Chapter 2: System Structures

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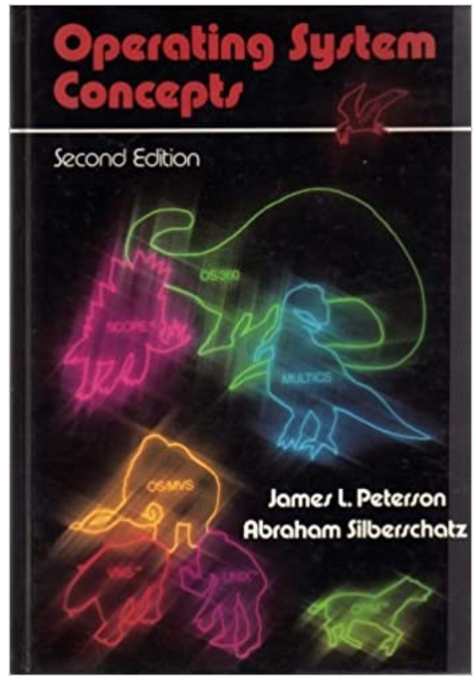


Objectives

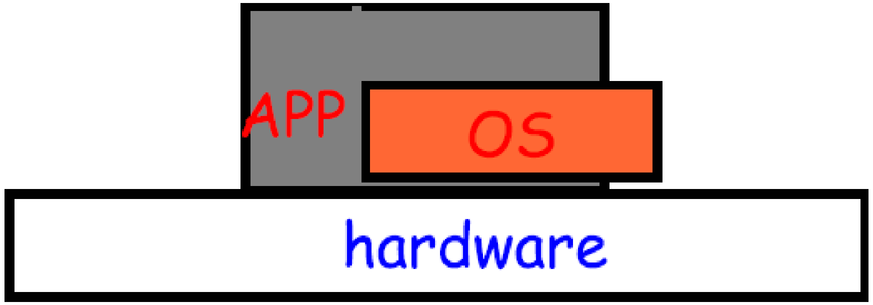
- To discuss the concepts of multitasking, interrupt, protection, system calls, and caching
- To discuss the various ways of structuring an operating system

Chapter 2: System Structures

- **Basic Operations**
  - Multitasking (Ch. 1.4)
  - Interrupt (Ch. 1.2)
  - Protection
    - Dual-mode operation (Ch. 1.4.2)
    - Types of System Calls
  - Cache Management (Ch. 1.5.5)
- Operating System Structure & Data Structures

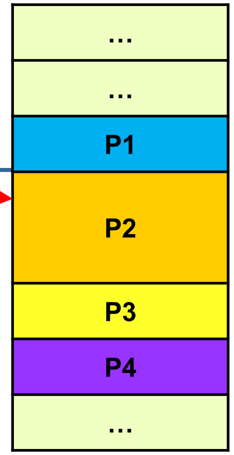
Primitive Operating Systems

- Just a library of standard services [no protection]

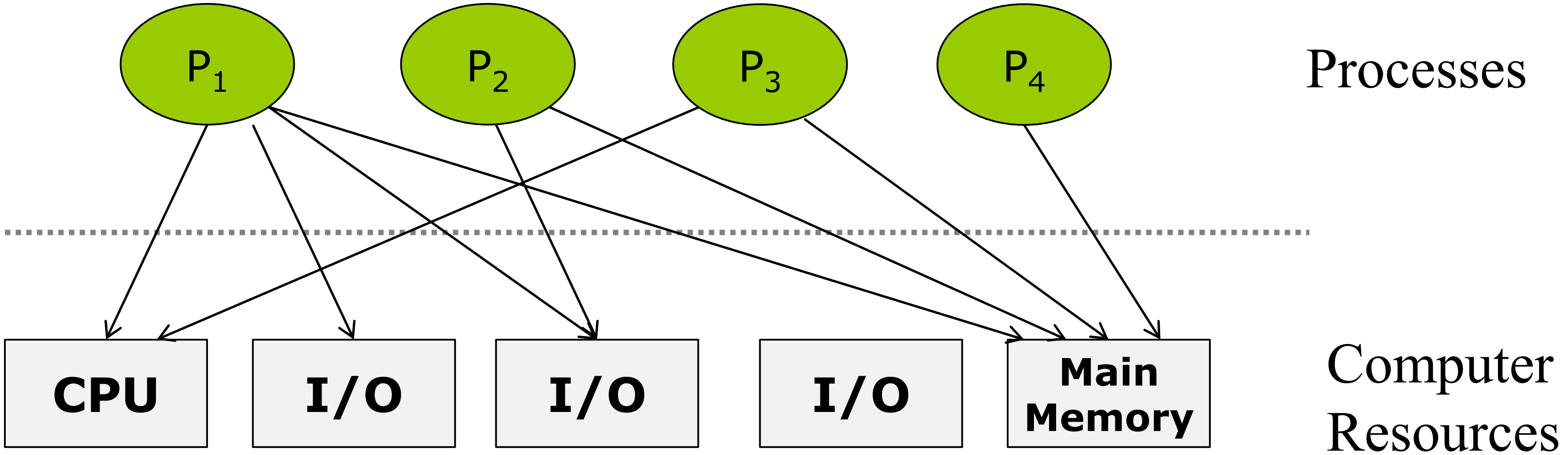


  - Standard interface above hardware-specific drivers, etc.
- Simplifying assumptions
  - System runs one program at a time
- **Problem: Poor utilization**
  - . . . of hardware (e.g., CPU idle while waiting for disk)
  - . . . of human user (must wait for each program to finish)

Multitasking (Ch. 1.4)



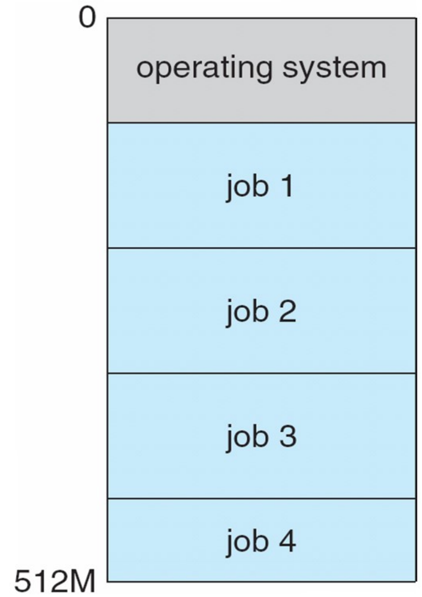
- Several jobs are kept in main memory at the same time, and these processes share the CPU time, I/O devices and other resources.

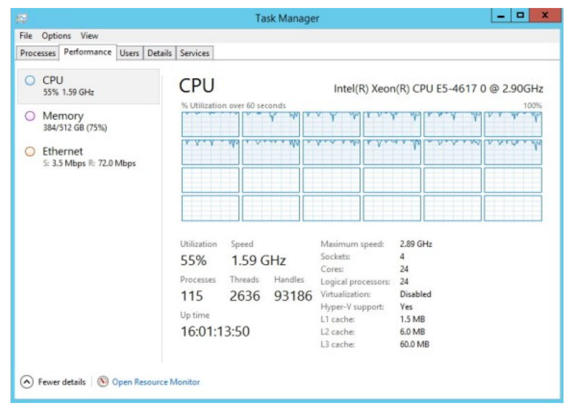


- Managing and controlling several processes simultaneously are challenging for ________

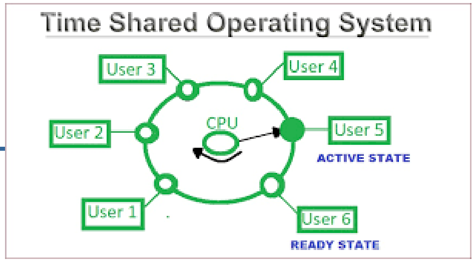
Multitasking

- **Multitasking** (=Multiprogramming, Multiprocessing) needed for efficiency
  - Users frequently have **multiple processes** loaded on **Main memory**
  - Single process *cannot* keep **CPU** and **I/O devices** busy at all times
- Adavantage1: **CPU utilization**
  - Keep several processes (=job, task) in memory simultaneously
  - One process selected and run via **scheduling**
  - When it has to wait (e.g., for I/O operation), OS **switches** to another process
  - As long as at least one process needs to execute, the CPU never stays idle
  - What happens if it is not switched?
    - Hint: Waste CPU cycles (why?)



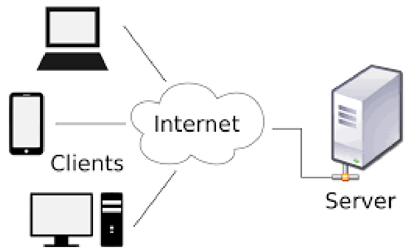


Multitasking

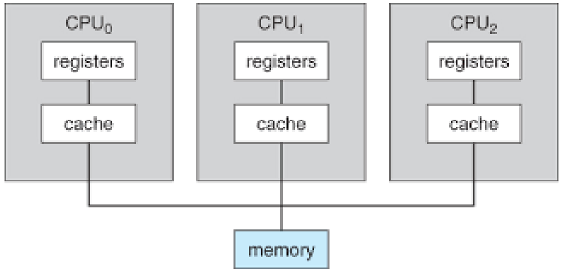


- Advantage 2: **Timesharing** (of **CPU** resource)
  - A logical extension in which CPU switches jobs so **frequently** that that the user have an **illusion of multitasking**
  - Allows many users to share the computer simultaneously
  - If several jobs ready to run at the same time, which process do we run first? ⇨ **CPU Job scheduling** (Ch. 5)

https://giphy.com/



- c.f., Multiprocessing vs. Multiprocessor (멀티프로세서)
  - Multiprocessor: Using **multiple CPUs** on a single computer



Challenging Issues of Multitasking

- At any given time, each resource (e.g., CPU core) can serve only one process
- Multiple processes can be executed while sharing memory
- Using I/O device takes a long time, and CPU is idle and underutilized
- An unauthorized process causes a system fault although other processes have no problem

What does an OS do? (Ch. 1.5)

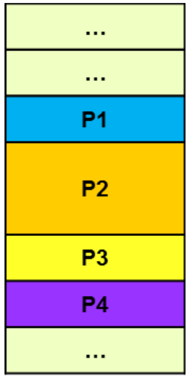
- At any given time, each resource (e.g. CPU) can serve only one process
  - OS → Process Management
- Multiple processes can be executed while sharing memory
  - OS → Memory Management
- Using I/O device takes a long time, and CPU is idle and underutilized
  - OS → I/O Management
- An unauthorized process causes a system fault although other processes have no problem
  - OS → Protection

Process Management (Ch. 1.5.1)

- A ***Process*** *:* a program in memory
  - A process needs certain resources, including CPU time, memory space, files, and I/O devices, to accomplish its task
- OS Functionality (Ch. 3-7)
  - Create/run/terminate processes/threads (Ch. 3-4)
  - Who goes first? CPU scheduling (Ch. 5)
  - Mechanisms for resource sharing and synchronization (Ch. 6-8)

Memory Management (Ch. 1.5.2)

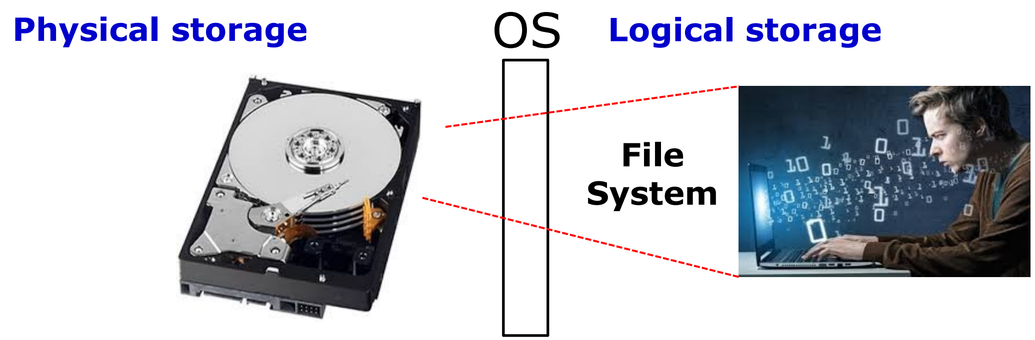
- Main memory (RAM)
  - A large array of bytes, each byte with its own address
  - CPU reads both **instructions** and **data** from main memory – it must first be loaded to main memory
- **Multitasking**
  - Multiple processes (= tasks, jobs) **<u>in main memory</u>**
  - Improves utilization of CPU and response to its users



- **Memory management** (Ch. 9-10)
  - Keeping track of which parts of memory are currently being used and by whom
  - Deciding which processes and data to move into and out of memory
  - Allocating and deallocating memory space as needed

File & Storage Management (Ch. 1.5.3-4)

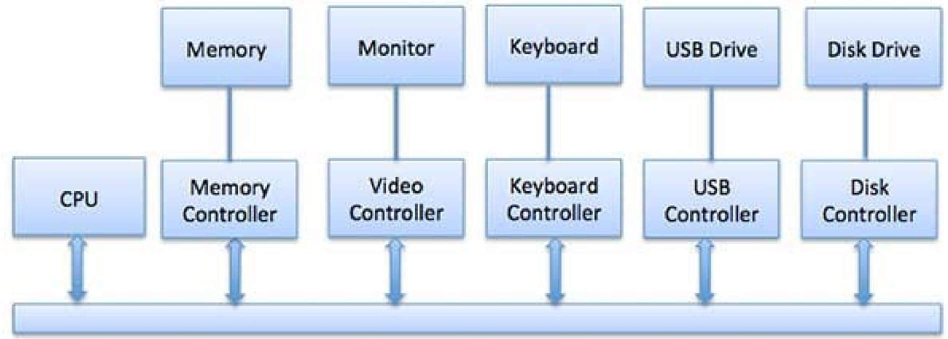
- OS provides uniform, logical view of storage
  - Abstracts physical storage (**disk**) to logical storage (**file**)



- OS Functionality
  - *File-system management* (Ch. 13-15)
  - *Mass-storage (disk) management* (Ch. 11)

I/O Subsystem (Ch. 1.2.3)

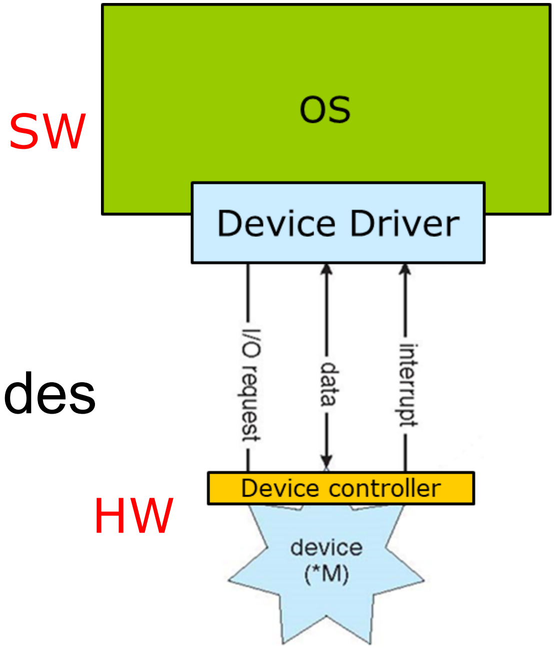
- **I/O Devices**
  - mouse, keyboards, touch pad, disk drives, display adapters, USB devices, network connections, audio I/O, printers
  - connected by system **bus**
  - There is always a **device driver** and **device controller** for each I/O device



I/O Subsystem

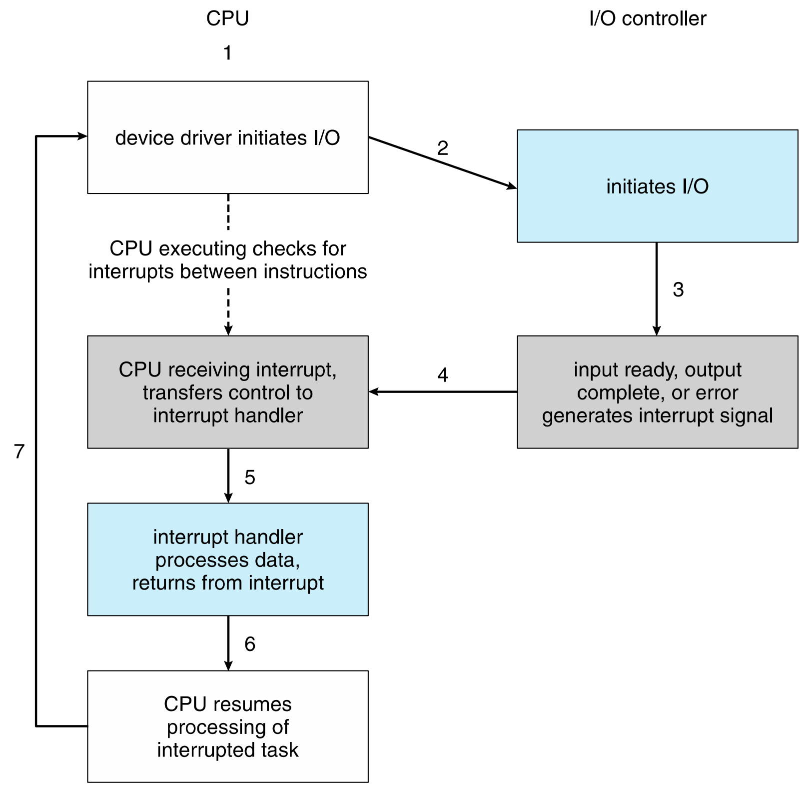
- **Device controller** (in I/O Device – HW or SW?)
  - In charge of one or more specific type of device (e.g., disk, USB, network controller).
  - Think of controller as a small CPU for a device
  - Move the data between the I/O devices and its **local buffer** (small memory in I/O device)

- **Device driver** (in OS – HW or SW?))
  - A device driver for each device controller
  - A program that understands the controller and provides OS with an interface to device controller.



I/O Subsystem contd.

- I/O Operation
  ① **I/O request** from application (e.g., read file from disk): device driver delivers command to device controller
  ② controller determines which action to take
    - e.g., "read block#369 from hard disk"
  ③ **device controller** takes action
    - e.g., read block from disk, and transfer data from the device to memory
  ④ device controller informs the CPU via an **interrupt** that it has finished
  ⑤ OS takes control and **handles** interrupt



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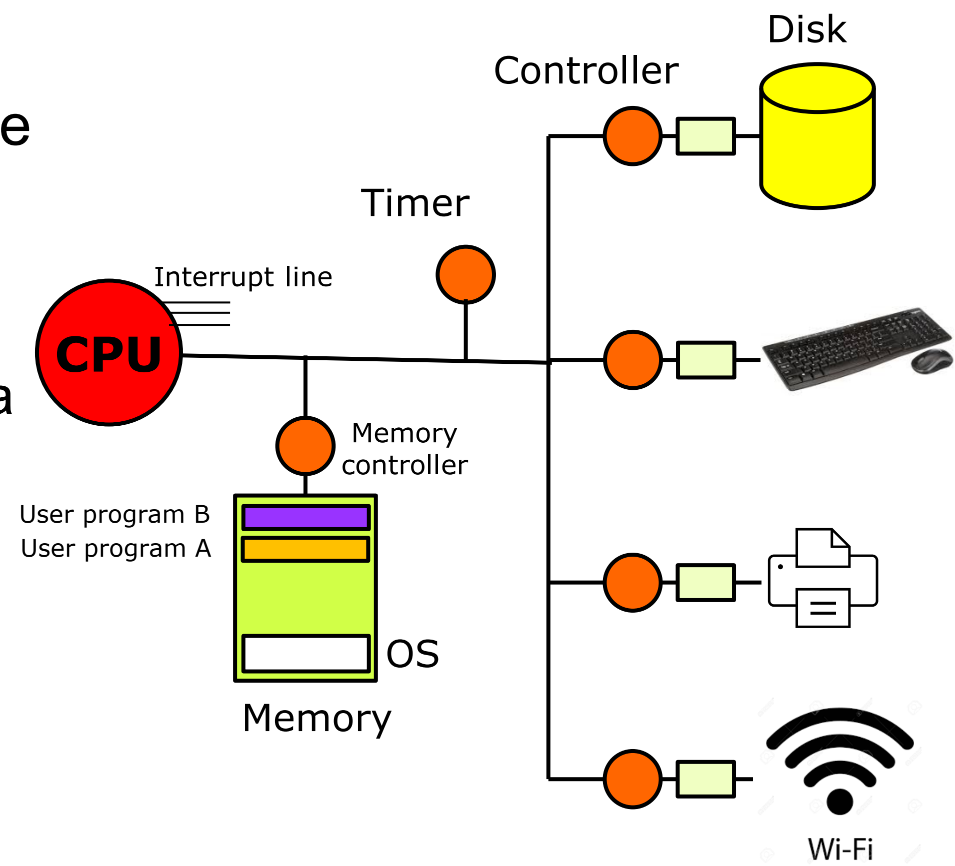

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  - Multitasking (Ch. 1.4)
  - Interrupt (Ch. 1.2.1)
  - Protection
    - Dual-mode operation (Ch. 1.4.2)
    - Types of System Calls
  - Cache Management (Ch. 1.5.5)
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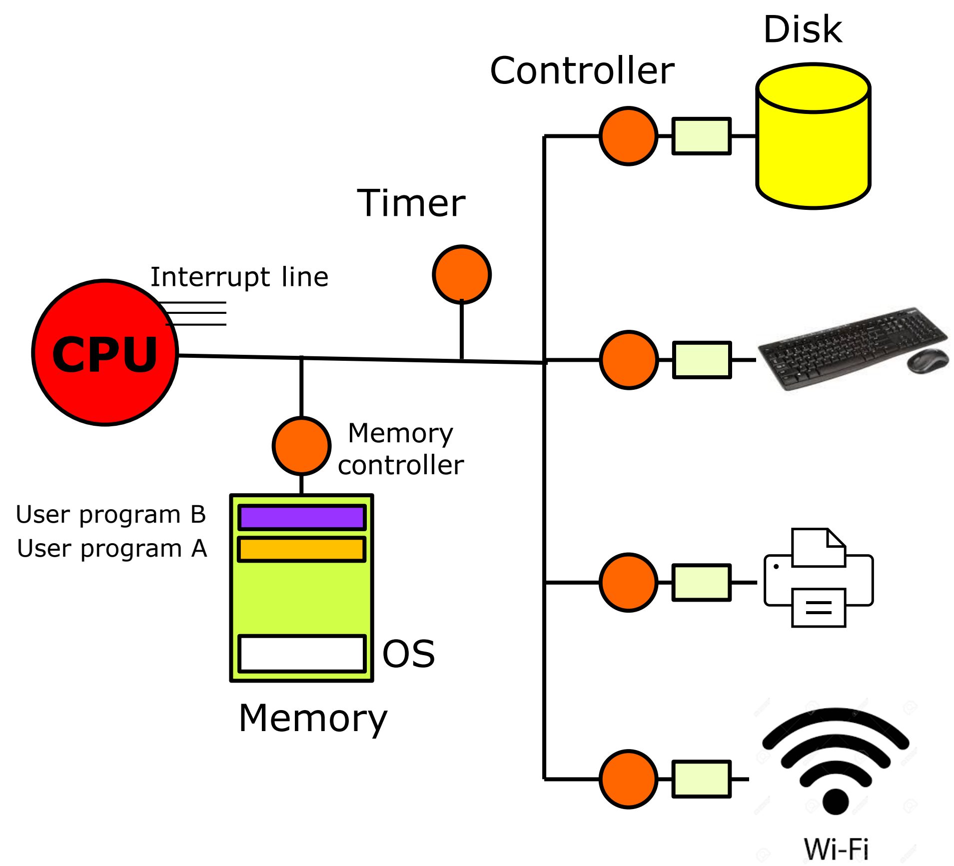
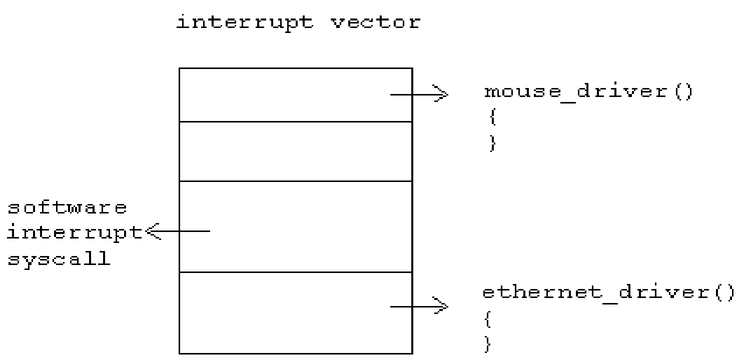
Interrupt (Ch. 1.2.1)

- Question:
  - Device controller needs to inform CPU that device has finished its operation
    - e.g., I/O request (read file from disk) → disk controller finished reading file
  - How? Through **Interrupt!**
- The CPU runs an instruction – after each instruction it checks if the interrupt line is set!
- If an interrupt occurs:
  - An Interrupt line is set
  - The CPU will **stop** anything it is doing and it will jump to an ***interrupt handler***.



Interrupt Handler

- When the CPU is interrupted, the CPU
  - transfer execution to **interrupt vector**
    - The interrupt vector has the **addresses** of the **service routine** for each type of interrupt
  - execute **interrupt service routine**
    - e.g., mouse driver, network driver
  - on completion of the service routine, the **CPU** resumes the previously executed computation (which was interrupted)



Vector of pointers to function with all interrupt drivers.
CPU knows where to jump to.

Interrupt

- An operating system is **interrupt driven**
  - **Interrupt** is a key part of OS-hardware interaction
- **Hardware and Software Interrupt**
  - **Hardware Interrupt**: **Hardware I/O devices** interrupt CPU
    - Hardware may trigger an interrupt at any time by sending a signal to CPU
    - Disk operation completed, mouse movement, keyboard type, Internet data packet, disk/CD/Tape driver, timer interrupts (used for scheduling multiple processes), sound (microphone)
  - **Software Interrupt** (= **traps**): **Software programs** interrupt CPU
    - **system calls**: application programs uses to call kernel functions
    - **exceptions**: divide by zero exception

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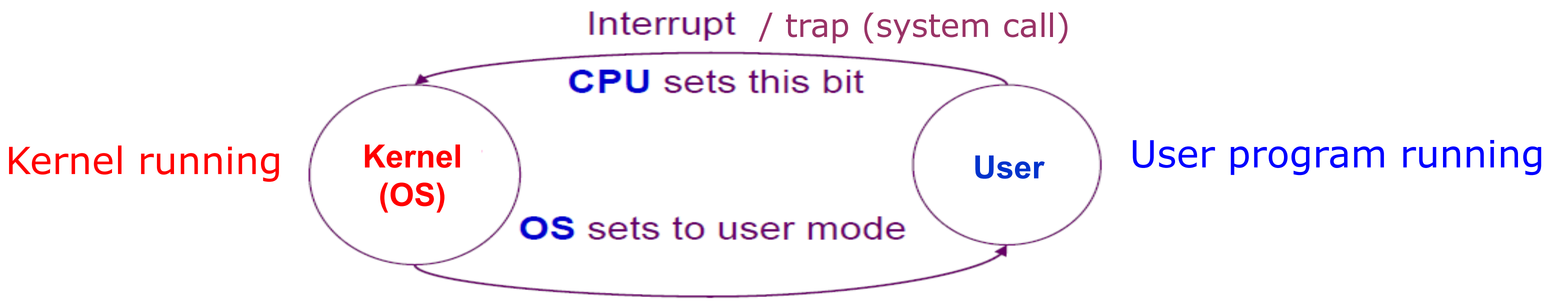
Dual-Mode Operation (Ch. 1.4.2)

- **Motivation**
  - OS and users share hardware/software of computer system
  - Malicious program should not harm other programs (including OS)
  - Should distinguish between OS code and user code

- **Dual-mode operation**
  - **Kernel mode** (=**supervisor, system, privileged mode**) vs. **User mode**
  - **Mode bit** provided by **hardware support** (e.g., CPU)
    - kernel(0) or user(1)

Dual-Mode Operation

- CPU ***Mode bit*** added to computer hardware to indicate the current mode: **kernel (0)** or **user (1)**.



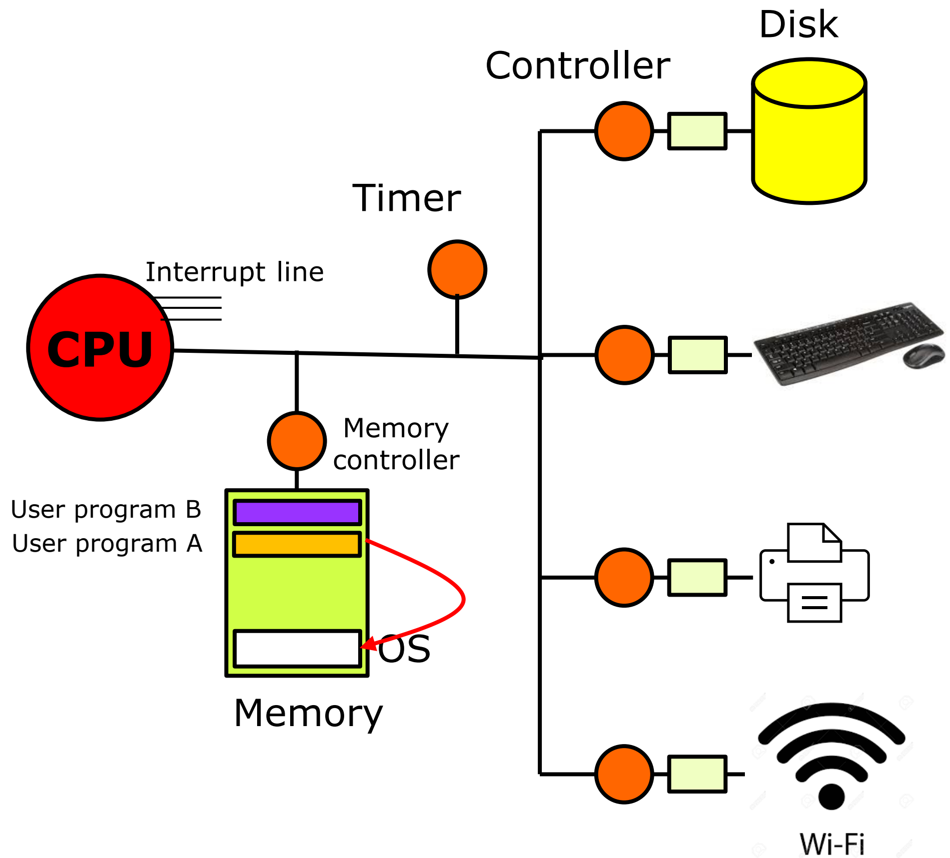
- Life cycle of instruction
  - OS running (kernel mode)
  - User programs running (user mode)
- Example
  - System boot time (_____ mode)
  - Starts user application (______ mode)
  - Hardware interrupt occurs (_____ mode)

Dual-Mode Operation

- Privileged instructions only executable in kernel mode (not in user mode)
  - **Privileged instructions:** Instructions that only OS can execute
    - e.g., request I/O hardware, file transfer etc.
- What happens if a user program tries to execute a privileged instruction?
  - Illegal operation! Software interrupt (trap) occurs.
  - Hardware *traps* to the operating system – terminate program abnormally and give error message
- But what if a user program wants to use the hardware? (e.g., send I/O request to read file)
  - Ask politely to OS – **System Calls**

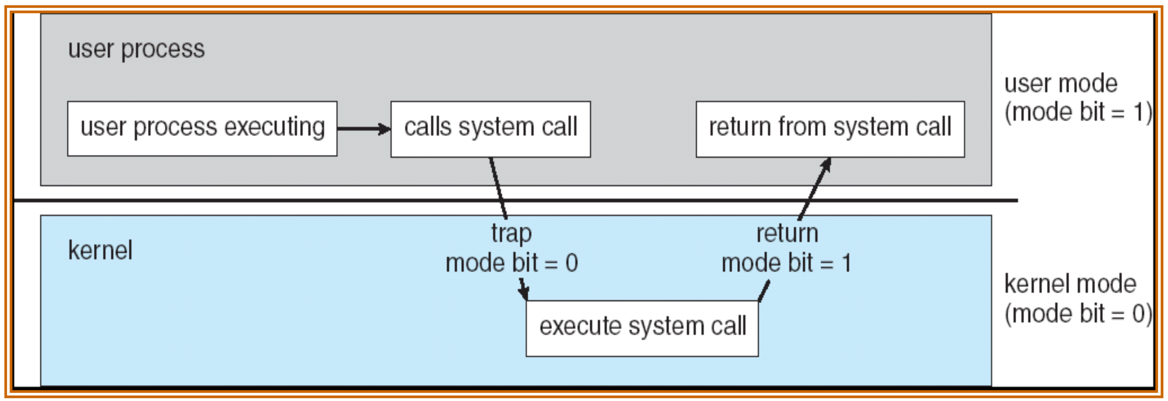
System Calls

- When user program
  - reads file from disk
  - uses printer
  - needs to use Internet (Wi-Fi)
  - …
- Need System Calls!
  - Since the above are all "privileged instructions"



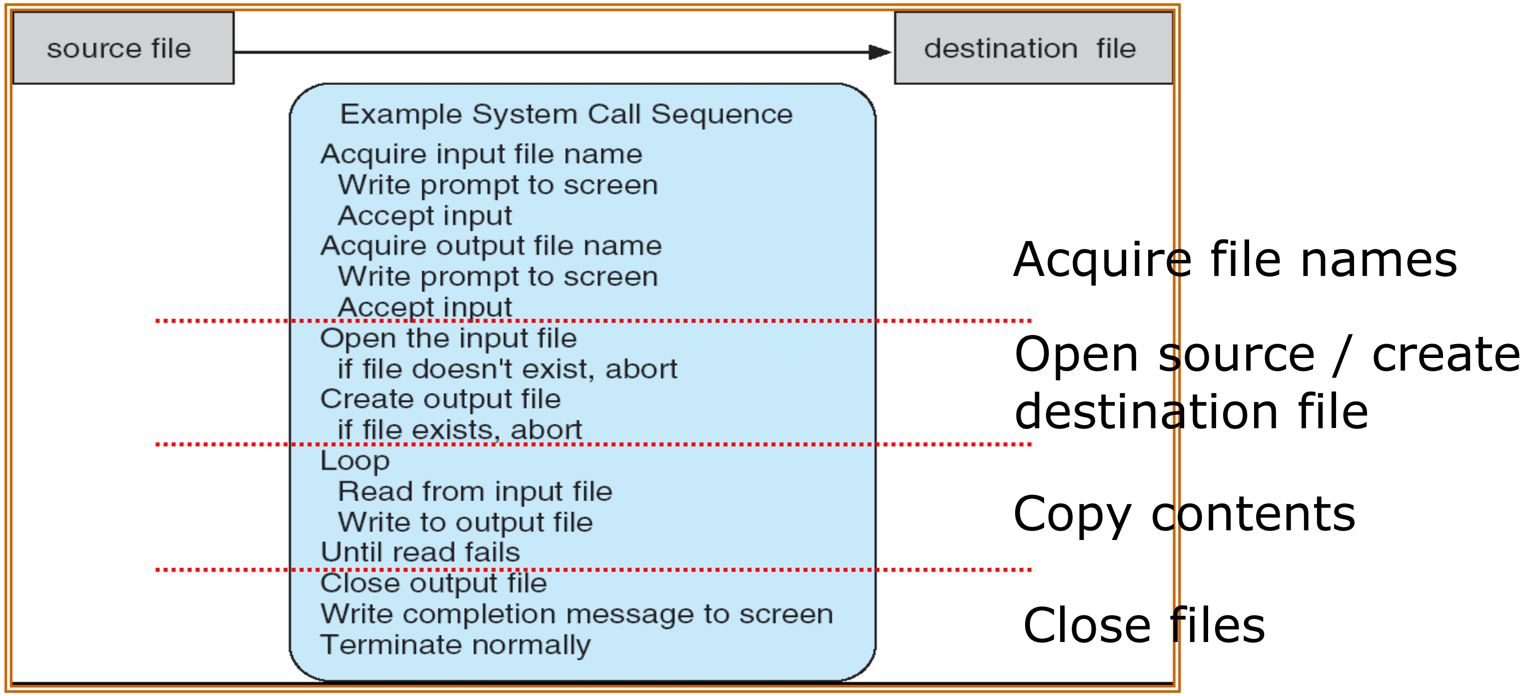
System Calls (Ch. 1.4.2 & 2.3)

- **System Calls**
  - A request **from user program to the operating system** to perform some task
  - **Software interrupt**
- Provide **interface** for the **user program** and the services provided by the **OS**



Example of System Calls: File Copy

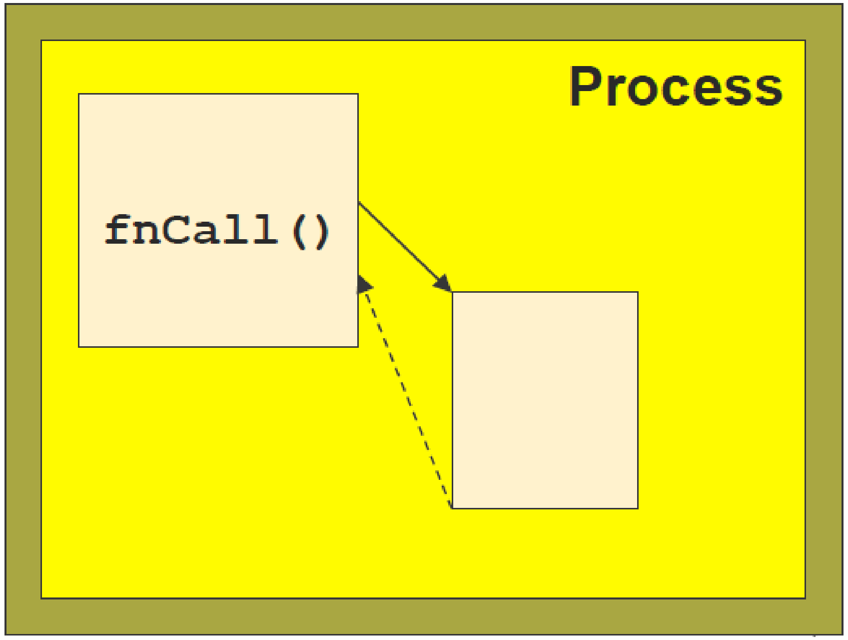
- Requires sequence of multiple system calls to make file copy



- Even simple programs make heavy use of the operating systems!
- Thousands of systems calls per second generally happen in an OS
- Read more details in pp. 62-63 (Ch. 2.3)

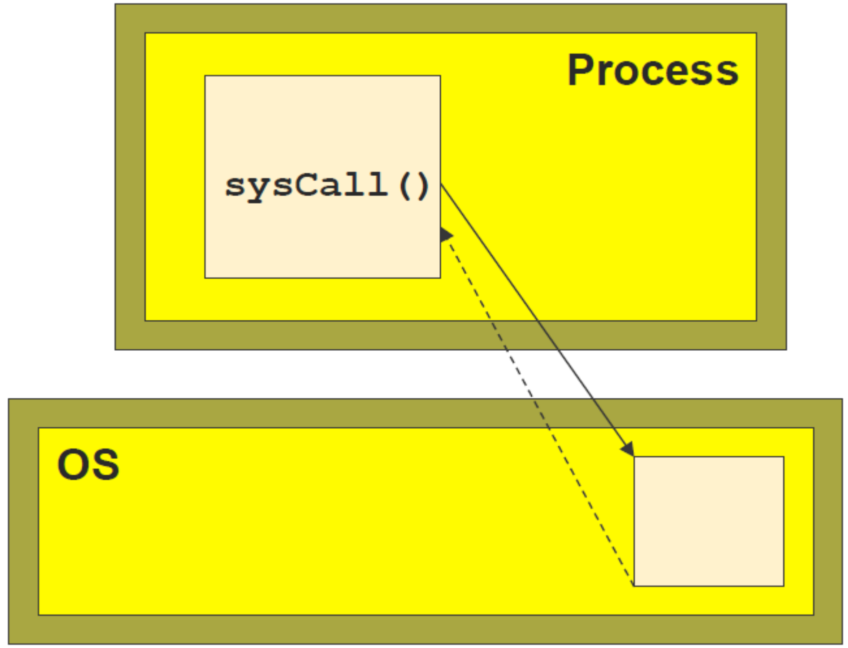
Function Call vs. System Call

Function call



Caller and callee are in the same Process
- Same user
- Same “domain of trust”

System call



- OS is trusted; user is not.
- OS has super-privileges; user does not
- Must take measures to prevent abuse

Timer (Ch. 1.5.2)

- OS needs maintain control over CPU
  - User program can go into infinite loop or not return system resources

- **Timer**
  - Timer is set to **interrupt** the computer after some time period
  - Keep a counter that is decremented by the physical clock
    - Operating system sets the counter (privileged instruction)
    - When counter zero, generate an interrupt
  - Set up before scheduling process to regain control that exceeds allotted time

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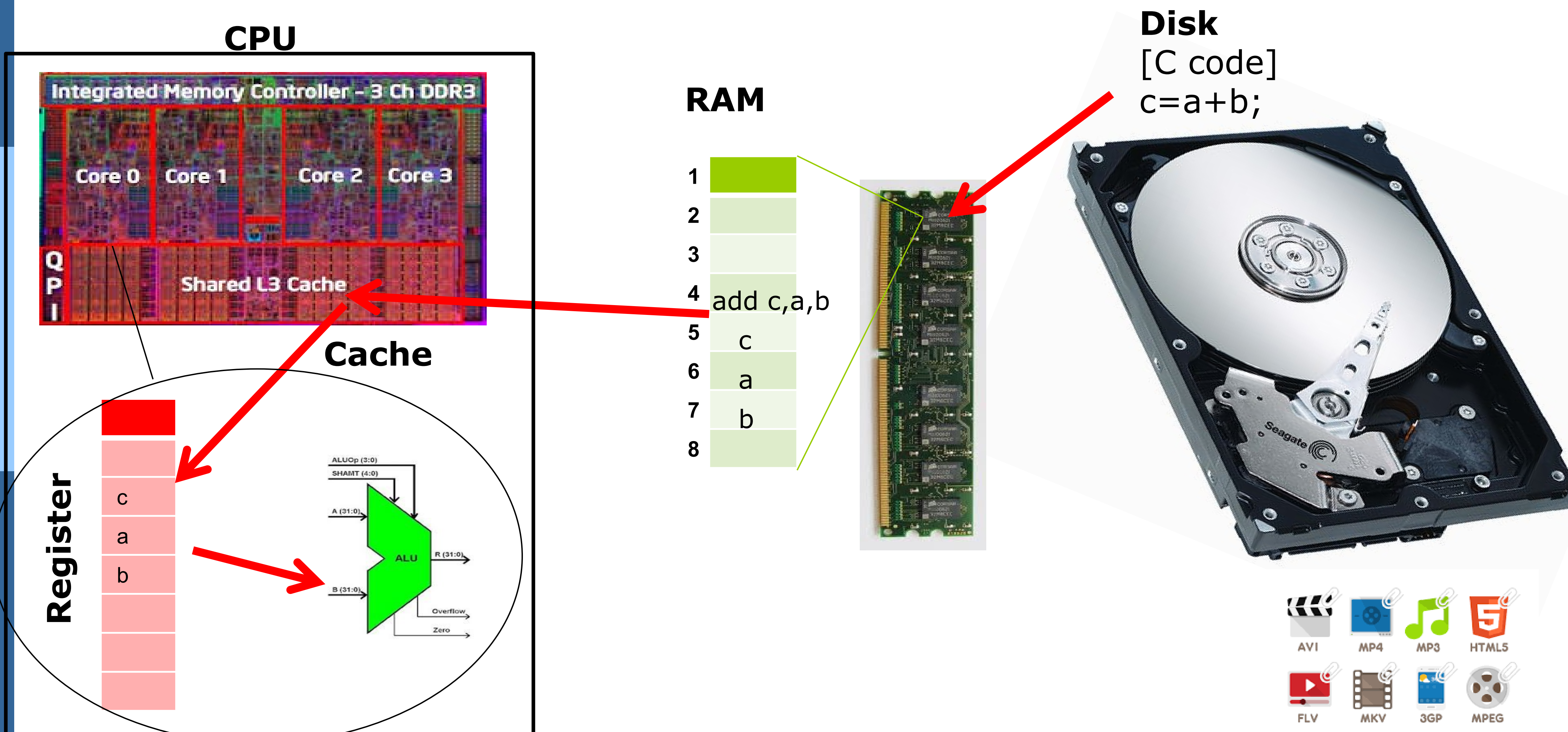
Basics: From Disk to Memory to CPU



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
  - Example: (previous page) variable ‘c’ is copied from RAM to cache memory
- 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 smaller than storage being cached
  - Cache management important design problem
  - Cache size and replacement policy

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

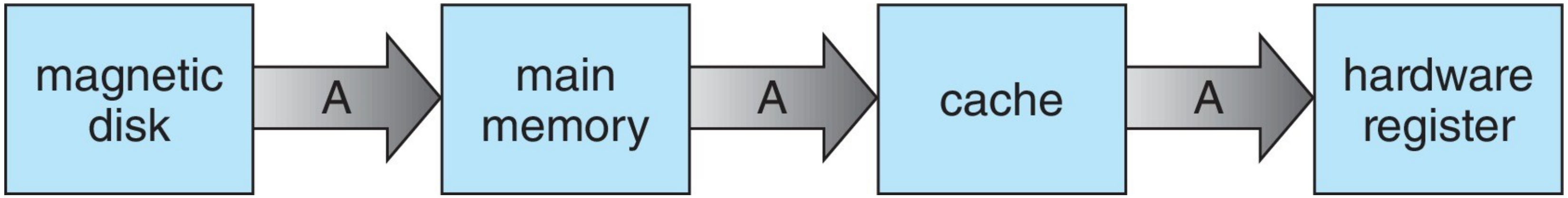
Data Caching

Caching

- Cache smaller than storage being cached
  - **Cache management** important design problem
  - **Cache size** and **replacement policy**
  - But this is a hardware issue: OS? or Computer Architecture?
- Hardware (Computer Architecture) issues in caching
  - Main memory (RAM) → Cache memory
  - Cache memory → CPU (Register)
- Software (OS) issues in caching
  - Disk → Main memory (RAM)

Migration of data "A" from Disk to Register

- Load integer A (in file B: disk), and increment by 1:



- A++: Increment is done on hardware (CPU) register
  - A differs in the various storage systems
  - Becomes same only after new value of A is copied from register all the way to disk
  - **Cache coherence** (균일) problem becomes complex in multitasking environment (discussed later on Ch. 9-10)

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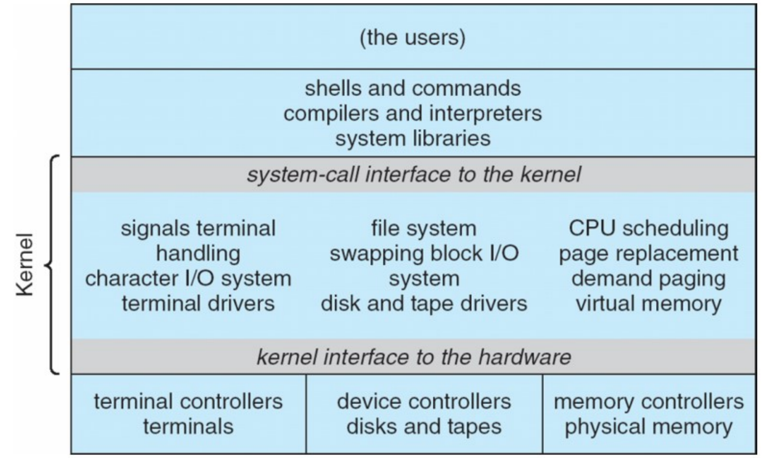
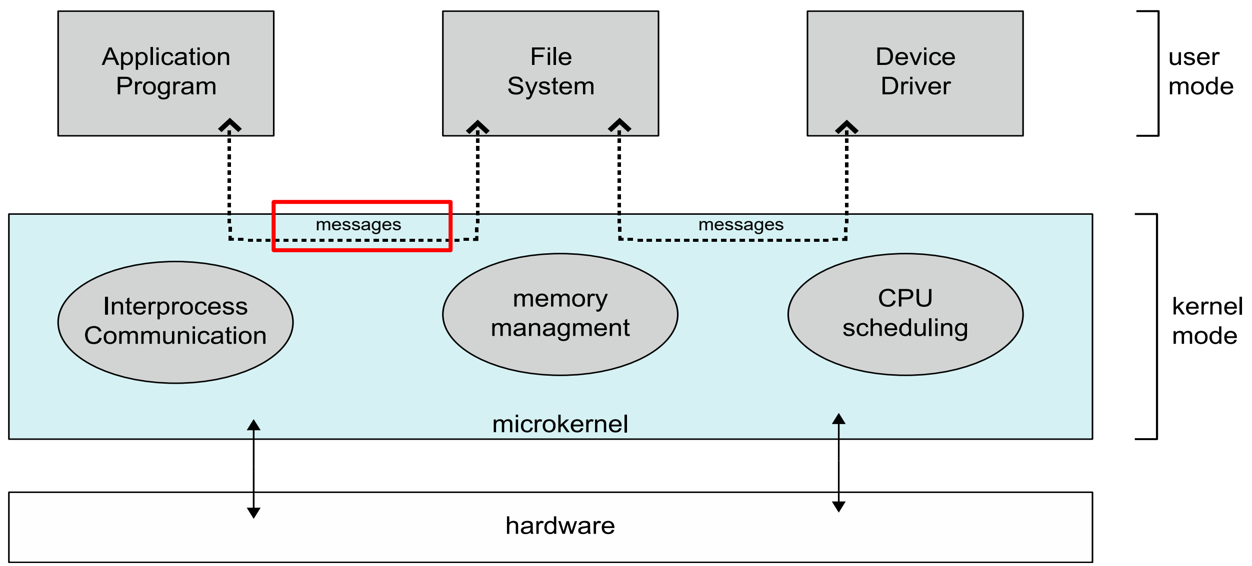
Monolithic structure



- Place all functionality of the kernel into a single, static binary file that runs in single address space
- Common technique for designing operating systems
  - UNIX, Linux, Windows still use this structure in part.
- Advantages: Performance is good –system call/kernel function is fast
- e.g., UNIX
  - Generally used for (Multi-user) Servers.
  - Source code written in C. (C language was invented to develop UNIX)
  - Base for various OSs (e.g., Linux, MAC OS).

Microkernel System Structure

- Motivation
  - Monolithic made the kernel too complex – as UNIX expanded.
  - Move non-essential components of the kernel into user space (system and user-level programs)
  - client program need to communicate with various services through **message passing** – increased system-function overhead

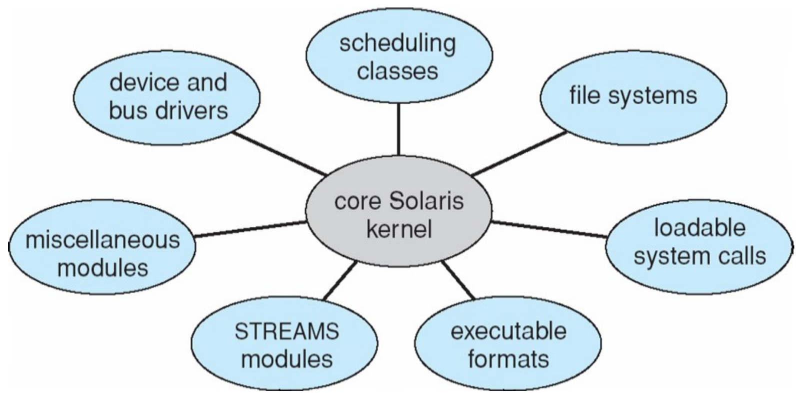


Microkernel System Structure

- Results
  - smaller kernel!
    - microkernel provides only minimal process and memory management, communication facility
    - extending kernel is easier – all new services are added to user space and do not need modification at kernel
- **Darwin**: Mac OS kernel, iOS
  - partly based on Mach microkernel
- **Windows NT 4.0** was microkernel based but very slow... why?

Loadable Kernel Modules (LKM)

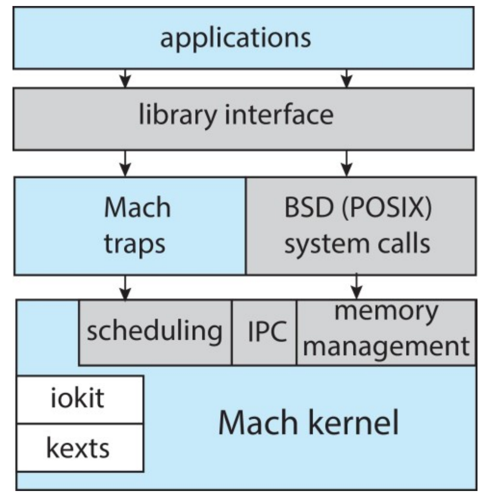
- Most modern operating systems implement **loadable kernel modules**
  - Closer to monolithic – most functions in kernel
  - However, each function is loadable as needed within kernel, as the kernel is running
  - e.g., Linux device drivers and file systems



- Advantages
  - Adding new features does not require recompilation of entire kernel – as in monolithic kernel
  - User program can talk directly to LKMs via system call, no need for message passing – as in microkernel

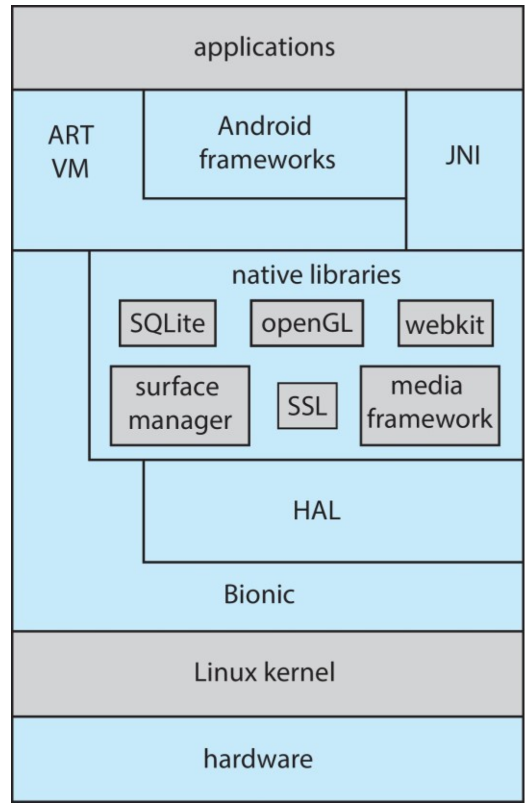
Hybrid Systems

- Most modern operating systems actually not one pure model
- Hybrid combines multiple approaches to address performance, security, usability needs
- Apple macOS and iOS
  - Darwin kernel: Mach microkernel + BSD UNIX kernel



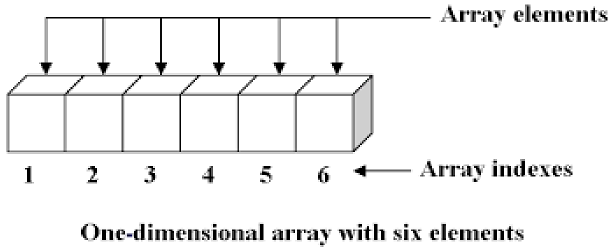
Hybrid Systems: Android

- **Android**
  - Developed by Open Handset Alliance (mostly Google)
  - Based on **Linux kernel** but modified
    - Provides process, memory, device-driver management
    - Adds power management
  - Apps developed in **Java** using Android API
    - Java applications are executed on the Android RunTime (ART)

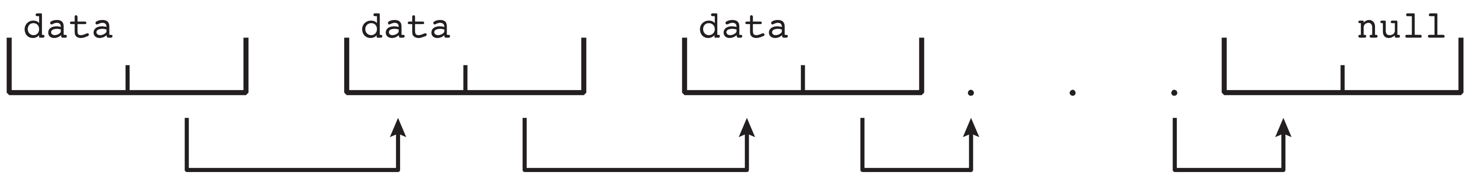


Kernel Data Structures: Lists (Ch. 1.10)

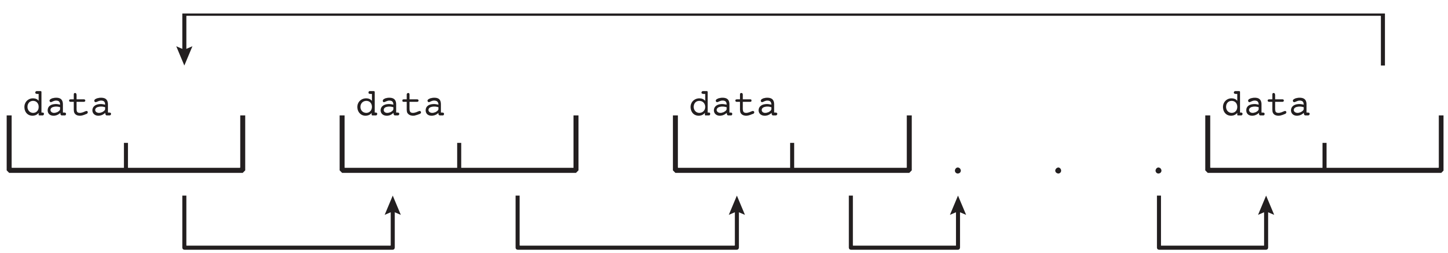
- Used by kernel algorithms
- *Array*



- *Singly linked list*



- *Circular linked list*



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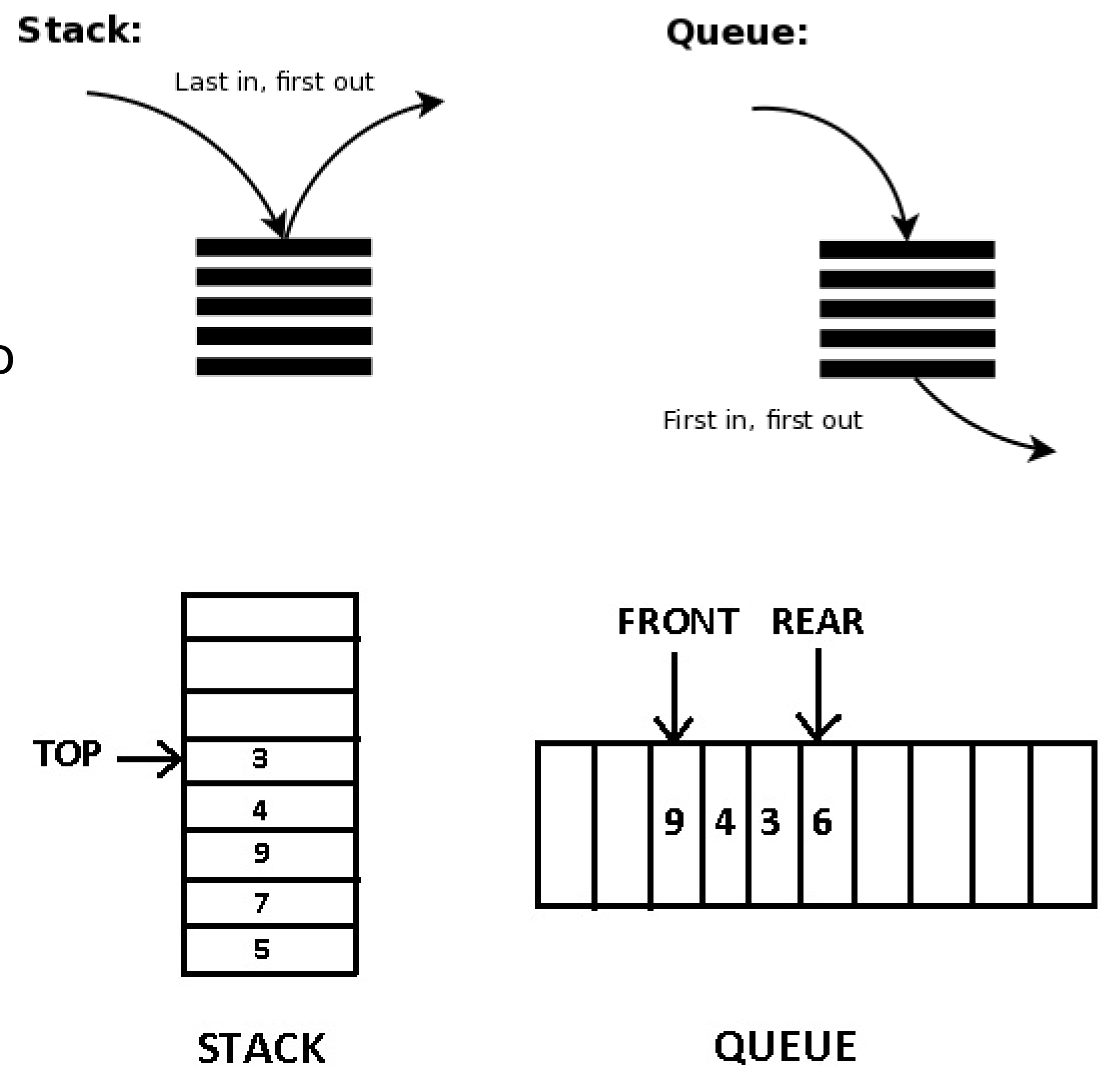
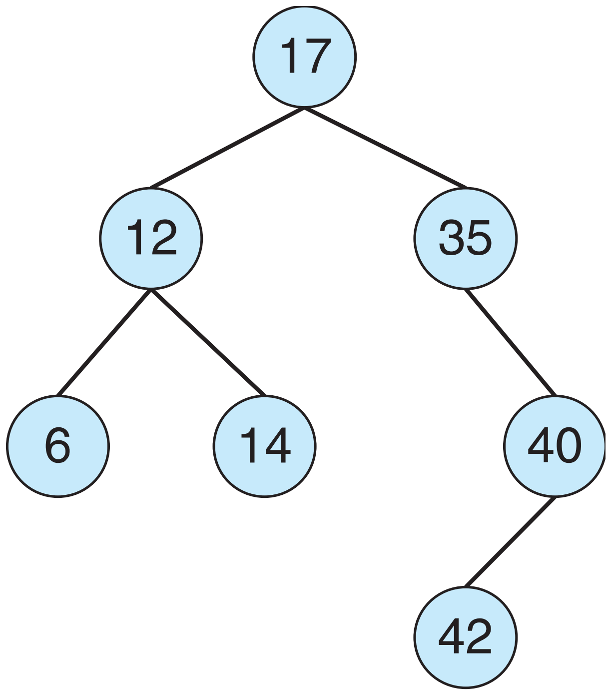
Kernel Data Structures: Stack/Queue

- Stack: LIFO
  - Push / Pop
  - Invoking **function calls**
    - Parameters, local variables, and return address are **pushed** on to stack when a function is called
    - Returning from the function call **pops** those items off the stack
- Queue: FIFO
  - Printer jobs
  - CPU scheduling



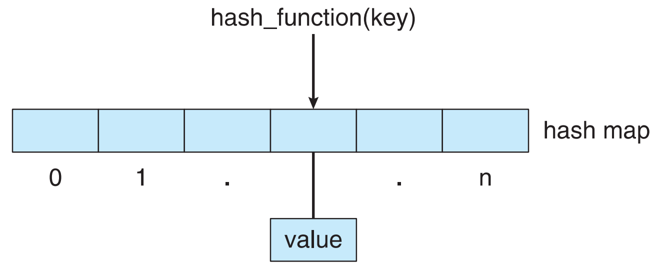
Kernel Data Structures: Trees

- **Binary search tree**
  left <= right
  - Search performance is *O(n)*
  - **Balanced binary search tree** is *O(log n)*
- Used for Linux CPU scheduling



Kernel Data Structures: Hash

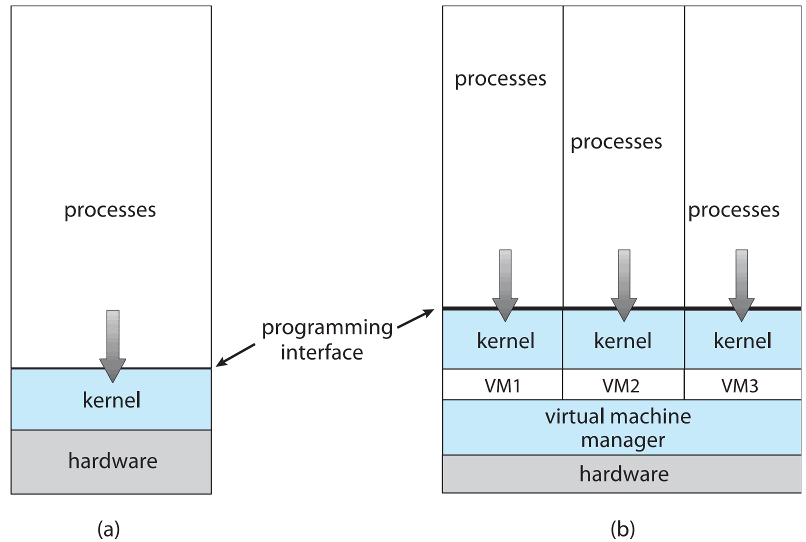
- **Hash function** can create a **hash map**
  - Used in Inverted page table



- Linux (open source) data structures defined in ***include*** files `<linux/list.h>`, `<linux/kfifo.h>`, `<linux/rbtree.h>`

Virtualization (Ch. 1.7)

- Allows operating systems to run applications within other OSes
  - Vast and growing industry
- **Virtualization** –running **guest** OSes also natively compiled
  - Consider VMware running Windows guests, each running applications, all on native Windows **host** OS
  - **VMM** (virtual machine Manager) provides virtualization services



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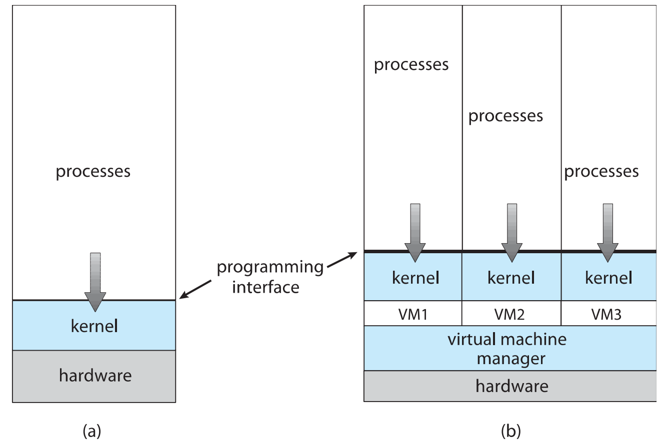
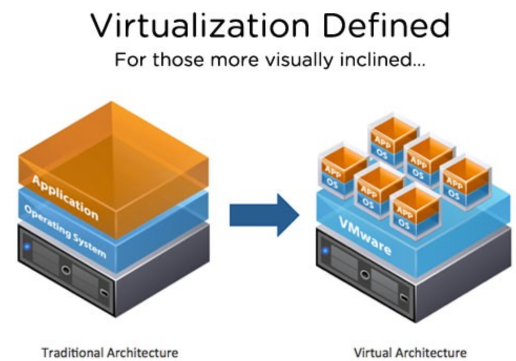
Virtualization (cont.)

- Use cases involve laptops and desktops running multiple OSes for exploration or compatibility
  - Apple laptop running Mac OS X host, Windows as a guest
  - Developing apps for multiple OSes without having multiple systems
- Executing and managing compute environments within data centers
  - VMM can run natively, in which case they are also the host

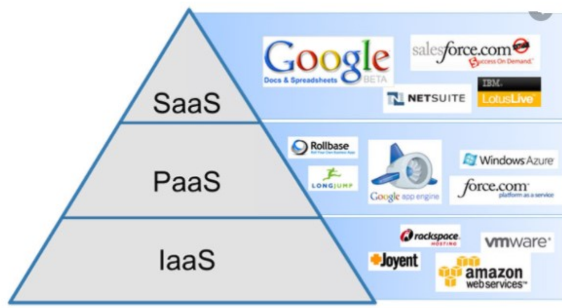




https://analytica.com/datacenter-capacity-planning-and-modeling-virtualization/

Computing Environments – Cloud Computing (Ch.1.10.5)

- Delivers computing, storage, even apps as a service across a network
- Logical extension of virtualization because it uses virtualization as the base for its functionality.
  - Amazon **EC2** has thousands of servers, millions of virtual machines, petabytes of storage available across the Internet, pay based on usage
- Many 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
  - 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)



https://cloudcomputinggate.com/saas-paas-iaas-examples/

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