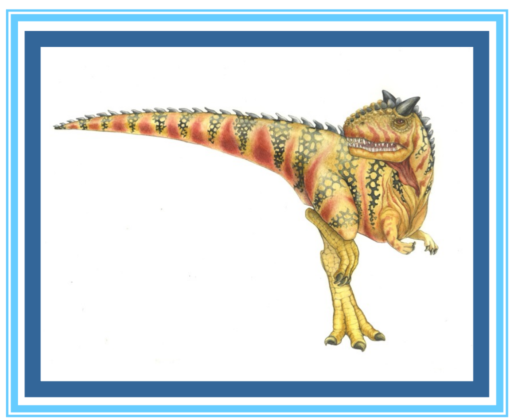
COMP 3511 Operating Systems
Spring 2024



Lectures and Labs/Tutorials

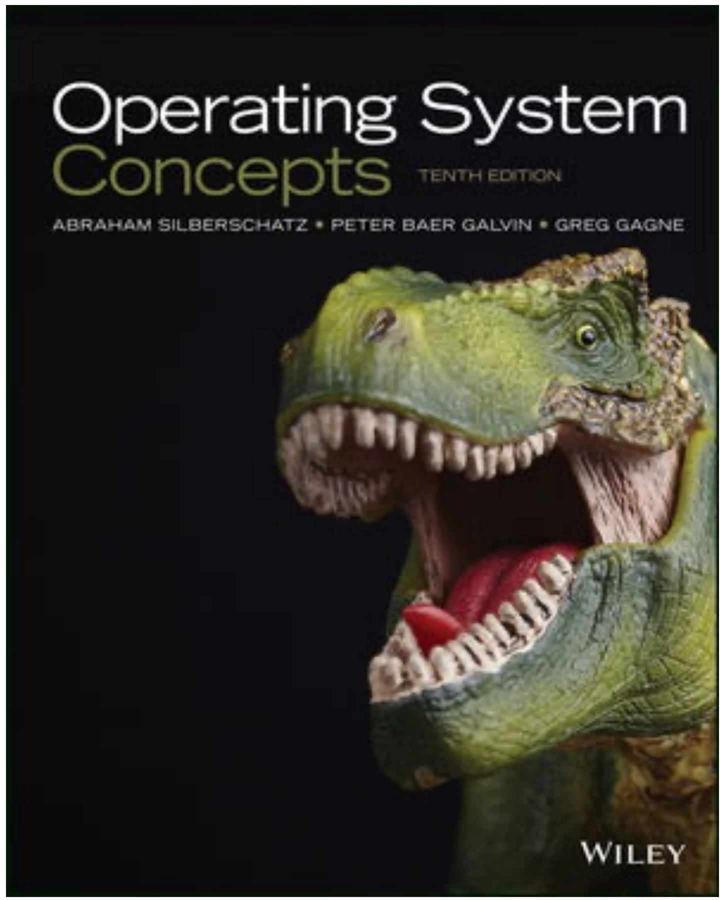
- **Lectures (31 January – 10 May 2024):**
  - **L1 Monday/Wednesday** 9:00AM - 10:20AM, Room 2407, Lift 17-18
  - **L2 Wednesday/Friday** 4:30PM - 5:50PM, Room 2464, Lift 25-26

- **Lab Tutorials**
  - **LA1 Monday** 4:30PM - 6:20PM Rm 2465, Lift 25-26
  - **LA2 Friday** 6:00PM - 7:50PM Rm 2407, Lift 17-18

- **Course Website**: https://course.cse.ust.hk/comp3511/
- **Instructors**: Mo LI (L1) and Bo LI (L2)

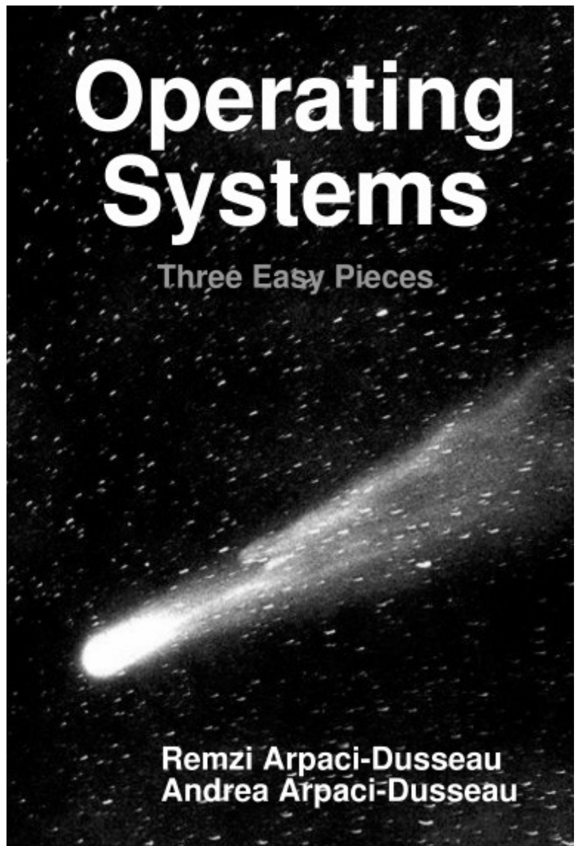
Textbook

- **Operating System Concepts, A. Silberschatz, P. B. Galvin and G. Gagne, 10th Edition**



Reference Book

- Operating Systems: Three Easy Pieces, Remzi H. Arpaci-Dusseau and Andrea C. Arpaci-Dusseau
- Online (free access): http://pages.cs.wisc.edu/~remzi/OSTEP/#book-chapters



Course Prerequisite

- **COMP 2611 or ELEC 2300 or ELEC 2350 (Computer Organization)**
  - Computer organization – von Neumann machine, CPU, pipelining, caching, memory hierarchy, I/O systems, interrupt, storage and hard drives
- **COMP 1029C or COMP 2011 or COMP 2012H (C programming)**
  - UNIX/Linux basic
  - Programming requirement - C programming

Labs and Tutorials

- **9 Labs and Tutorials – rough schedule**
  - No Labs on week 1
  - Lab #1 (week 2): Introduction to Linux
  - Lab #2 (week 3): C/C++ programming
  - Lab #3 (week 4): Linux process, pipe(), and Project #1
  - Lab #4 (week 5): Review
  - Lab #5 (week 6): Project #2
  - Lab #6 (week 7): Review
  - No Labs on week 8 (Midterm week)
  - Lab #7 (week 9): Review
  - Lab #8 (week 10): Project #3
  - Lab #9 (week 11) Review
  - Buffer week on week 12
  - The above schedule may change due to the lecture progress

Grading Scheme

- **4 Homework - written assignments – 20% (5% each)**
  - HW #1 (week 2-4)
  - HW #2 (week 5-7)
  - HW #3 (week 8-10)
  - HW #4 (week 11-13)
- **3 Projects - programming assignments – 30%**
  - Project #1 (week 4-6) (10%)
  - Project #2 (week 7-9) (10%)
  - Project #3 (week 10 -12) (10%)
- **Midterm Exam** (~week #8) - 20%
- **Final Exam** - 30%

Plagiarism Policy

- There are differences between collaborations, discussions and copy!

- First time: all involved get ZERO marks, and will be reported to ARR
- Second time: need to terminate (Fail grade)
- Any cheating in midterm or final exam results in automatic Fail grade

Lecture Format

- Lectures:
  - Lecture notes are made available before lectures
- Tutorials and Labs
  - Unix environment, editor (vim), compile and run programs, Makefile
  - C++ and C programming basic
  - Tutorials on programming assignments
  - C programming APIs and interfaces
  - Supplement materials with more examples and exercises
- Reading the corresponding materials in the textbook and reference book
  - Lecture notes do not and can not cover everything
- Chapter Summaries
  - Comprehensive summary at the end of each chapter

Assignments

- Written assignments
  - Due by time specified
  - Contact the corresponding TA for any disputes on the grading
  - Regrading requests be granted within **two weeks** after the homework grades are released
  - Late policy: **10% reduction**, **only one day delay is allowed**

- Programming assignments - **individual project**
  - Due by time specified
  - **Run on a CS Lab 2 Linux Machines**
  - Submit it using Canvas
  - Regrading requests be granted within **two weeks** after the grades are released
  - Late policy : **10% reduction**, **only one day delay is allowed**

Midterm and Final Examinations

- Midterm Exam
  - Time: March 18 Monday (week# 8) 7:00 pm – 9:00 pm
  - Venues: LSK G012, 1007, 1010, 1032, and 1034
- Final Exam
  - TBD

- **All exams are open-book and open-notes (hard copies)**
  - **NO electronic devices are allowed**

- **No make-up exams will be given unless**
  - Under special circumstances, e.g., sickness, with **letters of proof**
  - The instructor must be informed **before the exam**

Tips for Learning

- Attend lectures and lab tutorials
  - Download lecture/lab notes prior to lectures
  - Important concepts are explained, with examples
- Complete homework and projects independently
  - This is to test your knowledge and how much you comprehend
- **Spend 30 minutes or so each week to review the content**
  - Chapter summary helps
  - This can save you lots of time later when you prepare for exams
  - You can not expect to learn everything 2-3 days before exams
  - Knowledge is accumulated incrementally
- Start your project earlier
  - Have a plan for the project
- Raise questions during or after lectures !
  - Do not delay your questions until close to the exams

What you are supposed to learn

- Define the fundamental principles, strategies and algorithms used in the design and implementation of operating systems
- Analyze and evaluate operating system functions
- Understand the basic structure of an operating system kernel, and identify the relationship between the various subsystems
- Identify the typical events, alerts, and symptoms indicating potential operating system problems
- Design and implement programs for basic operating system functions and algorithms
- **Advanced OS course** – COMP 4511 System and Kernel Programming in Linux

Course Outline

- **Overview** (4 lectures)
  - Basic OS concept (2 lectures)
  - System architecture (2 lectures)
- **Process and Thread** (12 lectures)
  - Process and thread (4 lectures)
  - CPU scheduling (4 lectures)
  - Synchronization and synchronization examples (2 lectures)
  - Deadlock (2 lectures)
- **Memory and storage** (8 lectures)
  - Memory management (2 lectures)
  - Virtual memory (3 lectures)
  - Secondary storage (1 lectures)
  - File systems and implementation (2 lectures)
- **Protection** (1 lectures)
  - Protection (1 lecture)

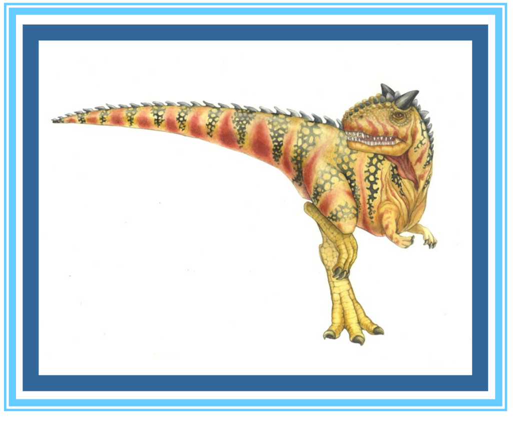
Course Coverage

- **Overview**
  - Chapter 1 – high-level description of OS, basic components in computer systems including multi-processor systems, virtualization
  - Chapter 2 – OS services including APIs and system calls, and common OS design approaches (monolithic, layered, microkernel, modular)
- **Process and Thread**
  - Chapter 3 (Process) – concept of a process capturing a program execution, creating and terminating a process, IPC
  - Chapter 4 (Thread) – concept of a thread and multi-threaded process for concurrent execution of a program
  - Chapter 5 (CPU scheduling) – CPU scheduling algorithms including real-time scheduling, and issues associated with multiprocessor scheduling and thread scheduling
  - Chapter 6-7 (Synchronization) – critical section problem, synchronization tools (hardware and software), and synchronization examples
  - Chapter 8 (Deadlock) – deadlock characterization, resource allocation graph, deadlock prevention, avoidance and detection algorithms

Course Coverage (Cont.)

- **Memory and Storage**
  - Chapter 9 (Memory) - contiguous memory allocation, segmentation, paging including hierarchical paging
  - Chapter 10 (Virtual memory) – virtual vs. physical memory, demand paging, page replacement algorithm, thrashing and frame allocation
  - Chapter 11 (Secondary storage) – hard drive, disk structure, disk scheduling algorithms and RAID (disk array) structure
  - Chapter 13-14 (File systems) – file access methods, directory structure and implementation, basic file system data structure (on-disk and in-memory), disk space management including disk block allocation
- **Protection**
  - Chapter 17 (Protection) – basic protection principles, protection rings, protection domain and implementation (access matrix)

Chapter 1: Introduction



Chapter 1: Introduction

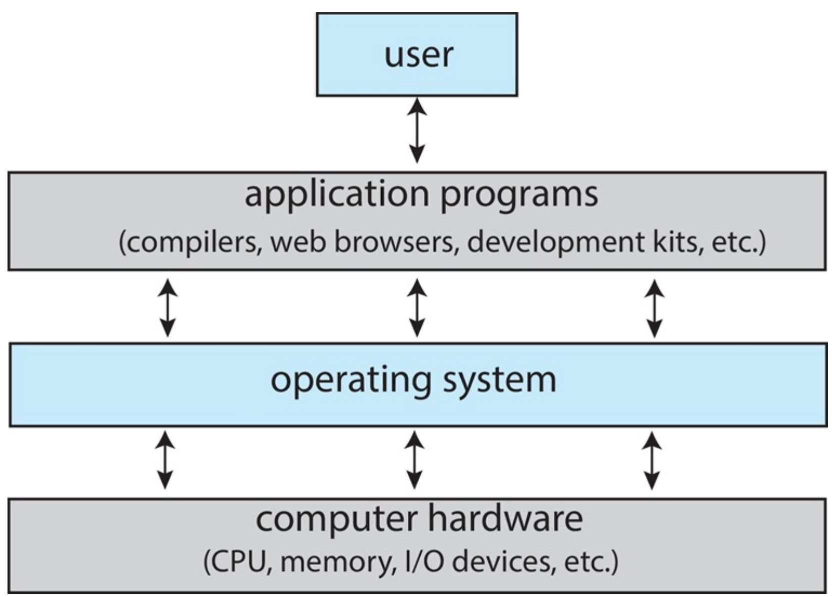
- What Operating Systems Do
- Computer System Organization and Architecture
- Multiprocessor and Parallel Systems
- Definition of Operating Systems
- Virtualization and Cloud Computing
- Free and Open-Source Operating Systems

Objectives

- Describe the general organization of a computer system and the role of interrupts.
- Illustrate the components in a modern multiprocessor computer system.
- Discuss how operating systems are used in various computing environments
- Provide examples of free and open-source operating systems

What is an Operating System?

- **Users** - people, machines, other computers or devices
- **Application programs** – define the ways how system resources are used to solve user problems
  - Editors, compilers, web browsers, database, video games, etc.
- **Operating system** – controls and coordinates use of computing resources among various applications and among different users
- **Hardware** – basic computing resources, CPU, memory, I/O devices



What is an Operating System?

- OS is a **program** (extremely complex) that acts as an intermediary between users or applications and computer hardware
- Operating system goals:
  - Execute user programs and make solving user problems easier
  - Make the computer system convenient to use
  - Manage and use the computer hardware in an efficient manner
- **User view**
  - Want convenience, ease of use, good performance and security
  - Users do not care about resource utilization, efficiency
- **System view**
  - OS as a resource allocator and a control program

What Operating Systems Do

- It depends on the point of view and target devices
- Shared computers such as mainframe or minicomputer
  - OS needs to try to keep all users satisfied – performance vs. fairness
- Individual systems such as workstations have dedicated resources, may also use shared resources from servers
- Mobile devices (e.g., smartphones and handheld devices) are resource constrained
  - Target specific user interfaces such as touch screen, voice control such as Apple's Siri, and optimized for usability and battery life
- Computers or computing devices with little or no user interface
  - Embedded systems - present within home devices (e.g., AC, toasters), automobiles, ships, spacecraft, may run real-time operating systems
  - Designed to run primarily without user intervention – some may have numeric keypads and indicator lights to show status

Operating System Definition

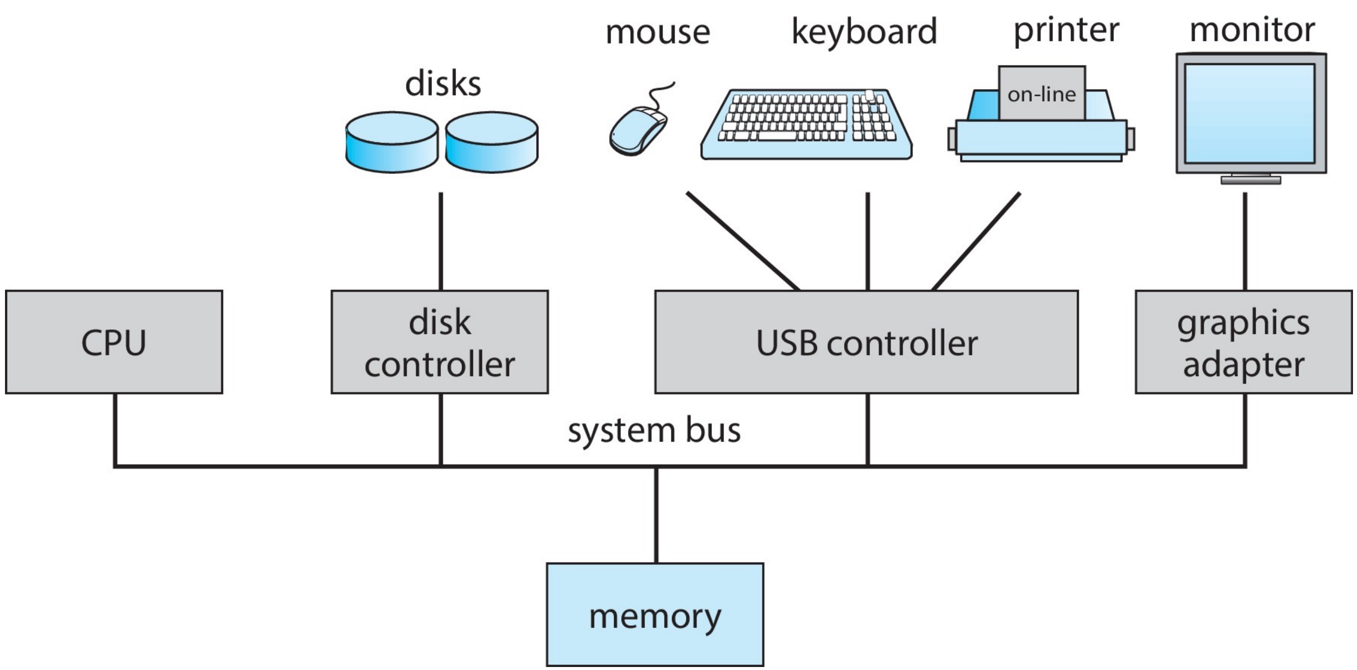
- There is no universally accepted definition on OS
  - “Everything a vendor ships when you order an operating system” is a good approximation, but it varies a great deal
- OS is a resource allocator
  - Manages all resources – hardware and software
  - Decides between conflicting requests for efficient and fair resource use
- OS is a control program
  - Controls execution of programs, prevent errors and improper use of the computer
- In a nutshell, OS manages and controls hardware, and helps to facilitate programs to run on computers.

Operating System Definition

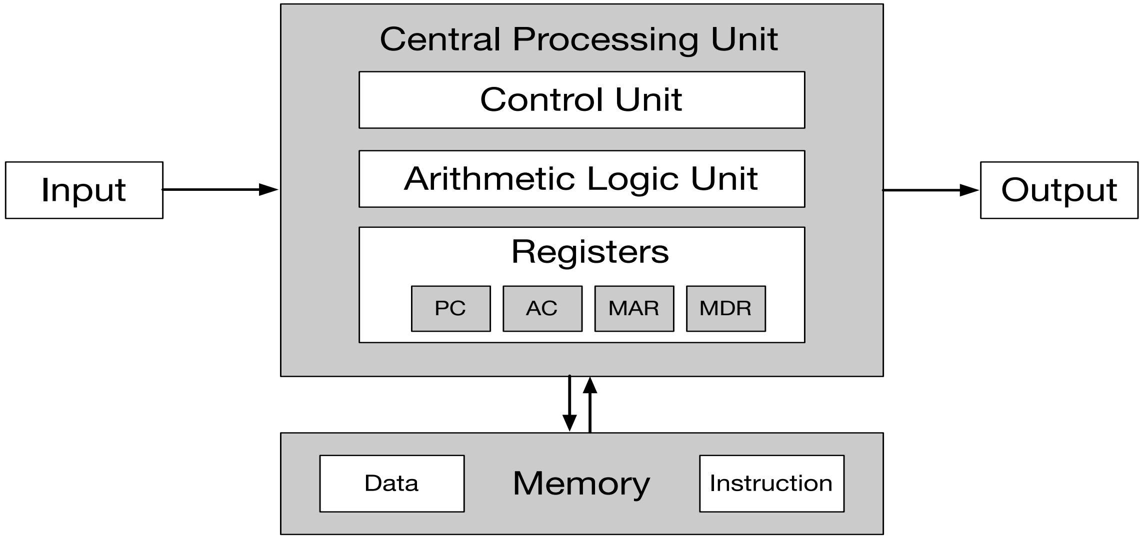
- **Kernel**
  - "The one program running at all times on the computer"
  - The essential functionalities - discussed in this introductory course
- **Middleware**
  - A set of software frameworks that provide additional services to application developers such as databases, multimedia, graphics
  - Popular in mobile OSes - Apple's iOS and Google's Android
- Everything else
  - **System programs** (ships with the operating system, but not part of the kernel), such as word processors, browsers, compilers
  - Application programs, not associated with the operating system – apps
- OS includes the always running kernel, middleware frameworks that ease application development and provide additional features, as well as system programs that aid in managing the system while it is running

Computer System Organization

- Computer-system operation
  - One or more CPU cores, device controllers connected through common bus providing access to shared memory
  - **Concurrent** execution of CPUs and devices - competing for memory cycles through shared bus

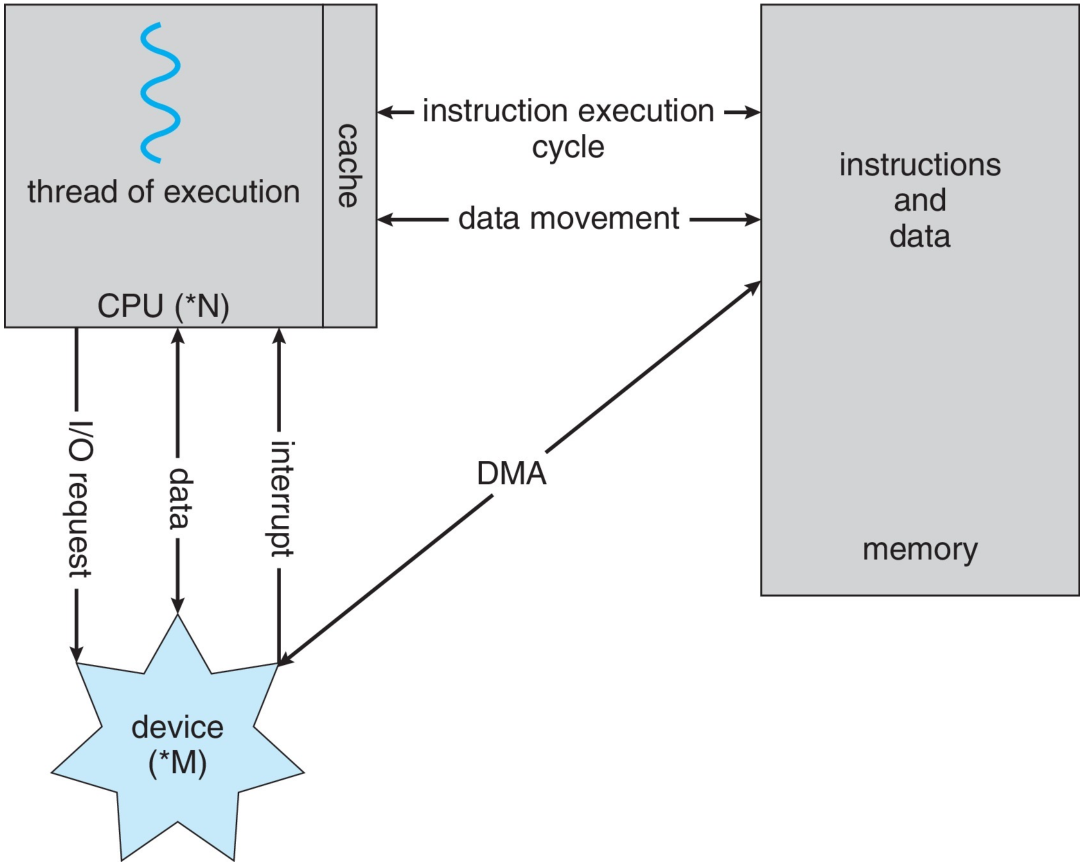


A Von Neumann Architecture



- A processing unit that contains an arithmetic logic unit (ALU) and processor registers – Program Counter (PC), Accumulator (AC), Memory Address Register (MAR), Memory Data Register (MDR)
- A control unit that contains an instruction register (IR) and program counter (PC)
- Memory stores data and instructions – along with caches
- External mass storage – secondary storage (not shown in the figure)
- Input and output mechanisms

How a Modern Computer Works



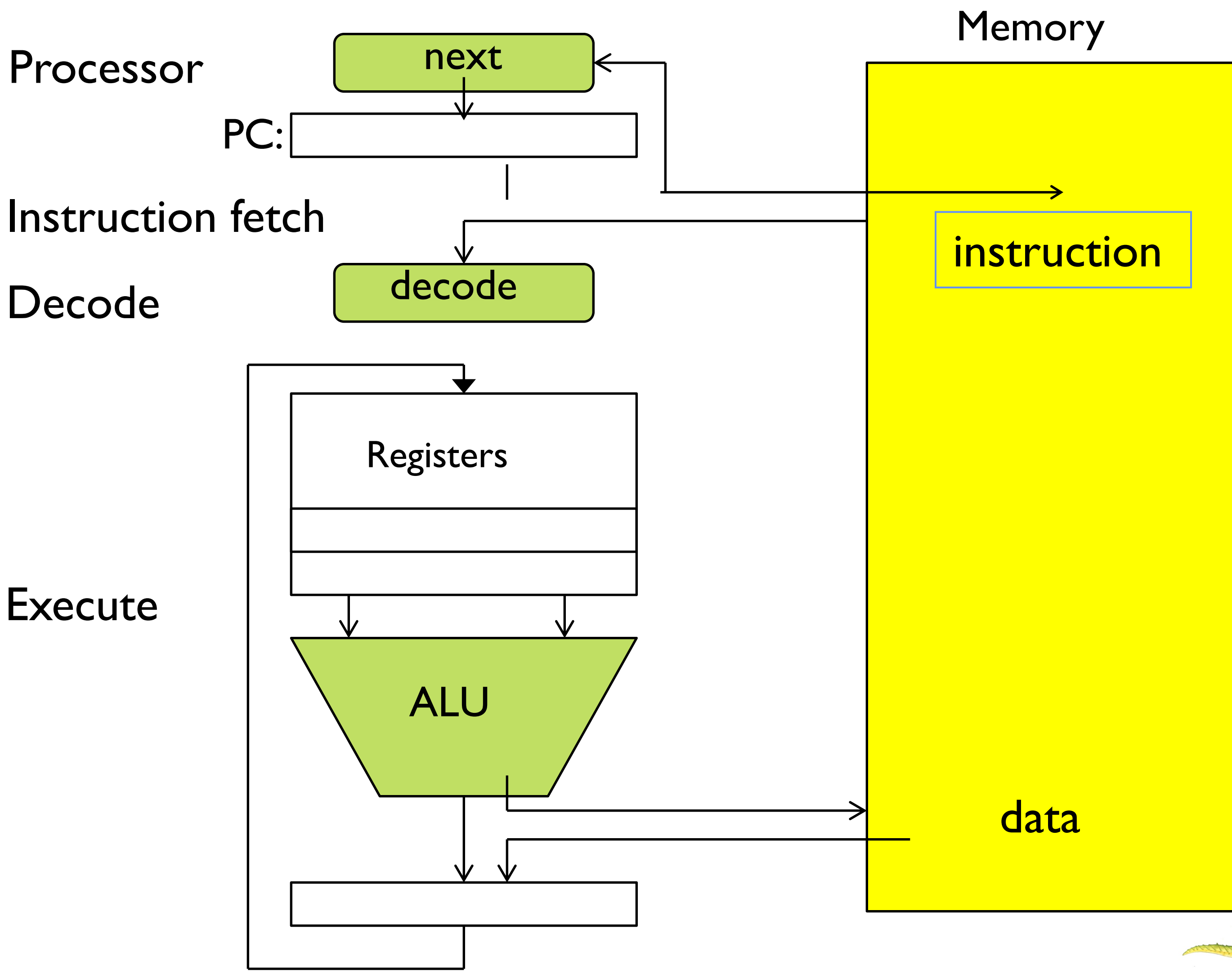
Steps in executing an instruction:

- Fetch instruction
- Decode instruction
- Fetch data
- Execute instruction
- Write back if any

The von Neumann architecture

Instruction Fetch/Decode/Execute

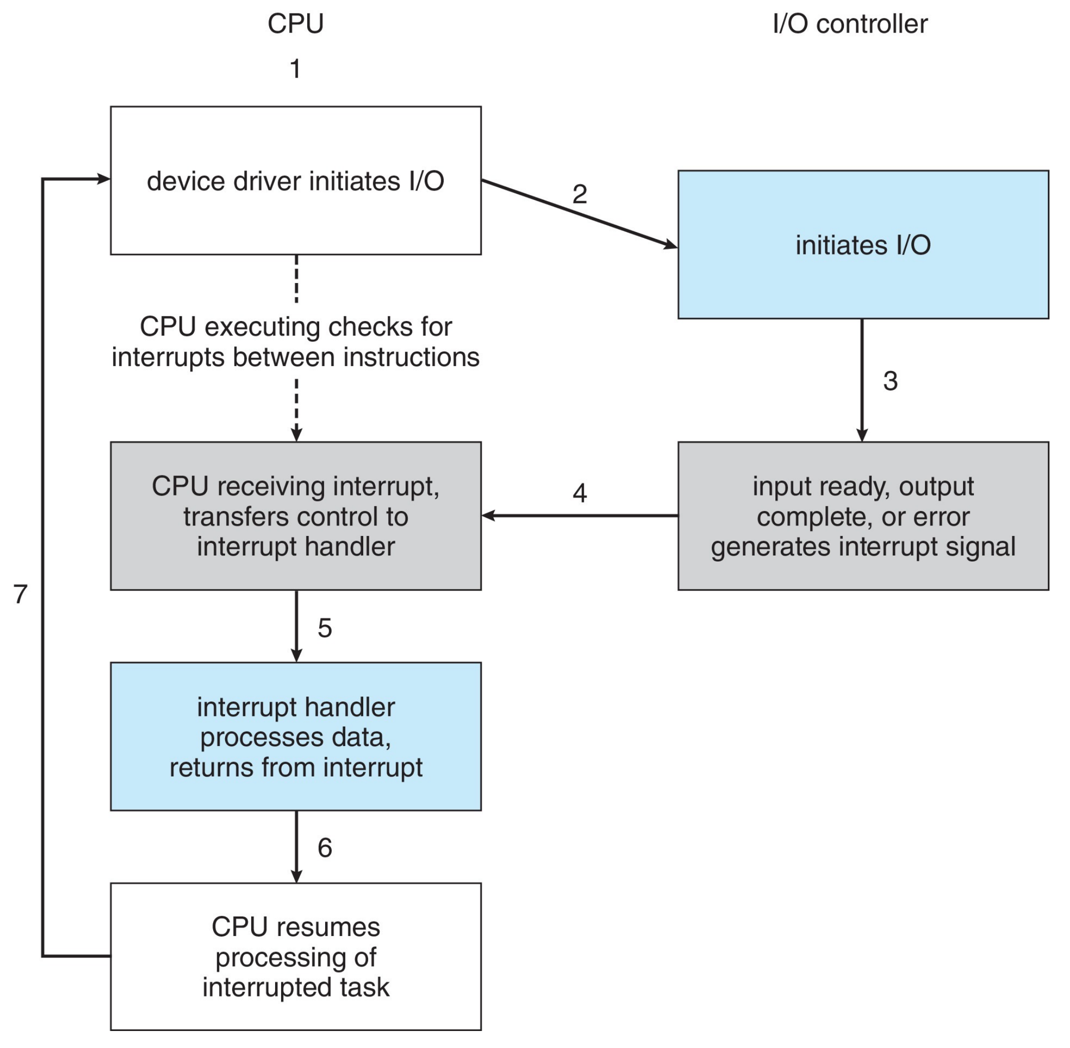
The instruction cycle



Computer-System Operation – I/O

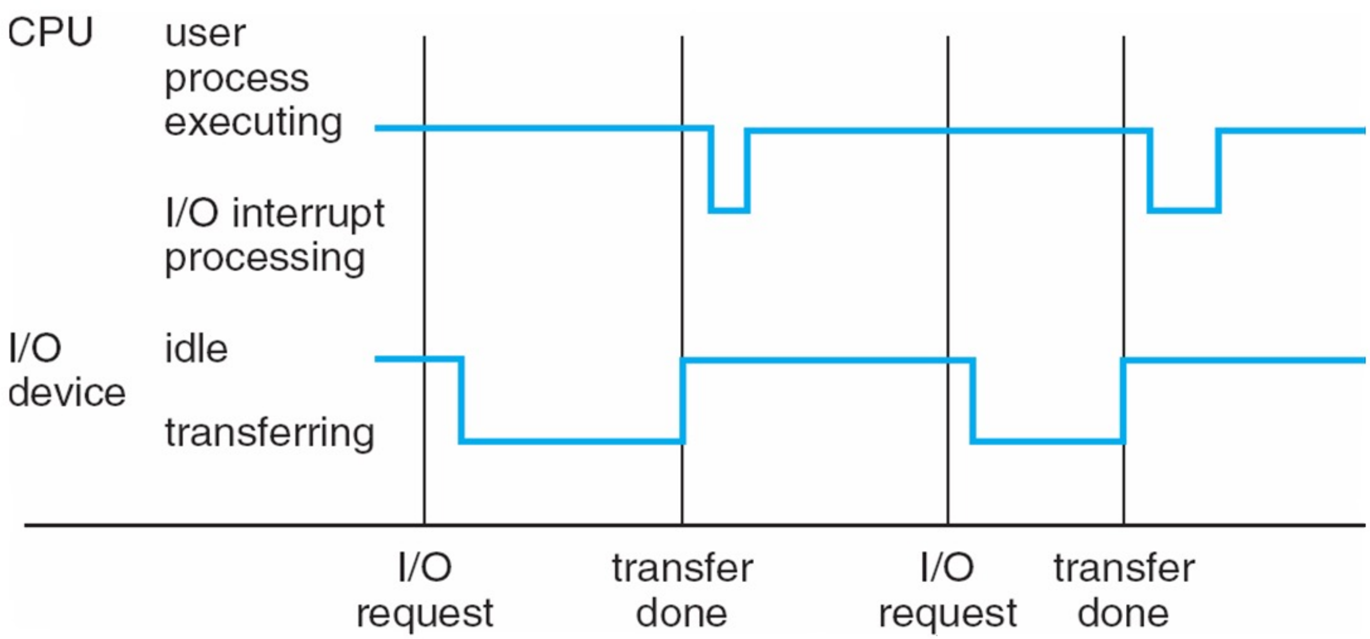
- I/O devices and CPU execute concurrently and asynchronously
- Each device controller is in charge of a particular device
- Each device controller has a local buffer
- The device controller is responsible for moving data between the peripheral devices that it controls and its local buffer storage
  - **I/O operations** are from the device to local buffer of the controller
- CPU moves data from/to main memory to/from local buffers, typically for slow devices such as keyboard and mouse
- **DMA** controller is used for move the data for fast devices like disks
- The device controller informs CPU that it has finished an operation by causing an **interrupt** – requiring CPU attention
  - For input devices, this implies that data is available in local buffer
  - For output devices, it informs CPU that an I/O operation is completed

Interrupt-Driven I/O Cycle



Interrupt Timeline

- CPU and devices execute concurrently
- An I/O device may trigger an interrupt by sending a signal to the CPU
- CPU handles the interrupt, and then returns to the interrupted instruction



Common Functions of Interrupts

- Interrupts are widely used in modern operating systems to handle asynchronous events - device controllers and hardware faults
- Interrupt transfers control to an interrupt service routine or interrupt handler – part of kernel code, which OS runs to handle a specific interrupt
- The interrupt mechanism also implements a system of interrupt priority levels, making it possible for a high-priority interrupt to preempt the execution of a low-priority interrupt
- A trap or exception is a software-generated interrupt caused either by an error (e.g., arithmetic errors) or a user request (e.g., a system call requesting OS services – to be discussed)
- All modern operating systems are interrupt-driven
- In a modern computer system, hundreds of interrupts occur per second – as CPU runs extremely fast in fraction of a nanosecond

Storage Definitions and Notation Review

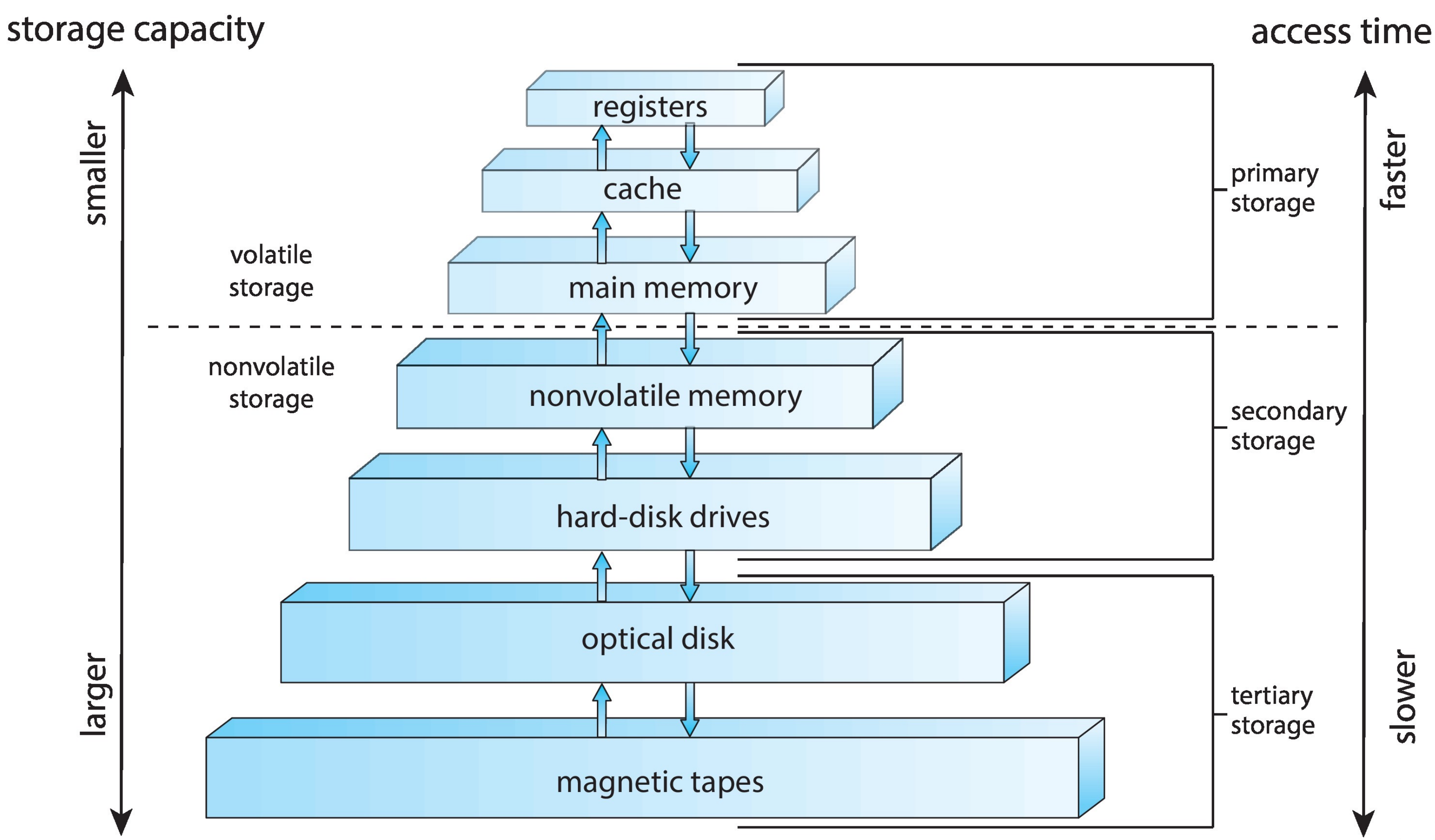
The basic unit of computer storage is the **bit**. A bit can contain one of two values, 0 and 1. All other storage in a computer is based on collections of bits. Given enough bits, it is amazing how many things a computer can represent: numbers, letters, images, movies, sounds, documents, and programs, to name a few. A **byte** is 8 bits, and on most computers it is the smallest convenient chunk of storage. For example, most computers don't have an instruction to move a bit but do have one to move a byte. A less common term is **word**, which is a given computer architecture's native unit of data. A word is made up of one or more bytes. For example, a computer that has 64-bit registers and 64-bit memory addressing typically has 64-bit (8-byte) words. A computer executes many operations in its native word size rather than a byte at a time.

Computer storage, along with most computer throughput, is generally measured and manipulated in bytes and collections of bytes.
A **kilobyte**, or **KB**, is 1,024 bytes
a **megabyte**, or **MB**, is $1,024^2$ bytes
a **gigabyte**, or **GB**, is $1,024^3$ bytes
a **terabyte**, or **TB**, is $1,024^4$ bytes
a **petabyte**, or **PB**, is $1,024^5$ bytes

Computer manufacturers often round off these numbers and say that a megabyte is 1 million bytes and a gigabyte is 1 billion bytes. Networking measurements are an exception to this general rule; they are given in bits (because networks move data a bit at a time).

Storage Hierarchy

- Storage systems organized in **hierarchy**, varied with speed, cost per unit, capacity (size) and volatility (non-volatile disk vs. volatile memory)



Memory

- Main memory – the only large storage media that CPU can access directly
  - Volatile, and typically random-access memory in the form of Dynamic Random-Access Memory (DRAM)
  - The basic operations **load** and **store** instructions to specific memory addresses, which is **byte addressable** – each address refers to one byte in memory
- Computers use other forms of memory as well. For example, the first program to run on computer power-on is a bootstrap program, which is stored on electrically erasable programmable read-only memory (EEPROM)

Second Storage

- The secondary storage – extension of main memory providing large **non-volatile** storage capacity, which can hold large quantities of data permanently.
- The most common secondary-storage devices are hard-disk drives (HDDs) and nonvolatile memory (NVM) devices, which provide storage for both programs and data.
- There are generally two types of secondary storage
  - **Mechanical**, such as HDDs, optical disks, holographic storage, and magnetic tape
  - **Electrical**, such as flash memory, SSD, FRAM, NRAM. Electrical storage is usually referred to as NVM
- Mechanical storage is generally larger and less expensive per byte than electrical storage. Conversely, electrical storage is typically costly, smaller, more reliable, and faster than mechanical storage.

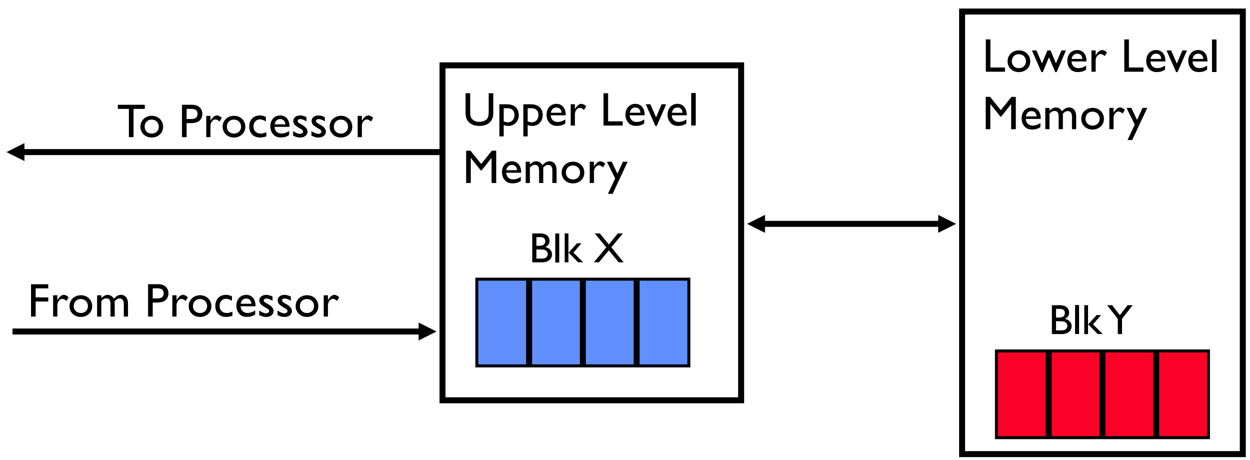
Caching

- **Important principle** - performed at many levels in computers
  - Cache for memory, address translation, file blocks, file names (frequent used), file directories, network routes, etc.
- Fundamental idea: A subset of information copied from a slower to a faster storage temporarily
  - Make frequently used case faster and less frequent case less dominant
- The access first checks to determine if information is inside the cache
  - Hit: if it is, information used directly from the cache (fast)
  - Miss: if not, data copied from slower storage to cache and used there
- Cache usually much smaller than storage (e.g., memory) being cached
  - Cache management: cache size and replacement policy
  - Major criteria – cache hit ratio; percentage content found in cache
- Important measurement

Average Access time = (Hit Rate x Hit Time) + (Miss Rate x Miss Time)

Why Does Caching Work? - Locality

- Temporal locality (Locality in Time)
  - The recently accessed items likely to be accessed again
- Spatial locality (Locality in Space)
  - The contiguous blocks (i.e., those near the recently accessed items) likely to be accessed shortly (both data and program)
- Without access locality pattern, for instance If all items are accessed with equal probability, cache would never work!



Characteristics of Various Types of Storage

Level	1	2	3	4	5
Name	registers	cache	main memory	solid-state disk	magnetic disk
Typical size	< 1 KB	< 16MB	< 64GB	< 1 TB	< 10 TB
Implementation technology	custom memory with multiple ports CMOS	on-chip or off-chip CMOS SRAM	CMOS SRAM	flash memory	magnetic disk
Access time (ns)	0.25-0.5	0.5-25	80-250	25,000-50,000	5,000,000
Bandwidth (MB/sec)	20,000-100,000	5,000-10,000	1,000-5,000	500	20-150
Managed by	compiler	hardware	operating system	operating system	operating system
Backed by	cache	main memory	disk	disk	disk or tape

Movement between levels of storage hierarchy can be explicit or implicit

Range of Timescales

Jeff Dean: "Numbers Everyone Should Know"

L1 cache reference	0.5 ns
Branch mispredict	5 ns
L2 cache reference	7 ns
Mutex lock/unlock	25 ns
Main memory reference	100 ns
Compress 1K bytes with Zippy	3,000 ns
Send 2K bytes over 1 Gbps network	20,000 ns
Read 1 MB sequentially from memory	250,000 ns
Round trip within same datacenter	500,000 ns
Disk seek	10,000,000 ns
Read 1 MB sequentially from disk	20,000,000 ns
Send packet CA->Netherlands->CA	150,000,000 ns

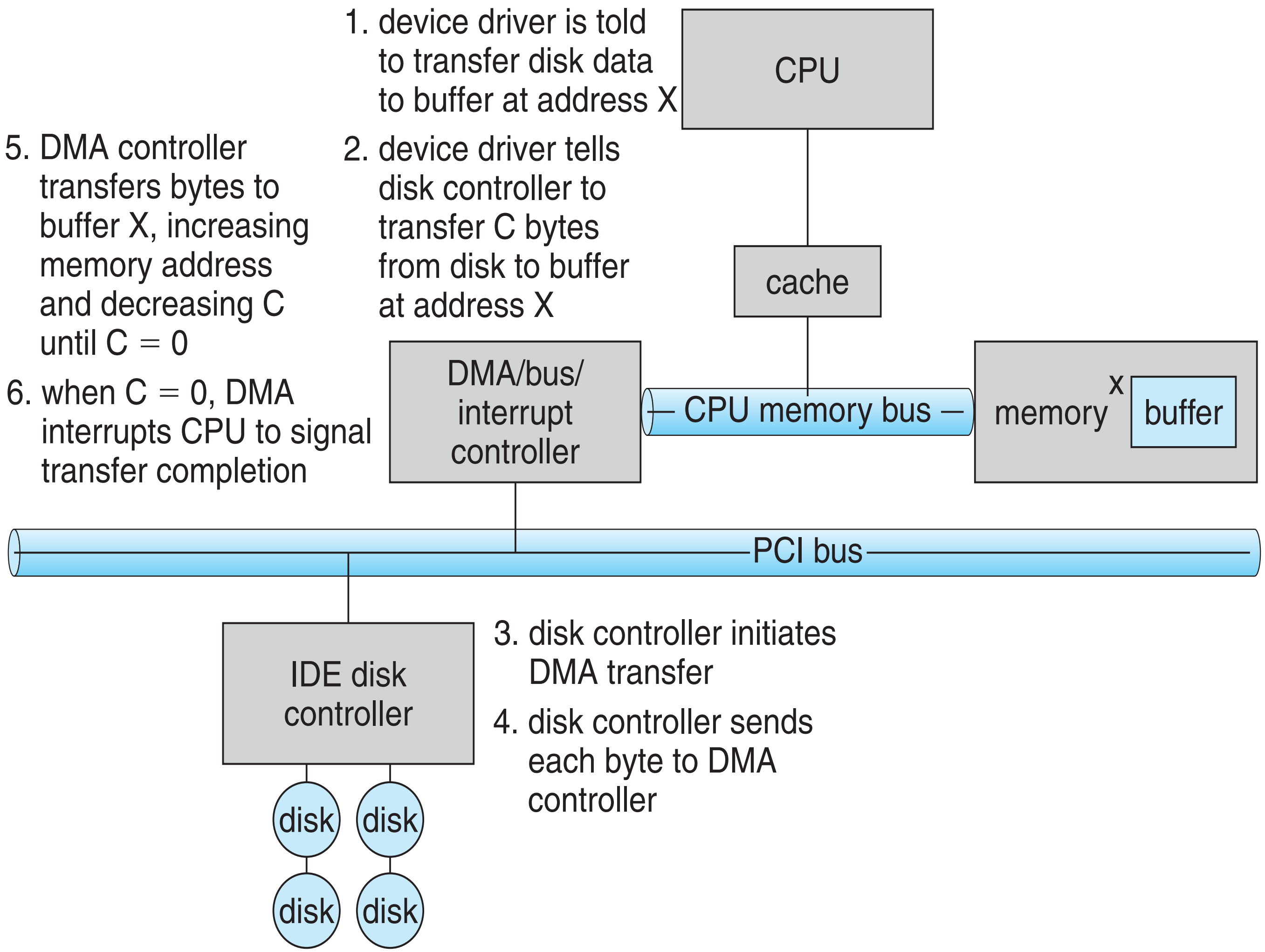
I/O Subsystem

- OS needs to accommodate a wide variety of devices, each with different capabilities, control-bit definitions, and protocols for interacting with host
- OS enables I/O devices to be treated in a standard, uniform way – that involves abstraction, encapsulation, and software layering, like for any complex software engineering design
- I/O system calls encapsulate device behaviours in a few generic classes, each is accessed through a standardized set of functions - interface
- One purpose of OS is to hide peculiarities of hardware devices from users
- I/O subsystem responsible for
  - Memory management of I/O including buffering (storing data temporarily while it is being transferred), caching (storing parts of data in faster storage for performance), spooling (the overlapping of output of one job with input of other jobs, e.g., printers)
  - General device-driver interface
  - Drivers for specific hardware devices

Direct Memory Access

- **Programmed I/O** - CPU runs special I/O instructions to move one byte at a time between memory and slow devices, e.g., keyboard and mouse
- To avoid programmed I/O, for fast devices and for large amount of data transfer, it uses direct memory access or **DMA** controller - bypasses CPU to transfer data between I/O device and memory directly - CPU or OS initializes DMA controller, and DMA controllers are responsible for moving the data between devices and memory without CPU involved.
- This relieves the CPU from slow data movement (I/O operations)
- OS writes DMA command block into memory
  - Source and destination addresses
  - Read or write mode
  - Number of bytes to be transferred
  - Writes location of command block to DMA controller
  - Bus mastering of DMA controller – grabs bus from CPU
  - When done, send interrupt to CPU for signaling completion

Six Step Process to Perform DMA Transfer



Single-Processor Systems

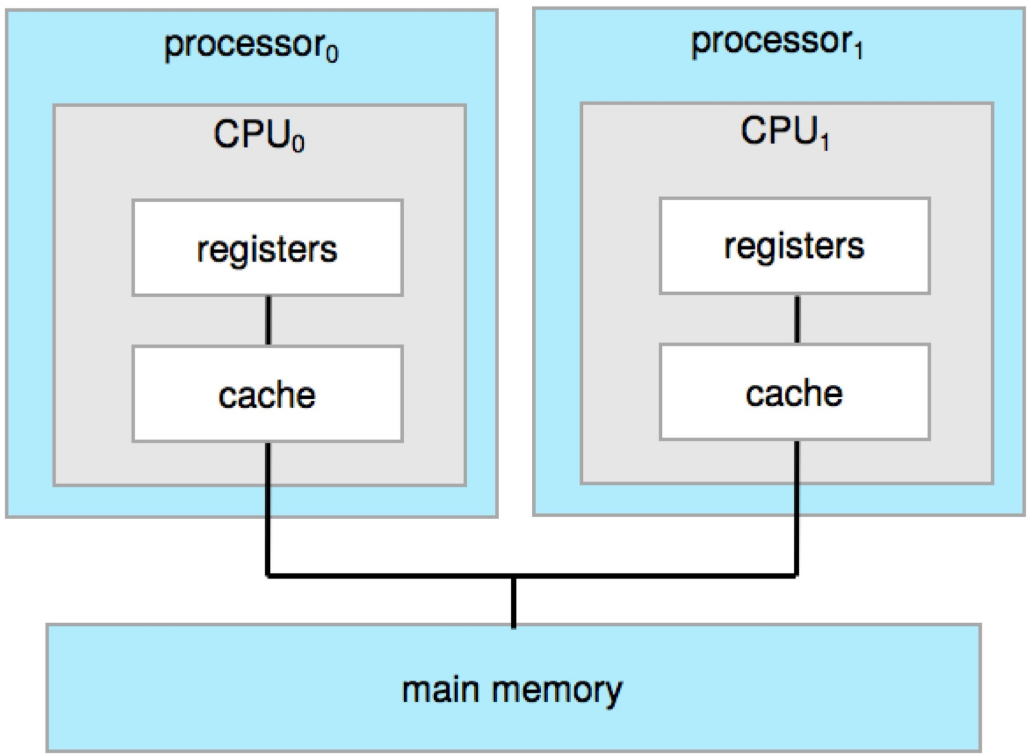
- In the past, most computer systems used a single processor containing one CPU with a single processing core
  - The core executes instructions and registers for storing data locally.
  - The processing core or CPU core is capable of executing a general-purpose instruction set
- Such systems have other special-purpose processors - device-specific processors, such as disk, and graphics controllers (GPU).
  - They run a limited instruction set, usually do not execute instructions from user processes

Multiprocessor Systems

- On modern computers, from mobile devices to servers, multiprocessors systems now dominate the landscape of computing
  - Traditionally, such systems have two (or more) processors, each with a single-core CPU
  - The speed-up ratio with N processors is less than N, because of overhead, e.g., contention for shared resources (bus or memory)
- Multiprocessors systems growing in use and importance, **advantages** are
  - Increased throughput – more computing capability
  - Economy of scale – share other devices such as I/O devices
  - Increased reliability – graceful degradation or fault tolerance
- Two types of multiprocessor systems
  - Asymmetric Multiprocessing – often master-slave manner, the master processor assign specific tasks to slaves, and the master handles I/O
  - Symmetric Multiprocessing – each processor performs all tasks, including operating-system functions and user processes

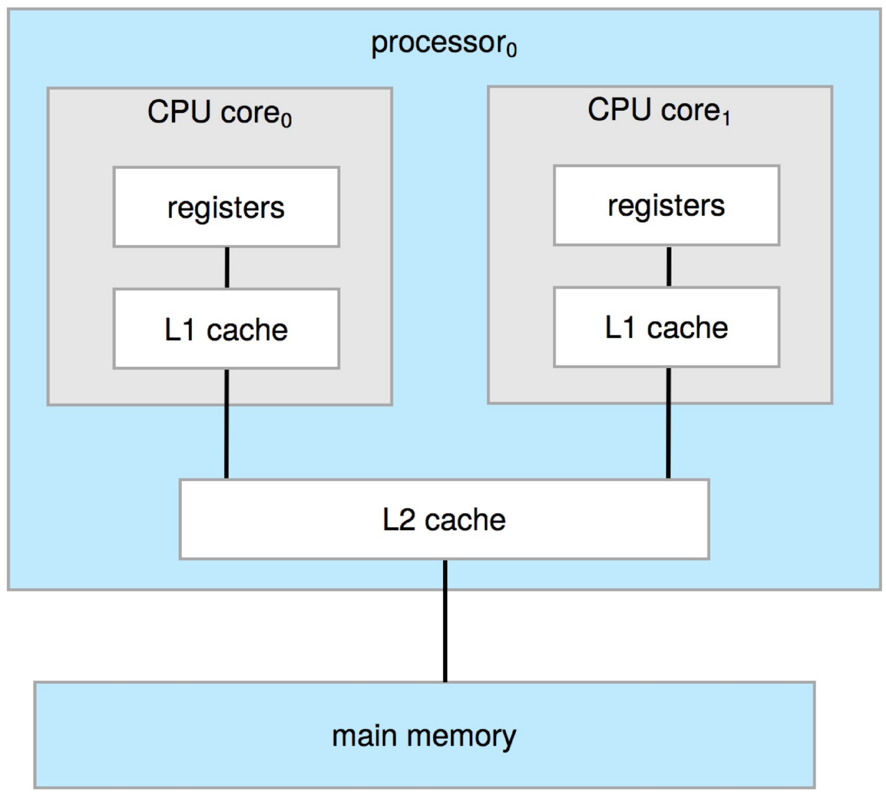
Symmetric Multiprocessor Systems

- Symmetric Multiprocessing or SMP – each CPU processor has its own set of registers, as well as a private or local cache. However, all processors share physical memory through system bus.



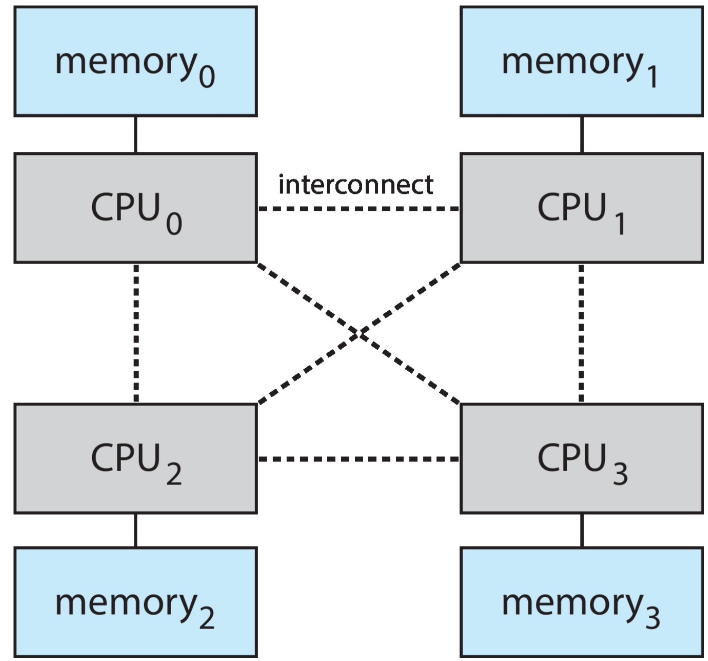
A Multi-Core Design

- The **multicore**, multiple computing cores reside on **a single physical chip**
  - Faster on-chip communication than between-chip communication
  - Uses significantly less power - important for mobile devices and laptops



Non-Uniform Memory Access (NUMA)

- Adding more CPUs to a multiprocessor system may not scale, due to the contention for system bus, which can become a bottleneck
- An alternative is to provide each CPU (or group of CPUs) with its own local memory that is accessed via a small, fast local bus.
- The CPUs are connected by a shared system interconnect, and all CPUs share one physical memory address space.
- This approach—known as non-uniform memory access or NUMA
- The potential drawback with a NUMA system is increased latency when a CPU must access remote memory across the system interconnect – scheduling and memory management implication



Computer System Component

- **CPU** - The hardware that executes instructions
- **Processor** - A physical chip that contains one or more CPUs
- **Core** – The basic computation unit of the CPU or the component that executes instructions and registers for storing data locally
- **Multicore** – Including multiple computing cores on a single physical processor chip
- **Multiprocessor system**– including multiple processors
  - Traditionally, such systems have two (or more) processors, each with a single-core CPU
  - This evolves with multiple computing cores reside on a single processor chip

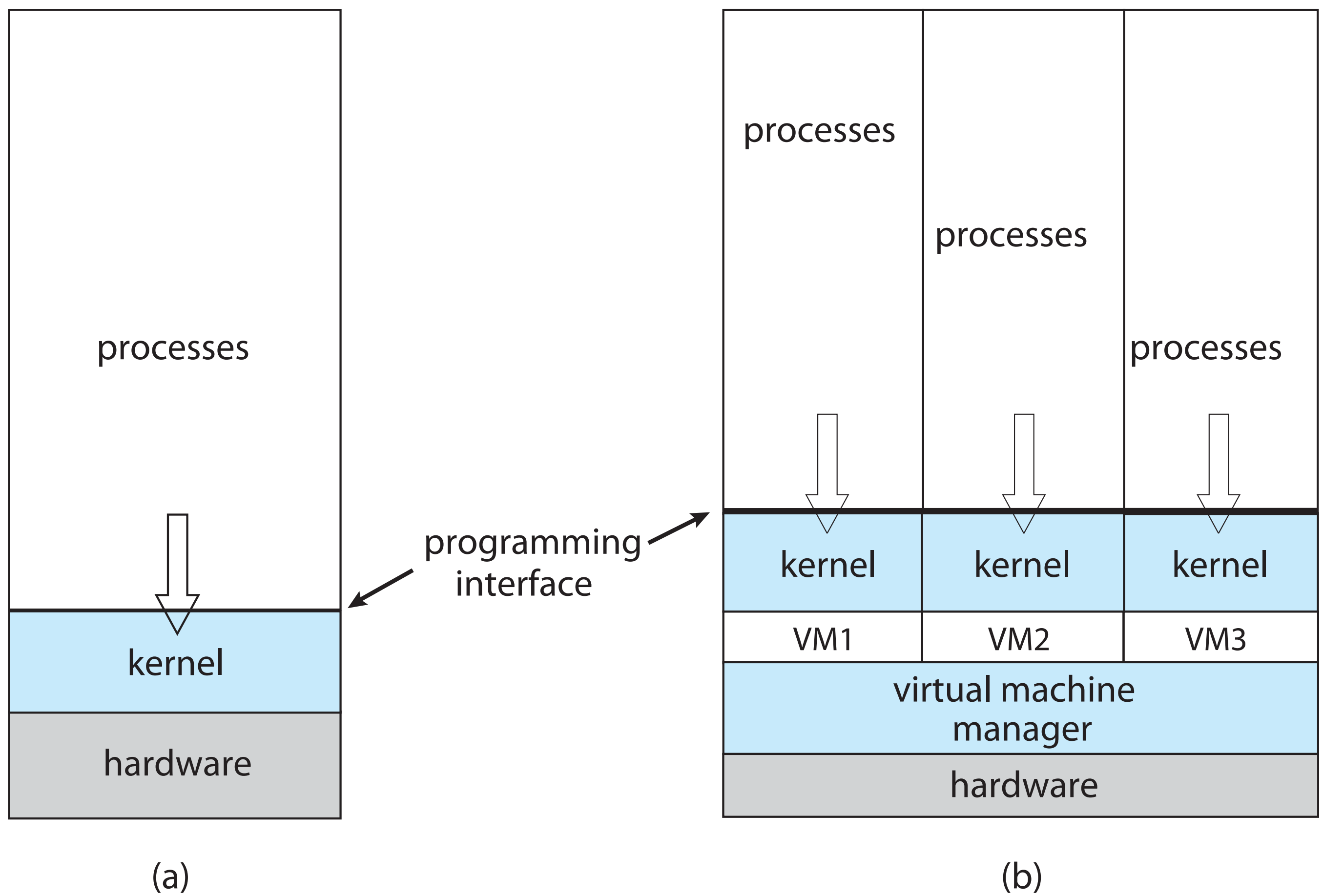
Operating System Structure

- There are two common characteristics in all modern operating systems
- Multiprogramming (batch system) is needed for efficiency
  - In old days, OS loads one program into the memory at a time for execution
  - Single program cannot always keep CPU or I/O devices busy as they become faster and faster– all modern computer systems are multi-programmed
  - Multiprogramming organizes jobs in a way hoping CPU always has one to execute
  - In mainframe computers, jobs are submitted remotely and queued, and jobs are selected and run via job scheduling – load into the memory (discussed later)
- Timesharing (multitasking) is logical extension of multiprogramming in which CPU switches "frequently" between jobs that users can interact with each job while it is running, enable interactive computing
  - Response time should be < 1 second
  - Each user has at least one program executing in memory ⇨ process
  - If several jobs ready to run at the same time ⇨ CPU scheduling
  - If processes donot fit in memory, swapping technique moves them in and out of memory during execution
  - Virtual memory allows execution of processes not completely in memory

Virtualization

- Virtualization abstracts the hardware of a single computer into multiple different execution environment(s) - creating an illusion that each user or program is running on its own “private computer”
  - It creates a virtual system - virtual machine or VM on which operation systems or applications can run
  - It also allows an operating system to run as an application within other operating system – this has been a vast and growing industry
- Several components
  - **Host** – underlying hardware system
  - **Virtual machine manager** (**VMM**) or **hypervisor** – creates and runs virtual machines by providing interface that is identical to the host
  - **Guest** – process provided with virtual copy of the host, usually an operating system – guest OS
- Single physical machine can run multiple operating systems concurrently, each in its own virtual machine

Virtualization – System Models

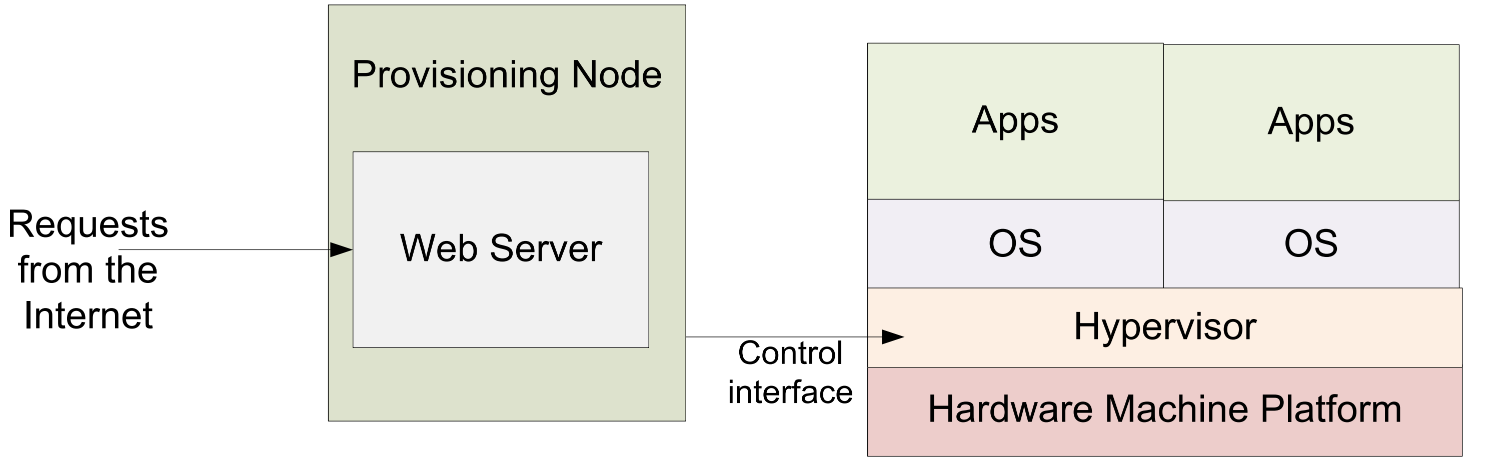


Virtualization – a bit history

- **Virtualization** – OS natively compiled for CPU, running guest OSes
  - Virtualization originally designed in IBM mainframes (1972) to allow multiple users to run tasks concurrently in a system designed for a single user or share a batch-oriented system
  - VMware runs one or more guest copies of Windows, each running its own applications, on Intel x86 CPU
  - A Virtual Machine Manager or VMM provides an environment for programs that is essentially identical to the original machine (interface)
  - Programs running within such environments show only minor performance decreases
  - The VMM is in complete control of system resources
- In late 1990s Intel CPUs fast enough - virtualization on general purpose PCs
  - **Xen** and **VMware** created technologies, still used today
  - Virtualization has expanded to many OSes, CPUs, VMMs

Cloud Computing and Virtualization

- Delivers computing, storage, and apps as a service over a network
- Logical extension of virtualization because it uses virtualization as the base for its functionality.
  - Amazon EC2 has millions of servers, tens of millions of VMs, petabytes of storage available across the Internet, pay based on usage



Cloud Computing Types

- Many types of clouds
  - Public cloud – available via Internet to anyone willing to pay
  - Private cloud – run by a company for the company’s own use
  - Hybrid cloud – includes both public and private cloud components
  - Software as a Service (SaaS) – one or more applications available via the Internet (i.e., word processor)
  - Platform as a Service (PaaS) – software stack ready for application use via the Internet (i.e., a database server)
  - Infrastructure as a Service (IaaS) – servers or storage available over Internet (i.e., storage available for backup use)
  - Increasingly provides other services, such as MaaS or Machine learning as a Service

Free and Open-Source Operating Systems

- Operating systems made available in source-code format rather than just binary closed-source and proprietary
  - Microsoft Windows is a well-known example of the closed-source approach.
- Started by Free Software Foundation (FSF), which has "copyleft" GNU Public License (GPL)
  - Free software and open-source software are two different ideas
    - http://gnu.org/philosophy/open-source-misses-the-point.html/
  - Free software not only makes source code available but also is licensed to allow no-cost use, redistribution, and modification. Open-source software does not necessarily offer such licensing
- Popular examples include GNU/Linux, FreeBSD UNIX (including core of Mac OS X - Darwin), and Solaris
- Open-source code is arguably more secure, allowing more programmers to contribute, and is certainly a better learning tool

End of Chapter 1