CSE 410
Computer Systems

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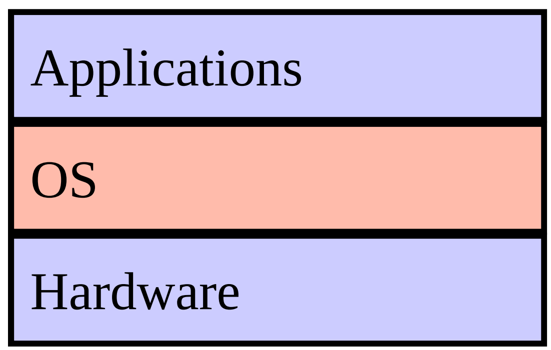
Lecture 14 – Intro to Operating Systems

Readings and References

- Reading
  - Operating System Concepts, Silberschatz, Galvin, and Gagne
    - Ch. 1 Introduction & Ch. 2 OS Structures for background
    - Most useful for us: Sec. 1.1, 1.4-1.9, 2.1, 2.3-2.4, 2.6-2.7
  - Slide credits: largely taken from CSE451, courtesy of Hank Levy.

What is an Operating System?

- An operating system (OS) is:
  - a software layer to abstract away and manage details of hardware resources
  - a set of utilities to simplify application development



  - “all the code you didn’t write” in order to implement your application
- Key idea: *virtualization* of resources

The OS and hardware

- An OS mediates programs' access to hardware resources
  - Computation (CPU)
  - Volatile storage (memory) and persistent storage (disk, etc.)
  - Network communications (TCP/IP stacks, ethernet cards, etc.)
  - Input/output devices (keyboard, mouse, display, sound card, ..)
- The OS abstracts hardware into logical resources and well-defined interfaces to those resources
  - processes (CPU, memory)
  - files (disk)
  - programs (sequences of instructions)
  - sockets (network)

Why bother with an OS?

- Application benefits
  - programming simplicity
    - see high-level abstractions (files) instead of low-level hardware details (device registers)
    - abstractions are reusable across many programs
  - portability (across machine configurations or architectures)
    - device independence: 3Com card or Intel card?
- User benefits
  - safety
    - program “sees” own virtual machine, thinks it owns computer
    - OS protects programs from each other (what if one crashes?)
    - OS fairly multiplexes resources across programs
  - efficiency (cost and speed)
    - share one computer across many users
    - concurrent execution of multiple programs

The major OS issues

- **structure**: how is the OS organized?
- **sharing**: how are resources shared across users?
- **naming**: how are resources named (by users or programs)?
- **security**: how is integrity of the OS and its resources ensured?
- **protection**: how is one user/program protected from another?
- **performance**: how do we make it all go fast?
- **reliability**: what happens if something goes wrong (either with hardware or with a program)?
- **extensibility**: can we add new features?
- **communication**: how do programs exchange information, including across a network?

More OS issues…

- **concurrency**: how are parallel activities (computation and I/O) created and controlled?
- **scale and growth**: what happens as demands or resources increase?
- **persistence**: how do you make data last longer than program executions?
- **distribution**: how do multiple computers interact with each other? how do we make distribution invisible?
- **accounting**: how do we keep track of resource usage, and perhaps charge for it?

There are a huge number of engineering tradeoffs
in dealing with these issues!

Hardware/Software Changes with Time

- 1960s: mainframe computers (IBM)
- 1970s: minicomputers (DEC)
- 1980s: microprocessors and workstations (SUN)
- 1990s: PCs (rise of Microsoft, Intel, then Dell)
- 2000: Internet Services / Clusters (Amazon)
- 2006: General Cloud Computing (Google, Amazon)
- …..
- 2020: it's up to you!!

OS history

- In the very beginning…
  – OS was just a library of code that you linked into your program; programs were loaded in their entirety into memory, and executed
  – interfaces were literally switches and blinking lights
- And then came **batch systems**
  – OS was stored in a portion of primary memory
  – OS loaded the next job into memory from the card reader
    - job gets executed
    - output is printed, including a dump of memory (why?)
    - repeat…
  – card readers and line printers were very slow
    - so CPU was idle much of the time (wastes $$)

Spooling

- Disks were much faster than card readers and printers
- Spool (Simultaneous Peripheral Operations On-Line)
  - while one job is executing, spool next job from card reader onto disk
    - slow card reader I/O is overlapped with CPU
  - can even spool multiple programs onto disk
    - OS must choose which to run next
    - job scheduling
  - but, CPU still idle when a program interacts with a peripheral during execution
  - buffering, double-buffering

Multiprogramming

- To increase system utilization, multiprogramming OSs were invented
  - keeps multiple runnable jobs loaded in memory at once
  - overlaps I/O of a job with computing of another
    - while one job waits for I/O completion, OS runs instructions from another job
  - to benefit, need asynchronous I/O devices
    - need some way to know when devices are done
      - interrupts
      - polling
  - goal: optimize system throughput
    - perhaps at the cost of response time…

Timesharing

- To support interactive use, create a timesharing OS:
  - multiple terminals into one machine
  - each user has illusion of entire machine to him/herself
  - optimize response time, perhaps at the cost of throughput
- Timeslicing
  - divide CPU equally among the users
  - if job is truly interactive (e.g. editor), then can jump between programs and users faster than users can generate load
  - permits users to interactively view, edit, debug running programs (why does this matter?)
- MIT Multics system (mid-1960's) was the first large timeshared system
  - nearly all OS concepts can be traced back to Multics

Timesharing

- In early 1980s, a *single* timeshared VAX/780 (like the one in the Allen Center atrium) ran computing for the *entire* CSE department.
- A typical VAX/780 was 1 MIPS (1 MHz) and had 16MB of RAM and 100MB of disk.
- An iPhone 3GS is 600 MIPS, has 256MB of RAM (way too little though) and 16GB disk.

Parallel systems

- Some applications can be written as multiple parallel threads or processes
  - can speed up the execution by running multiple threads/processes simultaneously on multiple CPUs [Burroughs D825, 1962]
    - true multiprocesssing (not just multiprogramming)
  - need OS and language primitives for dividing program into multiple parallel activities
  - need OS primitives for fast communication among activities
    - degree of speedup dictated by communication/computation ratio
  - many flavors of parallel computers today
    - SMPs (symmetric multi-processors, multi-core)
    - SMT (simultaneous multithreading ["hyperthreading"])
    - MPPs (massively parallel processors)
    - NOWs (networks of workstations) [clusters]
    - computational grid (SETI @home)

Personal computing

- Primary goal was to enable new kinds of interactive applications
- Bit-mapped display [Xerox Alto,1973]
  - New graphic/visual apps
  - new input device (the mouse)
- Move computing near the display
  - why?
- Window systems
  - the display as a managed resource
- Local area networks [Ethernet]
  - why?
- Effect on OS?

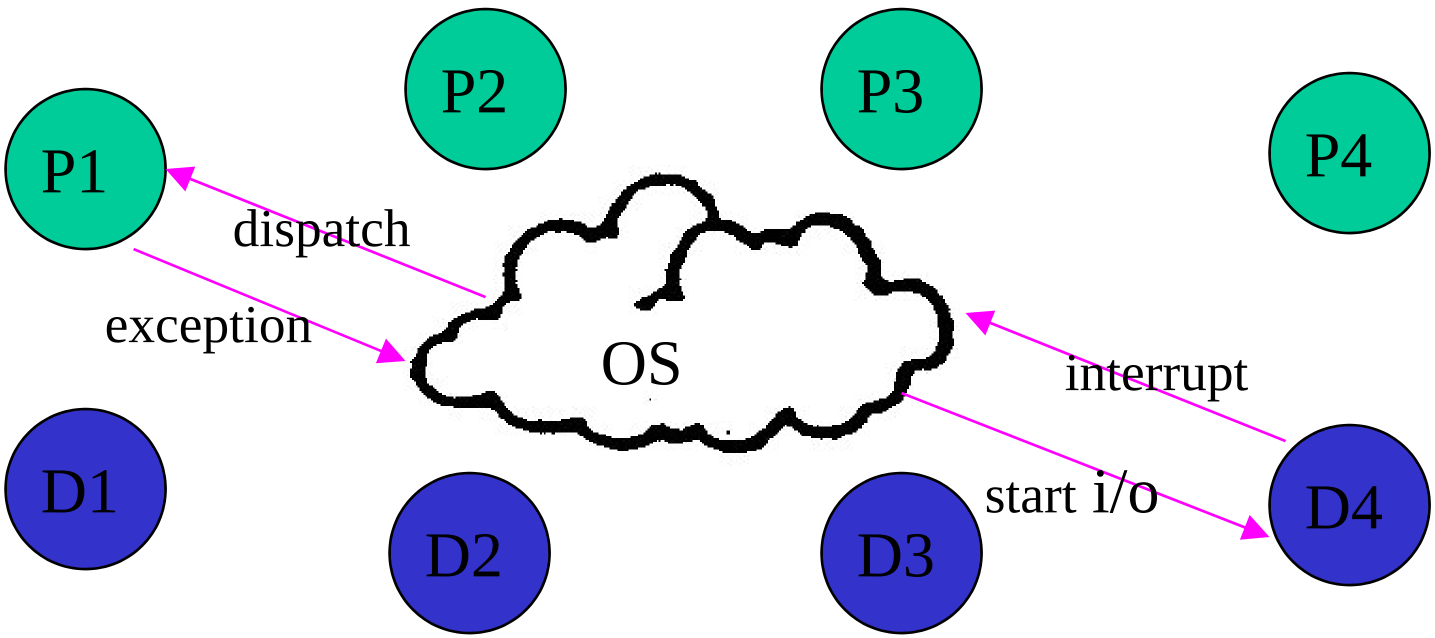
Embedded OS

- Pervasive computing
  - cheap processors embedded everywhere
  - how many are on your body now? in your car?
  - cell phones, PDAs, games, iPod, network computers, …
- Typically very constrained hardware resources
  - slow processors
  - small amount of memory
  - no disk or tiny disk
  - typically only one dedicated application
  - limited power

- But technology changes fast
  - embedded CPUs are getting faster
  - storage is growing rapidly

OS structure

- The OS sits between application programs and the hardware
  - it mediates access and abstracts away ugliness
  - programs request services via exceptions (traps or faults)
  - devices request attention via interrupts

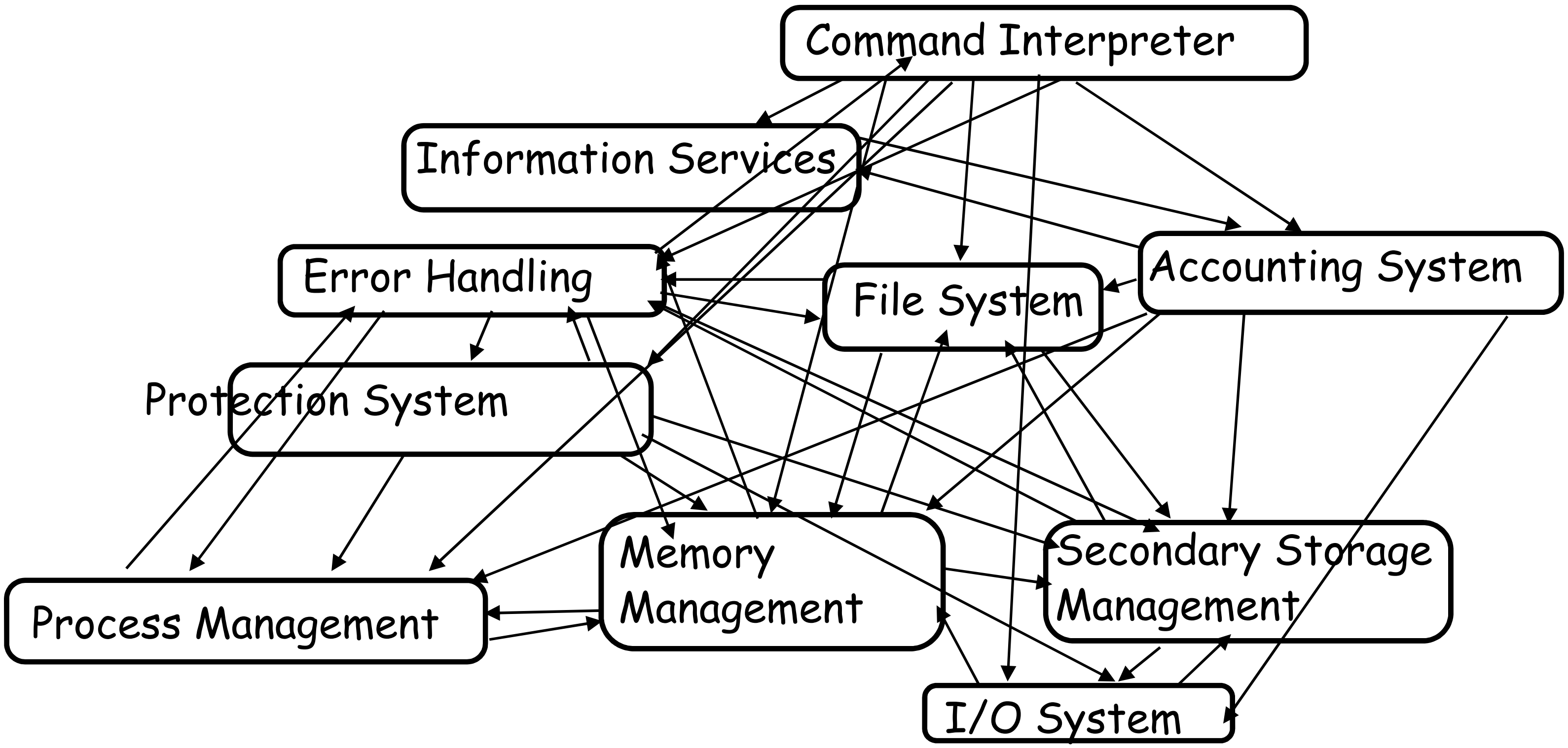


Major OS components

- processes
- memory
- I/O
- secondary storage
- file systems
- protection
- accounting
- shells (command interpreter, or OS UI)
- GUI
- networking

OS structure

- It's not always clear how to stitch OS modules together:

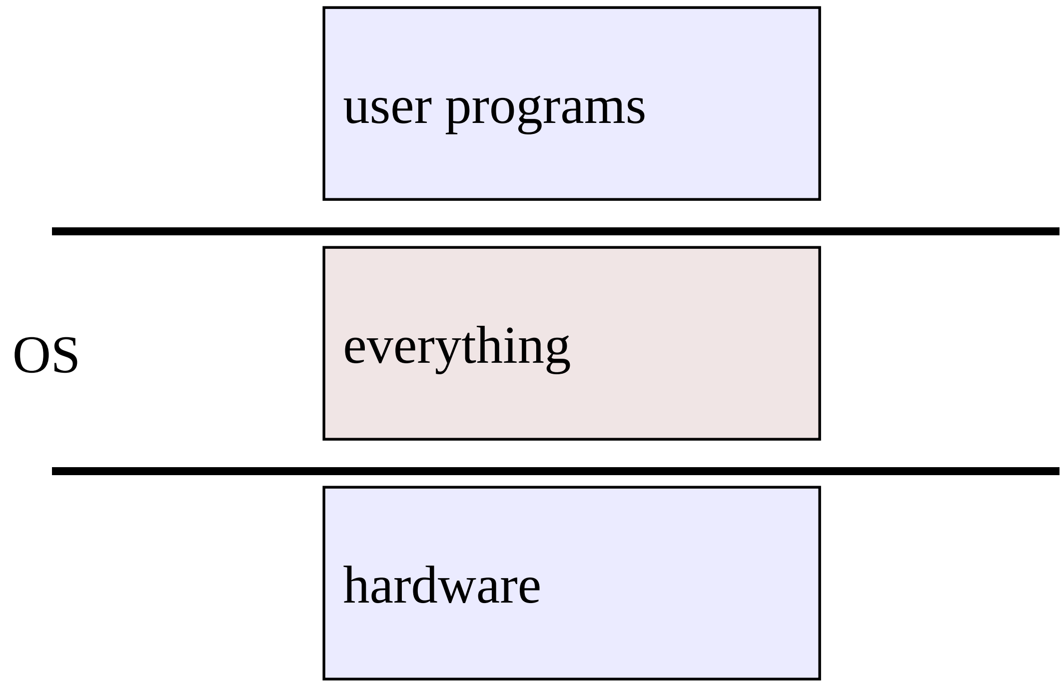


OS structure

- An OS consists of all of these components, plus:
  - many other components
  - system programs (privileged and non-privileged)
    - e.g., bootstrap code, the init program, …
- Major issue:
  - how do we organize all this?
  - what are all of the code modules, and where do they exist?
  - how do they cooperate?
- Massive software engineering and design problem
  - design a large, complex program that:
    - performs well, is reliable, is extensible, is backwards compatible, …

Early structure: Monolithic

- Traditionally, OS's (like UNIX) were built as a monolithic entity:



Monolithic design

- Major advantage:
  - cost of module interactions is low (procedure call)
- Disadvantages:
  - hard to understand
  - hard to modify
  - unreliable (no isolation between system modules)
  - hard to maintain
- What is the alternative?
  - find a way to organize the OS in order to simplify its design and implementation

Layering

- The traditional approach is layering
  - implement OS as a set of layers
  - each layer presents an enhanced ‘virtual machine’ to the layer above
- The first description of this approach was Dijkstra’s THE system
  - Layer 5: Job Managers
    - Execute users’ programs
  - Layer 4: Device Managers
    - Handle devices and provide buffering
  - Layer 3: Console Manager
    - Implements virtual consoles
  - Layer 2: Page Manager
    - Implements virtual memories for each process
  - Layer 1: Kernel
    - Implements a virtual processor for each process
  - Layer 0: Hardware
- Each layer can be tested and verified independently

Problems with layering

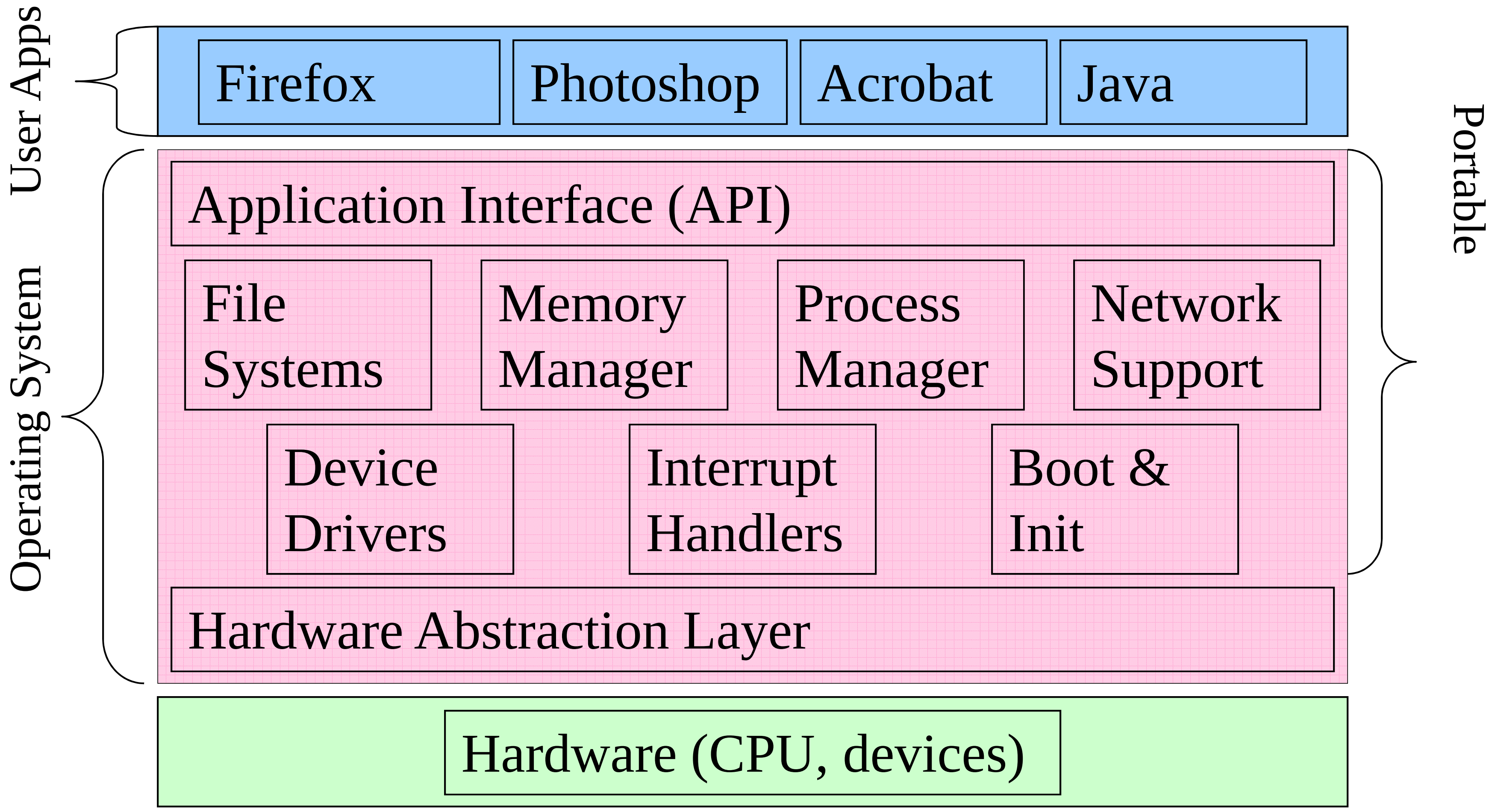
- Imposes hierarchical structure
  - but real systems are more complex:
    - file system requires VM services (buffers)
    - VM would like to use files for its backing store
  - strict layering isn't flexible enough
- Poor performance
  - each layer crossing has overhead associated with it
- Disjunction between model and reality
  - systems modeled as layers, but not really built that way

Hardware Abstraction Layer

- An example of layering in modern operating systems
- Goal: separates hardware-specific routines from the "core" OS
  - Provides portability
  - Improves readability

Core OS (file system, scheduler, system calls)
Hardware Abstraction Layer (device drivers, assembly routines)

The Sanitized Picture of OS Structure



Lower-level architecture and the OS

- Operating system functionality is dictated, at least in part, by the underlying hardware architecture
  - 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

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
  - protected modes of execution (kernel vs. user)
  - protected instructions
  - system calls (and software interrupts)

Protected 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, user/kernel mode bit
    - why?
  - halt instruction
    - why?

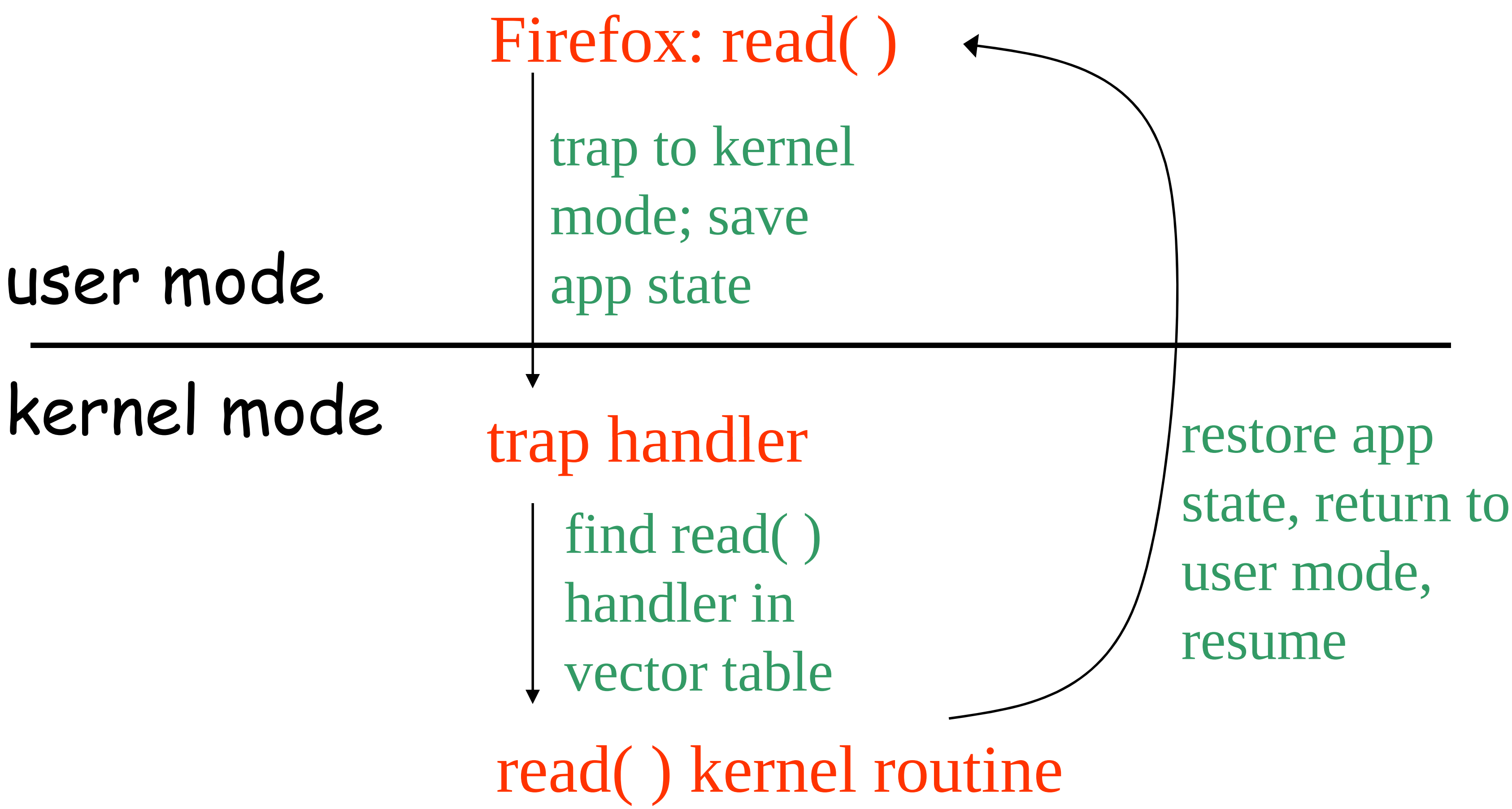
OS protection

- 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
  - 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 (generates a software interrupt), which vectors to a kernel handler
  - passes a parameter indicating which system call to invoke
  - saves caller's state (regs, 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?

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, MIPS ‘syscall’ instruction
    - e.g., a page fault, write to a read-only page, divide by 0
    - 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

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 asynch 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
  - CPU switches to address indicated by vector specified by interrupt signal

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

Architectures are still evolving

- New features are still being introduced to meet modern demands, e.g.:
  - Support for virtual machine monitors
  - Hardware transaction support (to simplify parallel programming)
  - Support for security (encryption, trusted modes)
  - Increasingly sophisticated video / graphics
  - Other stuff that hasn't been invented yet…

- In current technology transistors are free – CPU makers are looking for new ways to use transistors to make their chips more desirable.

- Intel's big challenge: finding applications that require new hardware support, so that you will want to upgrade to a new computer to run them.