



**Department of Physics,
Computer Science & Engineering**

CPSC 410 – Operating Systems I

Computer System Overview

Keith Perkins

Original slides by Dr. Roberto A. Flores

Additional content from https://onlinecourses.nptel.ac.in/noc17_cs29/preview

Topics

- Basic Elements

- Processor, main memory, I/O modules, system bus

- Microprocessors

- General purpose, graphics, digital signal, system on chip

- Instructions

- Execution, fetch & execute (F&E), instruction register

- Interrupts

- Types, flow of control, F&E&I, multiple interrupts

- Memory

- Hierarchy, principle of locality, cache

- I/O Techniques

- Programmed, interrupt-driven, direct memory access

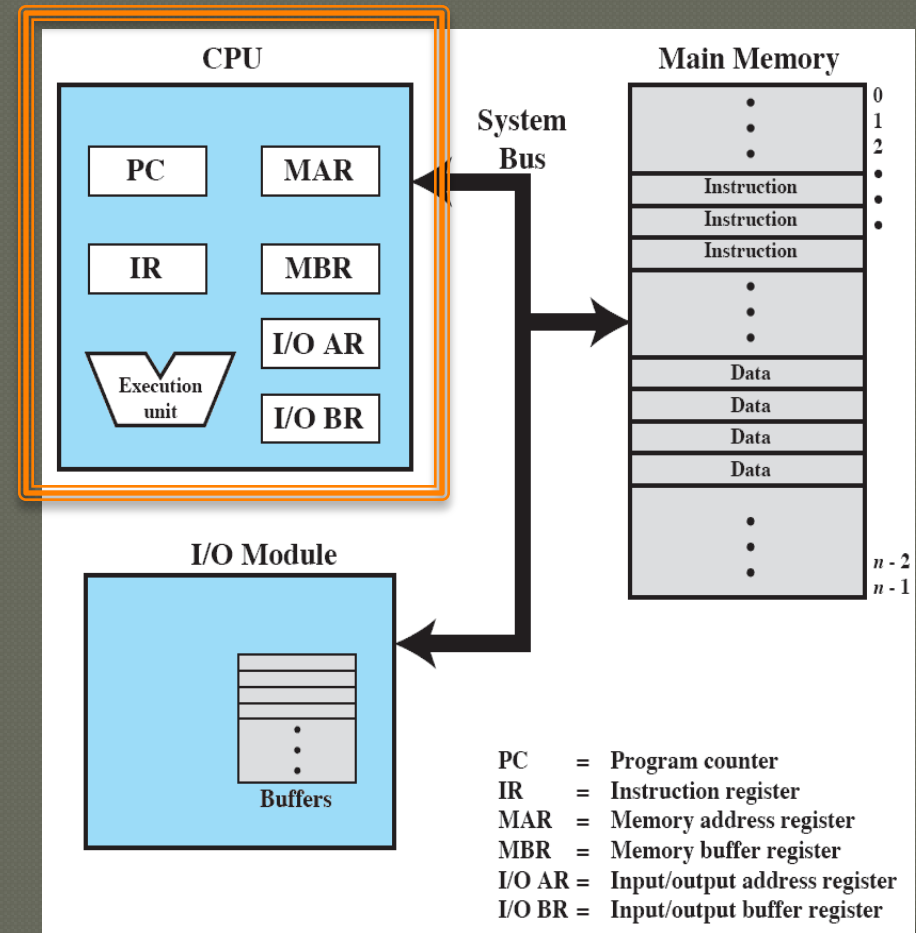
- Symmetric multi-processors

- Advantages, organization, multi-core

Basic Elements

● Processor

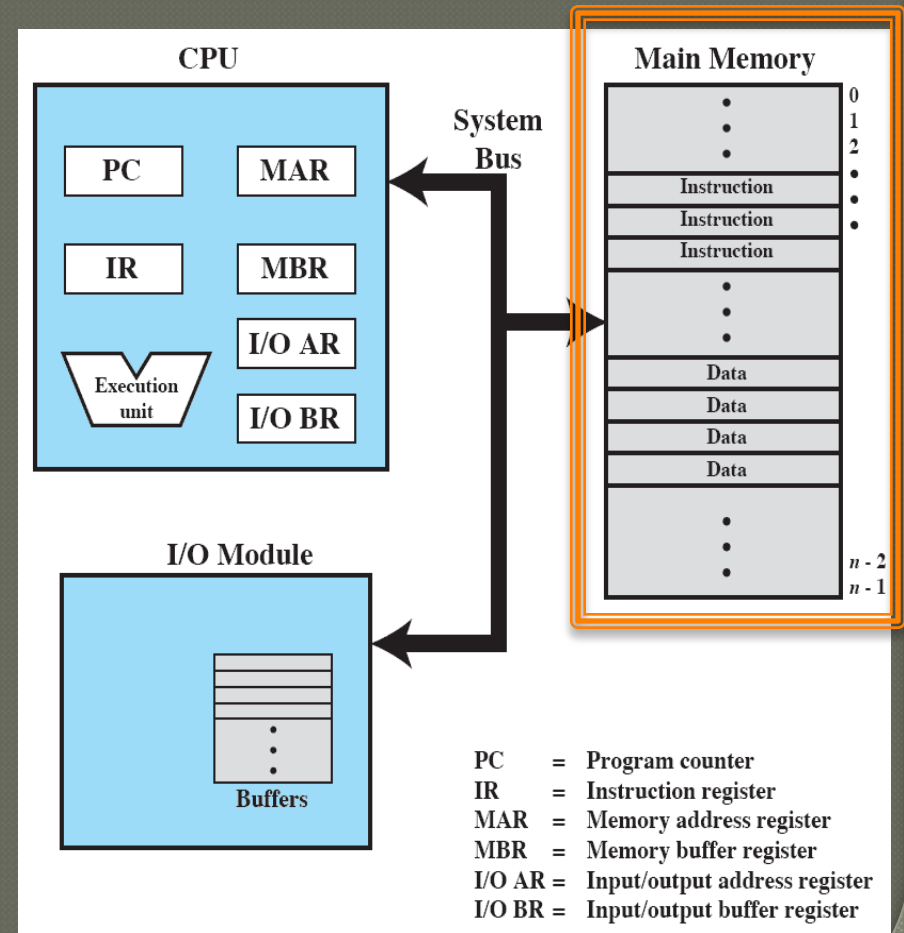
- aka CPU
 - Central Processing Unit
- Controls execution of instructions
- Performs data processing



Basic Elements

● Memory

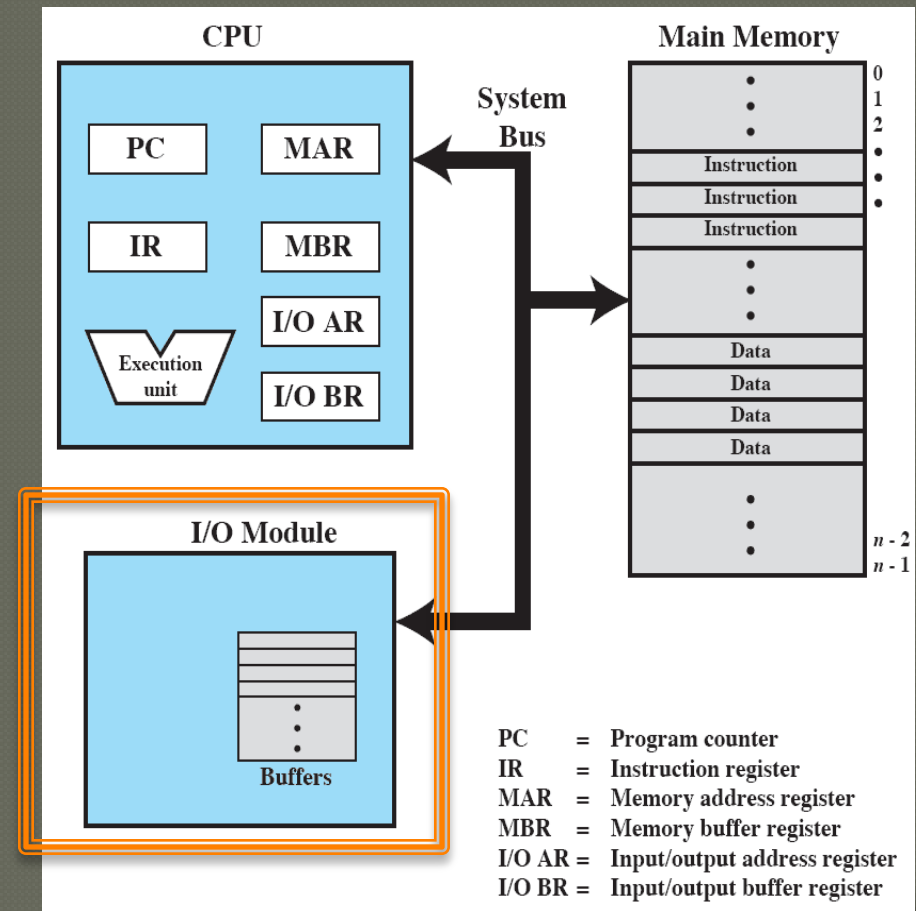
- aka primary/main memory, RAM
- Random Access Memory
- Stores instructions & data
- Volatile
 - Contents are lost when the computer is shut down



Basic Elements

● I/O Modules

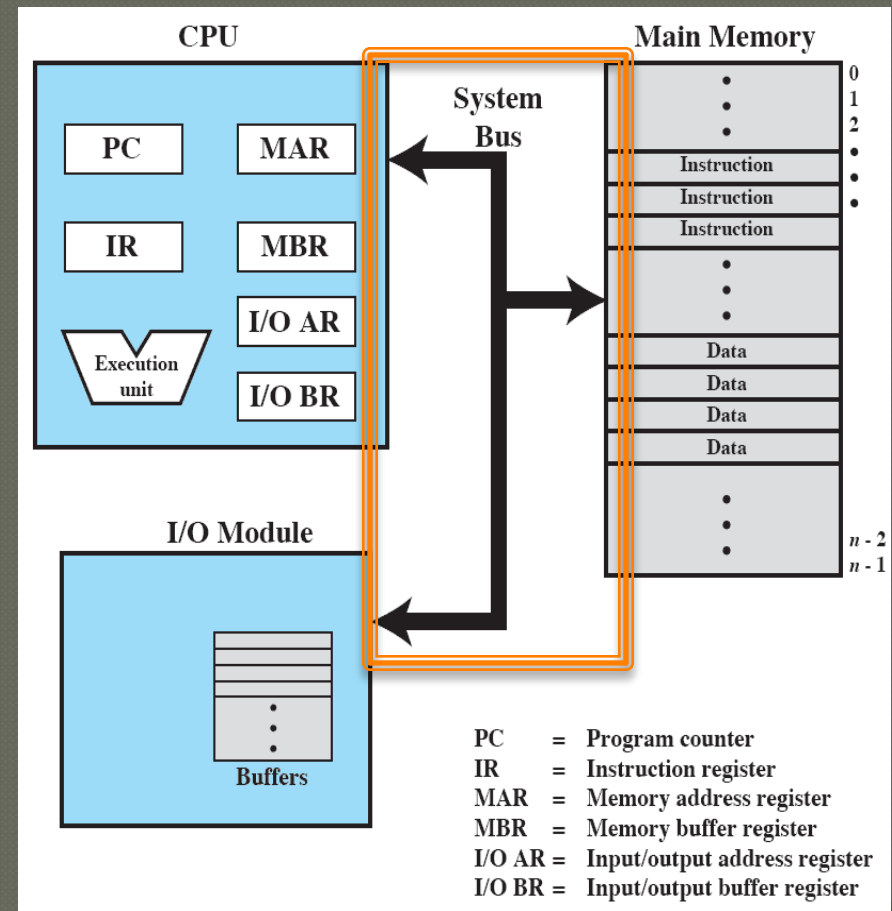
- aka device drivers
- Move data between the computer and external devices:
 - storage (e.g. hard drive)
 - communications equipment
 - terminals
- Have buffers to push/pull data



Basic Elements

● System bus

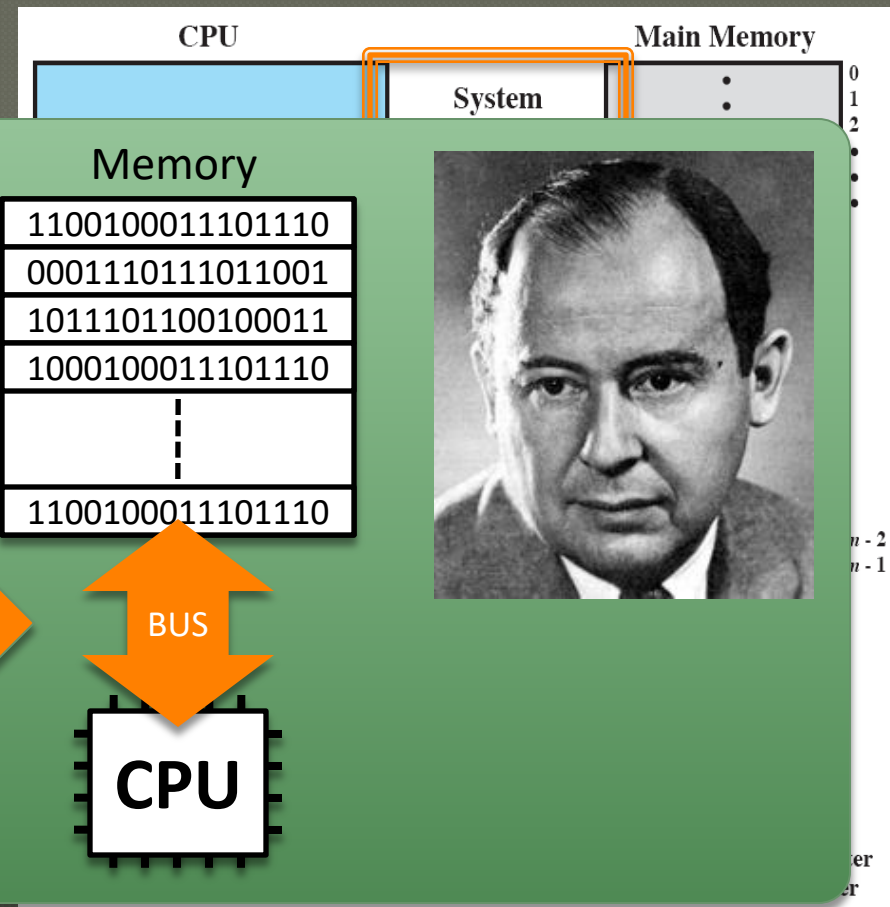
- Means of communication among processors, memory & I/O modules
- Its speed limits computer performance
 - Known as the....



Basic Elements

System bus

- Means of communication



* Backus (1978) "Can Programming Be Liberated from the von Neumann Style?" Communications of the ACM, Vol. 28, Num. 8

Topics

- ◉ Basic Elements

- Processor, main memory, I/O modules, system bus

- ◉ Microprocessors

- General purpose, graphics, digital signal, system on chip

- ◉ Instructions

- Execution, fetch & execute (F&E), instruction register

- ◉ Interrupts

- Types, flow of control, F&E&I, multiple interrupts

- ◉ Memory

- Hierarchy, principle of locality, cache

- ◉ I/O Techniques

- Programmed, interrupt-driven, direct memory access

- ◉ Symmetric multi-processors

- Advantages, organization, multi-core

Microprocessors

General Purpose

- It brought about PC & handheld computing
- 1 processor or more (cores) on a single chip

Graphical Processing Units (GPU)

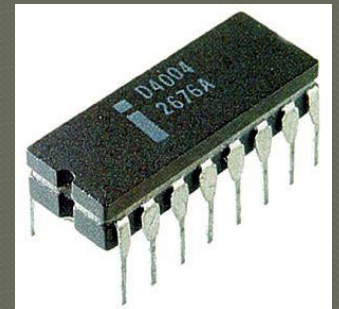
- Efficient computation on arrays of data, e.g., math & physics simulations (for games), large spreadsheets

Digital Signal Processors (DSP)

- Streaming audio or video signals; en/decoding (codecs)

System on a Chip (SoC)

- Embedded systems (handheld)
- CPU, GPU, DSP, memory in one chip



Intel 4004, wikipedia.org



Exynos5octa, samsung.com

Topics

- Basic Elements

- Processor, main memory, I/O modules, system bus

- Microprocessors

- General purpose, graphics, digital signal, system on chip

- Instructions

- Execution, fetch & execute (F&E), instruction register

- Interrupts

- Types, flow of control, F&E&I, multiple interrupts

- Memory

- Hierarchy, principle of locality, cache

- I/O Techniques

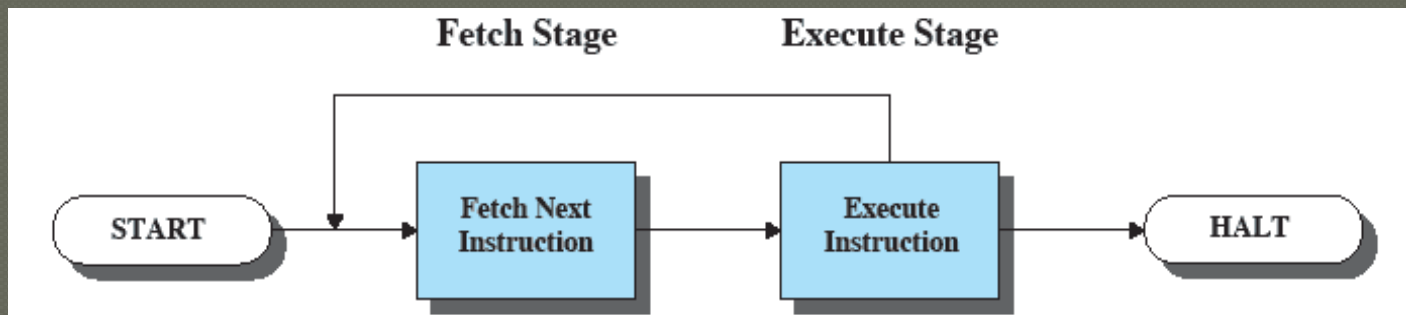
- Programmed, interrupt-driven, direct memory access

- Symmetric multi-processors

- Advantages, organization, multi-core

Instructions

- A program is a set of instructions stored in memory
- CPU instruction cycle (fetch & execute)
 - *program counter (PC) has address of next instruction*
 - **processor reads (fetches) an instruction from memory**
 - *instruction stored in instruction register (IR)*
 - *program counter increments address*
 - **processor executes instruction**; repeat until forever

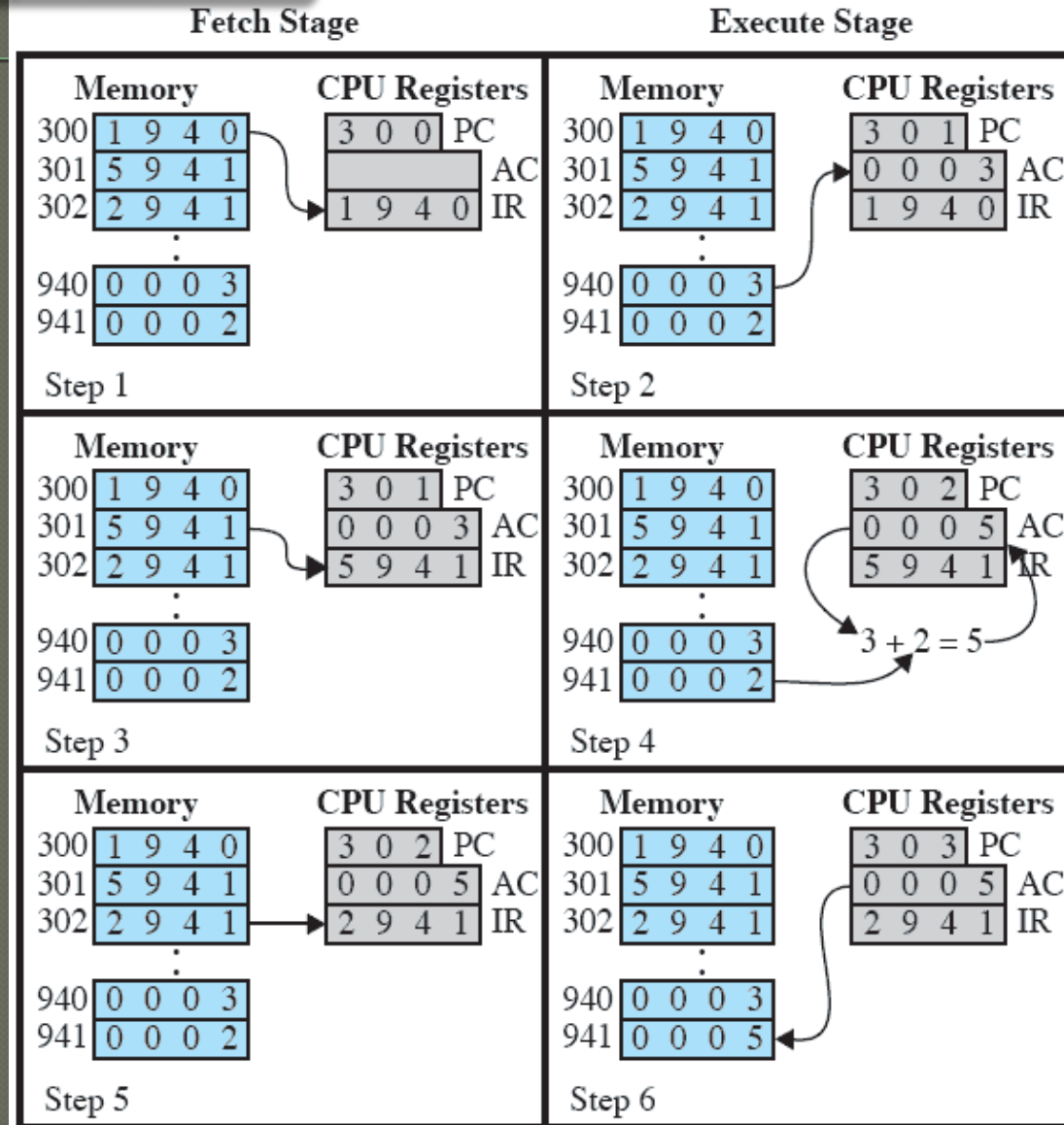


program counter (PC) has address of next instruction
 processor fetches instruction from memory
 instruction stored in instruction register (IR)
 program counter increments address
 processor executes instruction; repeat until forever

1 load AC from memory
 2 store store AC to memory
 5 add to AC from memory

Instructions

● Example



Topics

- ◉ Basic Elements

- Processor, main memory, I/O modules, system bus

- ◉ Microprocessors

- General purpose, graphics, digital signal, system on chip

- ◉ Instructions

- Execution, fetch & execute (F&E), instruction register

- ◉ Interrupts

- Types, flow of control, F&E&I, multiple interrupts

- ◉ Memory

- Hierarchy, principle of locality, cache

- ◉ I/O Techniques

- Programmed, interrupt-driven, direct memory access

- ◉ Symmetric multi-processors

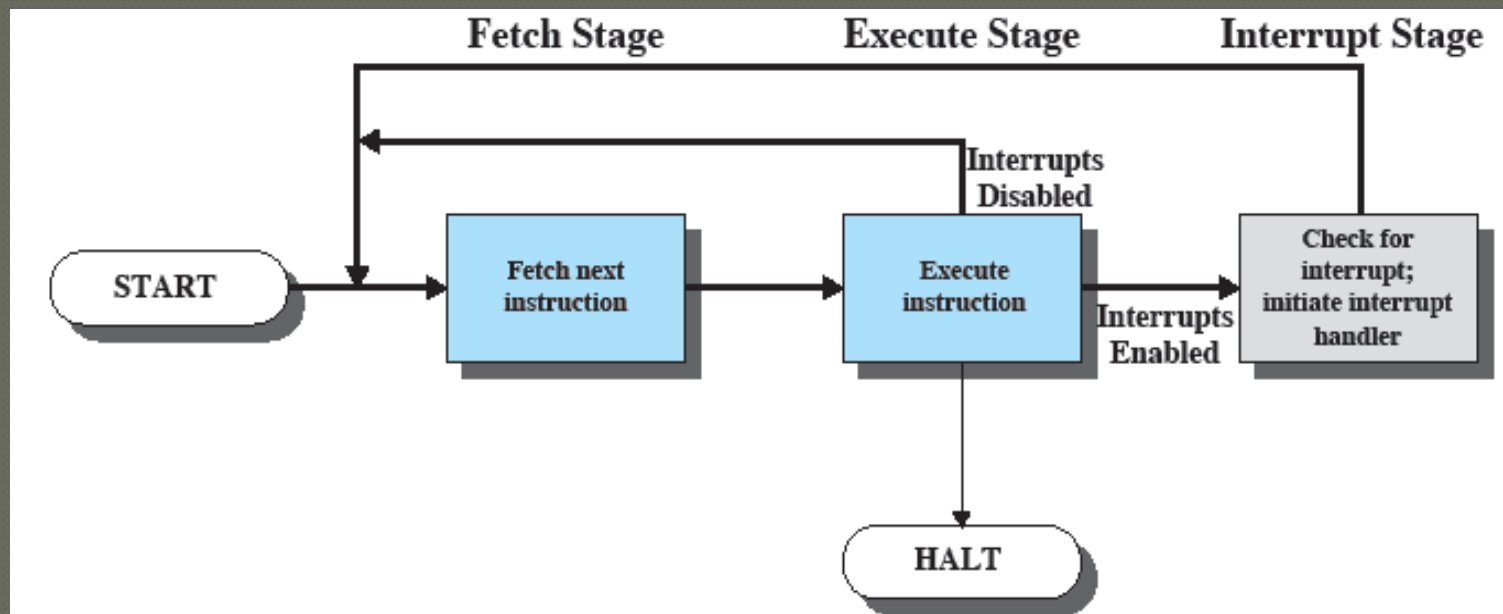
- Advantages, organization, multi-core

Interrupts

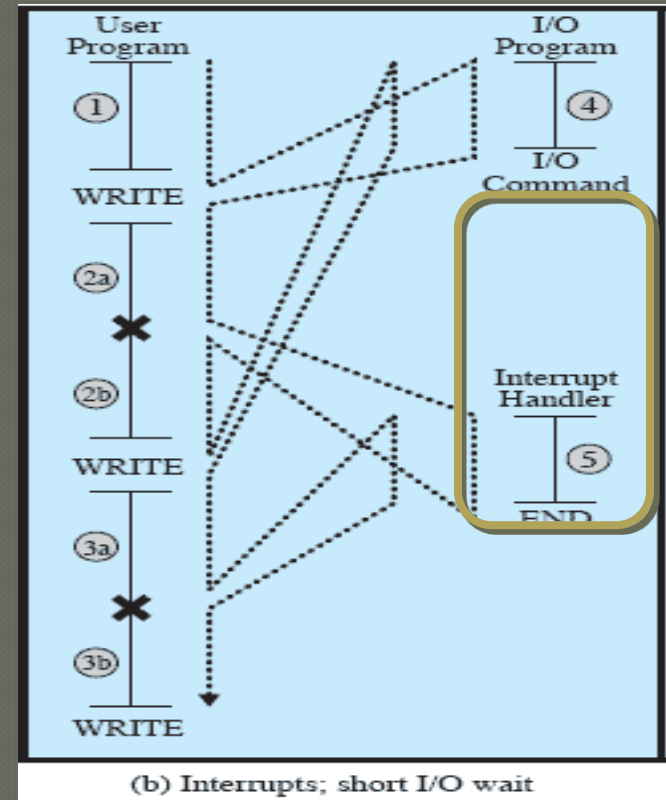
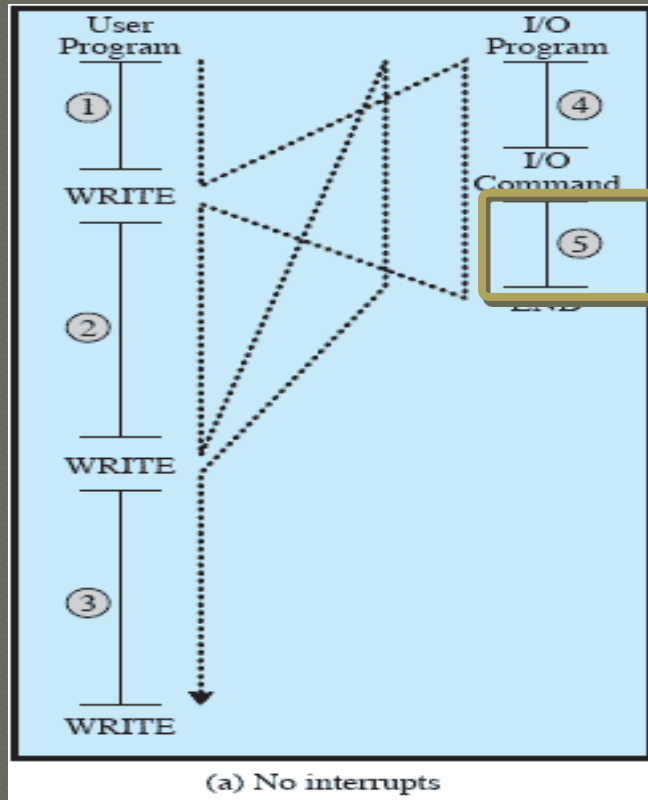
- Interrupts normal sequencing of the processor
- Provided to improve processor utilization
 - I/O devices are slower than CPU
 - Without interrupts, CPU must pause to wait for I/O device (wastes its time)
- Interrupts ensure timely process switches
- Interrupts provide safe user access to potentially dangerous instructions (like file read/write)

Interrupts- where in instruction cycle

- Fetch & Execute & Interrupt
 - Same as before, plus an Interrupt Stage



Interrupts-Why



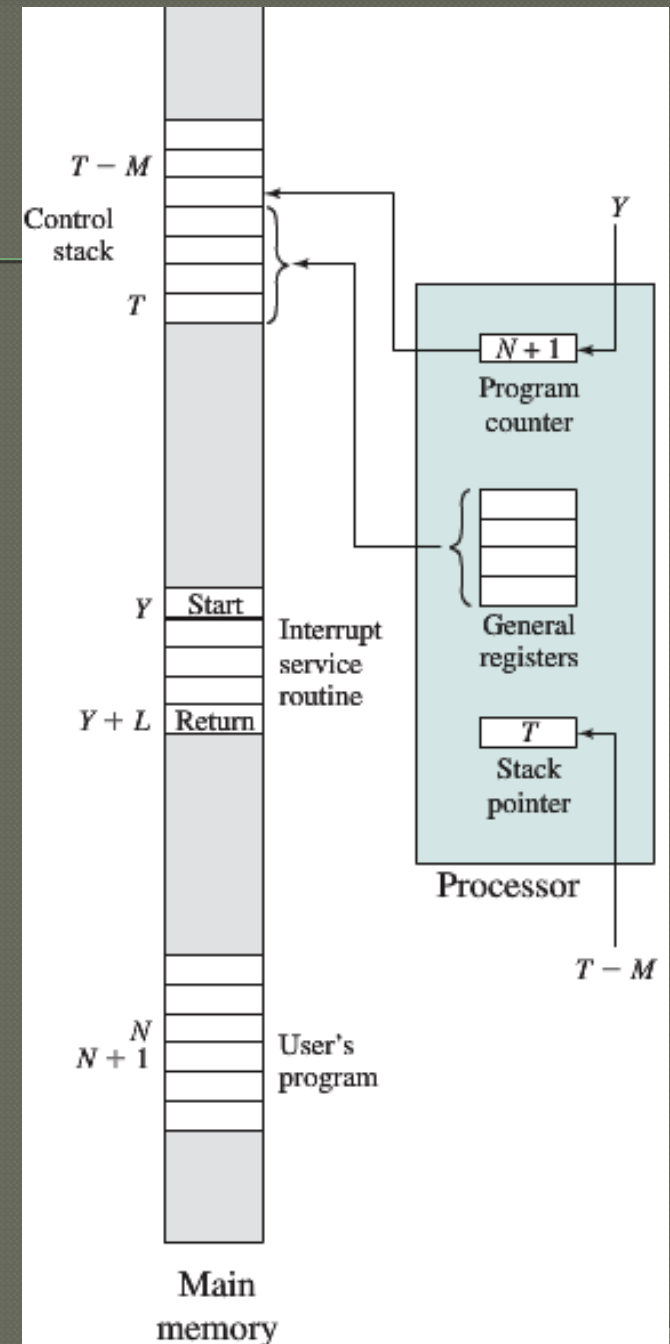
- Polling (left side) CPU periodically checks device to see if it needs attention. Almost always a huge waste of CPU time.
- Instead start operation, have CPU do other work until notified by interrupt that operation is finished

Example - why we need interrupts

- CPU clock 2.5 Ghz or 4×10^{-10} seconds per instruction
- Hard Drive 4×10^{-3} seconds per access
- CPU is 10 million times faster than HD
- Or, if 1 CPU instruction took 1 second, 1 HD access would take 16.5 weeks
- Don't want CPU to wait on HD

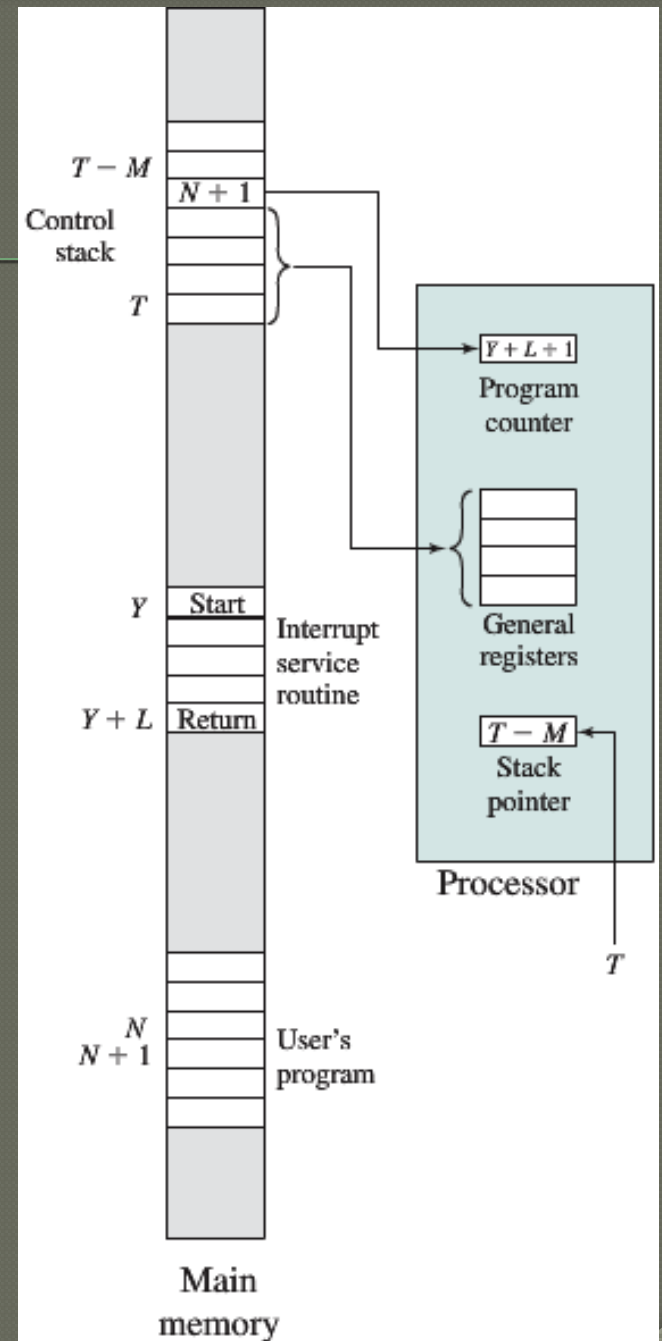
• What happens when CPU is disrupted by an interrupt?

- Finish executing instruction N
- { interrupt }
- store registers, PC (size M) in control stack @ T
- update stack pointer to T-M
- execute interrupt instruction @ Y until finishing @ Y+L
- load back top of control stack
- continue executing @ N+1



• What happens when CPU is disrupted by an interrupt?

- Finish executing instruction N
- { interrupt }
- store registers, PC (size M) in control stack @ T
- update stack pointer to $T-M$
- execute interrupt instruction @ Y until finishing @ $Y+L$
- load back top of control stack
- continue executing @ $N+1$



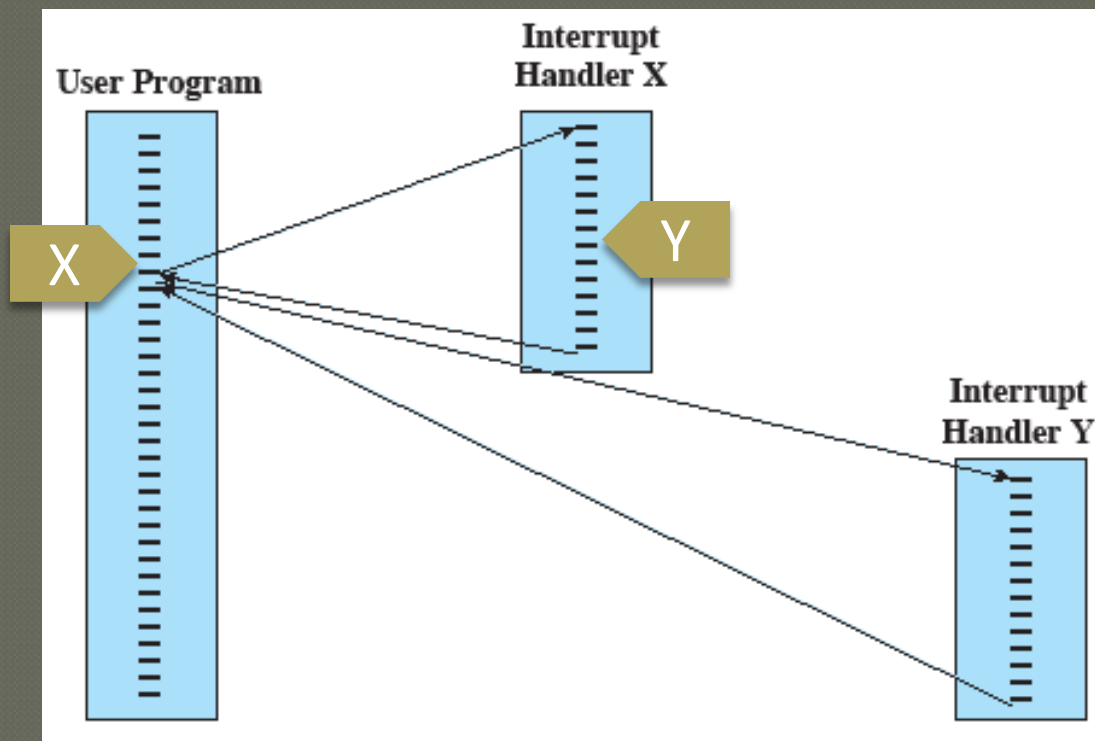
Interrupts

● Multiple overlapping interrupts

- An interrupt happens when another is being handled
- 1. **Disable interrupts** (when handling an interrupt)
 - 2nd interrupt waits until 1st interrupt is handled
 - Strictly sequential
- 2. Use a **priority scheme**
 - Interrupts can interrupt interrupt-handling...
 - ...but only if they have a higher priority; otherwise they wait
 - Hierarchical (by priority)

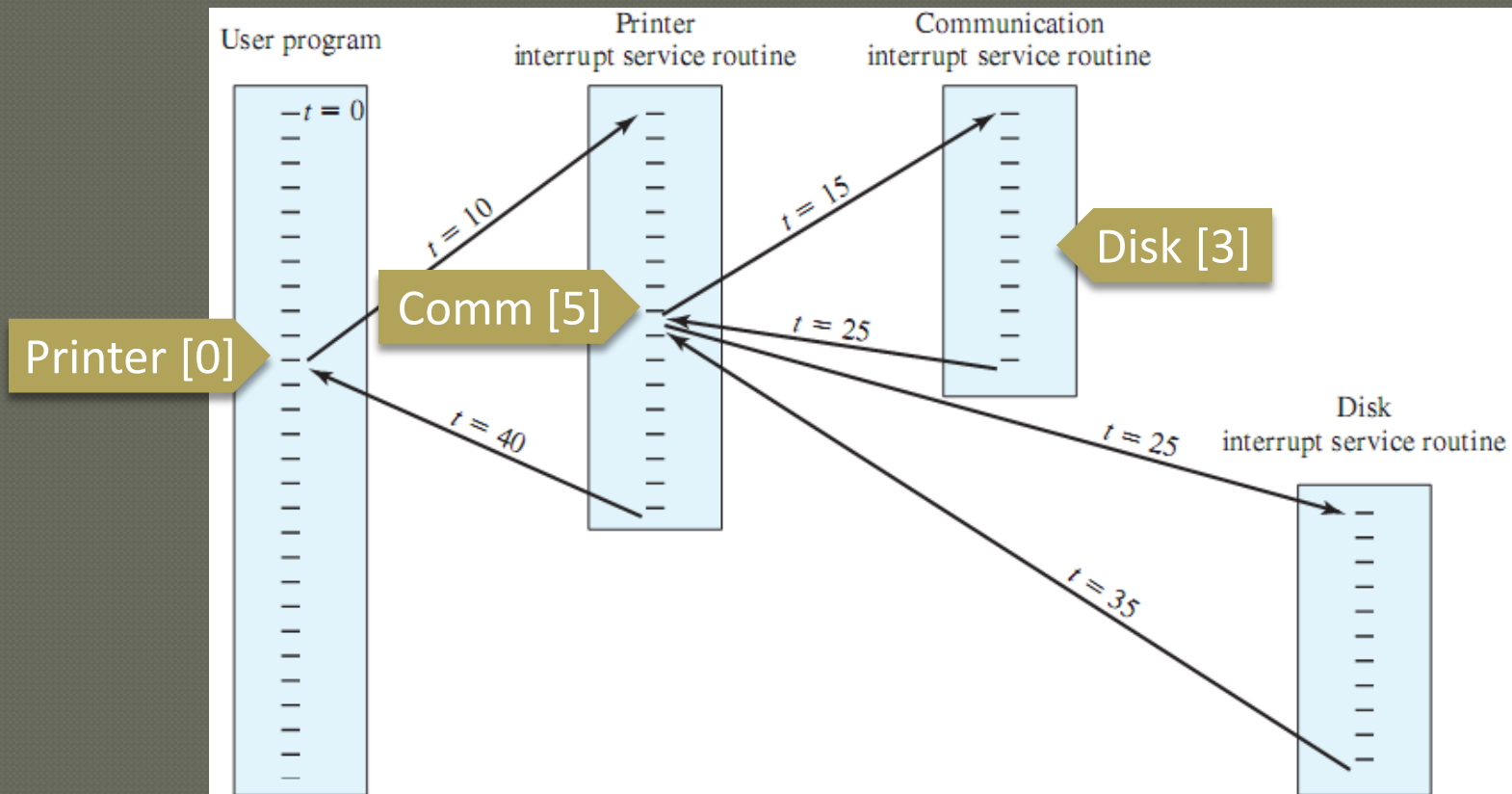
Interrupts

- Multiple overlapping interrupts
 - (approach 1) **Interrupts disabled**



Interrupts

- Multiple overlapping interrupts
 - (approach 2) **Priority Scheme**



Topics

● Basic Elements

- Processor, main memory, I/O modules, system bus

● Microprocessors

- General purpose, graphics, digital signal, system on chip

● Instructions

- Execution, fetch & execute (F&E), instruction register

● Interrupts

- Types, flow of control, F&E&I, multiple interrupts

● Memory

- Hierarchy, principle of locality, cache

● I/O Techniques

- Programmed, interrupt-driven, direct memory access

● Symmetric multi-processors

- Advantages, organization, multi-core

Memory

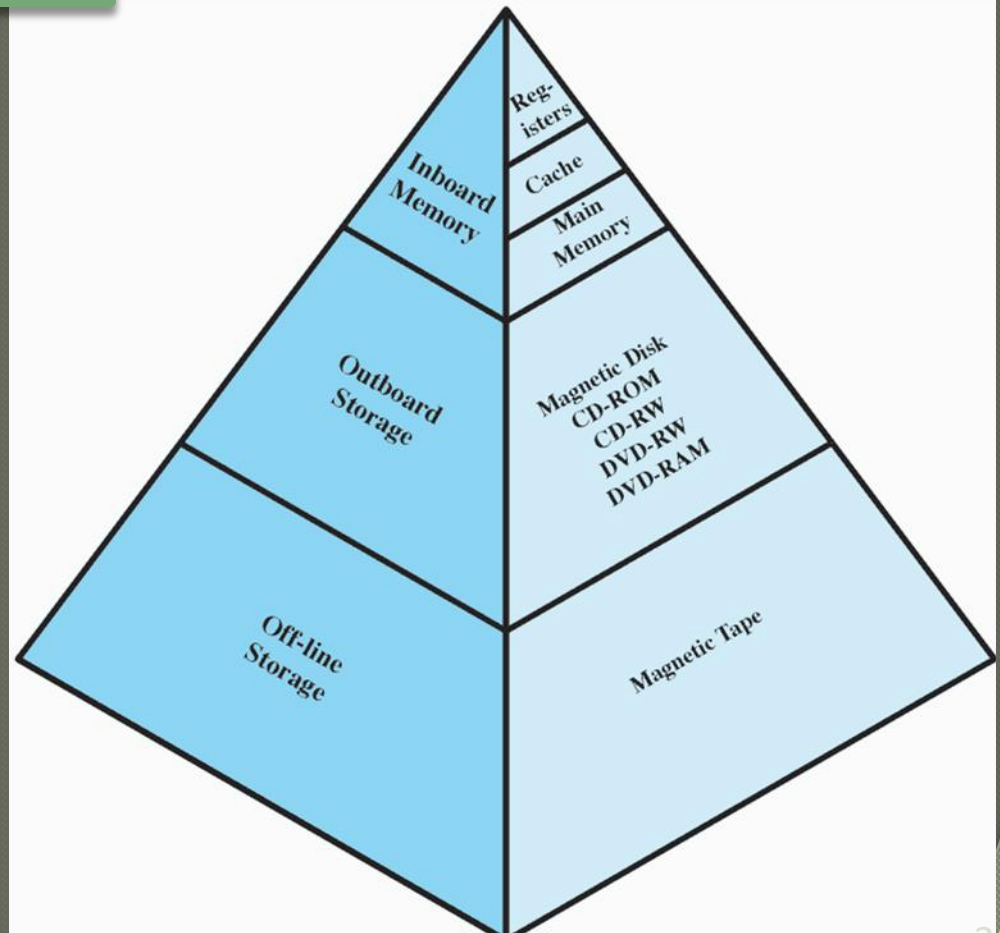
● Major (conflicting) constraints

- speed (access time), amount, cost
- Memory must keep up with CPU (speed)
 - Faster access time = greater cost
- Memory must satisfy data volumes (amount)
 - Greater capacity = smaller cost = slower access speed

Memory

● Hierarchy going down

- **cost** decreases
- **capacity** increases
- **access time** increases
- **frequency of access by CPU** decreases
- really? how does it happen?



Memory

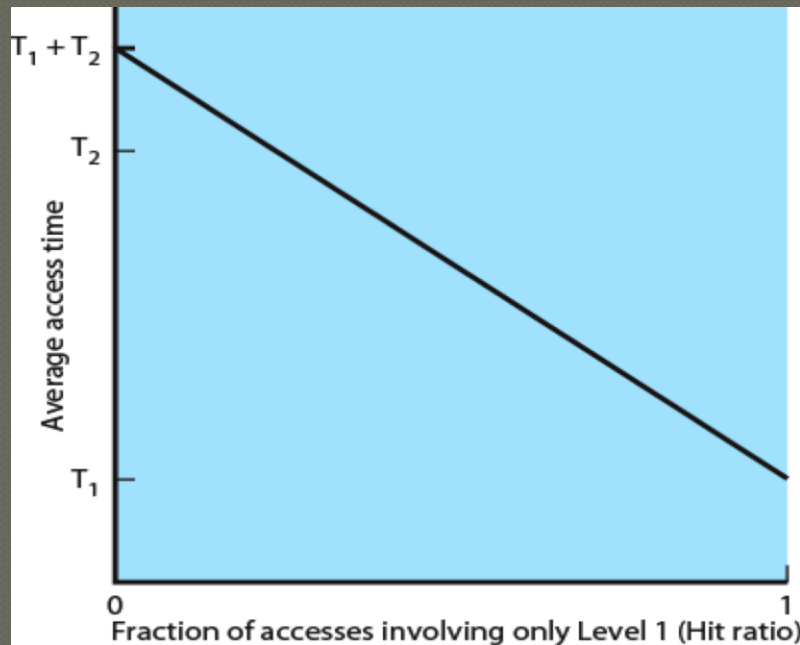
● Principle of Locality

- Why does **frequency of access by CPU** decrease?
 - Memory references (i.e., data) needed by CPU (i.e., the current set of instructions in a program) tend to cluster
 - e.g. array “a” being read in a loop
 - Data gets naturally clustered so that the percentage of accesses to each successively lower level is substantially less than that of the level above
- Eventually a set of data is replaced by another, but it's less frequent proportionally to the use within a set, which makes overhead bearable.

Memory

● Performance Example

- 2 levels of memory (L1,L2)
- T1 @ $0.1\mu\text{s}$ (1kb total) faster but scarce
- T2 @ $1\mu\text{s}$ (100kb total) slower but plenty



Memory

● Performance Example

- 2 levels of memory (L1,L2)
 - T1 @ $0.1\mu\text{s}$ (1kb total) faster but scarce
 - T2 @ $1\mu\text{s}$ (100kb total) slower but plenty
- What's the average access time if...
 - 95% of data in L1 and 5% in L2?

Memory

● Performance Example

- 2 levels of memory (L1,L2)
 - T1 @ 0.1 μ s (1kb) faster but scarce
 - T2 @ 1 μ s (100kb) slower but plenty _{μ s}
- What's the average access time if...
 - 95% of data in L1 and 5% in L2?
 - $0.95 * 0.1\mu s + 0.05 * (0.1\mu s + 1\mu s) = 0.15\mu s$
 - 5% of data in L1 and 95% in L2?

Looks in L1 first
then L2

Memory

● Performance Example

- 2 levels of memory (L1,L2)
 - T1 @ $0.1\mu\text{s}$ (1kb) faster but scarce
 - T2 @ $1\mu\text{s}$ (100kb) slower but plenty
- What's the average access time if...
 - 95% of data in L1 and 5% in L2?
 - $0.95 * 0.1\mu\text{s} + 0.05 * (0.1\mu\text{s} + 1\mu\text{s}) = 0.15\mu\text{s}$
 - 5% of data in L1 and 95% in L2?
 - $0.05 * 0.1\mu\text{s} + 0.95 * (0.1\mu\text{s} + 1\mu\text{s}) = 1.05\mu\text{s}$
 - It's to our advantage to have frequently accessed data in faster memory locations

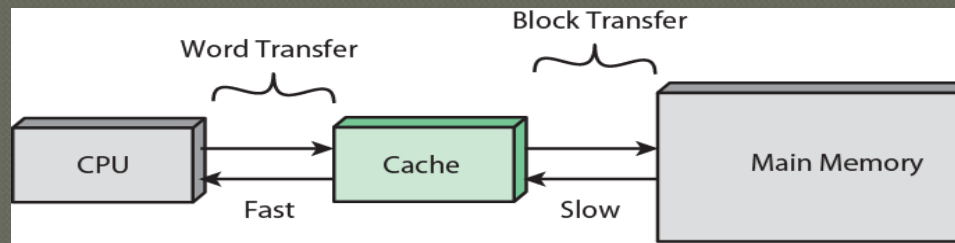
What if you have 3 levels?

reason why caches exist

Memory

● Cache

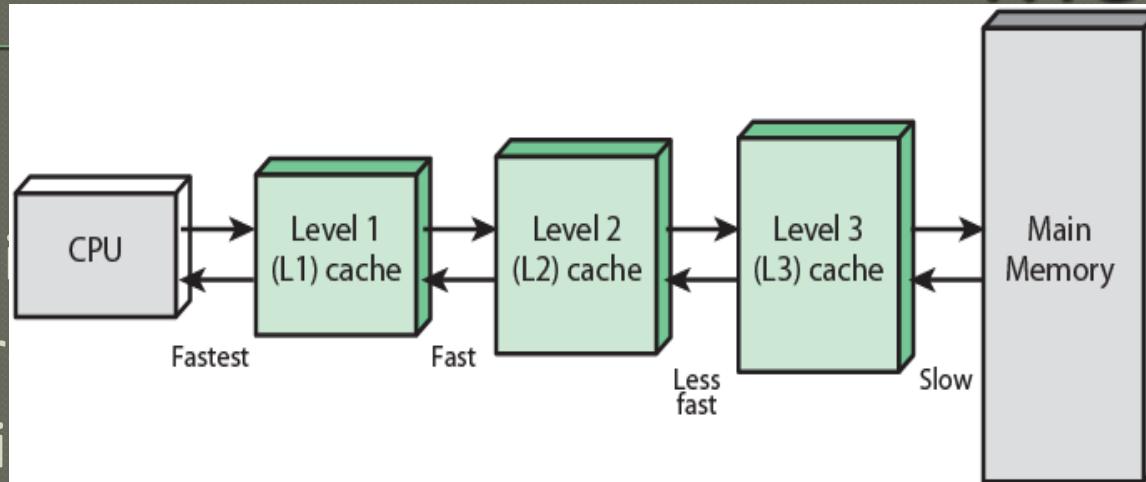
- Exploits the Principle of Locality
- Controlled by hardware (i.e., it is invisible to OS)
- Principles
 - Contains a copy of a portion of main memory
 - CPU checks cache for data
 - **if found**: use data
 - **if not found**: reads block of data from memory (where data is) and copies it into cache



Memory

Cache

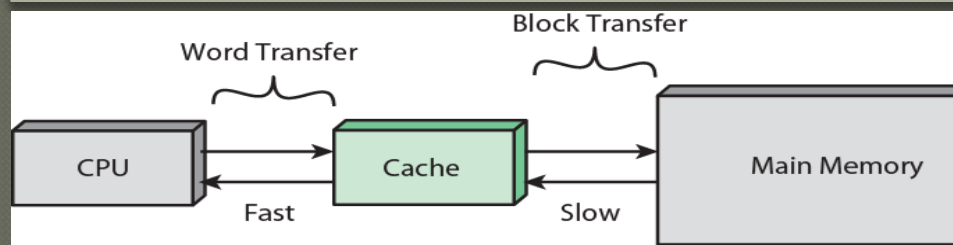
- Explo
- Contr
- Principi



- Conta
- CPU c
- if found
- if not found
- copies in

In practice:
several levels are common

data is) and



● Cache Design

- Cache size
 - Even small caches decrease access times
- Cache block
 - Unit of data exchanged between cache and memory
 - Too small: less data than needed (overhead: constant exchanges).
 - Too large: more data than needed (overhead: storing unused data).
- Mapping function
 - Finds location in cache of a newly read block
 - If space needed, an existing block is replaced

Topics

- Basic Elements

- Processor, main memory, I/O modules, system bus

- Microprocessors

- General purpose, graphics, digital signal, system on chip

- Instructions

- Execution, fetch & execute (F&E), instruction register

- Interrupts

- Types, flow of control, F&E&I, multiple interrupts

- Memory

- Hierarchy, principle of locality, cache

- I/O Techniques

- Programmed, interrupt-driven, direct memory access

- Symmetric multi-processors

- Advantages, organization, multi-core

I/O Techniques

* When the processor encounters an instruction relating to I/O, it executes that instruction by issuing a command to the appropriate I/O module

Three techniques are possible for I/O operations:

Programmed I/O

Interrupt-Driven I/O

Direct Memory Access (DMA)

I/O Techniques

What does the CPU do when finding an I/O (read/write) instruction?

◉ 1) Programmed I/O

- CPU waits for completion of command and periodically checks the status of the I/O module until it determines the instruction is complete
 - 1. CPU sends I/O command to I/O module
 - *If writing, CPU transfers data.*
 - 2. CPU waits until I/O module completes command.
 - *If reading, CPU transfers data*
 - 3. CPU resumes execution
- Extreme Inefficiency!

Remember the 1 sec verses
16 weeks example?

I/O Techniques

What does the CPU do when finding an I/O (read/write) instruction?

◎ 2) Interrupt-driven I/O

- CPU keeps executing while I/O command is completed
 - 1. CPU sends I/O command to I/O module
 - *If writing, CPU transfers data.*
 - 2. CPU resumes execution.
 - 3. I/O module triggers an interrupt when command is done
 - *If reading, CPU transfers data*
 - 4. CPU resumes execution
- No wait, but CPU still heavily involved in data transfer

I/O Techniques

● 2) Interrupt-driven I/O Drawbacks

- Transfer rate is limited by the speed with which the processor can service a device
- The processor is tied up in managing an I/O transfer since a number of instructions must be executed for each I/O transfer

I/O Techniques

What does the CPU do when finding an I/O (read/write) instruction?

③ Direct Memory Address (DMA)

- Performed by a separate module on the system bus (DMA)
- CPU keeps executing while I/O command is completed by DMA module
 - 1. CPU sends I/O command, memory address (where data is read or written), data size and I/O module to DMA
 - 2. CPU resumes execution.
 - 3. I/O module triggers an interrupt when command is done (including data transfer)
 - 4. CPU resumes execution
- No wait & CPU doesn't transfer data (may have bus contention though)

I/O Techniques

③ 3) Direct Memory Address (DMA)

- Transfers the entire block of data directly to and from memory without going through the processor
 - processor is involved only at the beginning and end of the transfer
 - processor executes more slowly during a transfer when processor access to the bus is required
- More efficient than interrupt-driven or programmed I/O
- But DMA module uses bus, so CPU might have to wait

Chapter 1 Topics

- Basic Elements

- Processor, main memory, I/O modules, system bus

- Microprocessors

- General purpose, graphics, digital signal, system on chip

- Instructions

- Execution, fetch & execute (F&E), instruction register

- Interrupts

- Types, flow of control, F&E&I, multiple interrupts

- Memory

- Hierarchy, principle of locality, cache

- I/O Techniques

- Programmed, interrupt-driven, direct memory access

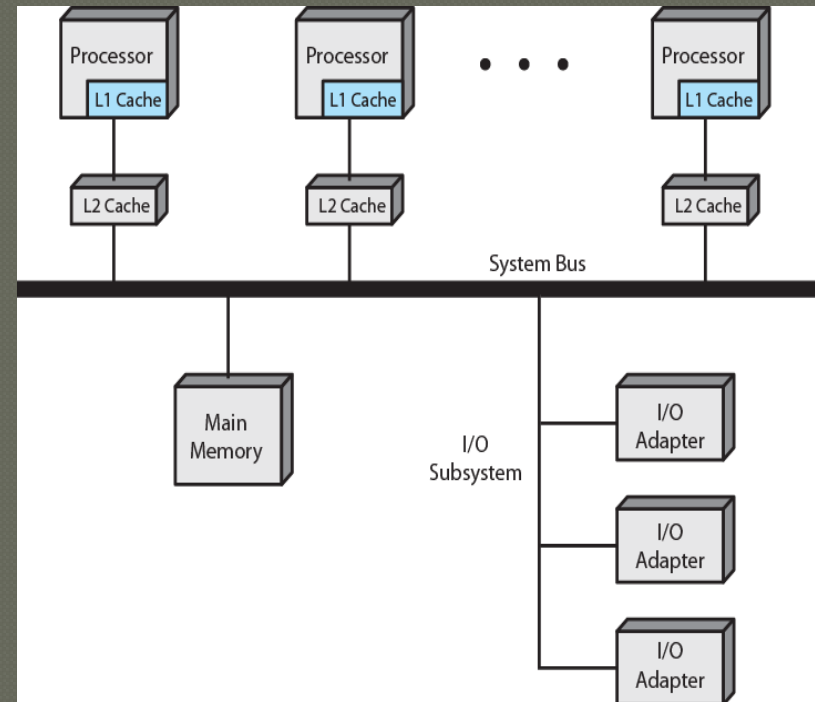
- Symmetric multi-processors

- Advantages, organization, multi-core

Symmetric Multi-Processors

- A stand-alone computer system with:

- 2+ similar processors:
 - capable of performing the same functions
- which (physically):
 - are interconnected by a bus
 - share memory & I/O devices
- are controlled by an OS that
 - provides interaction between processors and their programs (at the job, task, file, and data levels)



Symmetric Multi-Processors

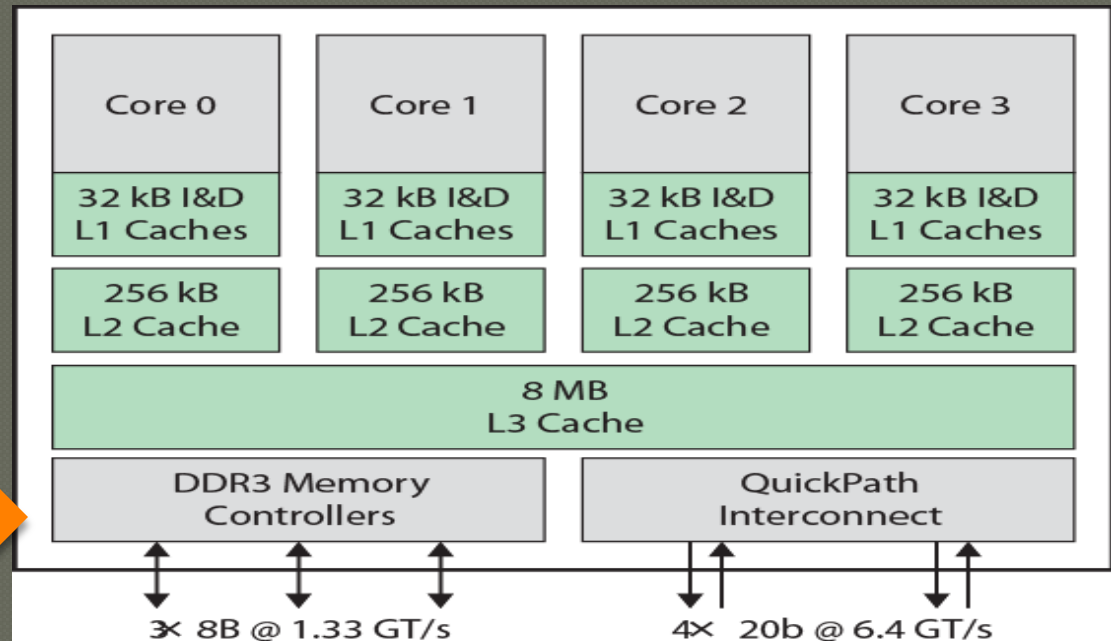
● Advantages

- Performance
 - can yield greater performance (if OS can handle work in parallel)
- Availability
 - failure of one processor does not halt the machine
- Scaling
 - additional processors result in a range of products of different price and performance

Symmetric Multi-Processors

Multi-Core

- 2+ processors (cores) in 1 micro-chip
 - each core has all components of an independent processor (including 2 or 3 cache levels)
- Intel Core i7
 - 4-8 cores
 - 8 Mb L3 cache
 - Intel Iris Pro GPU



Topics

- Basic Elements
 - Processor, main memory, I/O modules, system bus
- Microprocessors
 - General purpose, graphics, digital signal processor, system on chip
- Instructions
 - Execution, fetch & execute cycle, instruction register
- Interrupts
 - Types, flow of control, multiple interrupts
- Memory
 - Hierarchy, principle of locality, cache
- I/O Techniques
 - Programmed, interrupt-driven, direct memory access
- Symmetric multi-processors
 - Advantages, organization, multi-core

Done!