

# CS 370: OPERATING SYSTEMS

## [INTRODUCTION]

Shrideep Pallickara  
Computer Science  
Colorado State University

COMPUTER SCIENCE DEPARTMENT



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## Frequently asked questions from the previous class survey

- What's the difference between the kernel and a root/super-admin user?
- Where does the OS fit in the computer architecture?
- What is a Raspberry Pi?
- Masking hardware limitations?
- Kernel mode vs user mode?
- You reference a lot of different texts, are we expected to read all of them?
- How to leverage Claude Code effectively?
- Several variations of AI has no place in courses, academia, society, etc.



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## Topics covered in this lecture

- A (very) brief history of Operating Systems
- CPU, Caches and main memory
- Secondary storage
- Relative speeds of the memory hierarchy
- The Kernel Abstraction



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## A (VERY) BRIEF HISTORY OF OPERATING SYSTEMS

*A very brief history, in the academic sense of "Brief"*

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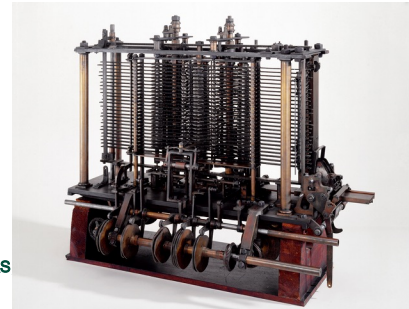


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## The first true digital computer was designed by Charles Babbage (1792-1871)

- Spent most of his life and fortune trying to build the analytical engine
- Never got it working properly
  - ▣ Purely mechanical
  - ▣ Technology of the day could not produce wheels, cogs, gears to the required precision
- Did not have an operating system



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## Babbage realized he would need software for his analytical engine

- Hired Ada Lovelace as the worlds first programmer
  - ▣ Daughter of British poet Lord Byron
- The programming language Ada® is named after her



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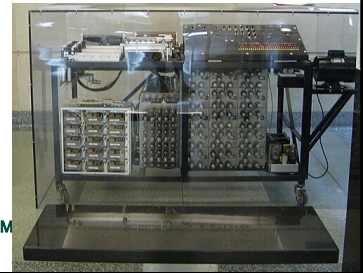
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## The First Generation (1945-55) Vacuum Tubes

- First fully functioning digital computer built at Iowa State University
  - ▣ Prof. John Atanasoff and grad student Clifford Berry
- All programming in absolute machine language
  - ▣ Also, by wiring up electrical circuits
    - Connect 1000s of cables to plug boards to control machine's basic functions
  - ▣ Operating Systems were unheard of
- Straightforward numerical calculations
  - ▣ Produce tables of sines, cosines, logarithms



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## The Second Generation (1955-1965): Transistors and Batch Systems

- **Separation** between designers, builders, operators, programmers, and maintenance
- Machines were called **mainframes**
- Write a program on paper, then punch it on cards
  - ▣ Give card deck to operator and go drink coffee
  - ▣ Operator gives output to programmer



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## The Third Generation (1965-1980) ICs and Multiprogramming

- Managing different product lines was expensive for manufacturers
  - ▣ Customers would start with a small machine, and then outgrow it
- IBM introduced the Systems/360
  - ▣ Series of **software-compatible** machines
  - ▣ All machines had the same instruction set
    - Programs written for one machine could run on all machines



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## The Fourth Generation (1980-Present) Personal Computers

- Large Scale Integration circuits (LSI)
  - ▣ Thousands of transistors on a square centimeter of silicon
- 1974: Intel came out with the 8080
  - ▣ General purpose 8-bit CPU
- Early 1980s IBM designed the IBM PC
  - ▣ Looked for an OS to run on the PC
  - ▣ Microsoft purchased Disk Operating System and went back to IBM with MS-DOS



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## Over the past 50 years ...

- The most striking aspect has been Moore's Law and comparable advances in related technologies, such as memory and disk storage
- The cost of processing and memory has decreased by almost  $10^6$  over this period; the cost of disk capacity has decreased by  $10^7$ 
  - ▣ Disk latency has improved, but at a much slower rate than disk capacity
- These relative changes have **radically altered** both the use of computers and the **tradeoffs** faced by operating system designers



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## Operating systems tend to be huge, complex and long-lived

- Source code of an OS like Linux or Windows?
  - ▣ Order of 5 million lines of code (for kernel)
    - 50 lines page, 1000 pages/volume = 100 volumes
- Application programs such as GUI, libraries and application software?
  - ▣ 10-20 times that



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## Why do operating systems live for a long time?

- Hard to write and folks are loath to throw it out
- Typically **evolve** over long periods of time
  - ▣ Windows 95/98/Me is one OS
  - ▣ Windows NT/2000/XP/Vista/7/8/10/11 is another
  - ▣ System V, Solaris, BSD derived from original UNIX
  - ▣ Linux is a fresh code base
    - Closely modeled on UNIX and highly compatible with it
  - ▣ Apple OS X based on XNU (X is not Unix) which is based on the Mach microkernel and BSD's POSIX API



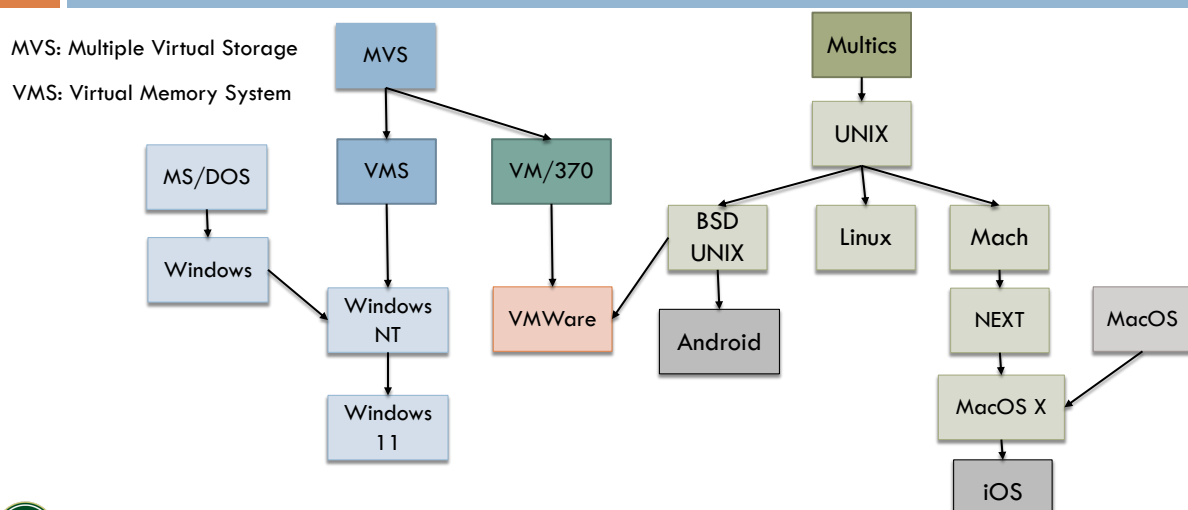
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## Genealogy of modern operating systems



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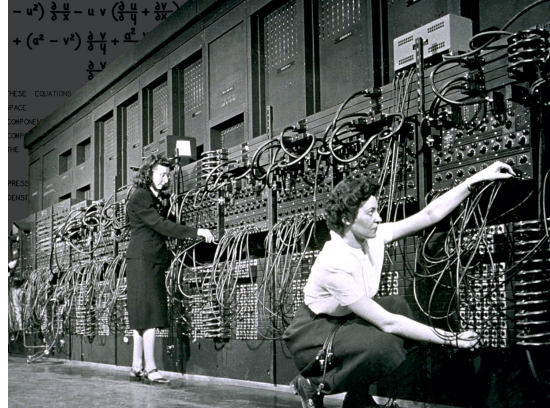
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## Modern computer systems design

- Has its origins dating back to 1947 as part of work on ENIAC
- Breaks up a computing machine into three main subsystems:
  - ▣ The central processing unit (**CPU**) for performing arithmetic operations
  - ▣ The **memory** for storage of instructions and data
  - ▣ The input-output (**I/O**) unit for communicating with the external world
- This way of organizing a machine became known as the “**von Neumann architecture**”



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## COMPONENTS OF A COMPUTER

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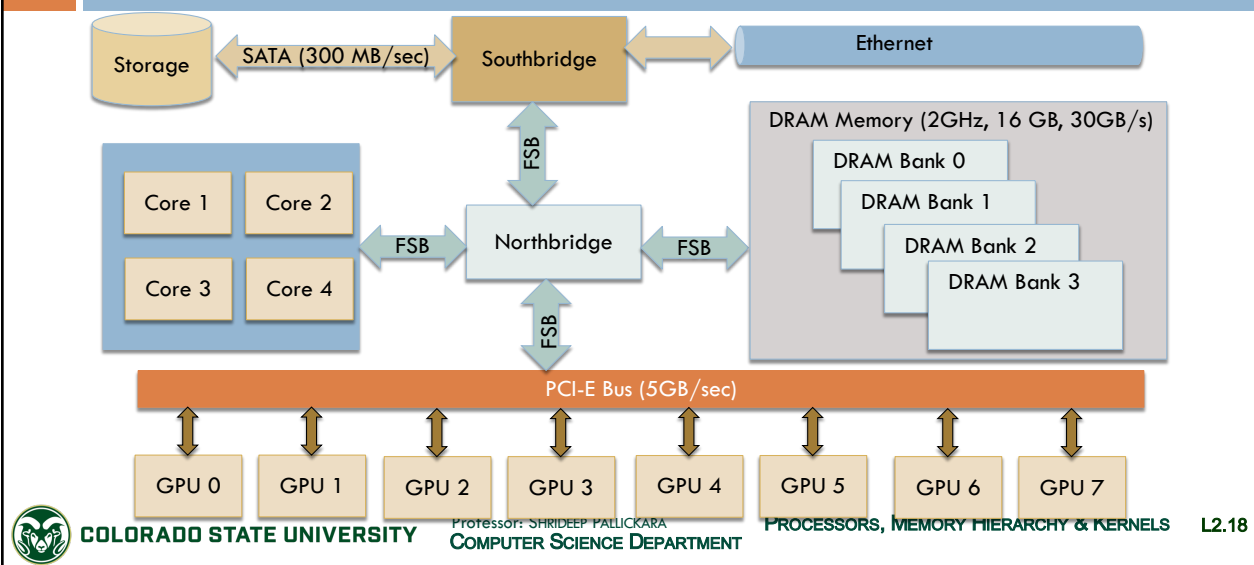


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## Typical PC architecture



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## Processors

- **Brain** of the computer
- Each CPU has a specific set of instructions that it can execute
  - An x86-64 processor cannot natively execute ARM64 instructions, and vice versa

\* The instruction set architecture (ISA) is how software interacts with the hardware.

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## Rationale for registers inside the CPU

- Accessing memory to get instruction or data
  - ▣ **Much longer** than executing the instruction
- Registers hold:
  - ▣ Key variables
  - ▣ Temporary results



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## What the instruction set looks like

- Load a word from memory into register
  - ▣ And, from register into memory
- Combine two (or more) operands from register, memory, or both into a result
  - ▣ E.g., add two words and store result in a register or in memory



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Besides the registers to hold variable and temporary results there are special registers

- **Program Counter**

- ▣ Contains the memory address of the next instruction to be fetched

- **Stack pointer**

- ▣ Points to the top of the current stack in memory

- **Program Status Word**

- ▣ Stores condition code bits and other control code bits
  - ▣ Plays an important role in system calls and I/O



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## Memory hierarchy: Cache memory

- Mostly *controlled by hardware*

- Main memory divided up into **cache lines**

- ▣ Usually 64 bytes
  - ▣ Addresses 0-63 in cache line 1, 64-127 in cache line 2, and so on

- Most heavily used cache lines are stored in a high-speed cache



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## When a program needs to read a memory word

- Cache hardware checks if the needed line is in the cache
- If it is, that's a **cache hit**
  - ▣ Request satisfied from cache in about *2 clock cycles*
  - ▣ No memory access needed
- If needed line is not present in cache
  - ▣ **Cache miss**, and must access memory
  - ▣ **Substantial** time penalty



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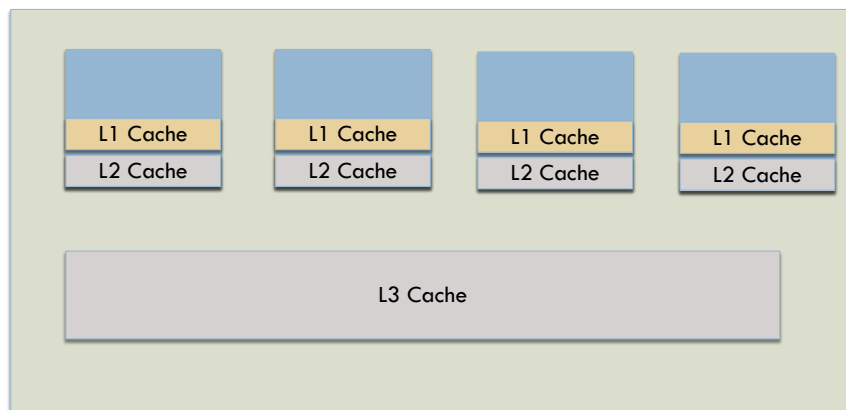
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## Logical view of the Processor, Cores, and Caches



L1: Typically in the order of 16 KB

L2, L3: Typically in the order of MBs

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## Caching is a powerful concept used elsewhere too. Let's see when ...

- ① Large resource *can be divided* into pieces
  - ② Some pieces *used more heavily* than others
- OS caching examples:
    - ▣ Pieces of heavily used files in main memory
      - Reduce disk accesses
    - ▣ Conversion of file names to disk addresses
    - ▣ Addresses of Web pages (URLs) as hosts



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## Main Memory

- Usually called **RAM** (Random Access Memory)
- Cache misses go to the main memory
- **Volatile**
  - ▣ Contents lost when power is turned off
- Memory size is in the order of several GB in most modern desktops



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## Memory

- Ideally the memory should be
  - ▣ Extremely **fast**: Faster than executing an instruction
    - CPU should not be held up by the memory
  - ▣ Abundantly **large**
  - ▣ Dirt **cheap**
- No current technology satisfies all these goals



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## Computers run most of their programs from (rewriteable) main memory

- Typically implemented in a technology called DRAM (dynamic random access memory)
- Ideal Scenario: Programs and data reside permanently in main memory. BUT ...
  - ▣ Space is *limited*
  - ▣ Main memory is **volatile** storage



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## Secondary storage is needed to hold large quantities of data permanently

- Programs use the disk as the source and destination of processing
- Seek time 7 ms
- SPIN: 7200 – 15000 RPM
- Transfer rate
  - ▣ Disk-to-buffer: 70 MB/sec (SATA or Serial Advanced Technology Attachment)
  - ▣ Buffer-to-Computer: 300 MB/sec
- Mean time between failures
  - ▣ 600,000 hours
- 1 TB capacity for less than \$75



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## Improvements in hard disk capacity

- 1980 - 5 MB
- 1991 - 100 MB
- 1995 - 2 GB
- 1997 - 10 GB



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## Improvements in hard disk capacity

- 2002 - 128 GB addressing space barrier [28 bits]
  - ▣ Old IDE/ATA interface: 28-bit addressing
  - ▣  $2^{28} \times 512 = 2^{28} \times 2^9 = 2^{37} = 128 \text{ GB} = 137,438,953,472 \text{ bytes}$
- 2003 – Serial ATA introduced
  - ▣ Bus interface providing connections to mass storage devices
- 2005 – 500 GB hard drives
- 2008 – 1 TB hard drives



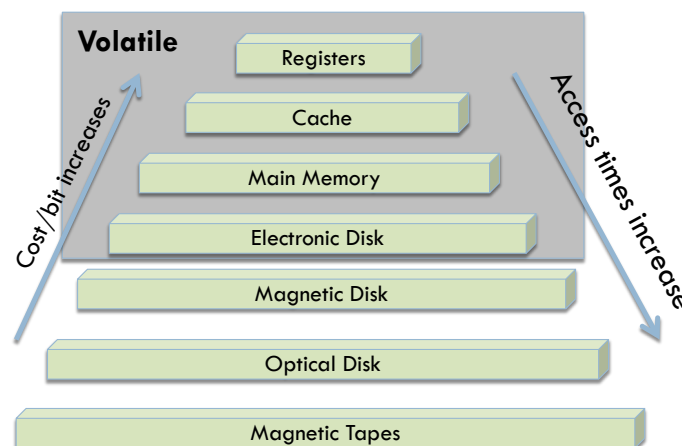
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## Storage system hierarchy based on speed, cost, size and volatility



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## Characteristics of peripheral devices & their speed relative to the CPU

| Item            | time                    | Scaled time in human terms<br>(2 billion times slower) |
|-----------------|-------------------------|--------------------------------------------------------|
| Processor cycle | 0.5 ns (2 GHz)          | 1 second                                               |
| Cache access    | 1 ns (1 GHz)            | 2 seconds                                              |
| Memory access   | 70 ns                   | 140 seconds                                            |
| Context switch  | 5,000 ns (5 $\mu$ s)    | 167 minutes                                            |
| Disk access     | 7,000,000 ns (7 ms)     | 162 days                                               |
| Quantum         | 100,000,000 ns (100 ms) | 6.3 years                                              |



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## Mechanical nature of disks limits their performance

- Disk access times *have not* decreased exponentially
  - ▣ Processor speeds are growing *exponentially*
- Disparity between processor and disk access times continues to grow
  - ▣ 1:14,000,000



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## RELATIVE SPEEDS OF THE MEMORY HIERARCHY

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Since caches have limited size, cache management is critical

| Level                     | 1                   | 2                     | 3           | 4             |
|---------------------------|---------------------|-----------------------|-------------|---------------|
| Name                      | registers           | cache                 | Main memory | Disk Storage  |
| Typical Size              | < 1 KB              | < 16 MB               | < 64 GB     | > 1 TB        |
| Implementation Technology | Custom memory, CMOS | On/off chip CMOS SRAM | CMOS DRAM   | Magnetic disk |
| Access times              | 0.25 ns             | 0.5-25 ns             | 80-250 ns   | > 5 ms        |
| Bandwidth (MB/sec)        | 20,000 – 100,000    | 5000-10,000           | 1000-5000   | 80-300        |
| Managed by                | compiler            | hardware              | OS          | OS            |
| Backed by                 | cache               | Main memory           | Disk        | CD/Tape       |

\* Complementary Metal-Oxide-Semiconductor (CMOS)



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## ONTOGENY RECAPITULATES PHYLOGENY

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After Charles Darwin's book ON THE ORIGIN OF SPECIES was published

□ German zoologist Ernst Haeckl stated

▣ **Ontogeny**

recapitulates

**Phylogeny**

*Development of an embryo*

*repeats*

*the evolution of the species*

- i.e. human egg goes through stages of being a fish, ... , before becoming human baby
- Modern biologists think this is a gross simplification!



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## Something vaguely similar has happened in the computer industry

- Each new species (*type of computer*) goes through the development its ancestors did
  - ▣ Both in hardware and software
  - ▣ Mainframe, mini computers, PC, handheld, etc



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## Much of what happens in computing and other fields is technology driven

- Ancient Romans lacked cars not because they liked walking
  - ▣ It is because they didn't know to build cars
- PCs exist not because people have a centuries-old pent-up desire to own one
  - ▣ It is now possible to manufacture them cheaply



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## Technology affects our view of systems

- A **change** in technology renders some idea *obsolete*
  - ▣ Another change could *revive* it
- Especially true when change has to do with **relative performance**
  - ▣ Of different parts of the system



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## Let's look at this **relative** performance

- When CPUs become faster than memories?
  - ▣ Caches become important to speed-up slow memory
- If new memory technology makes memories much faster than CPUs?
  - ▣ Caches will vanish!
- In biology extinction is forever
  - ▣ In computer science, it is sometimes only for a few years



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## Historical developments

### Large Memories

- IBM 7090/7094 1959-1964
  - ▣ 128 KB of memory
  - ▣ Programmed in assembly language (even the OS)
  - ▣ With time FORTRAN/COBOL and assembly was dead
- PDP-1 had only 4096 18-bit words of memory
  - ▣ Assembly is back!
  - ▣ Over time memory increases, assembly is out
- Microcomputers in 1980s
  - ▣ 4 KB memory and assembly is back again



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## Other places where such a cycle has gone on?

- Protection hardware
- Disks
- Virtual memory



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Good fences make good neighbors  
*17th century proverb*

## THE KERNEL ABSTRACTION

*Good fences and one very Powerful Neighbor*

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A central role of the OS is **protection**: the **isolation** of potentially misbehaving applications and users

- Implementing protection is the job of the OS **kernel**
- The kernel has full access to all of the machine hardware
  - ▣ The lowest level of software running on the system
  - ▣ Necessarily trusted to do anything with the hardware
- Everything *other than* the kernel is run in a restricted environment
  - Less than complete access to the full power of the hardware



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## What hardware is needed to let the kernel provide isolation?

- At a minimum, the hardware must support **three** things:
- **Privileged Instructions:** All potentially unsafe instructions are prohibited when executing in user mode
- **Memory Protection:** All memory accesses outside of a process's valid memory region are prohibited when executing in user mode
- **Timer Interrupts:** Regardless of what the process does, the kernel must have a way to periodically *regain control* from the current process



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## Conceptually, the kernel/user mode is a one-bit register

- When set to **1**, the processor is in kernel mode and can do anything
- When set to **0**, the processor is in user mode and is restricted



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## Privileged Instructions

- Instructions available in kernel mode, but not in user mode, are called **privileged instructions**
- To do its work, the kernel must be able to execute these instructions
  - ▣ Change privilege levels, adjust memory access, and disable and enable interrupts, set/reset timers
- If these instructions were available to applications?
  - ▣ A rogue application would in effect have the power of the kernel



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## Making memory sharing safe

- The kernel must be able to configure the hardware so that each application process can read and write **only its own memory**
  - ▣ Not the memory of the operating system or any other application
- While it might seem that read-only access to memory is harmless, the OS needs to provide both security and privacy
  - ▣ For example, user passwords may be stored in kernel memory while they are being verified



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## Hardware timers

- Timers can be set to **interrupt** the processor after a specified delay
  - ▣ Either in time or after some number of instructions have been executed
- Each timer interrupts one processor ... separate timer for each CPU
  - ▣ The kernel might set each timer to expire every few milliseconds
- Resetting the timer is a privileged operation
  - ▣ User-level process cannot inadvertently or maliciously disable the timer
- How does the kernel know if an application is in an infinite loop?
  - ▣ It doesn't!



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## Mode transitions

- The kernel places a user process in a carefully constructed **sandbox**
  - ▣ The next question is how to safely transition from executing a user process to executing the kernel, and vice versa
- These transitions are **not rare events**
  - ▣ E.g.: A web server might switch between user mode and kernel mode thousands of times per second
- Transitions must be both fast and safe



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## There are **three** reasons for the kernel to take control from a user process

- Reasons: interrupts, processor exceptions, and system calls
- Asynchronous events
  - ▣ **Interrupts** are triggered by an *external event* and can cause a transfer to kernel mode after any user-mode instruction
- Synchronous events
  - ▣ **Processor exceptions** and **system calls** are triggered by *process execution*
  - ▣ The term **trap** refers to any synchronous transfer of control from user mode to the kernel



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## Interrupts are also used to inform the kernel of the completion of I/O requests

- Mouse device hardware triggers an interrupt every time the user moves or clicks on the mouse
  - ▣ The kernel, in turn, notifies the appropriate user process; the one the user was “mousing” across
- Virtually **every I/O device generates an interrupt** whenever some input arrives for the processor and whenever a request completes
  - ▣ E.g.: the Ethernet, WiFi, hard disk, thumb drive, keyboard, mouse, etc.



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## As the processor executes instructions, it checks for whether an interrupt has arrived

- If so, it completes or stalls any instructions that are in progress
  - ▣ Instead of fetching the next instruction, the processor hardware saves the current execution state
  - ▣ Starts executing at a specially designated interrupt handler in the kernel



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## Processor exceptions

- A processor exception is a **hardware event** caused by user program behavior that causes a transfer of control to the kernel
- A processor exception occurs whenever a process
  - ▣ Attempts to perform a privileged instruction
  - ▣ Accesses memory outside of its own memory region
  - ▣ Causes an arithmetic overflow. E.g., divide-by-zero
  - ▣ Accesses a word of memory with a non-aligned address
  - ▣ Attempts to write to read-only memory



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## User processes can also transition into the kernel voluntarily

- To request that the kernel perform an operation on the user's behalf
- A **system call** is any procedure provided by the kernel that can be called from the user level
  - ▣ Examples include system calls to establish a connection to a web server, to send or receive packets over the network, to create or delete files, to read or write data into files, and to create a new user process



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## To protect the kernel from misbehaving user programs

- It is key that the hardware transfers control on a system call to a pre-defined address
  - ▣ User processes cannot be allowed to jump to arbitrary places in the kernel
- The kernel handles the details of:
  - ▣ Checking and copying arguments
  - ▣ Performing the operation, and
  - ▣ Copying return values back into the process's memory



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## System calls provide the illusion that the kernel is simply a set of library routines available to users

- Implementing system calls requires the operating system to define a **calling convention**
- Once the arguments are in the correct format, the user-level program can issue a system call by executing the trap instruction to transfer control to the kernel
- The kernel implement its system calls in a way that **protects itself** from all errors and attacks that might be launched
  - Extreme version of defensive programming: **always** assume that system call parameters are intentionally designed to be as malicious as possible!



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## The contents of this slide-set are based on the following references

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