CO2017
Operating Systems

Course Syllabus

Credits	3			Code	CO2017
Credits Hours	Total: 64	Lecture: **30**		Lab: **22**	Assignment: **12**
Evaluation	Exercise: *10%*	Lab: *10%*	Midterm:	Assignment: *30%*	Final exam: *50%*
Assessment method	Final exam: *Multiple choice questions*, ~ 90 minutes				
Prerequisites					
Co-requisites					
Undergraduate Programs	*Computer Science and Computer Engineering*				
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Course Outcomes

L.O.1	**Describe on how to apply fundamental knowledge of computing and mathematics in an operating system**
L.O.1.1	Define the functionality and structures that a modern operating system must deliver to meet a particular need.
L.O.1.2	Describe main operating system concepts and their aspects that are useful to realize concurrent systems and describe the benefits of each.
L.O.1.3	Explain virtual memory and its realization in hardware and software.
L.O.2	**Able to report the tradeoffs between the performance and the resource and technology constraints in a design of an operating system.**
L.O.2.1	Compare and contrast common algorithms used for both preemptive and non-preemptive scheduling of tasks in operating systems
L.O.2.2	Compare and contrast different approaches to file organization, recognizing the strengths and weaknesses of each.

Course Outline

- Introduction to Operating systems
- Processes/Threads management
  - Process and Threads
  - CPU scheduling
  - Synchronization
- Memory management
  - Main memory
  - Virtual memory
- Storage management
  - File systems
- Advanced topics
- Summary

Textbook and References

- [1] “Operating System Concepts”, Abraham Silberschatz, Greg Gagne, Peter B. Galvin, 10th Edition, John Wiley & Sons, 2018. ISBN1119439256, 9781119439257, 976 pages.
- [2] “Operating Systems: Three Easy Pieces”, Remzi H. Arpaci-Dusseau, Andrea C. Arpaci-Dusseau, CreateSpace Independent Publishing Platform, 2018.
ISBN198508659X, 9781985086593, 714 pages.

Acknowledgement

- Acknowledgement: The lecture uses mostly slides from "Operating system concepts" copyrighted by Silberschatz, Galvin and Gagne, 2018.

Chapter 1: Introduction

Chapter 1: Outline

- What Operating Systems Do
- Computer-System Organization
- Computer-System Architecture
- Operating-System Operations
- Resource Management
- Security and Protection
- Virtualization
- Distributed Systems
- Kernel Data Structures
- Computing Environments
- Free/Libre and Open-Source Operating Systems

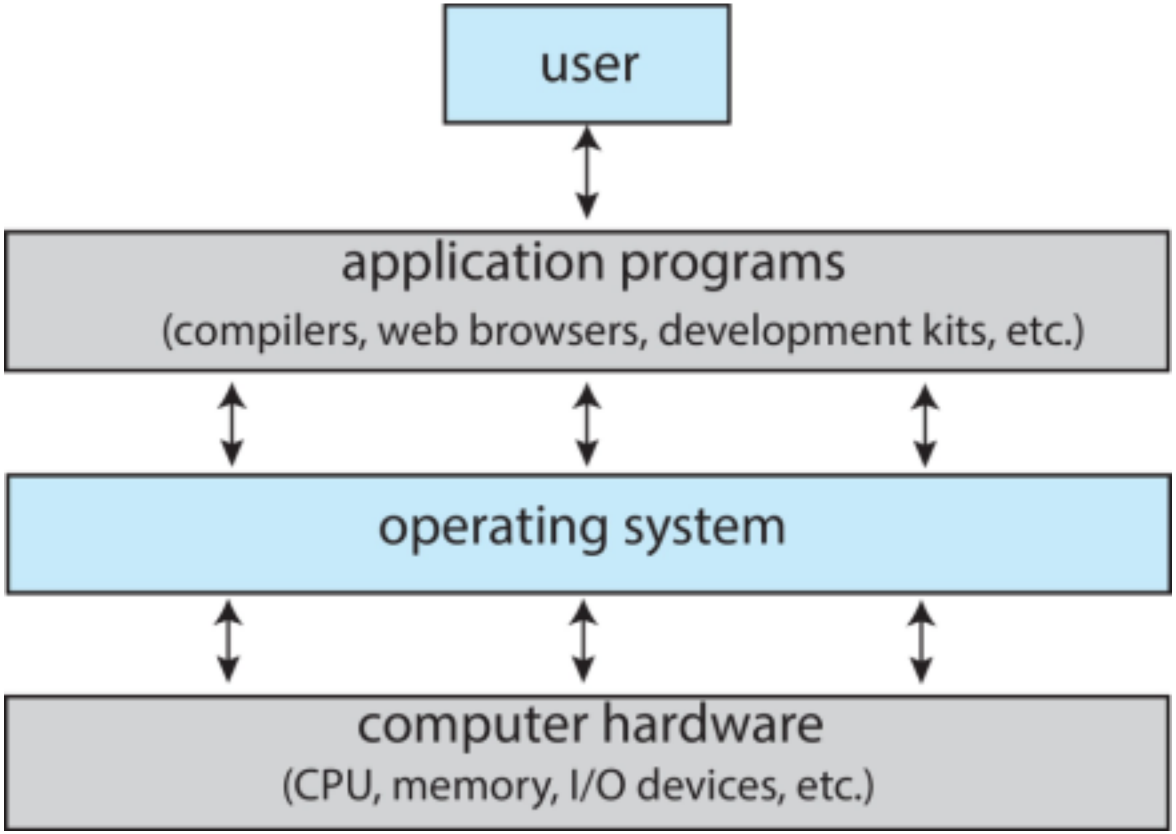
Objectives

- Describe the general organization of *a computer system* and the role of interrupts
- Describe the components in a modern, *multiprocessor computer system*
- Illustrate the transition from *user mode* to *kernel mode*
- Discuss how operating systems are used in various *computing environments*
- Provide examples of *free and open-source operating systems*

Computer-System Structure

- Computer system can be divided into **4** components:
  - **Hardware** (**HW**) – provides basic computing resources
    - E.g., **Central Processing Unit** (**CPU**), memory, **Input/Output** (**I/O**) devices
  - **Operating system** (**OS**) – controls and coordinates use of hardware among various applications and users
    - E.g., Microsoft Windows, Unix, Linux, Apple MacOS
  - **Application programs** – define the ways in which the system resources are used to solve the computing problems of the users
    - E.g., Compilers, web browsers, development kits, word processors, database systems, video games, multimedia players
  - **Users**
    - E.g., People, machines, other computers

Abstract View of Computer Components



What Operating Systems Do

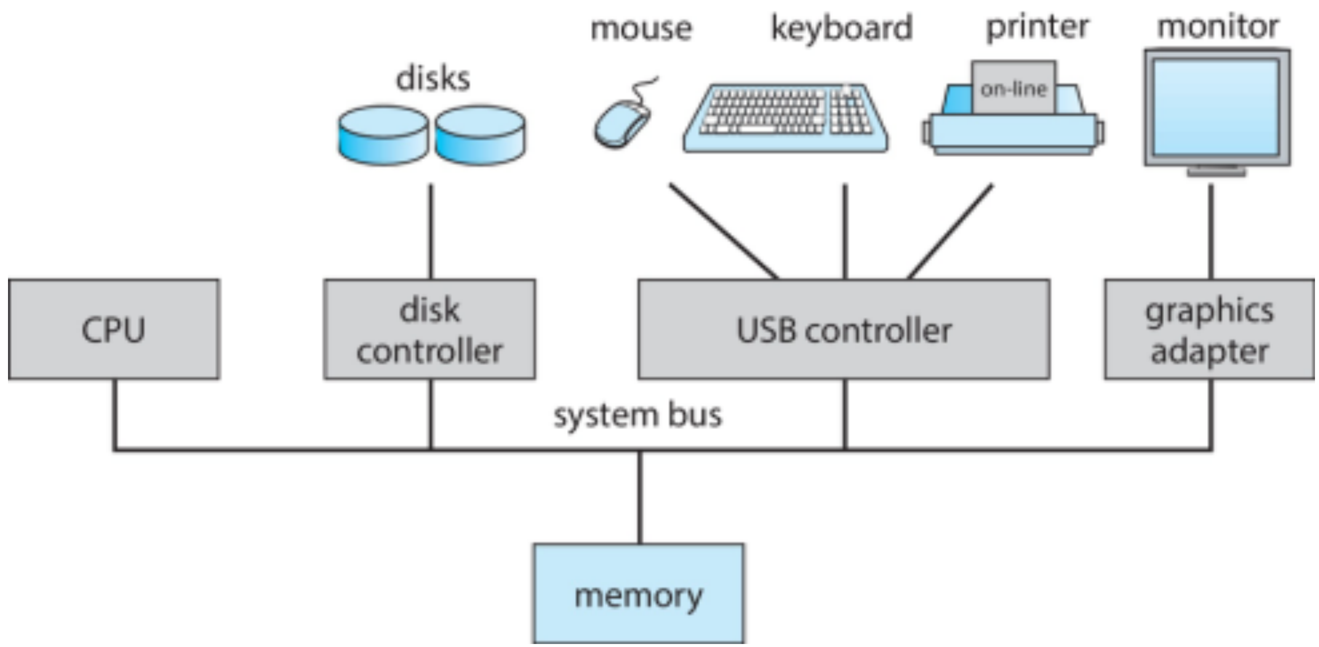
- **Users** want convenience, ease of use and good performance
  - But, don't care about resource utilization
- **Shared computers** (e.g, *mainframe* or *minicomputer*) keep all users happy
  - Operating system is a resource allocator and control program making efficient use of HW and managing execution of user programs
- **Dedicated systems** (e.g, *workstations*) have dedicated resources but users frequently utilize shared resources from *servers*
- **Mobile devices** (e.g., *smartphones* and *tablets*) are resource poor, have to be optimized for battery life and usability using user interfaces such as touch screens.
- Some computers have little or no user interface, such as **embedded computers** in devices and automobiles
  - Run primarily without user intervention

Operating System Definition (Cont.)

- "*Everything a vendor ships when you order an operating system*" is a good approximation (but varies wildly)
- "*The one program running at all times on the computer*" is the **kernel,** part of the operating system
- Everything else is either
  - a **system program** (ships with the operating system, but not part of the kernel), or
  - an **application program**, all programs not associated with the operating system
- Today's OSes for general purpose and mobile computing also include **middleware** – a set of software frameworks that provide addition services to application developers such as databases, multimedia, graphics

Computer-System Organization

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



Computer-System Operation

- **I/O devices** and the **CPUs** can execute *concurrently*
- The **device controller** (on device) determines the logical interaction between the device and the computer
  - Each device controller is in charge of a particular device type
  - Each device controller has a *local buffer*
- CPU moves data from/to *main memory* to/from *local buffers*, I/O device does from the *device* to *local buffer* of controller
- Each device controller type has a **device driver** (installed inside an operating system) to manage I/O operation
  - Provides uniform interface between controller and kernel

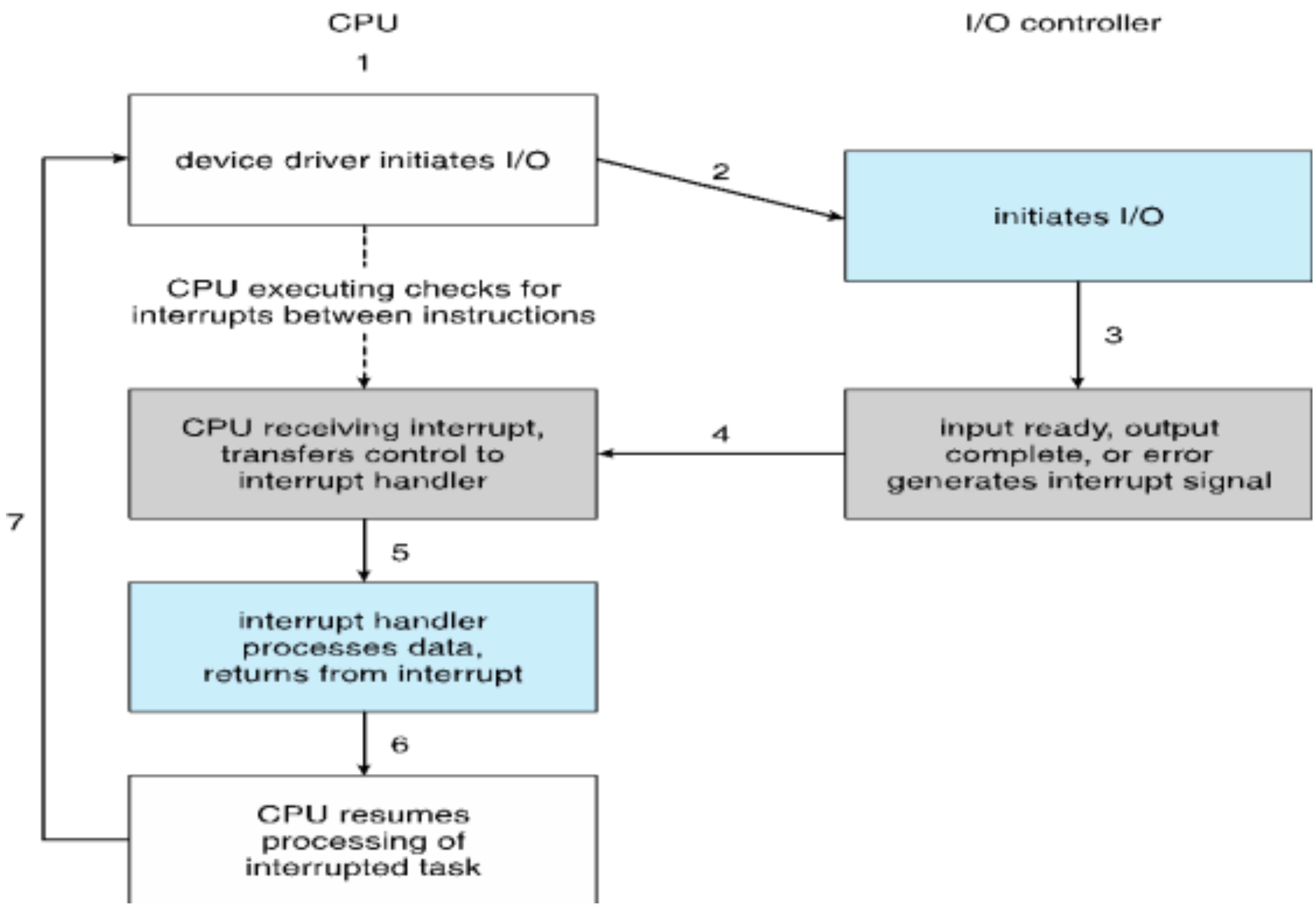
Common Functions of Interrupts

- Device controller informs CPU that it has finished its operation by raising an **interrupt** or CPU has to do a **polling** for an I/O completion (possibly waste a large number of CPU cycles)
- **Interrupt** transfers control to the *interrupt service routine* generally, through the *interrupt vector*, which contains the addresses of all the service routines
  - *Interrupt architecture* must save the address and status of the *interrupted instruction*
- A **trap** (or **exception)** is a software-generated interrupt caused either by an error or a user request
- An operating system is *interrupt-driven*

Interrupt Handling

- The operating system preserves the state of the CPU by storing **registers** and the **program counter** (**PC**)
- Determines which type of interrupt has occurred:
  - *Vectored interrupt system* used to handle asynchronous events and to trap to supervisor-mode routines in the kernel
  - Separate segments of code determine what action should be taken for each type of interrupt
- Some device drivers use *interrupts* when the I/O rate is low and switch to *polling* when the rate increases to the point where polling is faster and more efficient.

Interrupt-driven I/O Cycle



I/O Structure

- After I/O starts, *control returns to user program only upon I/O completion*
  - `Wait` instruction idles the CPU until the next interrupt
  - Wait loop (e.g., contention for memory access)
  - At most one I/O request is outstanding at a time, no simultaneous I/O processing
- After I/O starts, *control returns to user program without waiting for I/O completion*
  - **System call** – request to the OS to allow user to wait for I/O completion
  - **Device-status table** contains entry for each I/O device indicating its *type*, *address*, and *state*
    - OS indexes into **I/O device table** to determine device status and to modify table entry to include interrupt

Storage Structure

- **Main memory** – only storage media that the CPU can access directly
  - *Random access*, typically in the form of **Dynamic Random-Access Memory** (**DRAM**)
  - Typically *volatile*
- **Secondary storage** – extension of main memory that provides large *nonvolatile* storage capacity
  - **Hard Disk Drives** (**HDD**) – rigid metal or glass platters covered with magnetic recording material
    - Disk surface is logically divided into *tracks*, which are subdivided into *sectors*
  - **Non-volatile memory** (**NVM**) devices– *faster* than hard disks, *nonvolatile*
    - Becoming more popular as capacity and performance increases, price drops
    - Various technologies

Storage Definitions and Notation Review

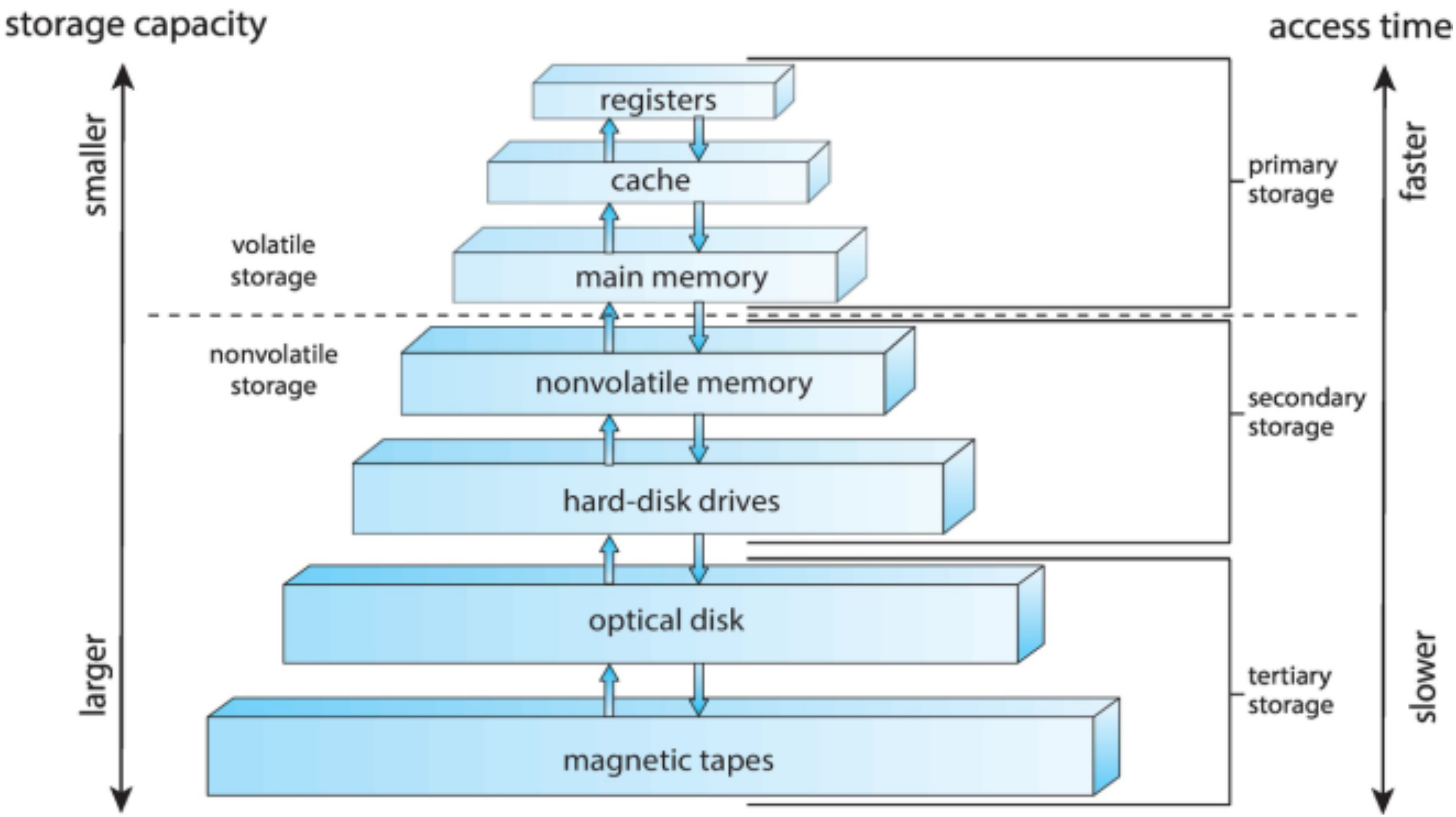
- The basic unit of computer storage is the **bit**. A bit can contain one of two values, 0 and 1. All other storage in a computer is based on collections of bits. Given enough bits, it is amazing how many things a computer can represent: numbers, letters, images, movies, sounds, documents, and programs, 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; and 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).

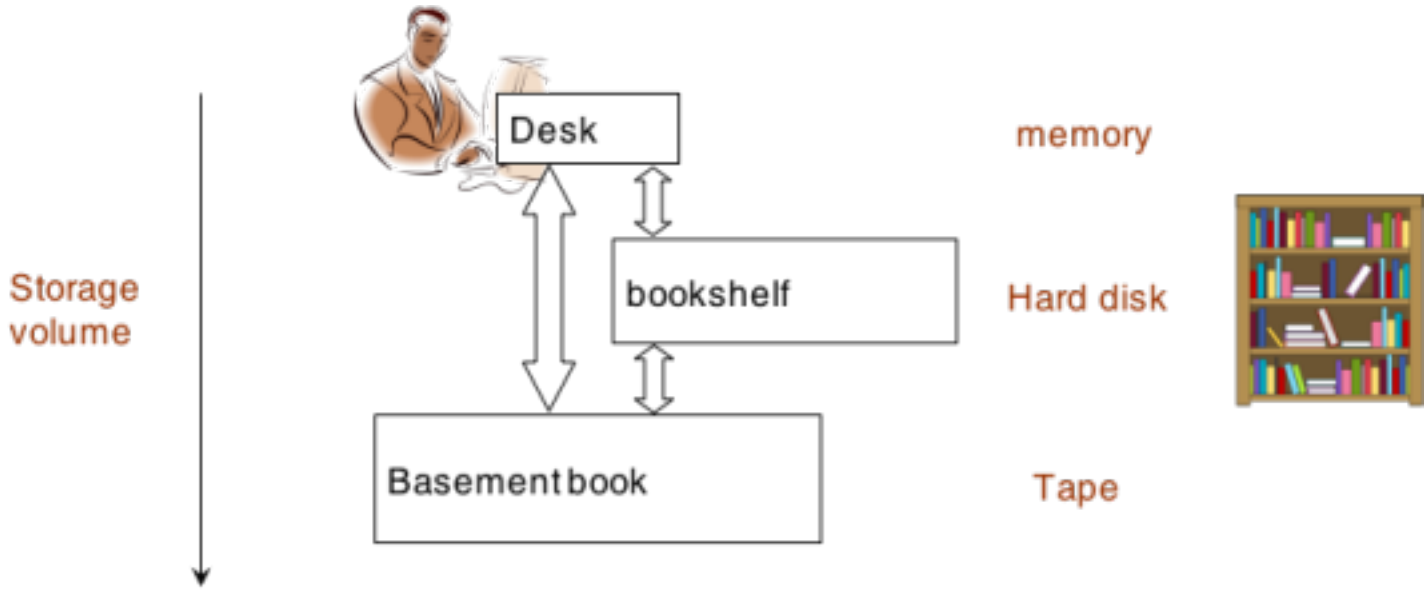
Storage Hierarchy

- Storage systems are organized in hierarchy according to
  - *Speed* (or *access time*)
  - *Capacity*
  - *Volatility*
  - *Cost*
- **Caching** – mechanism copying data into faster storage system
  - Main memory can be viewed as a cache for secondary storage

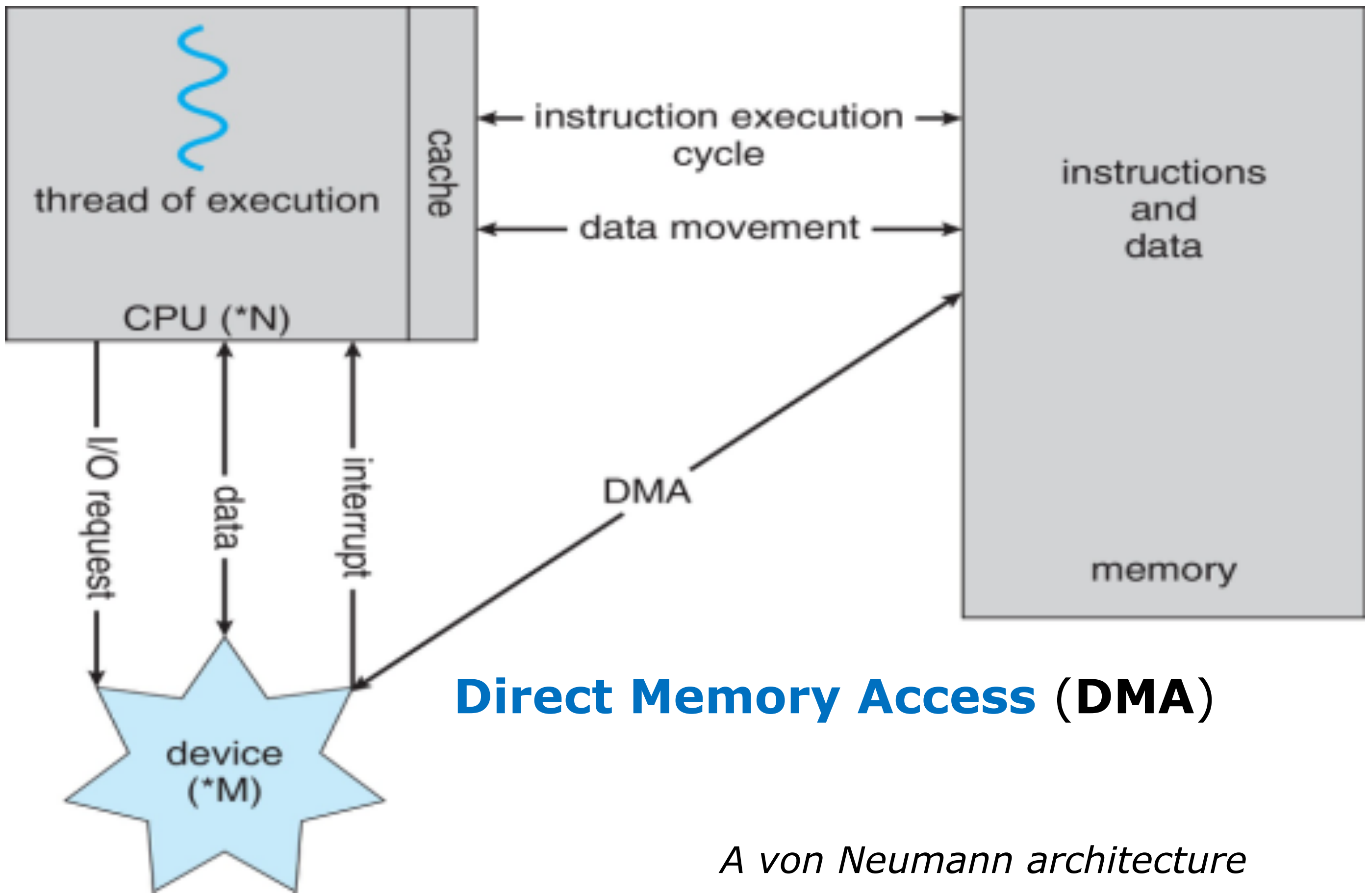
Storage-Device Hierarchy



An example of storage hierarchy



How a Modern Computer Works



Direct Memory Access (**DMA**)

A von Neumann architecture

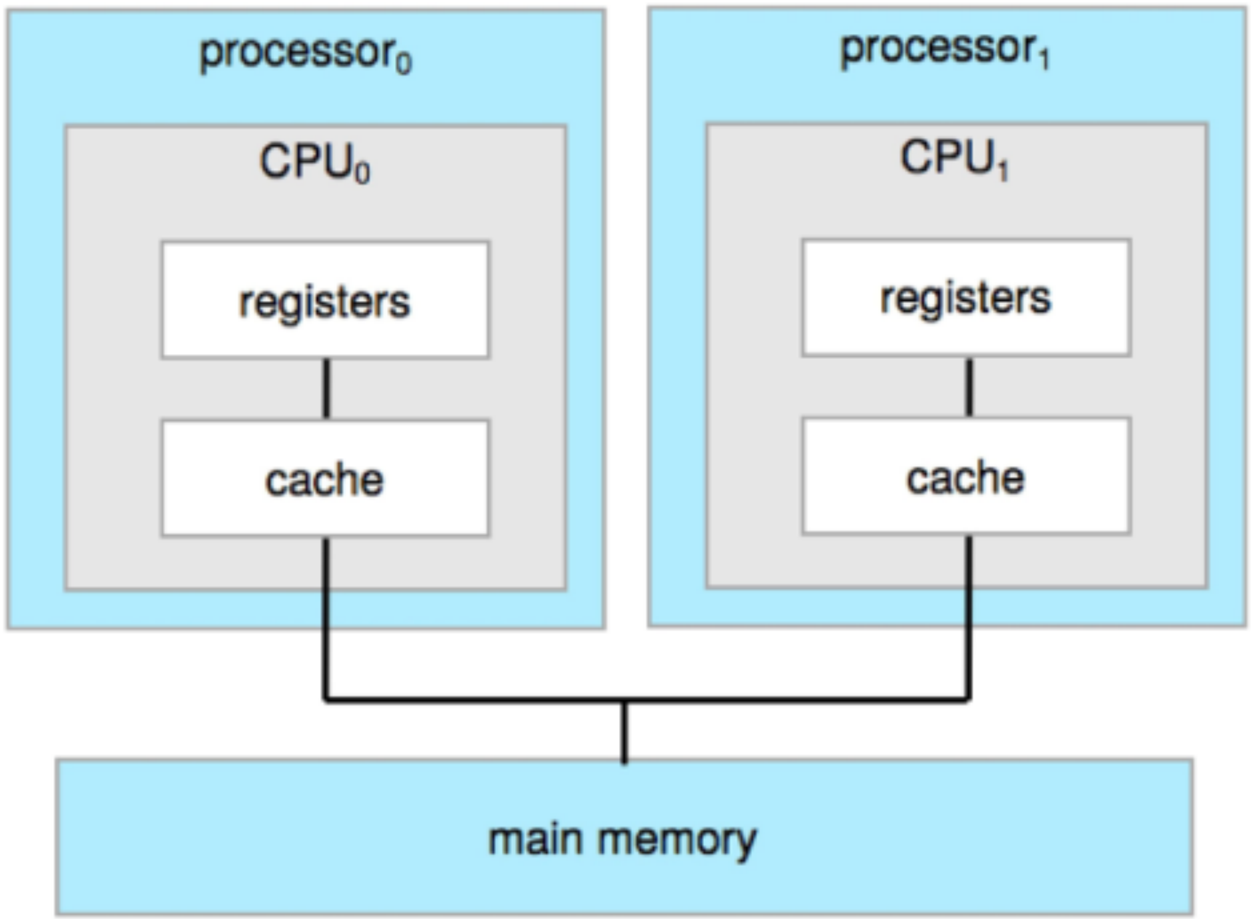
Direct Memory Access Structure

- Used for **high-speed I/O devices** able to transmit information at close to memory speeds
- *Device controller transfers blocks of data from local buffer directly to main memory without CPU intervention*
- Only one interrupt is generated per block, rather than the one interrupt per byte

Computer-System Architecture

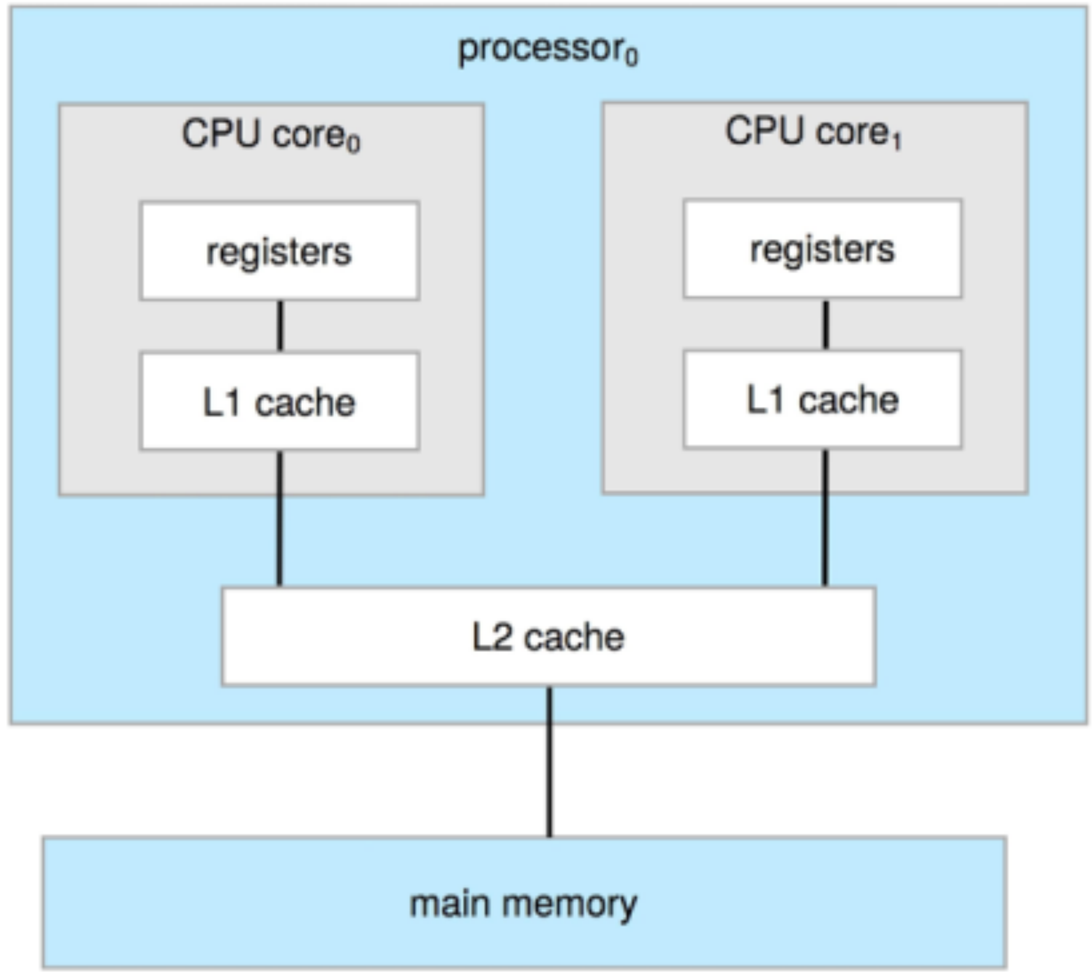
- Most older systems use a single *general-purpose processor*
  - Most systems have *special-purpose processors* as well
- **Multiprocessors** systems growing in use and importance
  - Also known as **parallel systems**, **tightly-coupled systems**
  - Advantages include:
    - *Increased throughput*
    - *Economy of scale, increased reliability* – graceful degradation or fault tolerance
  - Two types:
    - **Asymmetric Multiprocessing** – each processor is assigned a special task.
    - **Symmetric Multiprocessing** – each processor performs all tasks

Symmetric Multiprocessing Architecture

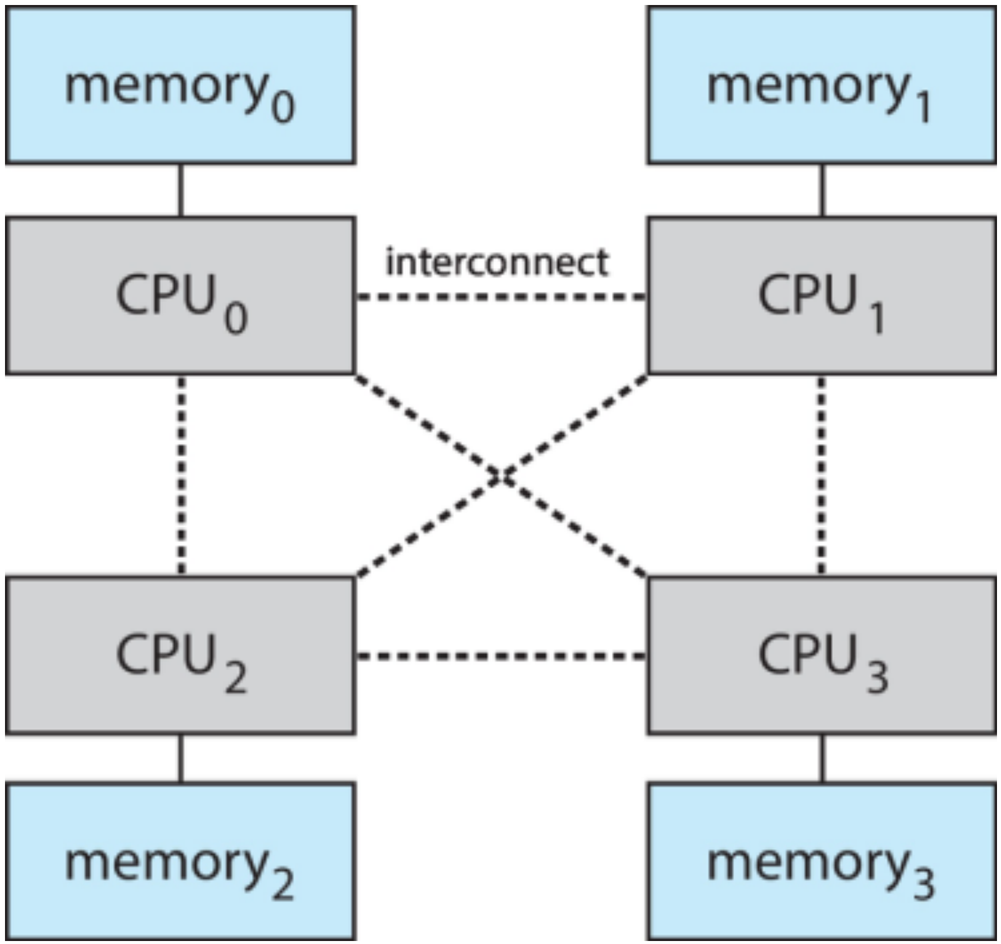


A Dual-Core Design

- **Multi-chip** and **multicore**
- **Systems** containing all chips
- **Chassis** containing multiple separate systems



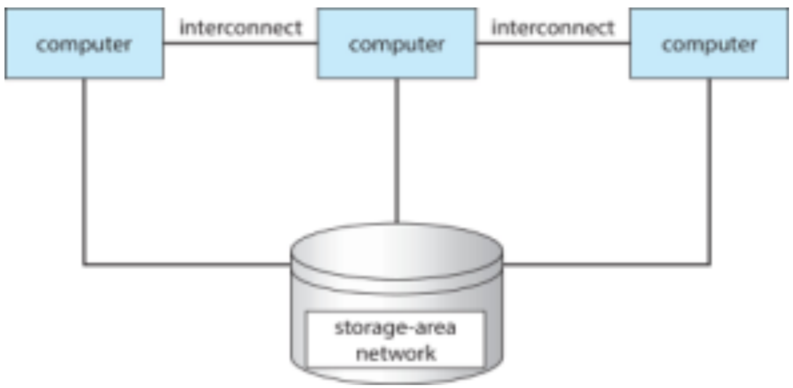
Non-Uniform Memory Access System



Non-Uniform Memory Access (**NUMA**)

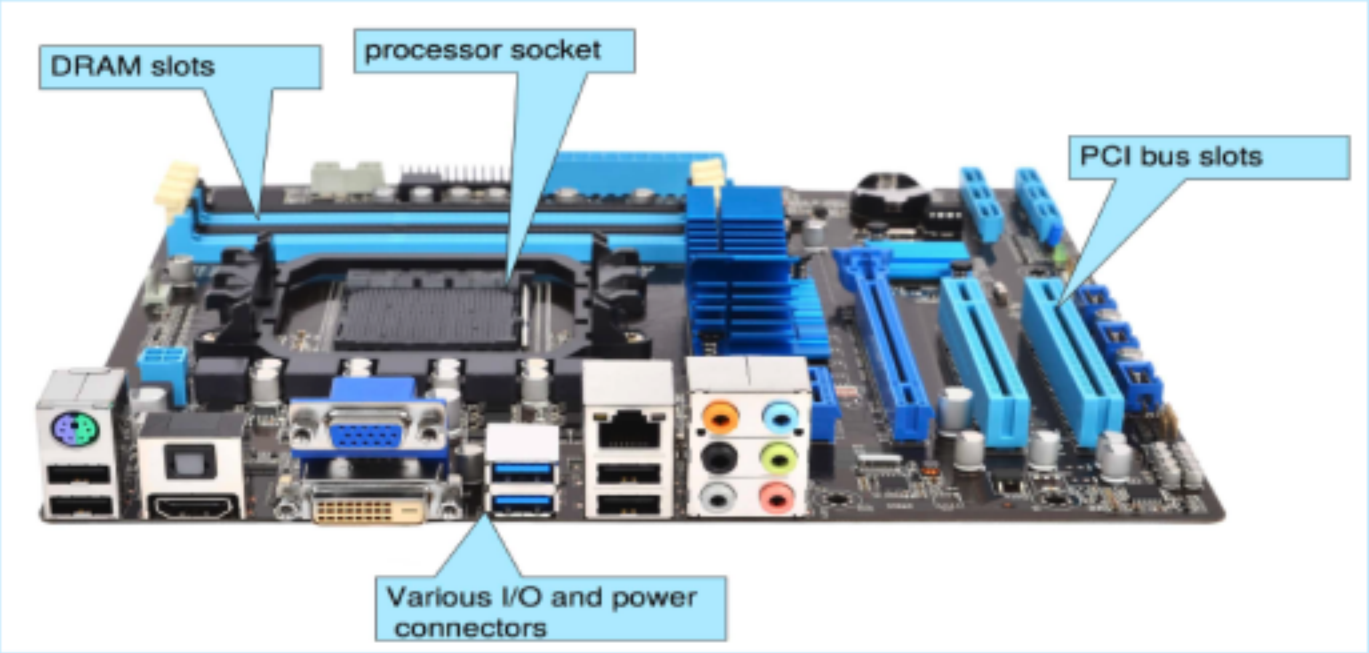
Clustered Systems

- Like multiprocessor systems, but *multiple systems working together*
  - Usually *sharing storage* via a **Storage-Area Network** (**SAN**)
  - Provides a *high-availability service* which survives failures
    - *Asymmetric clustering* has one machine in hot-standby mode
    - *Symmetric clustering* has multiple nodes running applications
  - Some clusters are used for **High-Performance Computing** (**HPC**)
    - Applications must be written to use *parallelization*
  - Some clusters have **Distributed Lock Manager** (**DLM**) to avoid conflicting operations



PC Motherboard

Consider the desktop PC motherboard with a processor socket shown below:



This board is a fully-functioning computer, once its slots are populated. It consists of a processor socket containing a CPU, DRAM sockets, PCIe bus slots, and I/O connectors of various types. Even the lowest-cost general-purpose CPU contains multiple cores. Some motherboards contain multiple processor sockets. More advanced computers allow more than one system board, creating NUMA systems.

Operating-System Operation

- **Bootstrap program** loaded at power-up (or reboot)
  - Typically stored in **ROM** or **EPROM**, generally known as **firmware**
  - Initializes all aspects of system
  - Loads operating system kernel and starts execution
- Loads **kernel**
  - Kernel is *interrupt-driven* (hardware and software)
    - **Hardware interrupt** by one of the devices
    - **Software interrupt** (exception or trap)**:** Software error (e.g., division by zero), request for operating system service (i.e., **system call)**, other process problems include infinite loop, processes modifying each other or modifying the operating system
- Starts **system daemons** (services provided outside of the kernel)

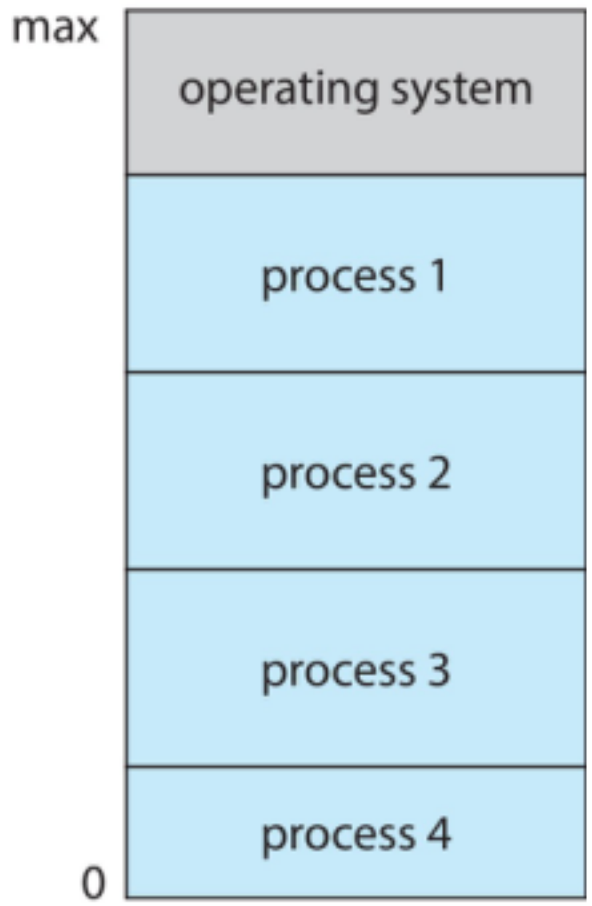
Multiprogramming

- **Multiprogramming** needed for efficiency
  - Single user cannot keep CPU and I/O devices busy at all times
  - *Multiprogramming organizes jobs (i.e., code and data) so that CPU always has one to execute*
  - A subset of total jobs in system is kept in memory
  - One job is selected and runs via job scheduling
  - When it has to wait (e.g., for I/O), OS switches to another job

Multitasking

- **Time-sharing** (**multitasking**) is a logical extension in which CPU switches jobs so frequently that users can interact with each job while it is running, creating *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 don't fit in memory, *swapping* moves them in and out to run
  - *Virtual memory* allows execution of processes not completely in memory

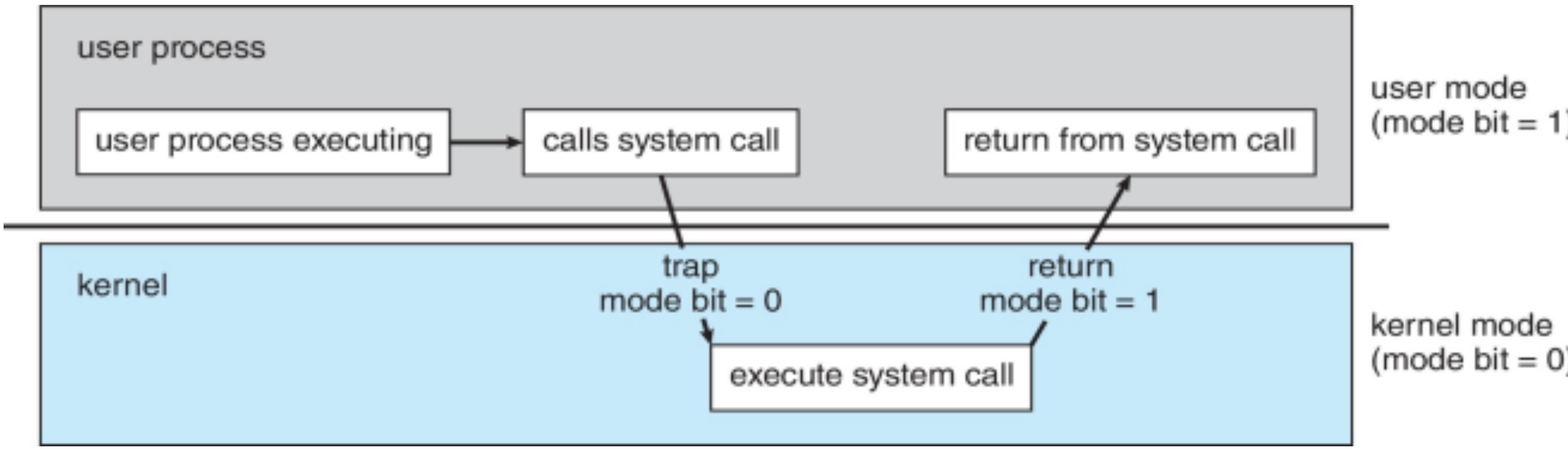
Memory Layout for Multiprogrammed System



Dual-mode and Multimode Operation

- **Dual-mode** operation allows OS to protect itself and other system components
  - **User mode** and **kernel mode**
  - **Mode bit** provided by hardware
    - Provides ability to distinguish when system is running user code or kernel code
    - Some instructions designated as *privileged*, only executable in kernel mode
    - System call changes mode to kernel, return from call resets it to user mode
- Increasingly CPUs support **multimode** operations
  - e.g., **Virtual machine manager** (**VMM**) mode for guest **Virtual Machine** (**VMs)**

Transition from User to Kernel Mode



- **Timer** to prevent infinite loop / process hogging resources
  - Timer is set to interrupt the computer after some time period. Operating system sets a counter (privileged instruction), keeps the counter that is decremented by the physical clock, when counter zero generate an interrupt.
  - Set up before scheduling process to regain control or terminate program that exceeds allotted time.

Process Management

- A **process** is a program in execution. It is a unit of work within the system. Program is a *passive entity*, process is an *active entity*.
  - Process needs **resources** to accomplish its task
    - CPU, memory, I/O, files, initialization data
    - Process termination requires reclaim of any reusable resources
  - **Single-threaded process** has *one program counter* specifying location of next instruction to execute
    - Process executes instructions sequentially, one at a time, until completion
  - **Multi-threaded process** has *one program counter per thread*
- Typically system has many processes (some user & some operating system processes) running concurrently on one or more CPUs
  - **Concurrency** by multiplexing the CPUs among the processes / threads

Process Management Activities

- The operating system is responsible for the following activities in connection with process management:
  - *Creating* and *deleting* both user and system processes
  - *Suspending* and *resuming* processes
  - Providing mechanisms for *process synchronization*
  - Providing mechanisms for *process communication*
  - Providing mechanisms for *deadlock handling*

Memory Management

- To execute a program,
  - All (or part) of the **instructions** must be in memory
  - All (or part) of the **data** needed by the program must be in memory
- Memory management determines what is in memory and when
  - Optimizing CPU utilization and computer response to users
- OS activities
  - *Keeping track* of which parts of memory are currently being used and by whom
  - *Deciding* which processes (or parts thereof) and data to move into and out of memory
  - *Allocating* and *deallocating* memory space as needed

Filesystem Management

- OS provides uniform, logical view of *data storage*
  - Abstracts physical properties to logical storage unit - **file**
  - Each medium is controlled by device (i.e., disk drive, tape drive)
    - Varying properties include *access speed, capacity, data-transfer rate, access method (sequential or random)*
- Filesystem management
  - **Files** usually organized into **directories**
  - **Access control** on most systems to determine who can access what
- OS activities
  - *Creating* and *deleting* files / directories, primitives to *manipulate* files / directories, to *backup* files onto stable (non-volatile) storage media
  - *Mapping* files onto secondary storage

Mass-Storage Management

- Usually **disks** used to store **programs** and **data** that do not fit in **main memory** or that must be kept for a "long" period of time
- Proper management is of central importance
- *Entire speed of computer operation hinges on disk subsystem and its algorithms*
- Some storage need not be fast
  - **Tertiary storage** includes optical storage, magnetic tape
  - Still must be managed – by OS or applications
- OS activities
  - *Mounting* and *unmounting*
  - *Free-space* management
  - Storage *allocation*
  - Disk *scheduling*
  - *Partitioning*
  - *Protection*

Caching

- Important principle, performed at many levels in a computer (in hardware, operating system, software)
- *Information in use copied from slower to faster storage temporarily*
- Faster storage (**cache**) checked to determine if information is there?
  - If it is, information used directly from the cache (fast)
  - If not, data copied to cache and used there
- Cache is smaller than storage being cached
  - Cache management is an important design problem
  - *Cache size and replacement policy*

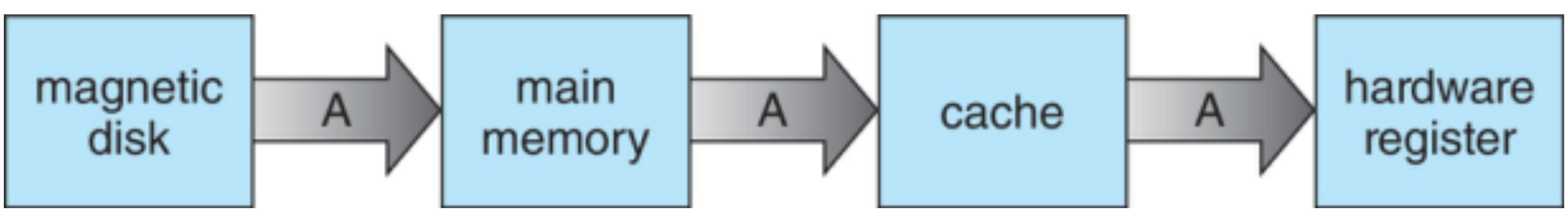
Various Types of Storage

- Movement between levels of storage hierarchy can be *explicit* or *implicit*

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

Migration of Data from Disk to Register

- **Multitasking environment** must be careful to use most recent value, no matter where it is stored in the storage hierarchy
- **Multiprocessor environment** must provide cache coherency in hardware such that all CPUs have the most recent value in their cache
- In **distributed environment**, the situation is even more complex
  - Several copies of a datum can exist
  - Various solutions



I/O Subsystem

- One purpose of OS is to hide peculiarities of hardware devices from the user
- **I/O subsystem** is 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)
- I/O subsystem includes
  - *General device-driver interface*
  - *Drivers* for specific hardware devices

Protection and Security

- **Protection** – any mechanism for controlling access of processes or users to resources defined by the OS
- **Security** – defense of the system against internal and external attacks
  - Huge range, including *denial-of-service, worms, viruses, identity theft, theft of service*
- Systems generally first distinguish among users, to determine who can do what
  - **User identity** (**UID**, or security ID) includes name and an associated number. User ID is then associated with all files, processes of that user to determine access control
  - **Group identifier** (**GID**) allows set of users to be defined for access control, then also associated with each process or file
  - **Privilege escalation** allows user to change to *effective ID* with more rights

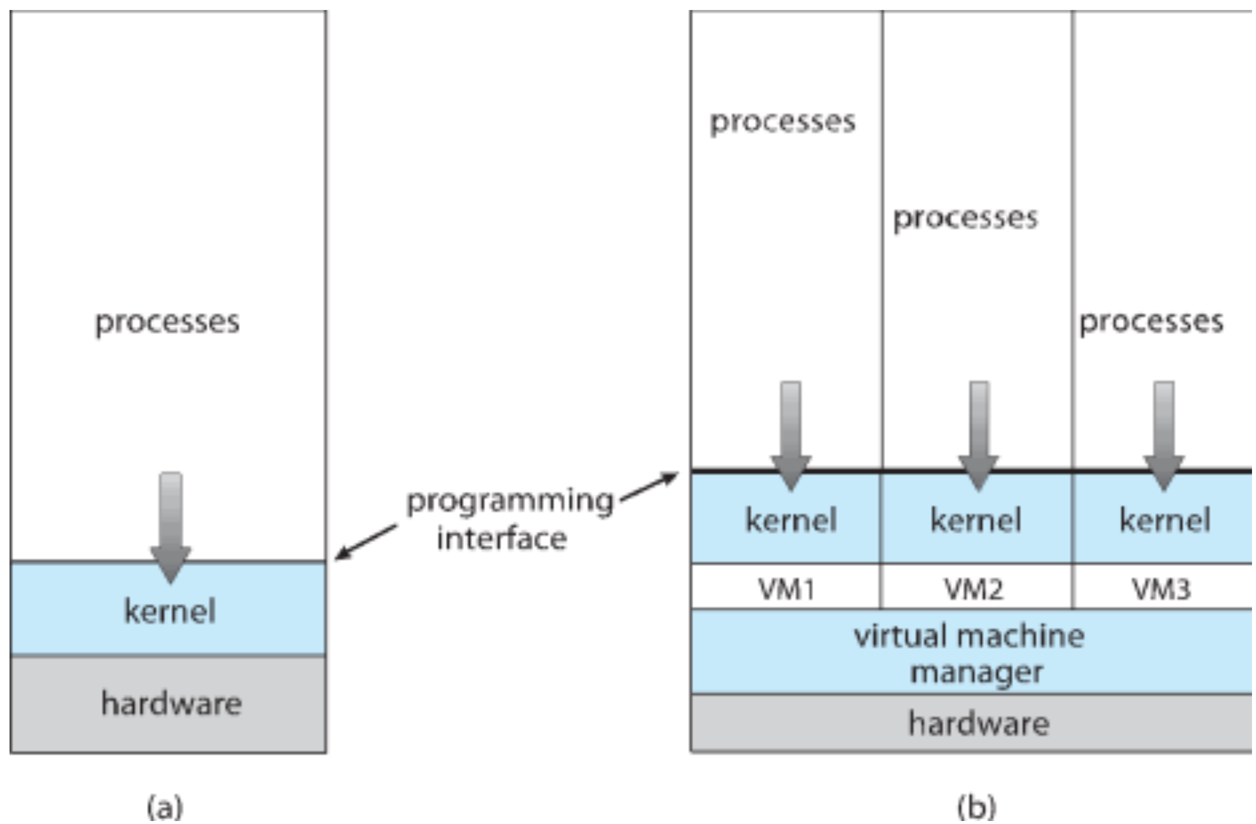
Virtualization

- *Allows operating systems to run applications within other OSes*
  - Vast and growing industry
- **Emulation** used when source CPU type different from target CPU type (e.g., PowerPC to Intel x86)
  - Generally slowest method
  - When computer language not compiled to native code – *Interpretation*
- **Virtualization** – OS natively compiled for CPU, running **guest** OSes also natively compiled
  - E.g., Consider VMware running WinXP **guests**, each running applications, all on native WinXP **host** OS
  - **Virtual Machine Manager** (**VMM**) provides virtualization services

Virtualization (cont.)

- Use cases involve laptops and desktops running multiple OSes for exploration or compatibility
  - E.g.,
    - Apple laptop running **Mac OS X** host, **Windows** as a guest
    - Developing apps for multiple OSes without having multiple systems
    - Q&A testing applications without having multiple systems
    - Executing and managing computing environments within data centers
- VMM can run natively, in which case they are also the host
  - There is no general purpose host then (e.g., **VMware ESX** and **Citrix XenServer**)

Computing Environments - Virtualization



A single operating system

A virtualization system with 3 OSes

Distributed Systems

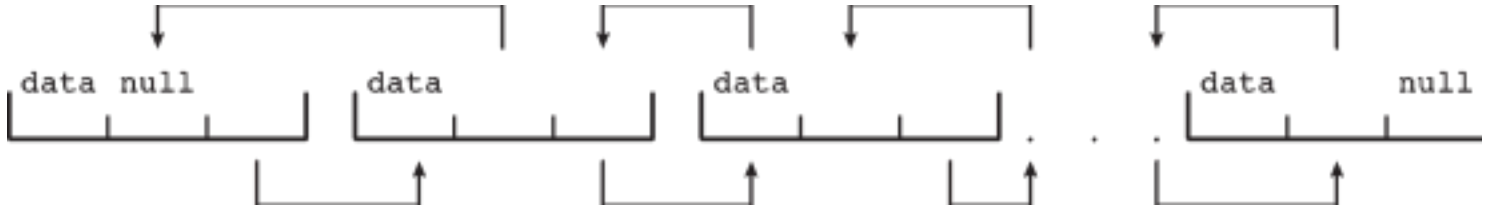
- **Distributed computing**
  - Collection of separate (possibly heterogeneous) systems networked together
    - **Network** is communications paths (**TCP/IP** is most common protocol stack)
      - **Local Area Network** (**LAN**)
      - **Wide Area Network** (**WAN**)
      - **Metropolitan Area Network** (**MAN**)
      - **Personal Area Network** (**PAN**)
  - **Network Operating System** (**NOS**) provides features between systems across network
    - Communication scheme allows systems to exchange messages
    - Illusion of a single system

Kernel Data Structures

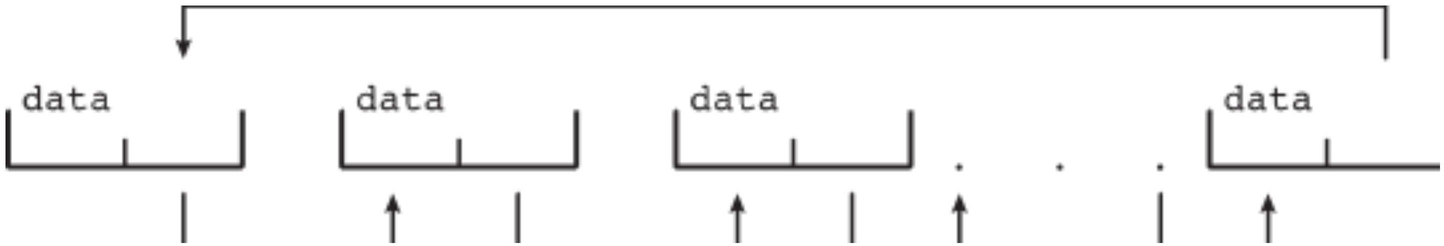
Many similar to standard programming data structures

- ***Singly linked list***

- ***Doubly linked list***

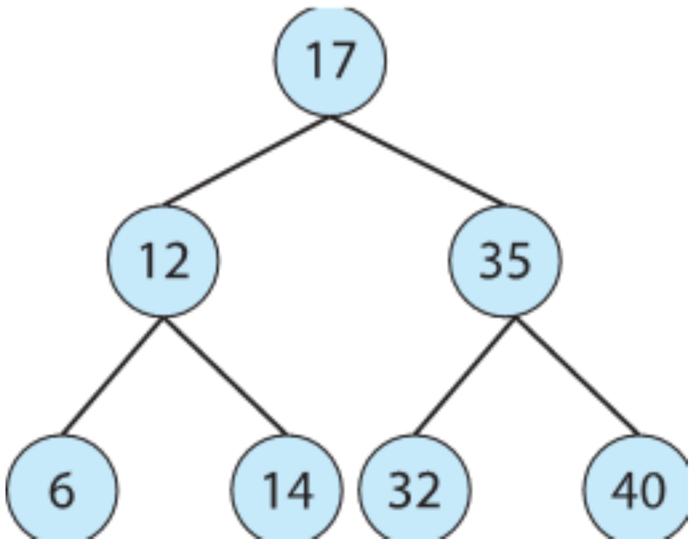


- ***Circular linked list***



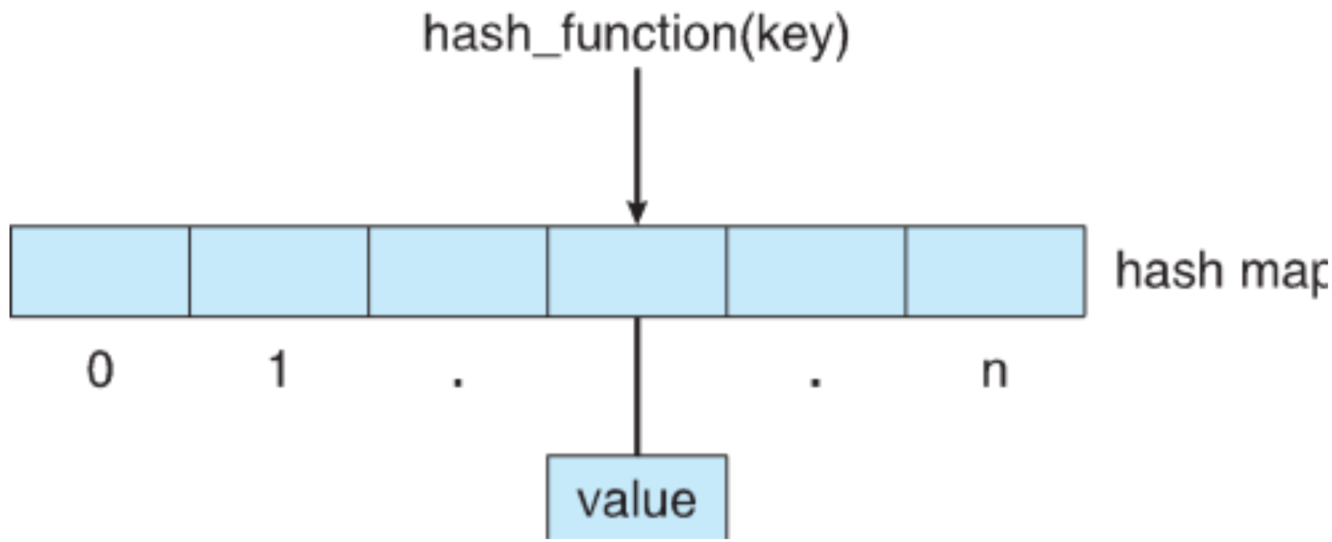
Kernel Data Structures

- **Binary search tree** (left <= right)
  - Search performance is *O(n)*
  - **Balanced binary search tree** is *O(log n)*



Kernel Data Structures

- **Hash function** can create a **hash map**



- **Bitmap** – string of ***n*** binary digits representing the status of ***n*** items
- E.g., Linux data structures defined in ***`include`*** files:
  - **`<linux/list.h>, <linux/kfifo.h>, <linux/rbtree.h>`**

Evolution

- Mainframe system
- Desktop system
- Multiprocessor system
- Distributed system
- Real-time system
- Handheld system/mobile system

Computing Environments - Traditional

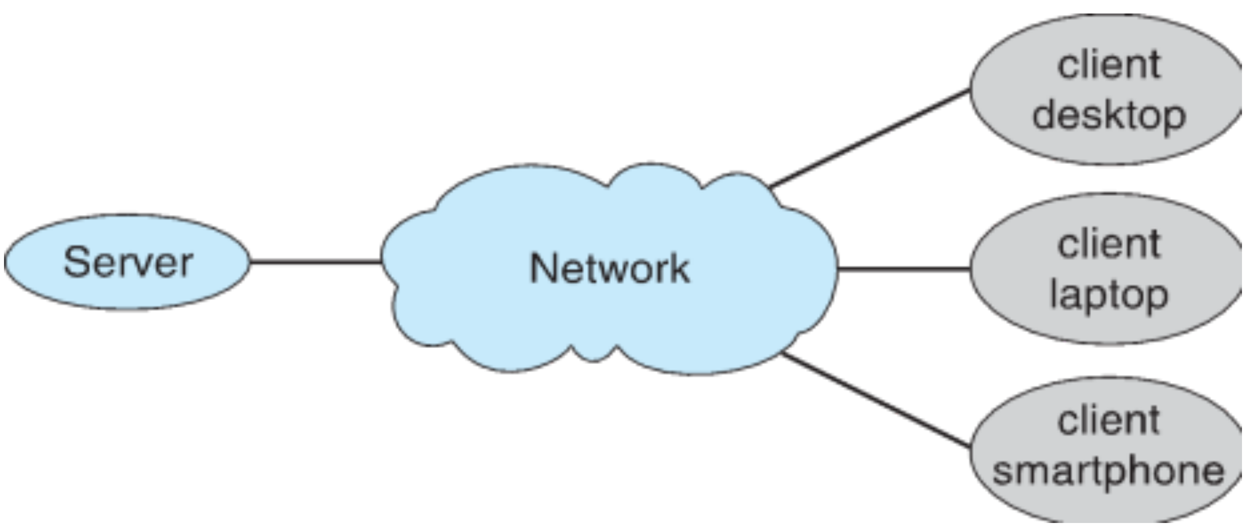
- *Stand-alone general purpose machines*
- But blurred as most systems interconnect with others (i.e., the Internet)
- **Portals** provide web access to internal systems
- **Network computers** (or *thin clients*) are like Web terminals
- **Mobile computers** interconnect via *wireless networks*
- Networking becoming ubiquitous – even home systems use **firewalls** to protect home computers from Internet attacks

Computing Environments - Mobile

- Such as *handheld smartphones, tablets, etc.*
- What is the functional difference between them and a "traditional" laptop?
  - Extra feature – *more OS features* (e.g., GPS, gyroscope)
  - Allows *new types of apps* like **Augmented Reality** (**AR**)
  - Use IEEE 802.11 wireless, or cellular data networks for *connectivity*
- Leaders are **Apple iOS** and **Google Android**

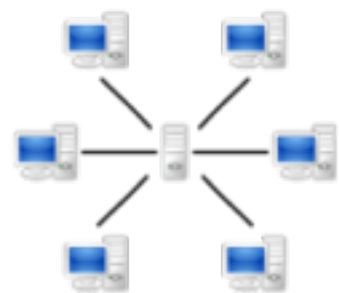
Computing Environments – Client-Server

- **Client-Server Computing**
  - Dumb terminals supplanted by *smart PCs*
  - Many systems now **servers**, responding to requests generated by **clients**
    - **Compute-server system** provides an interface to client to request services (i.e., database)
    - **File-server system** provides interface for clients to store and retrieve files



Computing Environments - Peer-to-Peer

- Another model of **distributed system**
- **P2P** does not distinguish clients and servers
  - Instead all nodes are considered **peers**
  - May each act as client, server or both
  - Node must join **P2P network**
    - Registers its service with *central lookup service* on network, or
    - Broadcast request for service and respond to requests for service via *discovery protocol*
  - Examples include **Napster** and **Gnutella**, **Voice over IP** (**VoIP**) such as **Skype**

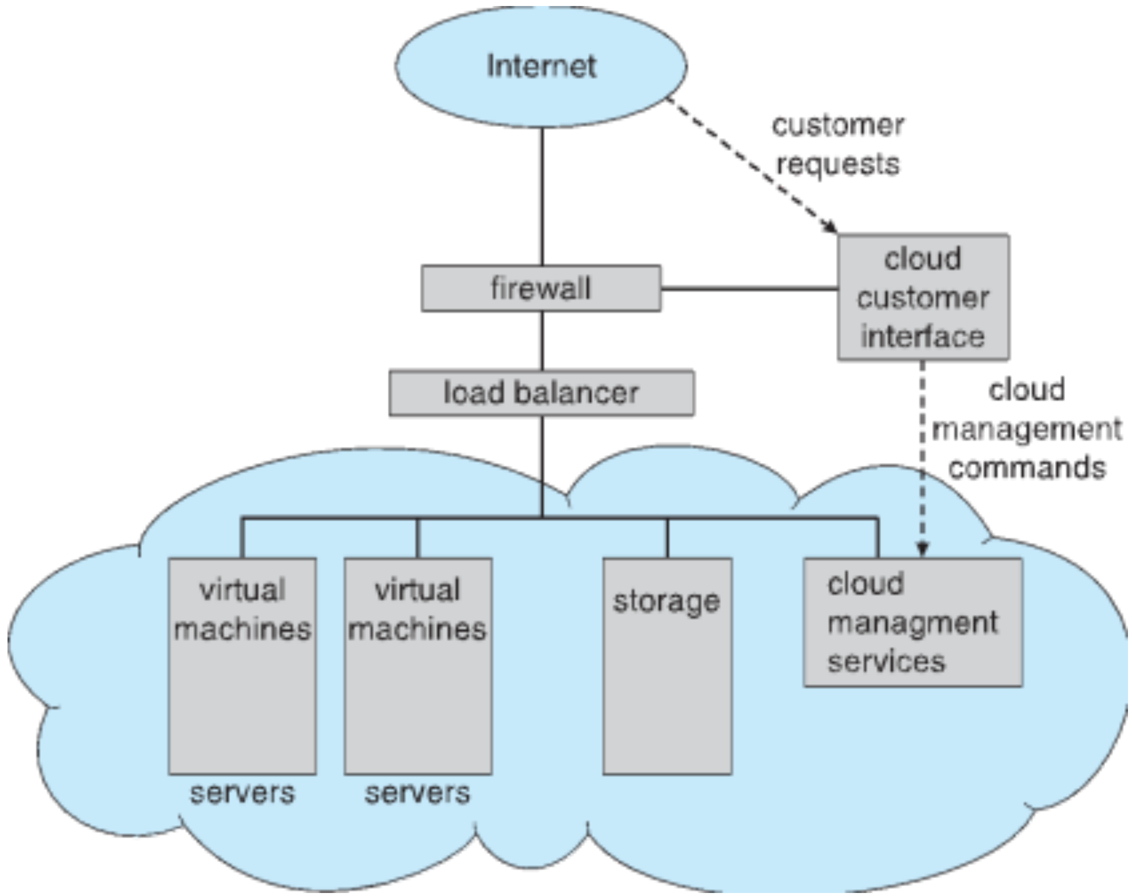


Computing Environments – Cloud Computing

- Delivers *computing*, *storage*, *apps* as a service across a network
- Logical extension of *virtualization* because it uses virtualization as the base for it functionality.
  - E.g., **Amazon EC2** has thousands of servers, millions of virtual machines, petabytes of storage available across the Internet
- Many types of **services**
  - **Software as a Service** (**SaaS**) – one or more applications available via the Internet
  - **Platform as a Service** (**PaaS**) – software stack ready for application use via the Internet
  - **Infrastructure as a Service** (**IaaS**) – servers or storage available over Internet (i.e., storage available for backup use)
- Many types of **structure**
  - **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

Computing Environments – Cloud Computing

- Cloud computing environments composed of **traditional OSes**, plus **VMMs**, plus **cloud management tools**
  - Internet connectivity requires security like *firewalls*
  - *Load balancers* spread traffic across multiple applications



Computing Environments – Real-Time Embedded Systems

- **Real-time embedded systems** most prevalent form of computers
  - Vary considerable, special purpose, limited purpose OS, **real-time OS**
  - Use expanding
- Many other *special computing environments* as well
  - Some have OSes, some perform tasks without an OS
- *Real-time OS has well-defined fixed time constraints*
  - Processing must be done within constraints
  - Correct operation only if constraints met

Free and Open-Source Operating Systems

- Operating systems made available in source-code format rather than just binary *closed-source* and *proprietary*
- Counter to the *copy protection* and **Digital Rights Management** (**DRM**) movement
- Started by **Free Software Foundation** (**FSF**), which has "copyleft" **GNU Public License** (**GPL**) or **Lesser GPL** (**LGPL**)
  - Free software and open-source software are two different ideas championed by different groups of people
    - http://gnu.org/philosophy/open-source-misses-the-point.html/
  - E.g., **GNU/Linux** and **BSD UNIX** (including **Darwin**, core of **Mac OS X**)
- Use VMM like **VMware Player** (Free on Windows), **VirtualBox**
  - Use to run guest operating systems for exploration

The Study of Operating Systems

- There has never been a more interesting time to study operating systems, and it has never been easier. The open-source movement has overtaken operating systems, causing many of them to be made available in both **source** and **binary** (executable) format. The list of operating systems available in both formats includes **Linux**, **BSD UNIX**, **Solaris**, and part of **macOS**. The availability of source code allows us to study operating systems from the inside out. Questions that we could once answer only by looking at documentation or the behavior of an operating system we can now answer by examining the code itself.
- Operating systems that are no longer commercially viable have been open-sourced as well, enabling us to study how systems operated in a time of fewer CPU, memory, and storage resources. An extensive but incomplete list of **open-source operating-system** projects is available from https://curlie.org/Computers/Software/Operating_Systems/Open_Source/
- In addition, the rise of **virtualization** as a mainstream (and frequently free) computer function makes it possible to run many operating systems on top of one core system. For example, **VMware** (http://www.vmware.com) provides a free "player" for Windows on which hundreds of free "virtual appliances" can run. **VirtualBox** (http://www.virtualbox.com) provides a free, open-source virtual machine manager on many operating systems. Using such tools, students can try out hundreds of operating systems without dedicated hardware.
- *The advent of open-source operating systems has also made it easier to make the move from student to operating-system developer*. With some knowledge, some effort, and an Internet connection, a student can even create a new operating-system distribution. Just a few years ago, it was difficult or impossible to get access to source code. Now, such access is limited only by how much interest, time, and disk space a student has.

Summary

- An **operating system** is software that manages the computer hardware, as well as providing an environment for application programs to run.
- **Interrupts** are a key way in which hardware interacts with the operating system. A hardware device triggers an interrupt by sending a signal to the CPU to alert the CPU that some event requires attention. The interrupt is managed by the interrupt handler.
- For a computer to do its job of **executing programs**, the programs must be in main memory, which is the only large storage area that the processor can access directly.
- The **main memory** is usually a volatile storage device that loses its contents when power is turned off or lost.

Summary (Cont.)

- **Nonvolatile storage** is an extension of main memory and is capable of holding large quantities of data permanently.
- The most common nonvolatile storage device is a **hard disk**, which can provide storage of both programs and data.
- The wide variety of **storage systems** in a computer system can be organized in a hierarchy according to speed and cost. The higher levels are expensive, but they are fast. As we move down the hierarchy, the cost per bit generally decreases, whereas the access time generally increases.
- Modern computer architectures are **multiprocessor systems** in which each CPU contains several computing cores.

Summary (Cont.)

- To best utilize the CPU, modern operating systems employ **multiprogramming**, which allows several jobs to be in memory at the same time, thus ensuring that the CPU always has a job to execute.
- **Multitasking** is an extension of multiprogramming wherein CPU scheduling algorithms rapidly switch between processes, providing users with a fast response time.
- To prevent user programs from interfering with the proper operation of the system, the system hardware has two modes: **user mode** and **kernel mode**.
- **Various instructions are privileged** and can be executed only in kernel mode. Examples include the instruction to switch to kernel mode, I/O control, timer management, and interrupt management.

Summary (Cont.)

- A **process** is the fundamental unit of work in an operating system. Process management includes creating and deleting processes and providing mechanisms for processes to communicate and synchronize with each other.
- An operating system manages **memory** by keeping track of what parts of memory are being used and by whom. It is also responsible for dynamically allocating and freeing memory space.
- **Storage space** is managed by the operating system; this includes providing file systems for representing files and directories and managing space on mass-storage devices.
- Operating systems provide **mechanisms for protecting and securing** the operating system and users. Protection measures control the access of processes or users to the resources made available by the computer system.

Summary (Cont.)

- **Virtualization** involves abstracting a computer's hardware into several different execution environments.
- **Data structures** that are used in an operating system include lists, stacks, queues, trees, and maps.
- **Computing** takes place in a variety of **environments**, including traditional computing, mobile computing, client-server systems, peer-to-peer systems, cloud computing, and real-time embedded systems.
- **Free and open-source operating systems** are available in source-code format. Free software is licensed to allow no-cost use, redistribution, and modification. GNU/Linux, FreeBSD, and Solaris are examples of popular open-source systems.

End of Chapter 1