Chapter 1
Introduction

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Source: Abraham Silberschatz, Peter B. Galvin, and Greg Gagne, "Operating System Concepts", 10th Edition, Wiley.

Objectives

- Introduce the major operating system components and functions
- To provide coverage of basic computer system organization
- Many of the topics will be discussed in detail in the following chapters

Outline

- What Is an Operating System
- Computer-System Organization/Architecture
- Operating-System Structure/Operations
- Process Management
- Memory Management
- Storage Management
- Protection and Security
- Virtualization
- Basic Kernel Data Structures
- Computing Environments
- Open-Source Operating Systems

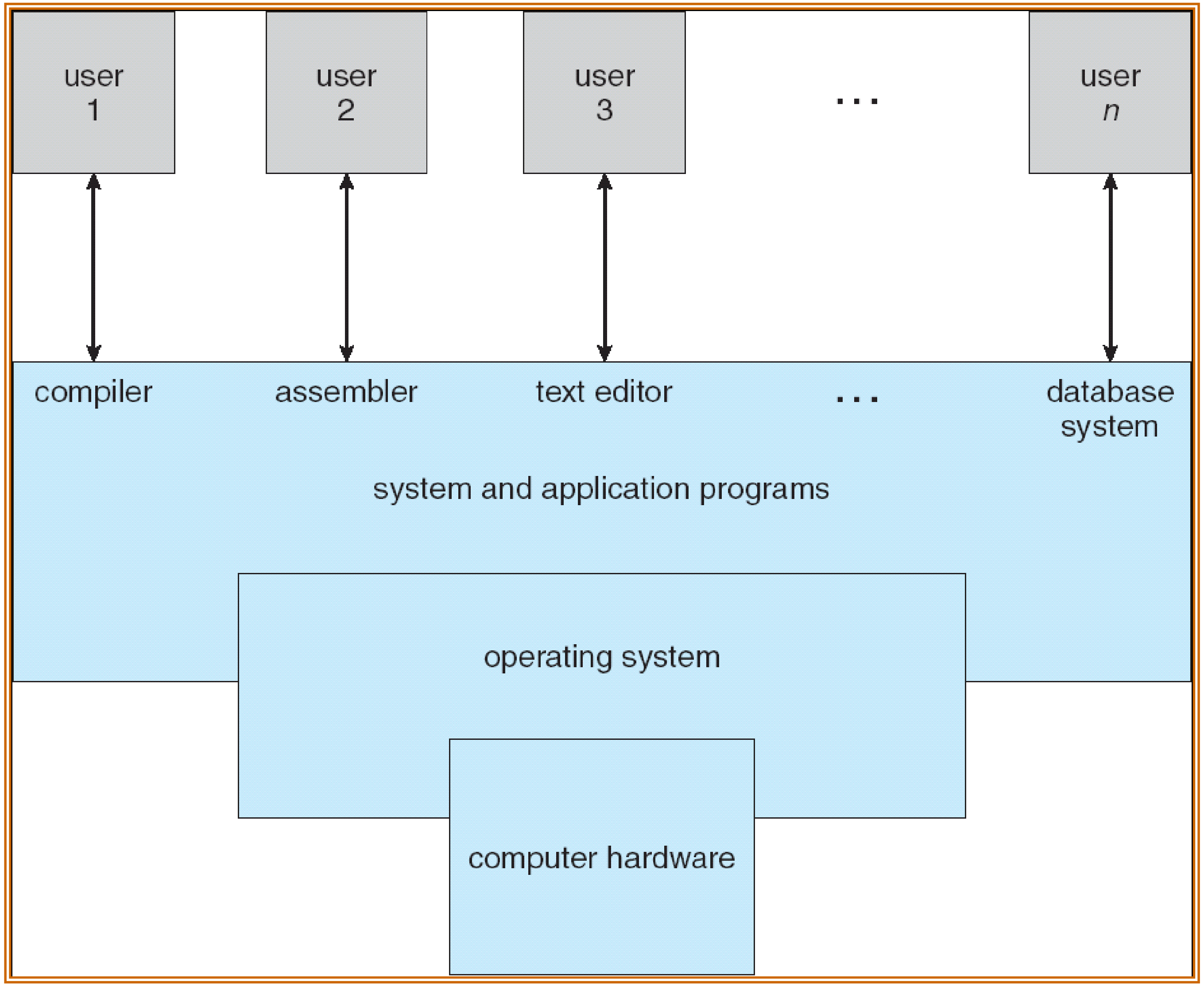
What is an Operating System?

- A program that acts as an intermediary between user programs/applications and the computer hardware
- Operating system goals
  - Execute user programs
  - Make the computer system convenient to use
    - Applications do not have to deal with HW directly
    - OS ensures efficient resource sharing

Computer System Structure

- A computer system can be divided into 4 components (from bottom to top)
  - Hardware – provides basic computing resources
    - CPU, memory, I/O devices
  - Operating system
    - Controls and coordinates use of hardware among various applications and users
  - System and application programs – solve the computing problems of the users
    - Word processors, compilers, web browsers, database systems, video games
  - Users
    - People, machines, other computers

Four Components of a Computer System



Operating System Definition

- **What is an operating system?**

- No universally accepted definitions

- "Everything a vendor ships when you order an operating system" is good approximation
  - But varies widely

- "The one program running at all times on the computer" (i.e., the **kernel**) Everything else is either a system program (ships with the operating system) or an application program

Operating System Definition

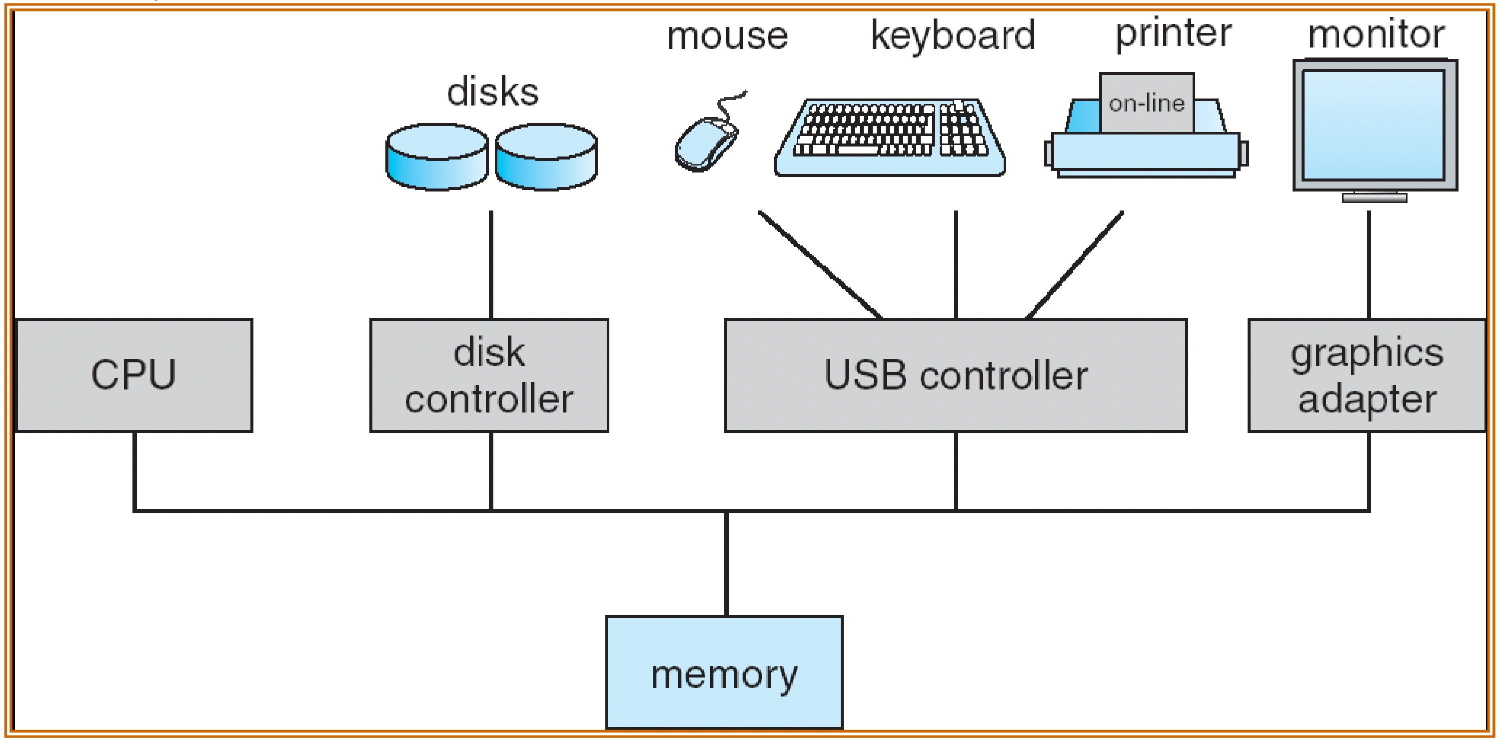
- Two points of view (in the text book)
  - OS is a **resource allocator**
    - Manages all resources
    - Decides between conflicting requests for efficient and fair resource use
    - Applications do not have to manage resources directly
      - OS hides HW interface
  - OS is a **control program**
    - Controls execution of programs to prevent errors and improper use of the computer
- Other definitions
  - A program that can monitor the other programs
  - A program that that allows the other programs to share resources in a controlled manner
    - CPU, memory, IO devices….

Computer Startup

- **Who loads the OS ?**
- **Bootstrap program** is loaded at power-up or reboot
  - Typically stored in ROM or EEPROM, generally known as **firmware**
  - Jobs
    - Initializes all aspects of system
    - Loads operating system kernel and starts OS execution
- A bootstrap program is also called a boot loader
- Who loads the boot loader?
  - In PC, BIOS loads the (in-disk) boot loader
  - In many other platforms, boot loader is placed at a predefined memory address (in ROM or EEPROM)
    - Hardware jumps to the boot loader directly

Computer System Organization

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



Computer-System Operation

- I/O devices and the CPU can execute concurrently.
- Each device controller is in charge of a particular device type.
- Each device controller has a local buffer.
- For data writes

  a part of OS
  - (Device driver running on the) CPU moves data from main memory to local buffers
  - Device controller writes the data from the local buffer to the device
  - Device controller informs CPU that it has finished its operation by generating an *interrupt*

- One of the jobs of an operating system is to manage interrupts.

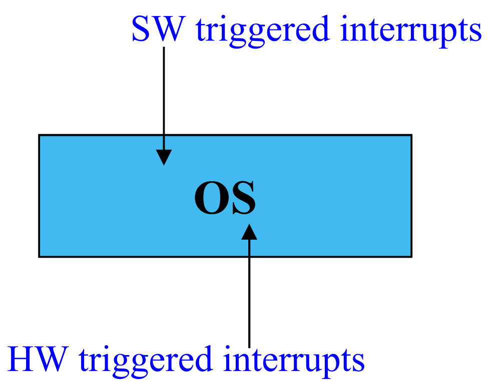
Common Functions of Interrupts

- Interrupt transfers control to the interrupt service routine (ISR), generally through the *interrupt vector (table)*
  - *interrupt vector* contains the addresses or instructions of all the service routines
    - X86: addresses
    - ARM: instructions
- The processor must save the address of the interrupted instruction before jumping to the ISR

- Generally, interrupts are raised by IO device controllers
  - ***Hardware*** interrupts

Common Functions of Interrupts

- However, ***software*** can also generate/raise interrupts
  - Software interrupts (or **traps**)
- A *trap* is a software-generated interrupt caused either by an error or a user request
  - Error
    - Division by zero, invalid memory access…
  - User request
    - Requests for OS services
      - ***int*** instruction in x86
      - ***svc/swi*** instruction in ARM

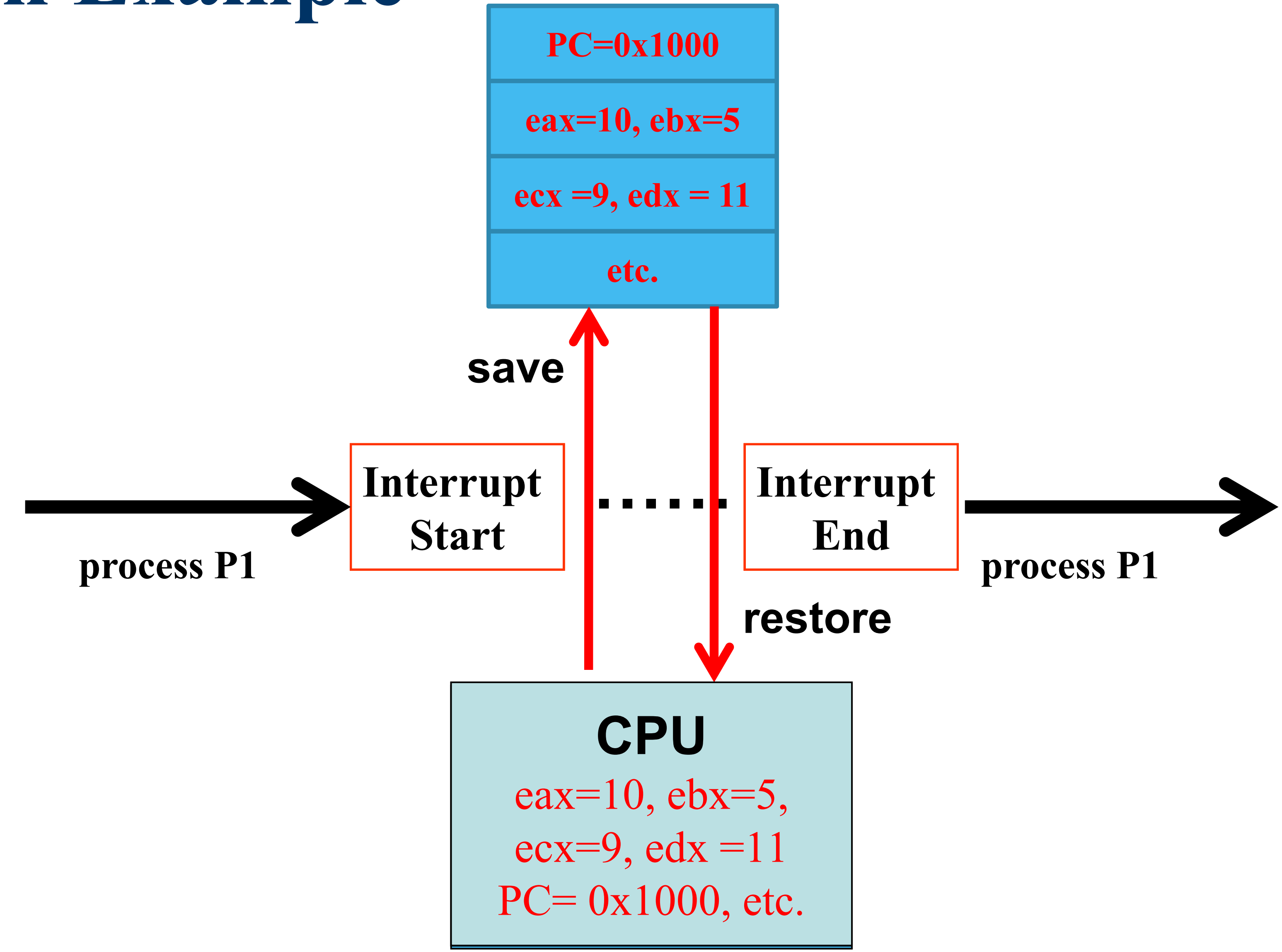


- **An operating system is *interrupt* driven!**

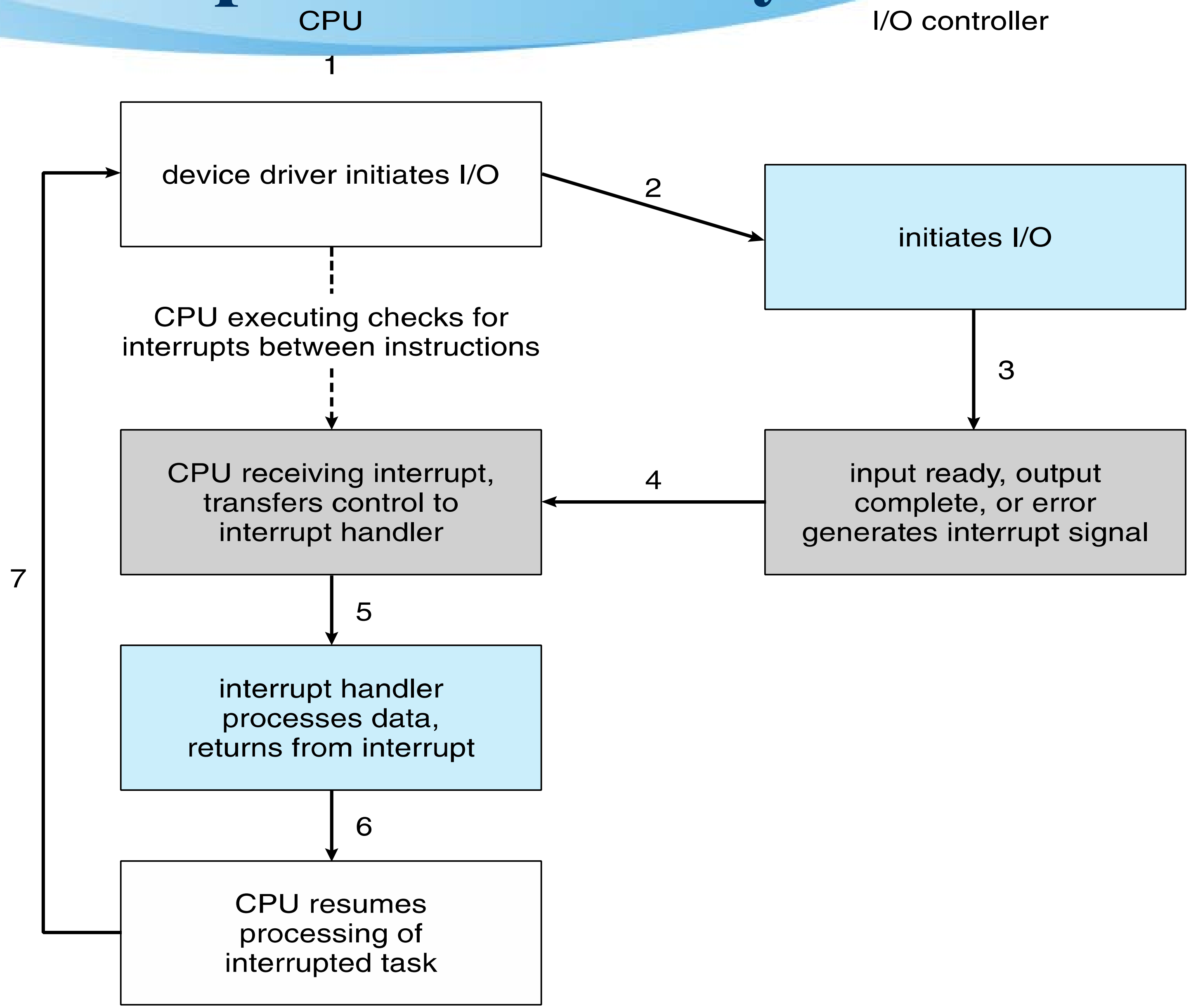
Interrupt Handling

- Save the CPU state (registers, including program counter)
  - Done by HW or OS
- Call the corresponding Interrupt Service Routine (ISR) or interrupt handler
  - How do you know the address of the ISR?
    - Interrupt vector table (IVT)
- Execute the ISR
- Continue the interrupted work by restoring the CPU state

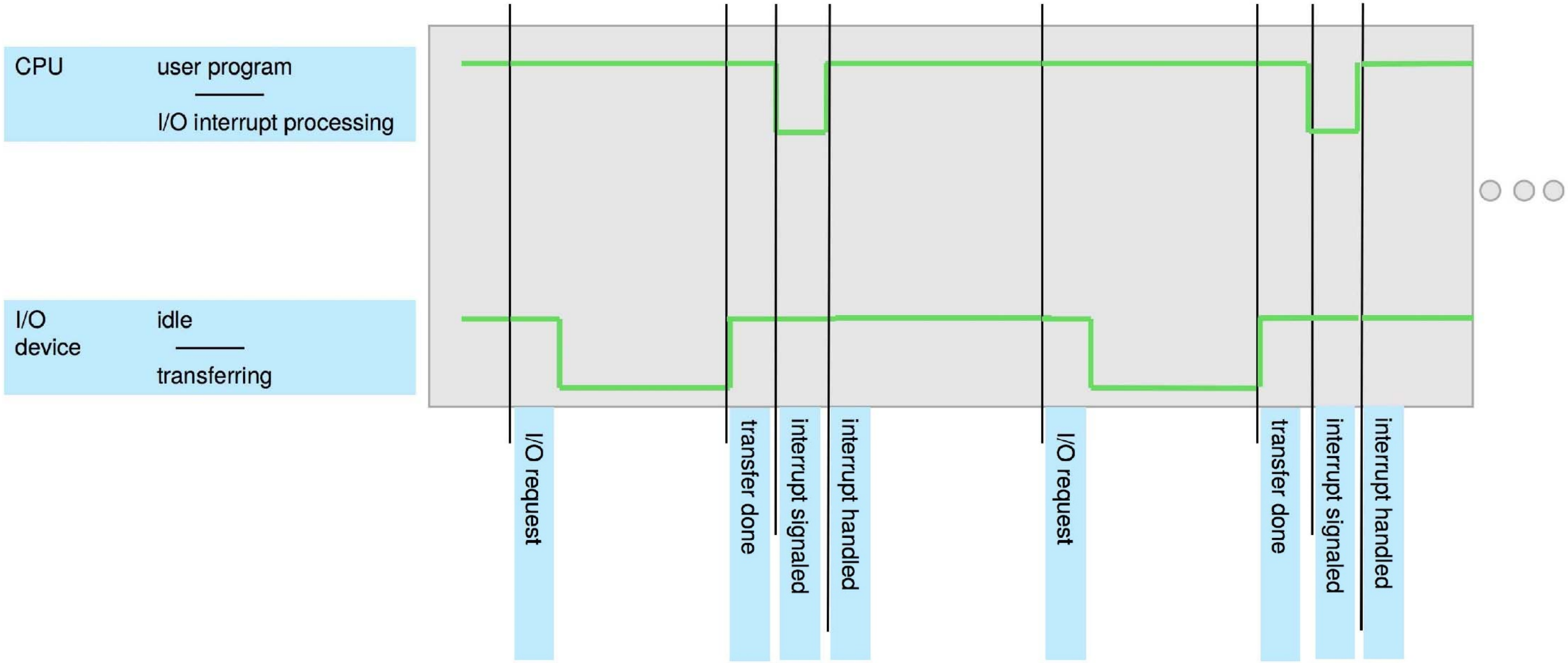
Saving/Restoring CPU State – An Example



Interrupt-drive I/O Cycle

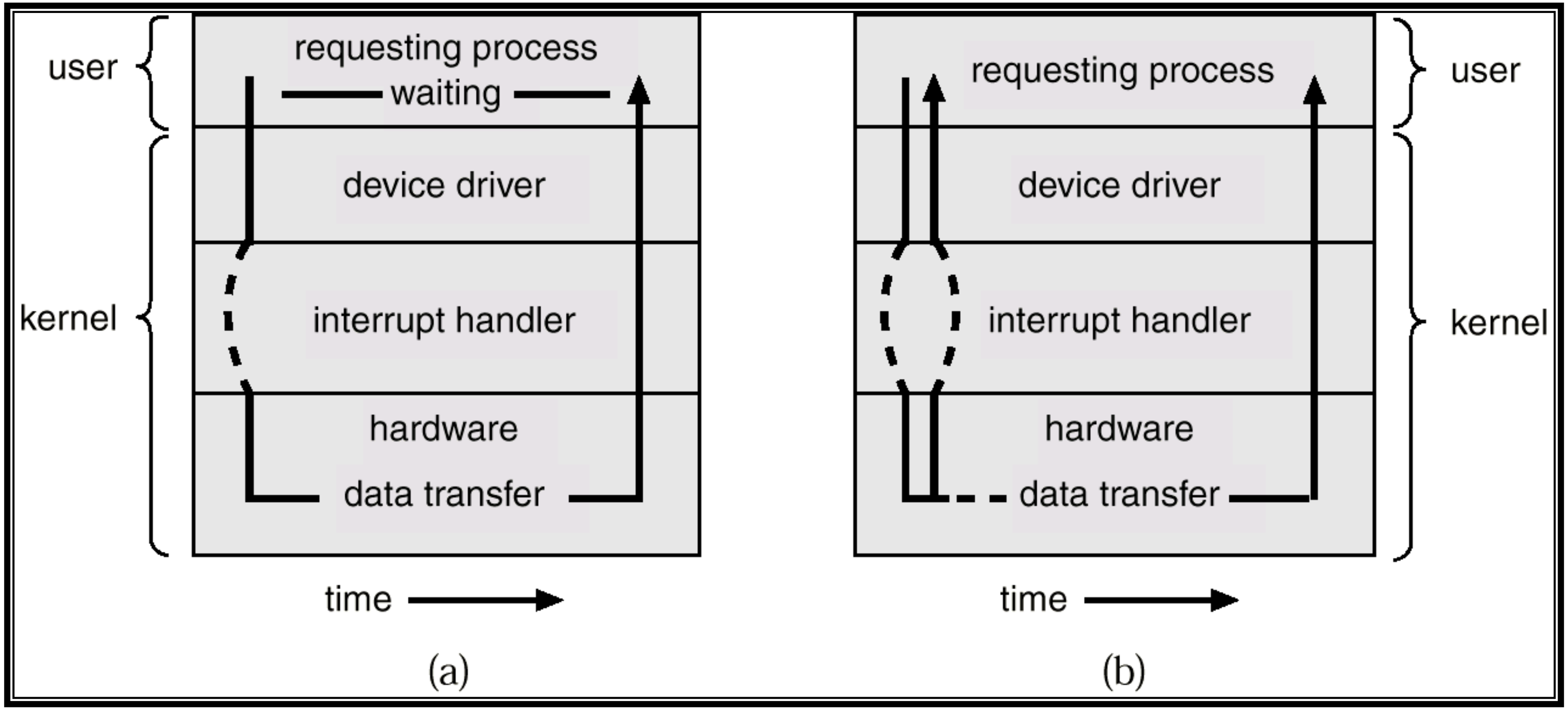


Interrupt Timeline



Two I/O Methods

Synchronous I/O | **Asynchronous I/O**

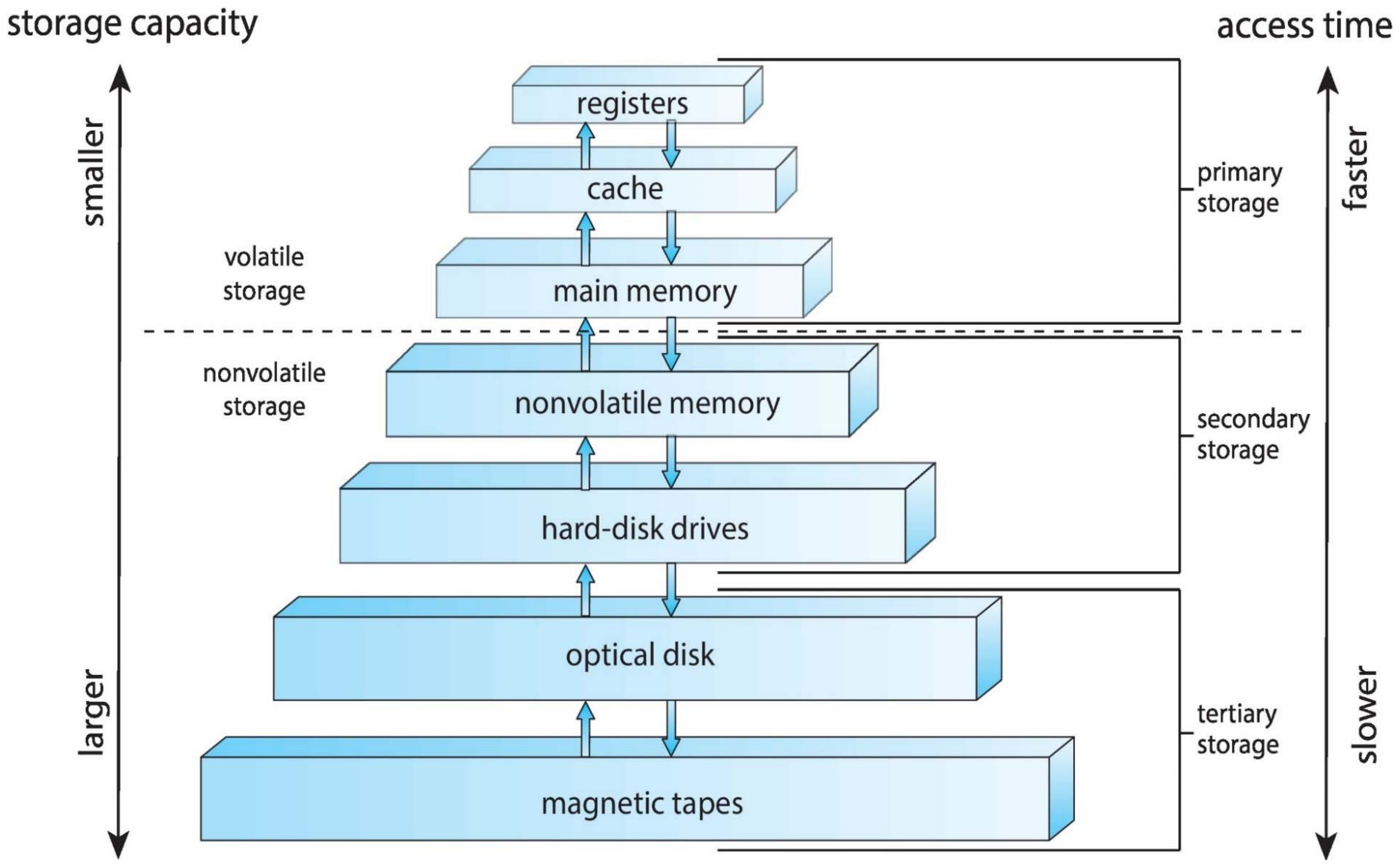


Direct Memory Access (DMA)

- Who moves the data between memory and device buffer?
  - CPU? device controller?
- DMA
  - Device controller transfers blocks of data from local buffer directly to main memory without CPU intervention
  - Raise interrupt when DMA transfer is done

Storage Structure

- Storage systems organized in hierarchy
  - The layers differ in Sizes, Speed, Cost, Volatility…



Storage Structure

- Primary Storage
  - Main memory –the only large storage media that the CPU can access directly (e.g., via load/store instructions)
- Secondary storage – extension of main memory that provides large nonvolatile storage capacity
  - Magnetic disks (HDD)
    - metal or glass platters covered with magnetic recording material
    - disk surface is logically divided into ***tracks***/***sectors***
    - the most common secondary-storage device
  - Nonvolatile Memory (NVM)
    - SSD (Solid State Drive)
    - Becoming more popular as capacity increases and price drops
    - *Various technologies: **flash memory**, PCM, RRAM, STT-MRAM*
- Tertiary storage
  - Usually for storing backup copies

Caching

- *Caching* – information in use copied from slower to faster storage temporarily
  - main memory can be viewed as a *cache* for secondary storage
- Faster storage (cache) checked first 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 the storage being cached
  - Cache management is an important design problem
  - Cache size and replacement policy
- Performed at many levels in a computer system (in hardware, operating system, software)

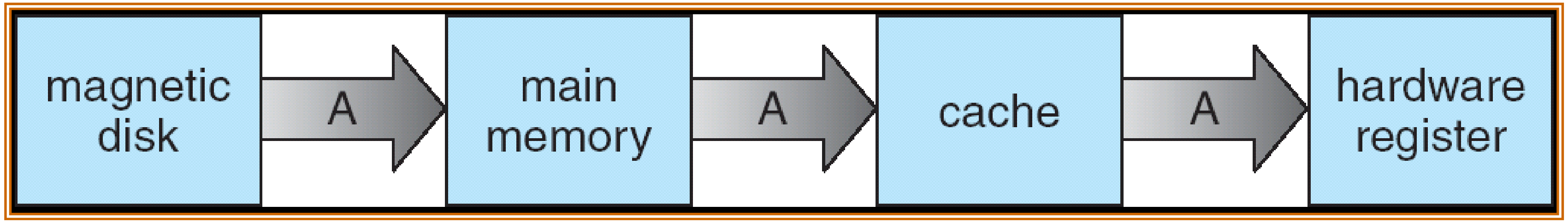
Performance of Various Levels of Storage

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	DRAM	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 (to software)

- SW-managed caching (explicit) : register, memory, disk
- HW-managed caching (implicit): cache

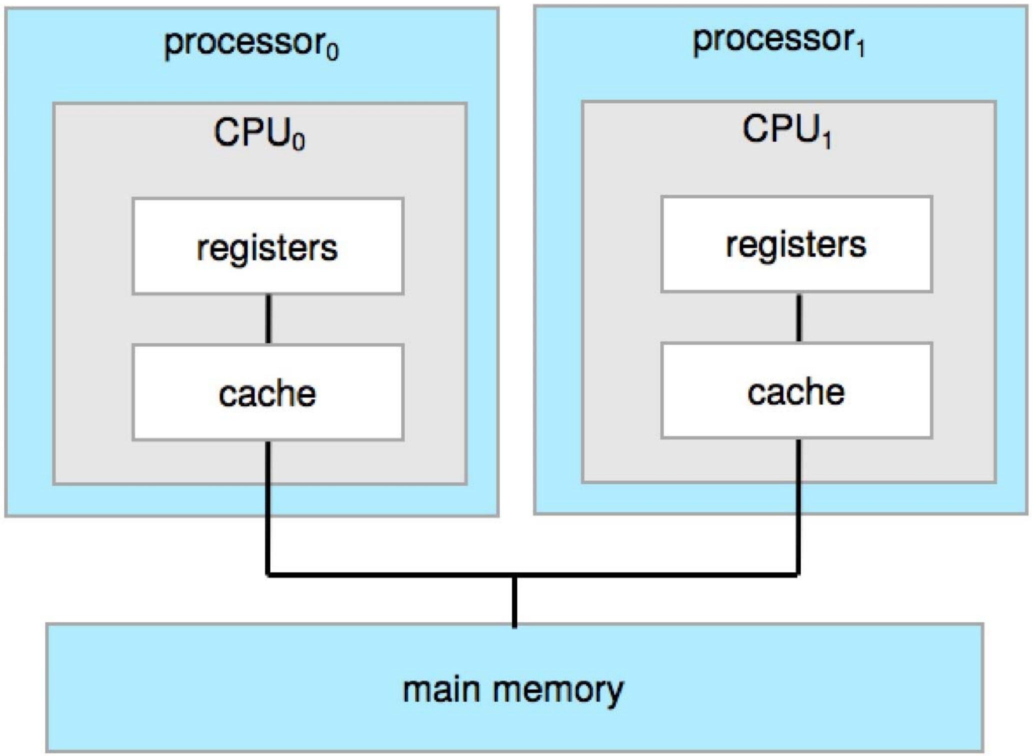
Migration of Data *A* from Disk to Register



Computer-System Architecture

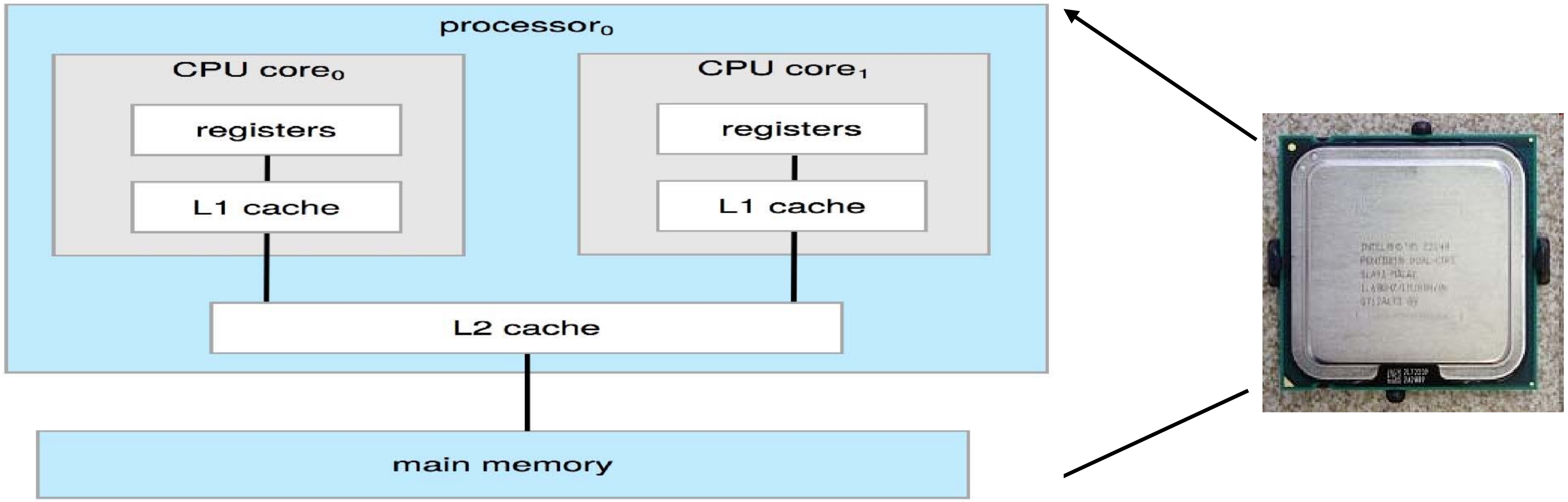
- Many systems use general-purpose processors (from PCs to mainframes)
  - Some systems have special-purpose processors as well
- Multi-processor systems growing in use and importance
  - Also known as parallel systems, tightly-coupled systems
  - Advantages
    1. Increased throughput
    2. Economy of scale
       - Multicore, cheaper than multiple single-processors
    3. Increased reliability – graceful degradation or fault tolerance
  - Types
    1. Asymmetric Multiprocessing (e.g. Qualcomm Snapdragon, MTK Helio)
    2. Symmetric Multiprocessing (e.g. Intel i7 based PC)

Symmetric Multiprocessing Architecture



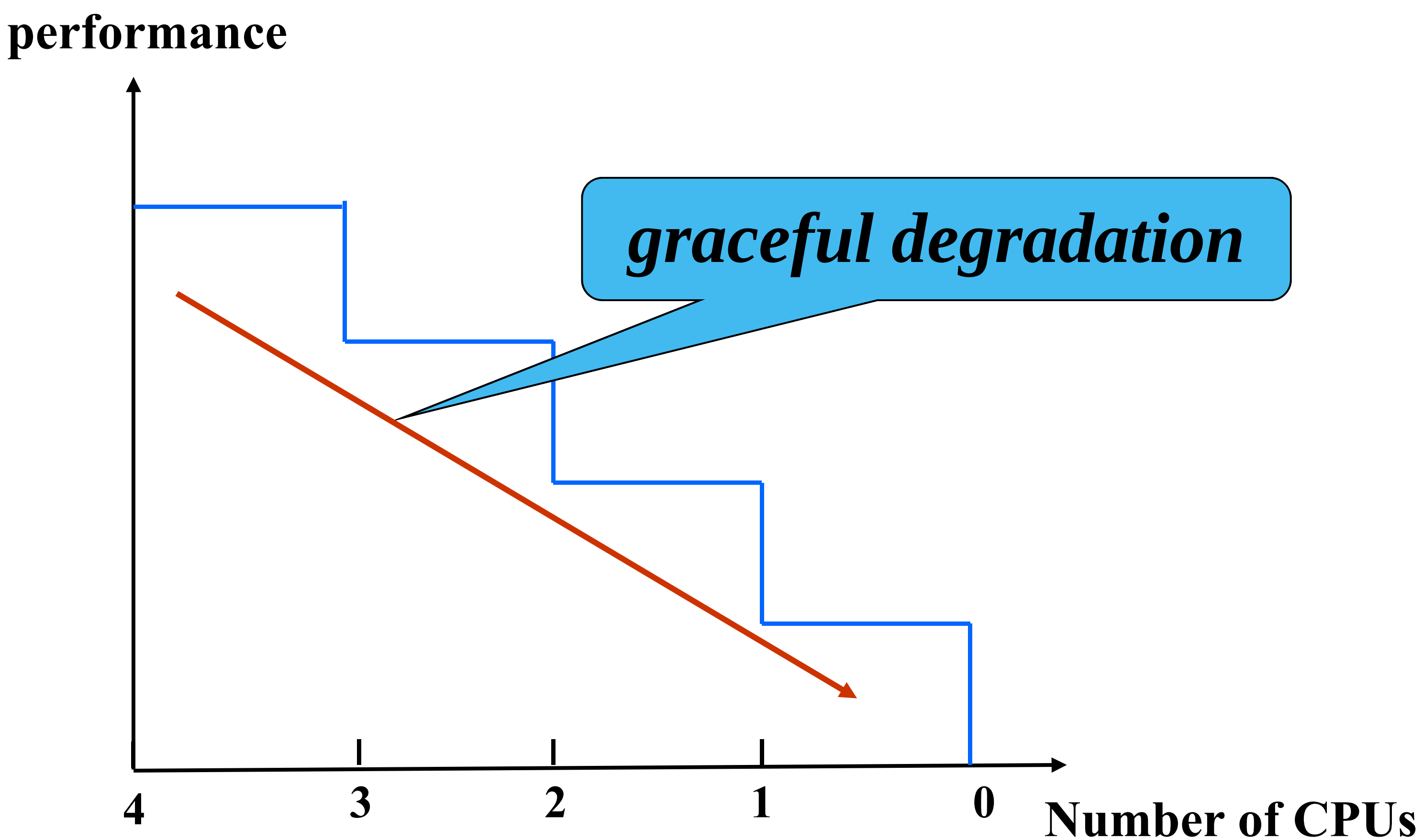
Multi-core Systems

- ***Multi-core***: multiple ***compute cores*** on a single chip
  - More efficient than multiple single-core chips
    - On-chip communication is faster than cross-chip communication



A dual-core design with two cores on the same chip

Graceful Degradation

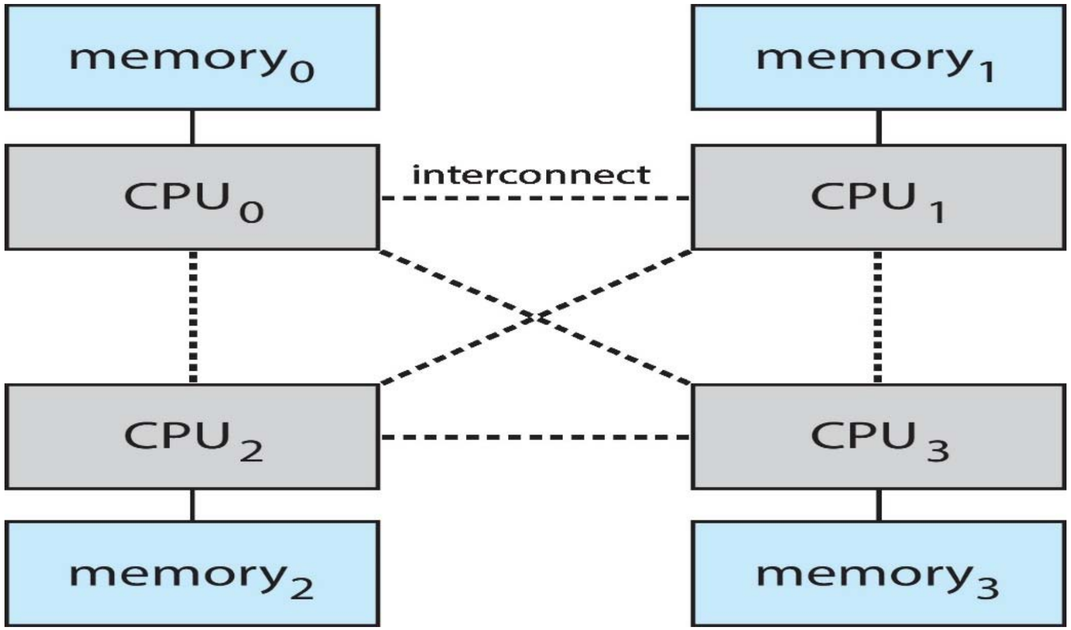


suppose a four-core system

Non-Uniform Memory Access (NUMA)

- Adding too many CPUs on multiprocessor systems will cause
  - contention for **system bus**
    - Since each CPU needs to access main memory
  - Performance begins to degrade
- Alternative approach: **NUMA**
  - Provide each CPU with its own local memory
    - Accessed via a local bus (next slide)
  - Increasing popular on servers and high-end computing systems

Non-Uniform Memory Access (NUMA)



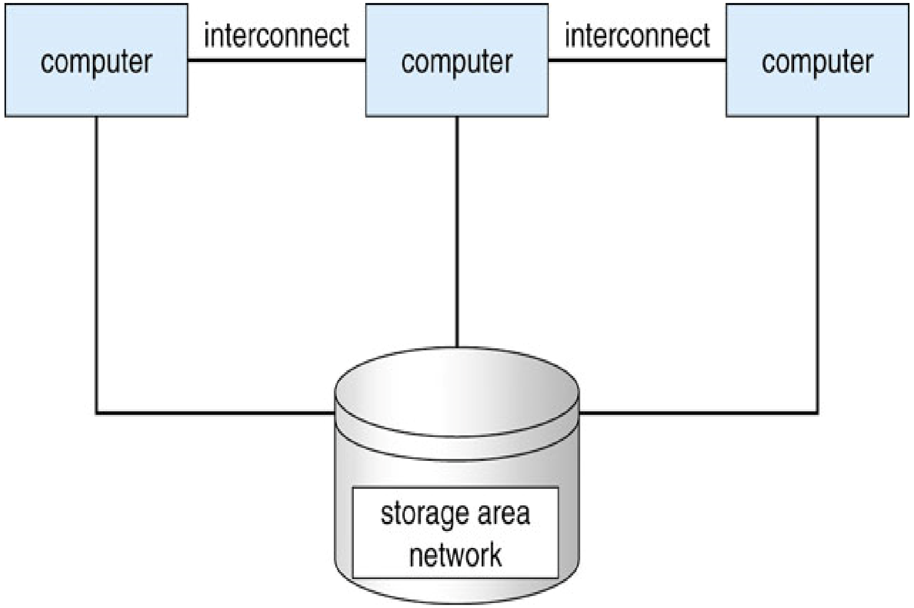
- Problem: memory access time is not the same
  - Accessing remote memory >> accessing local memory
  - OS need to manage carefully

Clustered Systems

- A ***clustered system***
  - Multiple computers that are closely linked via a *local area network (LAN)* or a *faster interconnection network*.

- The key of a clustered system is ***high availability***
  - ***Fault tolerant***: suffer a failure of any single component and continue operation
    - ***Graceful degradation***: continue providing service *proportional* to the level of surviving hardware

General Structure of a Clustered System



*Now, some clusters support **thousands** of systems as well as nodes separated by **miles***

http://www.win.tue.nl/hashclash/rogue-ca/

Clustered Systems

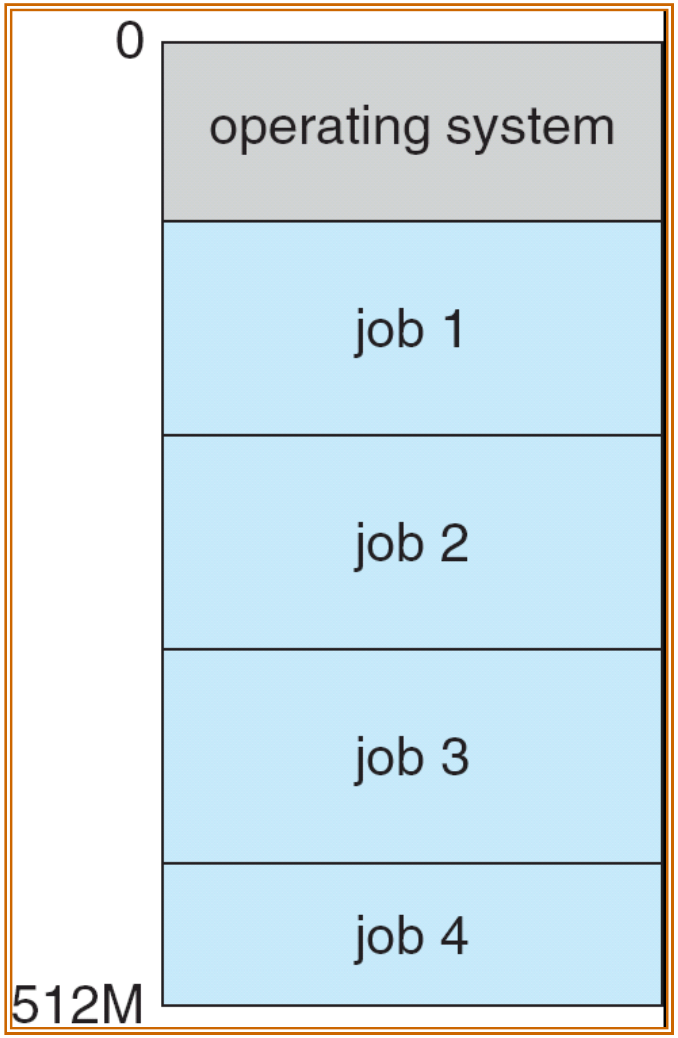
- ***Asymmetric Clustering***
  - One machine is in ***hot-standby mode*** while others are running applications.
  - The hot-standby machine (i.e., does nothing but) monitors other machines and becomes active if one server fails.

- ***Symmetric Clustering***
  - Machines run applications while monitoring each other
    - more efficient as it uses all available hardware

Multiprogramming & Timesharing

- **Multiprogramming** is needed for **efficiency**
  - a single job cannot keep CPU and I/O devices busy at all times
    - E.g., CPU idle if the job is waiting for IO
  - Multiprogramming organizes jobs (code and data) so CPU always has one to execute
    - increase CPU utilization
  - A subset of total jobs in system is kept in memory
    - When one in-memory job has to wait (for I/O for example), OS switches to another job in the memory
  - Other jobs are kept in the on-disk job pool
    - A job is selected and put in memory via **job scheduling**

Memory Layout for a Multiprogrammed System



Multiprogramming & Timesharing

- **Timesharing (multitasking)** is logical **extension** to multiprogramming 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
  - If several jobs ready to run at the same time ⇨ **CPU scheduling**
    - differences with job 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
    - Allows a program that is larger than the physical memory to run

Operating System Operations

- An OS must prevent user jobs/processes from modifying the operating system
- **Dual-mode operation** allows OS to protect itself
  - Processor provides **user mode** and **kernel mode**
    - User processes run in user mode (non-privileged mode)
    - OS runs in kernel mode (privileged mode)
    - Some instructions designated as **privileged**, only executable in kernel mode
      - E.g. I/O control, timer, special registers, interrupt related instructions…
    - a **mode bit** is provided
      - to distinguish when system is running user code or kernel code
  - A **system call** changes the mode to the **kernel mode**
    - return from the system call resets the mode to **user mode**

Transition from User to Kernel Mode

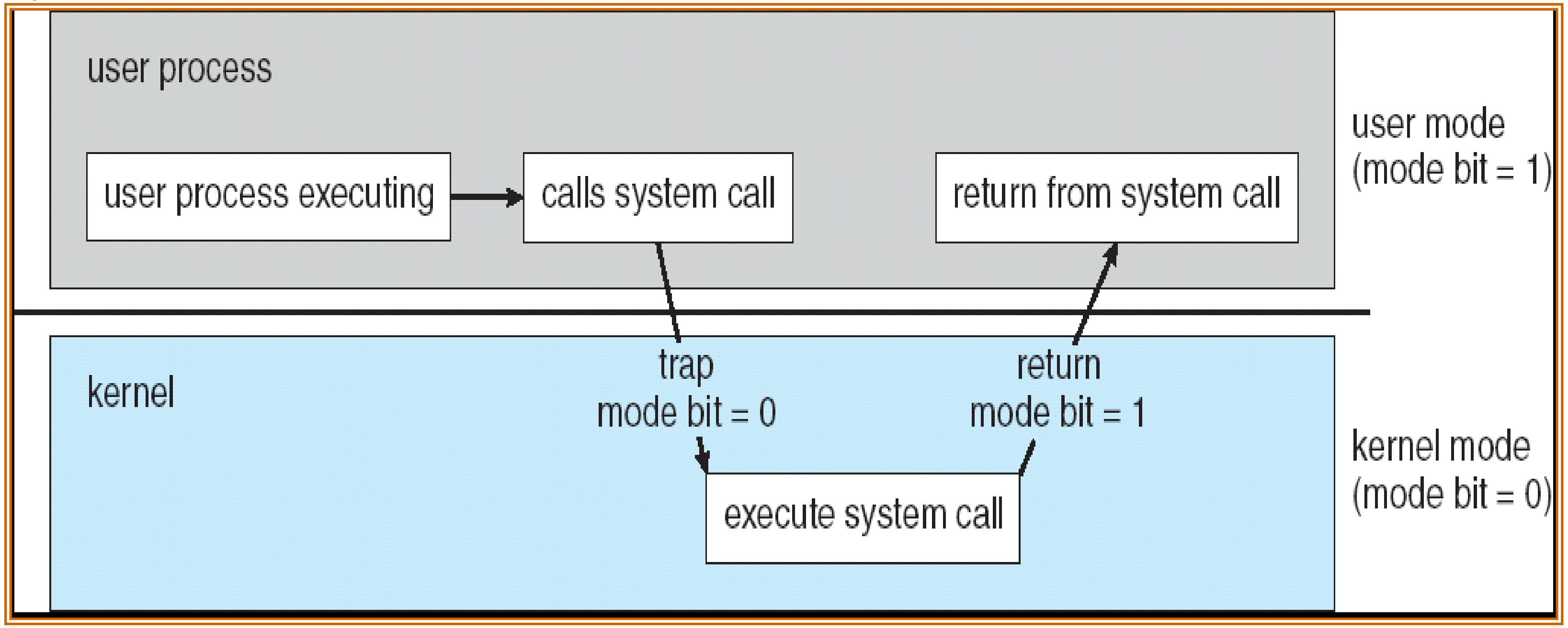
At system boot time, the HW starts in the kernel mode.

- after system initialization, the OS run applications in user mode.

When a user process needs an OS service, it issues an system call

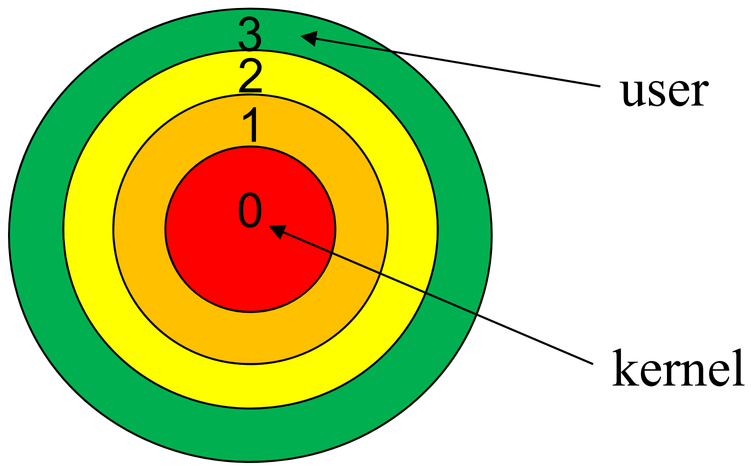
e.g., read a file, send a packet…

System call flow---



Transition from User to Kernel Mode

- Modes are provided by HW (CPU)
  - Intel's 8088 CPU has only a single mode
    - The OS (e.g., MS-DOS) can be crashed by a user program
  - Modern x86 has (more than) 4 modes/rings



Timers

- Conceptually, user processes run on top of the OS
  - ***In fact, they run on the CPU directly!!!***
- How to ensure that the OS maintains control over the CPU?
- Prevent an infinite loop in a process from hogging resources
  - By setting up a timeout period for the process
  - Done by timers
    - Operating system decrements the time count for the process periodically (whenever a **timer interrupt** is generated)
    - When the count becomes zero (i.e., the current process has used up its time period)
      - hand the CPU to another process

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
- Process termination requires reclaiming 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 program counters
  - One program counter per thread
- Typically, a system has many processes running concurrently on one or more CPUs
  - Concurrency by multiplexing the CPUs among the processes/threads

Process Management Activities

- Activities related to process management
  - Creating and deleting processes
  - Suspending and resuming processes
  - Providing mechanisms for process synchronization
  - Providing mechanisms for process communication
  - Providing mechanisms for deadlock handling

- We will discuss the above topics later

Memory Management

- Data have to be put in memory before being processed
- Instructions have to be put in memory before being executed
- Memory management determines what is in memory
  - Goal: optimizing CPU utilization and computer's response to users
- Memory management activities
  - Allocating and deallocating memory space as needed
  - 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

Storage Management

- OS provides uniform, logical view of information storage
  - – 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)
  - – Abstracts physical properties to logical storage unit - **file**
  - – OS stores files into the storage devices

Storage Management

- **File-System Management (provide file interface)**
  - File content is determined by its creator
    - Free format – e.g. text files…
    - Fixed format – e.g. executable files…
  - Files usually organized into directories
  - Access control on most systems to determine who can access what
  - OS activities include
    - Creating and deleting files and directories
    - Primitives to manipulate files and dirs
      - read/write/append files, set/get file status, set/get file permissions

Storage Management

- **Mass-Storage Management** **(focus on efficient operation)**
  - Usually, disks
  - Mass storages are used to store
    - data that do not fit in main memory, or
    - data that must be kept for a "long" period of time
  - OS activities
    - Free-space management (bitmap? free list?)
    - Storage allocation
    - Disk scheduling
  - Critical to system performance
    - Because disk is usually the performance bottleneck
    - Latency of a computer operation usually depends on disk subsystem and its algorithms

I/O Subsystem

- One purpose of OS is to hide peculiarities of hardware devices from the user
- I/O subsystem
  - Drivers
    - Manages specific hardware devices
    - In an OS, only drivers are device-specific
      - Have knowledge about its own device
    - OS provides a general driver interface to allow easy cooperation of OS and its drivers
  - 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)

- Description here is also valid for storage devices
  - Disks are IO devices

Protection and Security

- **Protection –** mechanisms for controlling access (of processes or users) to resources
  - Distinguish between authorized and unauthorized usage

- **Security –** defense of the system against internal and external attacks
  - Huge range, including denial-of-service, viruses…

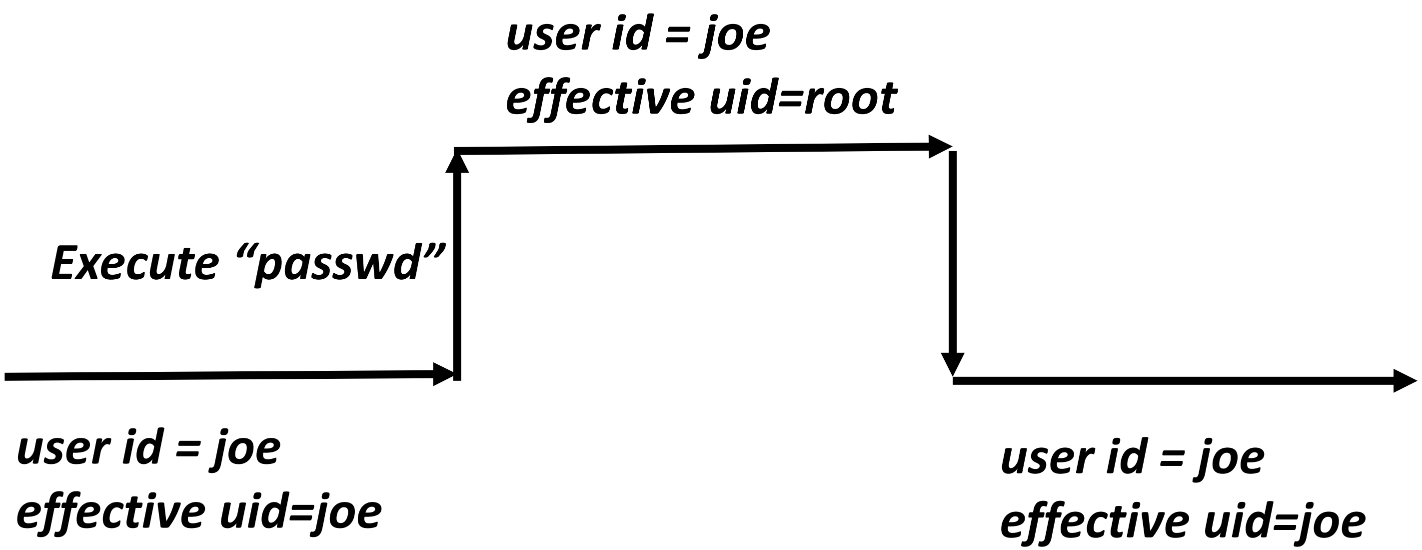
Protection and Security

- Systems generally first distinguish among users, to determine who can do what
  - Each user has a user identifier (**user ID**)
  - User IDs are associated with all files & processes to determine access control
    - Process owners and file owners are all users…
  - Group identifier (**group ID**) allows set of users to be defined and managed, also associated with each process or file

  - **Privilege escalation** allows user to change to effective ID with more rights *temporarily*
    - Setuid in UNIX **(see next slide)**
      - Causes a program to run with a user ID of the file owner, rather than the user's ID
        - » E.g., change your own password, which requires the root privilege to update the password file.
    - Might become a vulnerability if the program is attacked…

Setuid in Linux

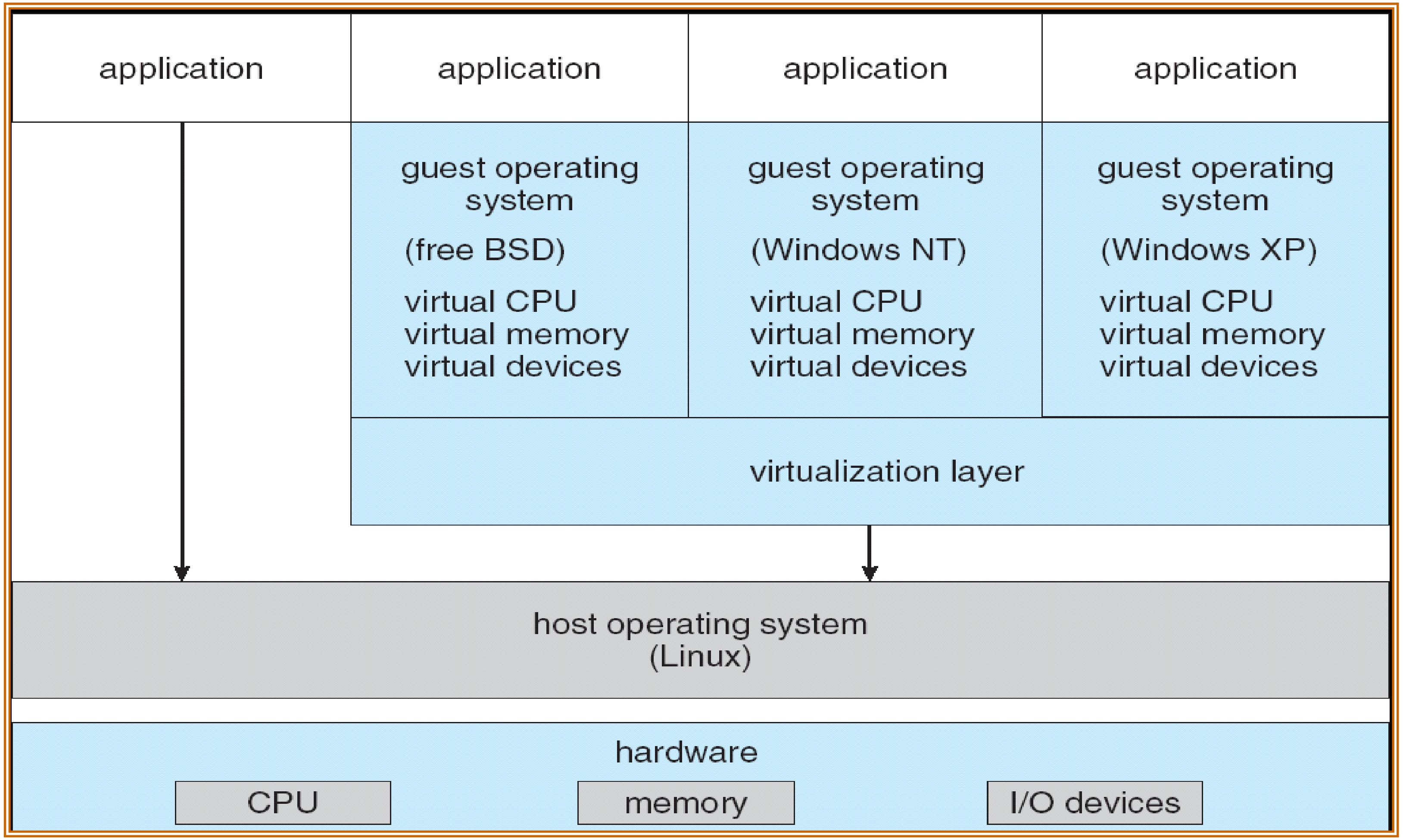
```
cissoll> ls -al passwd
-r-sr-sr-x 1 root sys 27228 Aug 17  2007 passwd*
cissoll>
```



Virtualization

- **Virtualization**
  - Abstract **the hardware of a single computer** into several different execution environments
  - Create an illusion that each environment is running on its own private computer
    - An OS can be run in each environment
  - Allows OSes to run on other OSes

Virtualization



host operating system vs. guest operating system

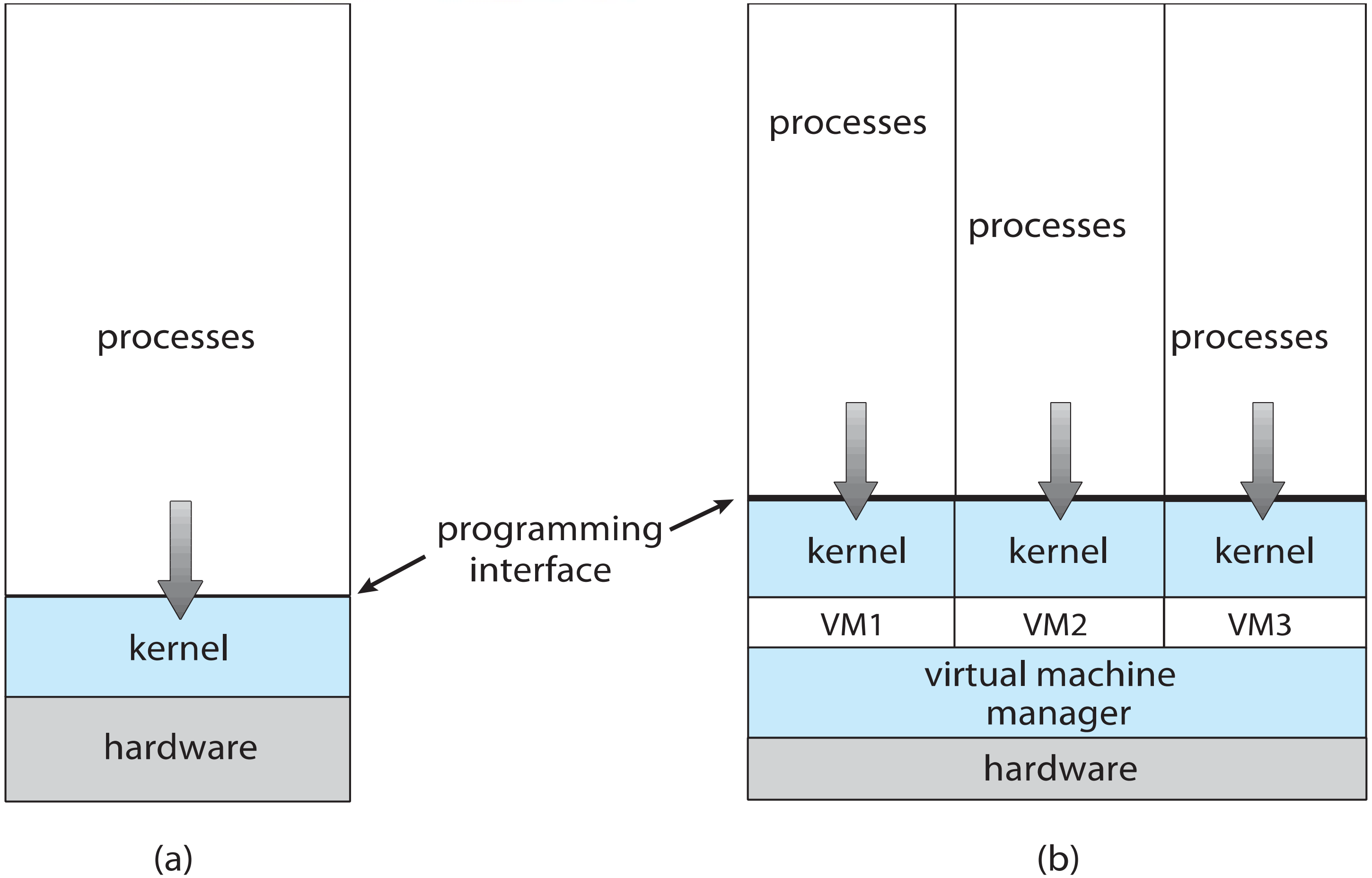
Virtualization

- **Emulation** –
  - Simulating computer hardware in software
    - Used when source CPU type **different** from target type
  - For Example
    - We want to run the PowerPC applications on the Intel x86
    - Every instruction of PowerPC must be **translated** to the instructions on Intel x86
  - Slow…

Virtualization (Cont.)

- **Virtualization** –
  - An OS natively compiled for a CPU, running on another OS also natively compiled to **that CPU**
  - Example
    - Run Linux for x86 on the Windows 10 (also for x86)
    - Linux: **guest OS**
    - Window7: **host OS**
  - **VMM (Virtual Machine Manager)** provides virtualization services
    - Also called **Hypervisor**
  - VMM can also run **natively** without the host OS
    - Example: VMware ESX and Citrix XenServer

VMM without Host OS



Without virtualization

With virtualization

VMM directly runs on hardware (do not need host OS)

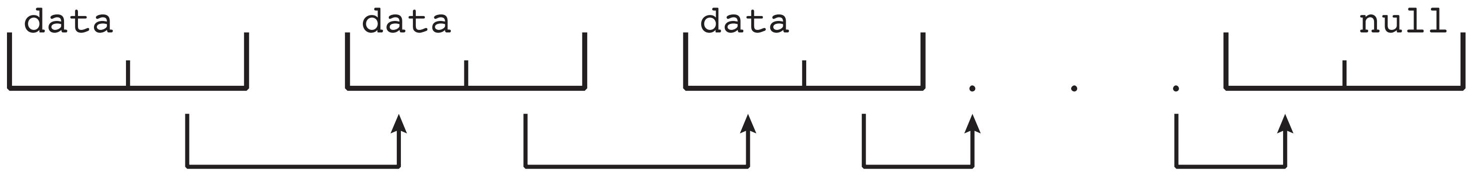
Kernel Data Structures

- Lists, Stacks, and Queues
- Trees
- Hash Tables

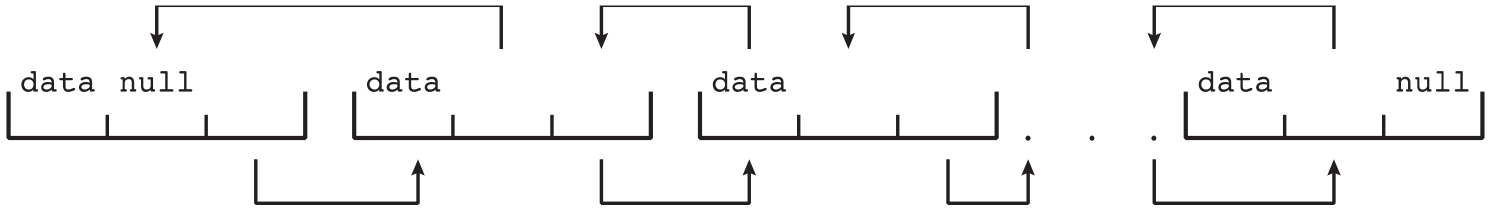
- Linux data structures defined in ***include*** files
  - e.g., `<linux/list.h>, <linux/kfifo.h>, <linux/rbtree.h>`

List

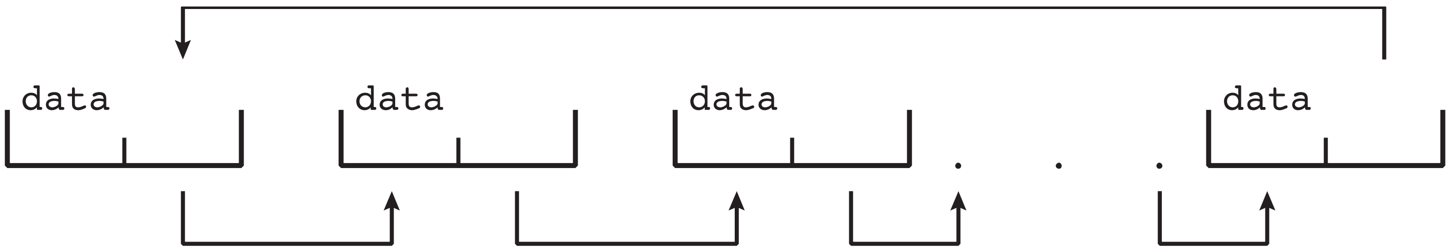
- ***Singly linked list***



- ***Doubly linked list***



- ***Circular linked list***



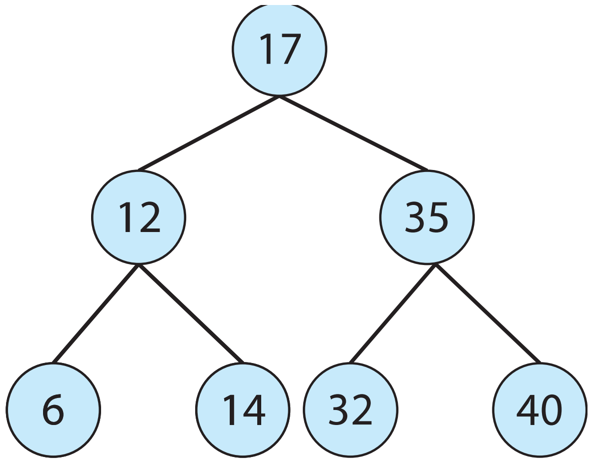
Stack and Queue

- **Stack**: last in, first out (LIFO)
  - Insert an item**: push**
  - Remove an item: **pop**

- **Queue**: first in, first out (FIFO)

Tree

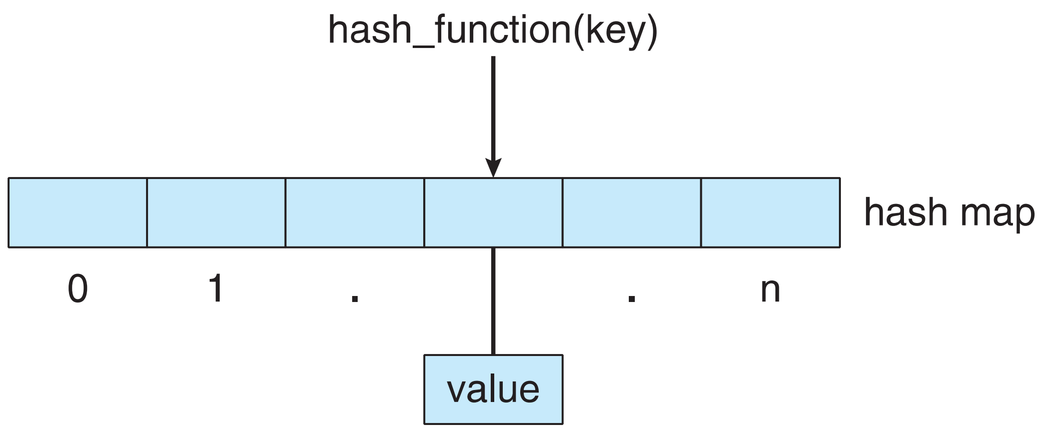
- **General tree**
  - **A parent may have an unlimited number of children**
- **Binary tree**
  - **A parent may have at most two children**
- **Binary search tree**
  - Two children, left <= right
  - Search performance is *O(n)*
  - **Balanced binary search tree**
    - Search performance is *O(lg n)*



Binary search tree

Hashing and Bitmap

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



- **Bitmap** – string of *n* binary digits representing the status of *n* items

Computing Environments

- Traditional Computing
- Mobile Computing
- Client-Server Computing
- Peer-to-Peer Computing
- Cloud Computing
- Real-Time Embedded Systems

Computing Environments

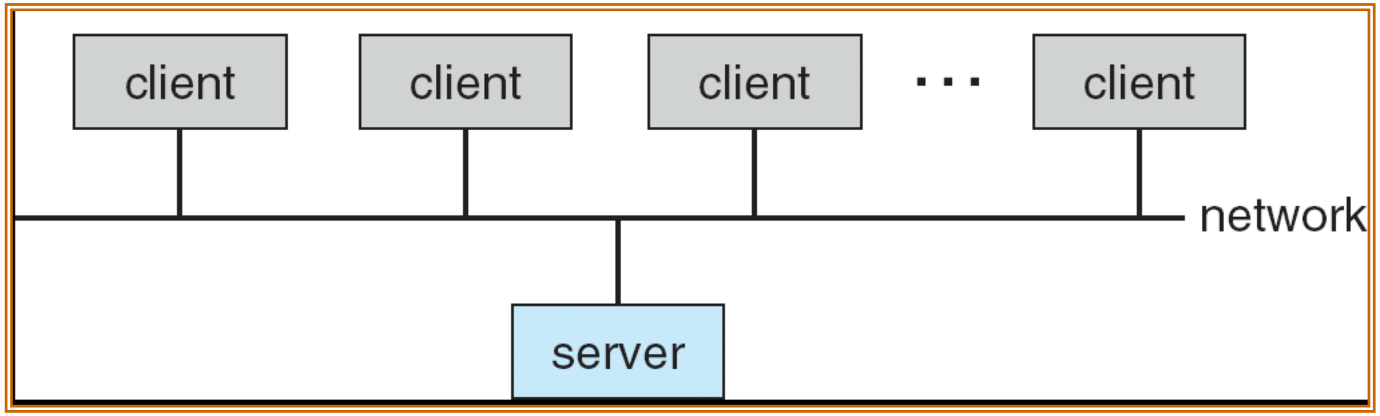
- Traditional Computing
  - Office environment
    - PCs connected to a network, terminals attached to mainframe or minicomputers providing batch and timesharing functionalities
    - Now portals allowing remote systems to access internal resources
  - Home networks
    - Used to be single system, then modems
    - Now firewalled, networked

Mobile Computing

- Computing on **handheld devices**
  - Smartphones
  - Tablets
- Issues
  - Limited memory
  - Slower processors
  - I/O constraints: small display screens, small keyboards…..
  - Limited power
- Extra features
  - GPS, accelerometers, and gyroscope
- Leaders are **Apple iOS** and **Google Android**

Client-Server Computing

- **Servers**: serving requests, **Clients**: issuing requests
  - **Application-server** provides an interface to client to request services
  - **File-server** provides interface for clients to store and retrieve files
- For clients, dumb terminals are replaced by smart PCs/phones



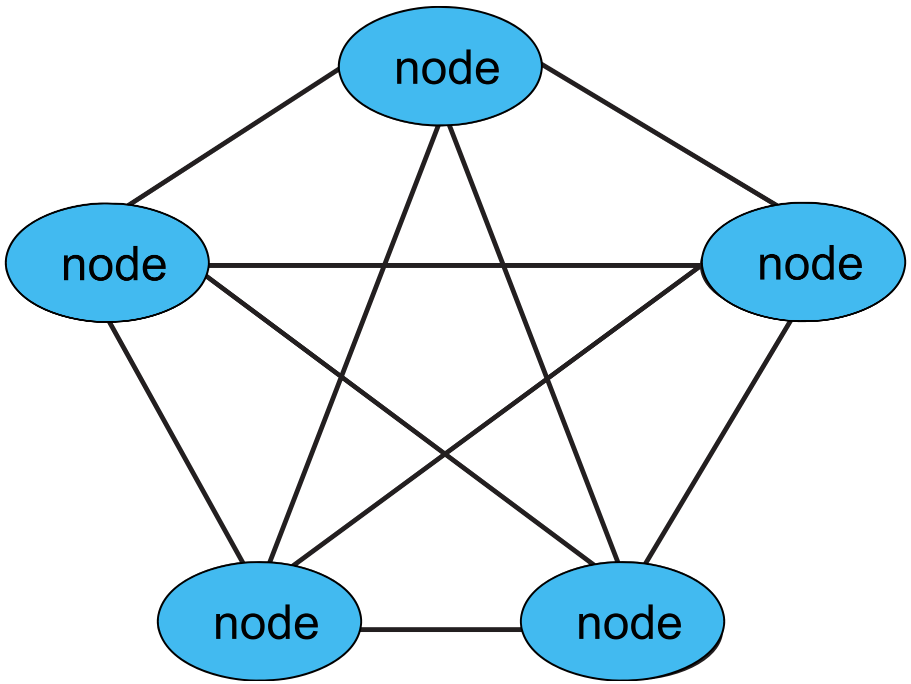
Peer-to-Peer Computing

- 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

- Advantage
  - In client-server system, the server may become a bottleneck. In P2P, services can by provided by several nodes
- Example
  - skype

Peer-to-Peer Computing

- Node must join P2P network
  - Registers its service(s) with central lookup service on network, or
  - Broadcast requests for services and respond to requests for services via ***discovery protocol***



Cloud Computing

- Delivers computing, storage, even apps as a service across a network

- Logical extension of **virtualization** (see next slide)
  - Typically based on virtualization
  - Amazon **EC2** has thousands of servers, millions of **VM**s, PBs of storage available across the Internet, pay based on usage

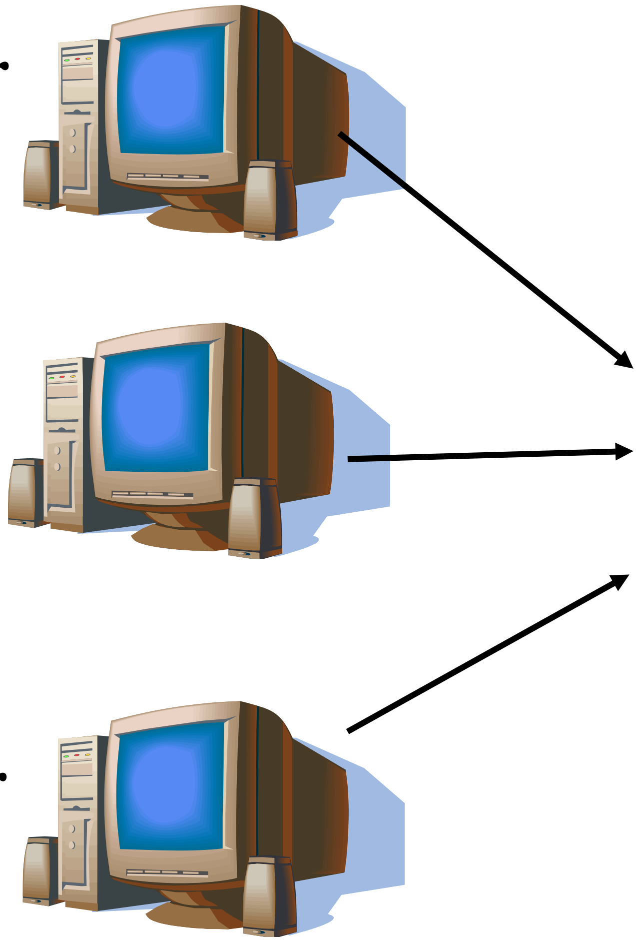
- Different types
  - **Public cloud** – available via Internet to anyone willing to pay
  - **Private cloud** – run by a company for the company's own use
  - **Hybrid cloud** – includes both public and private cloud components

Logical Extension of Virtualization

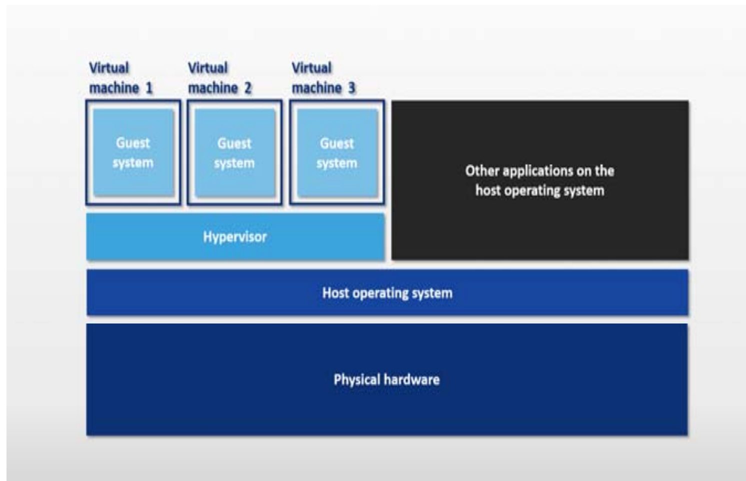
WWW Server
Solaris

File Server
Win10

Database Server
Linux



WWW + File + Database
Servers

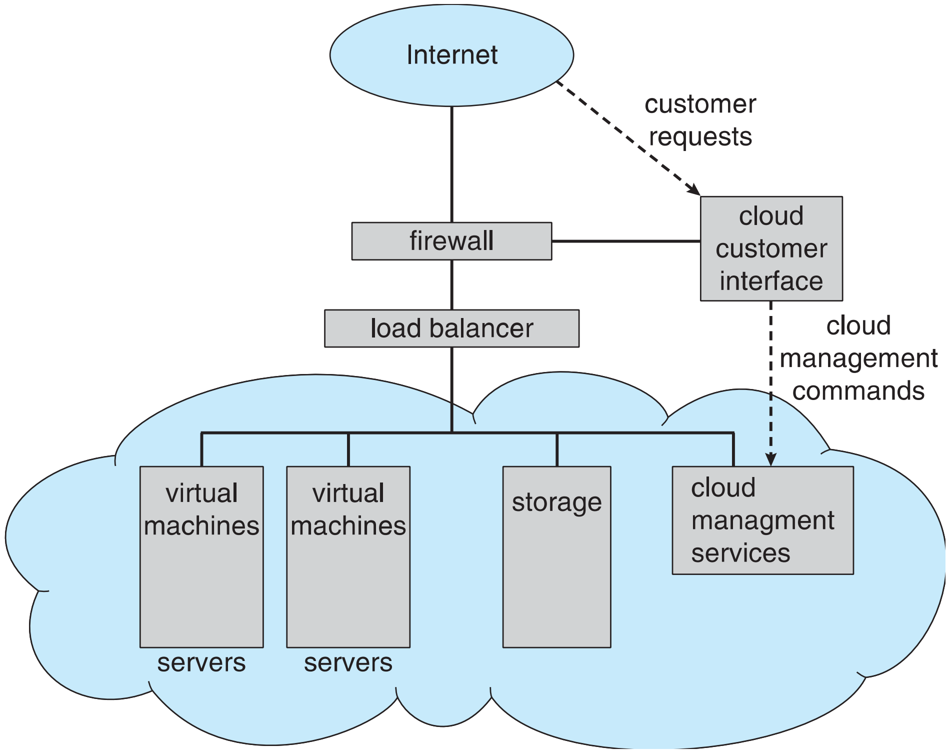


Cloud Computing

- Categories
  - **Software as a Service (SaaS)** –
    - one or more applications available via cloud (e.g., word processor)
  - **Platform as a Service (PaaS)** –
    - software stack ready for application use via cloud (e.g., a database server)
  - **Infrastructure as a Service (IaaS)** –
    - servers or storage available via cloud (e.g., storage available for backup use)

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



Real-Time Embedded Systems

- Embedded computers
  - Most prevalent form of computers
    - Cars, routers, robots, printers,…
  - Tend to have very **specific** tasks
- Different OS implementation schemes
  - No OS
  - A tiny embedded OS
  - A standard OS (e.g., Linux)

Real-Time Embedded Systems

- Embedded systems sometimes run ***real-time operating systems***
  - Processing must be done within a predefined time constraint (i.e., **deadlines**)
  - Otherwise, the system will fail
    - e.g., missile systems

Open-Source Operating Systems

- Many operating systems are open source
  - e.g., Linux, FreeBSD, OpenSolaris, Illumos,…