buffer overruns, which are just sloppy programming

Some questions

- Why wouldn't you want a user program to be able to access an I/O device (e.g., the disk) directly?
- OK, so what keeps this from happening? What prevents user programs from directly accessing the disk?
- So, how does a user program cause disk I/O to occur?
- What prevents a user program from scribbling on the memory of another user program?
- What prevents a user program from scribbling on the memory of the operating system?
- What prevents a user program from running away with the CPU?

Next Time

- We now know what the hardware gives us to use, so
- How do we conceptually organize an OS to put it all together?