# Computer systems

## course "Essentials of computing systems"

Feb.2022

# contents

# contents

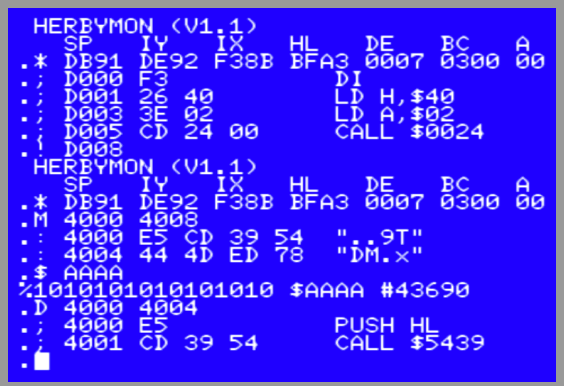
# computer

- A computer is a device that can do work for its users by executing instructions given to it.
- A computing device is considered as a computer if it has the following characteristics:
  - **Data-dependent instruction sequence**. A computer must include conditional branch constructors, whose execution depends on values that can only be calculated during execution time.
  - **Data-dependent data selection**. A computer must be able to use data to determine the actual data to be used in calculations.
- It is a calculator if it lacks either or both characteristics.

# program

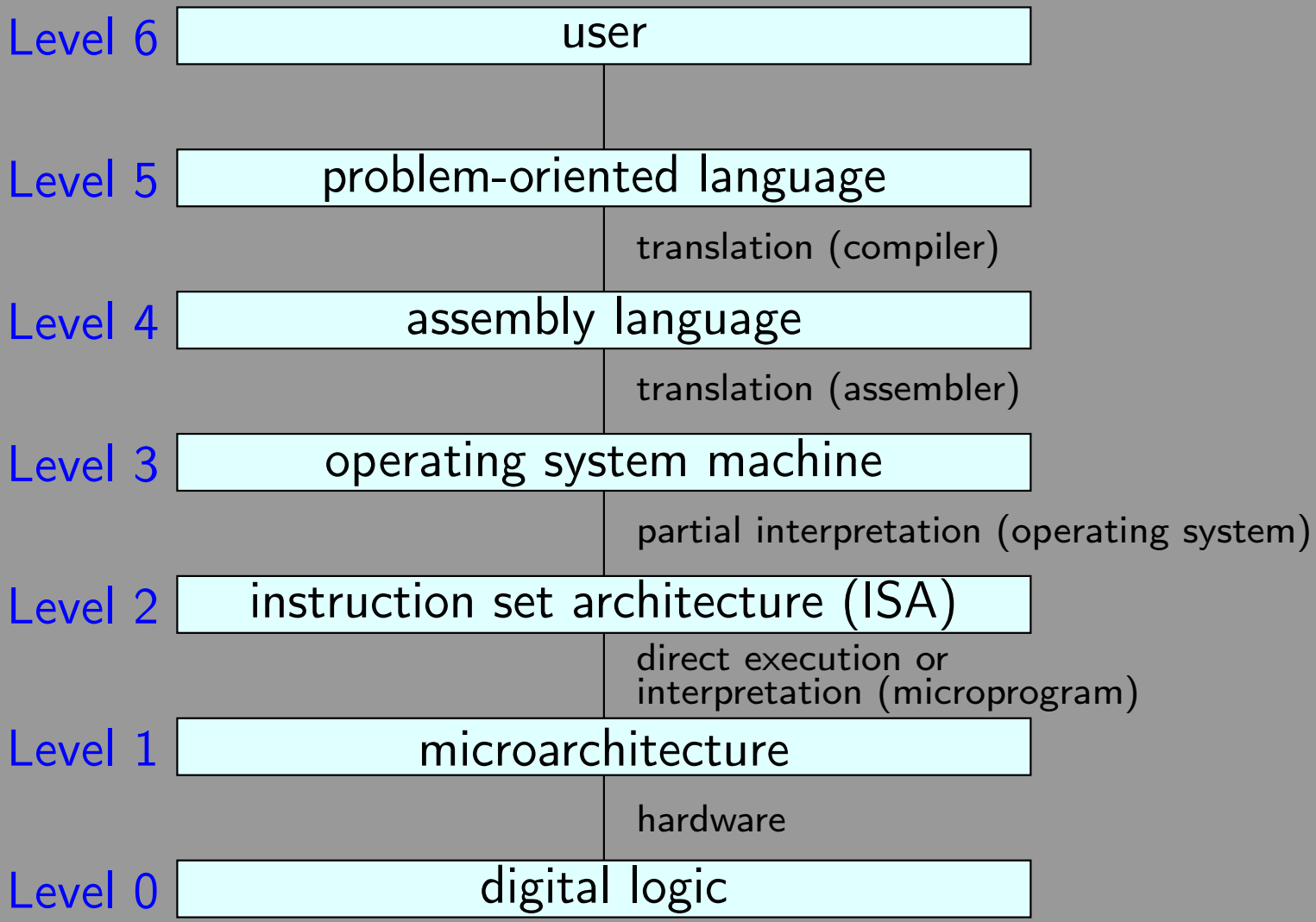
- The sequence of instructions that describe the task to be performed is the program.
- The electronic circuits of each computer are able to directly execute a limited set of simple instructions, into which all its programs must be converted before they can be executed.
- These simple instructions are operations like:
  - add two numbers;
  - test if a number is equal to zero;
  - copy a piece of data from one part to another;
  - decide what instruction to execute next based on the evaluation of some logical condition.

# machine language




- The primitive instructions constitute a language, called a machine language.
- Programmers use these instructions to operate the computer.
- Programming with machine languages is usually difficult and tedious for people.
- The machine language exists mainly to be executed by the computer.
- New languages can be constructed on top of the machine language to rise the abstraction level.

# a seven-level computer



# Levels 4 and 3

- A fundamental frontier exists between levels 4 and 3.
- The lowest three levels are intended for running the interpreters and translators needed to support the highest levels.
- These interpreters/translators are developed by systems programmers (specialised in constructing virtual machines).
- Levels 4 and above are intended for the applications programmer with a given problem to solve in a specific domain.
- The machine languages of levels 1, 2, and 3 are numeric.
- Programs in these levels consist of long series of numbers (bits), which are appropriate for machines.
- At level 4 and above, the languages contain words and mnemonics that humans are able to easily understand.

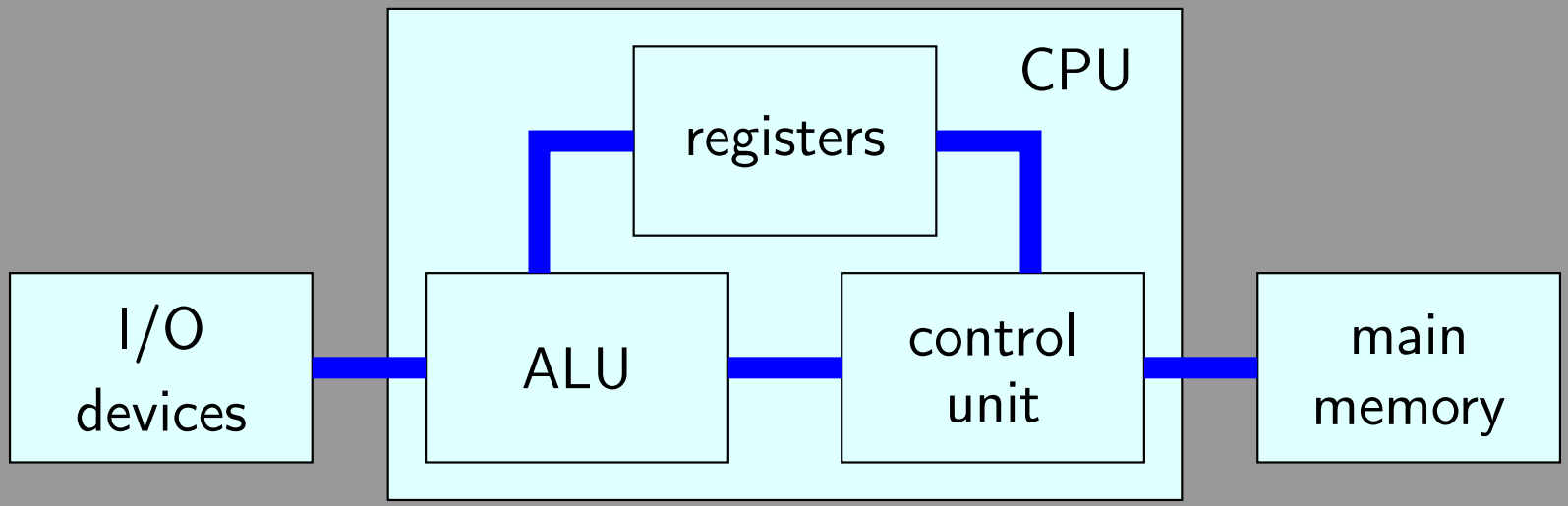
# programmer's perspective

- Each level represents a distinct abstraction of the computer, with different concepts, objects and operations.
- This division is convenient as it permits those that work at a given level to be unaware of what happens in the other levels.
- From a programmer's perspective, it is relevant to understand how computers work at the lower levels.
- Whenever a program written in a high-level language is not behaving as expected, it is seldom necessary to analyse what happens at the lower levels.

# contents

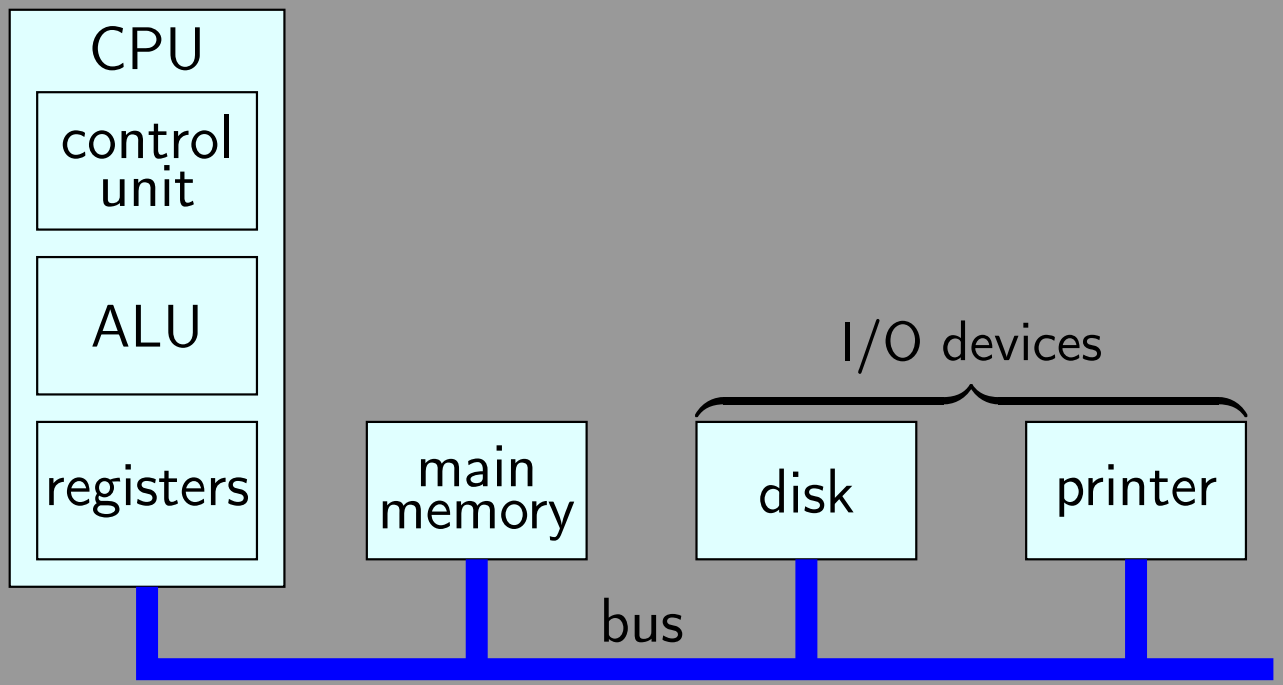
# von Neumann architecture

- A computer is a complex system that contains millions of electronic components.
- To describe a computer, it is essential to follow an hierarchical approach.
- Almost all uniprocessor (or scalar) computers follow the so-called von Neumann architecture.



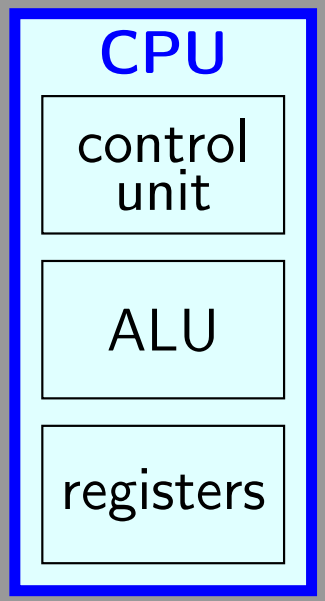
# von Neumann architecture

- The von Neumann architecture has been extended in several ways to address some of its limitations.
- A well-known proposal is the inclusion of a system bus that connects the components of the computer.
- The system bus has three main elements: data bus, address bus, and control bus.



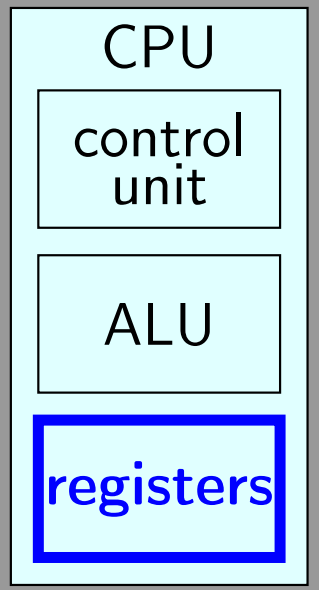
# central processing unit (CPU)

- The CPU is the "brain" of the computer.
- The CPU is responsible for the execution of the program, stored as a sequence of machine language instructions in the main memory.
- Each instruction directs the CPU to perform some basic task.
- The CPU does all this mechanically, without understanding what is the purpose for executing the instruction.
- The CPU is composed of several distinct components: control unit, ALU, and registers.



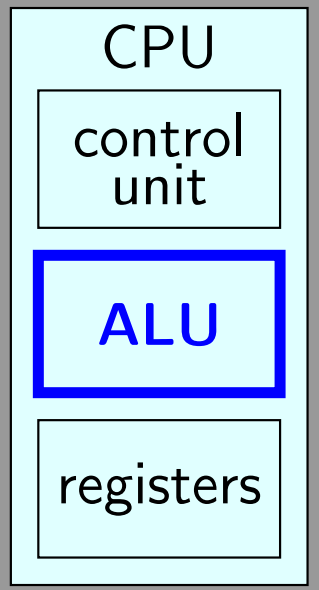
# registers

- The CPU contains a small number of high-speed memory registers.
- A register is used to store temporary results and status information.
- All the registers have usually the same size.
- Registers can be read and written at a very high speed, since they are internal to the CPU.
- The instruction pointer (IP) indicates the address of the next instruction to be executed.
- The instruction register (IR) stores the instruction currently being executed.



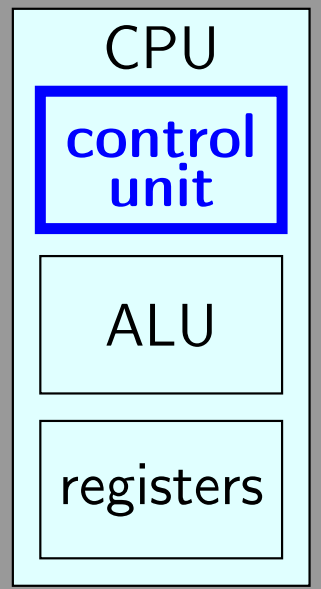
# arithmetic logic unit (ALU)

- The ALU performs basic operations such as addition, subtractions, and comparisons.
- Usually, an ALU has two data inputs and one data output.
- The operations carried on by the ALU affect the status registers, which indicate attributes related to the last arithmetic or logic operation.
- The operation that the ALU performs is signalised by the control unit, based on the instruction that is executed in each instant.



# control unit

- The control unit is responsible for orchestrating the components of the computer.
- It ensures that the instruction that is being executed produces its expected effects.
- This is accomplished by activating in the right sequence the control signals that are sent to the computer components.
- This process is repeated indefinitely, while the computer is powered on.
- The CPU receives an instruction from the memory, decodes it, and executes it using data obtained from the memory or stored in the registers.
- When the execution of an instruction is finished, the cycle starts again for the next instruction.



# fetch-decode-execute cycle

- The control unit can be seen as a cyclic (micro)program that goes through the set of steps to execute the instructions of another program.
- The fetch-decode-execute cycle is a central to the operation of computers, since they all just execute instructions:
  1. Fetch the instruction from memory and store it into the IR.
  2. Determine the type of instruction.
  3. If a word in memory is used by the instruction, determine its location.
  4. Store the word into a CPU register, if needed.
  5. Produce the effects of the instruction, i.e., perform some simple operation dictated by the instruction.
  6. Change the IP to refer to the next instruction.

# clock

- Most computer systems have a clock signal that acts like a heartbeat.
- The clock regulates the passage of time within the computer.
- A clock emits periodically a pulse.
- A clock cycle is the time between two consecutive ticks (represents one discrete time unit).
- The different operations performed by a processor are synchronised by the clock.
- All these operations begin with the pulse of the clock.
- The speed at which the instructions are executed depends on the frequency of the clock (cycles per second or Hertz).

# main memory

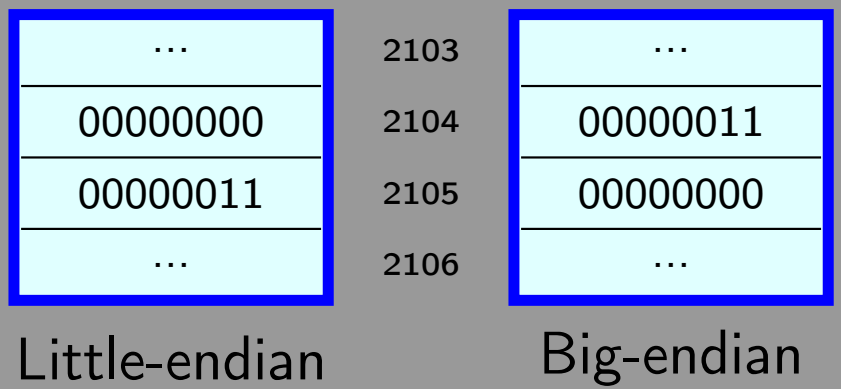
- The main memory is the component of the computers, where programs and data are both stored.
- A memory consists of a number of cells or locations, each of which can store a piece of information.
- Each cell has a number, called its address, by which programs can refer to it.
- A memory with $n$ cells uses addresses from 0 to $n - 1$.
- All cells in a memory contain the same number of bits.
- The main memory is a random-access memory (RAM).
- RAM memories are volatile, which means that the information disappears if the supply voltage is turned off.

# bytes and words

- The cell is the smallest addressable unit.
- Almost all modern computers use 8-bit (1 byte) cells.
- Bytes are grouped into words (a computer with a 32-bit word has 4 bytes/word).
- The word is also important since most instructions operate on entire words, for example, adding two words together.
- A 32-bit machine has 32-bit registers and instructions for manipulating 32-bit words.

# little- and big-endian

- When storing a multibyte value in a byte-addressable memory, the order of the individual bytes is relevant.
- The number 11 0000 $0000_2$ requires two bytes of memory: 0000 $0000_2$ and 0000 $0011_2$.

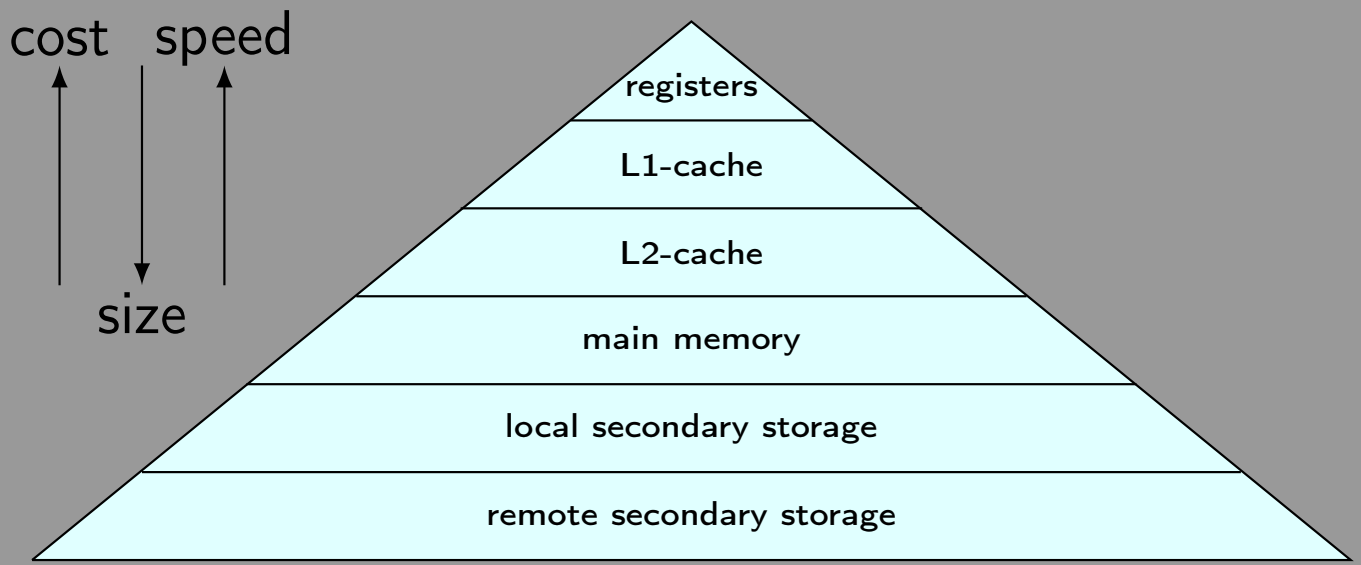


# stored-program computer

- Digital computers possess a great versatility, as they can execute whatever programs their users wish.
- This flexibility is related to the ability of a computer to load the programs in its internal memory.
- By changing the program in the memory, one changes the problem the computer is solving.
- This justifies the notion of a stored-program computer, one that can be used for any problem.
- During a computation, a given instruction may also be modified, i.e., changed to a different instruction
- This gives rise to self-modifying code, which is straightforward to perform at the machine-level.

# memory hierarchy

- The main memory of a computer is never enough.
- The traditional solution to store a great quantity of data is to use a memory hierarchy.




- The aim is to establish a system with cost almost as low as the cheapest level and speed almost as fast as the fastest level.
- All data in a given level can be found in the next lower level.

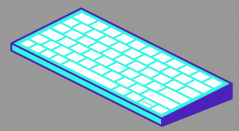
# memory hierarchy

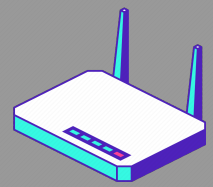
| **level** | **1** | **2** | **3** | **4** |
|---|---|---|---|---|
| name | registers | cache | main memory | disk storage |
| typical size | $<$ 1 kB | $<$ 16 MB | $<$ 512 GB | $>$ 1 TB |
| implementation | CMOS | SRAM | DRAM | magnetic disk |
| access time (ns) | 0.25–0.5 | 0.5–25 | 50–250 | 5,000,000 |
| bandwidth (MB/s) | 50,000–500,000 | 5000–20,000 | 2500–10,000 | 50–500 |

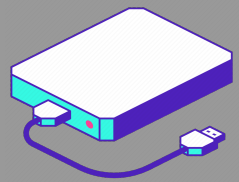
Adapted from [Hennessy and Patterson; 2007]

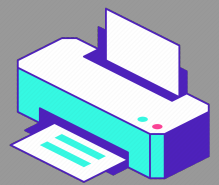
# I/O devices

- Computers are built so that they can be expanded with new I/O (input/output) devices: hard disk, keyboard, mouse, monitor, printer, network interface, scanner.
- An I/O device is a hardware system used by humans or systems to communicate with a computer.
- The CPU must communicate with and control these devices.
- For each device, there is a device driver, which is software that the CPU executes when it has to deal with that device.
- A new device can be installed by connecting the device into the computer and installing its device driver software.
- The device driver allows the CPU to communicate with the respective device.









# polling

- When a given device produces data that needs to be processed, somehow the CPU needs to take some action.
- With polling, the CPU keeps checking for incoming data over and over.
- Whenever it detects that data was made available by the device, it processes it.
- Polling is very simple, but is also very inefficient.

# interrupts

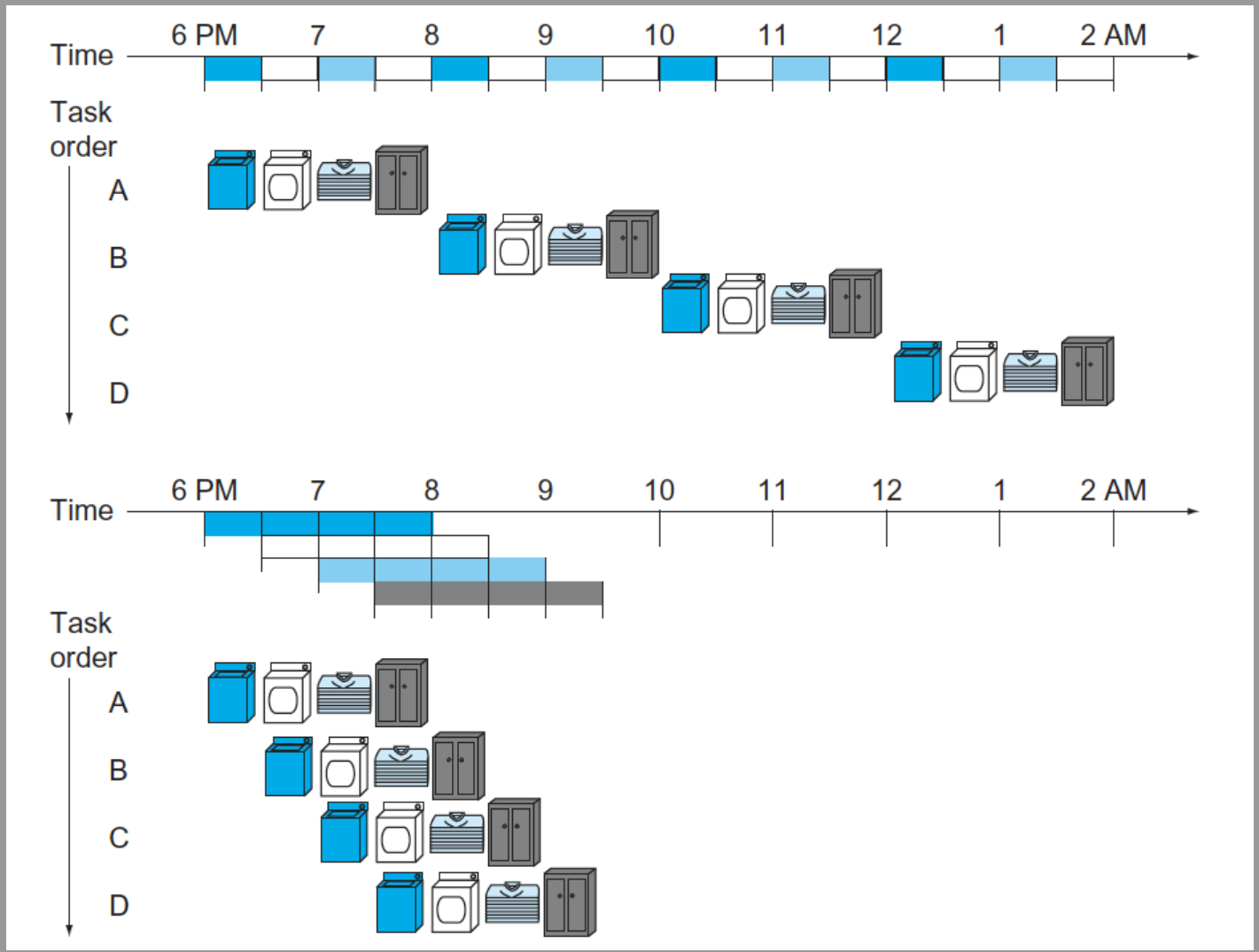
- Interrupts are generally used instead of polling.
- An interrupt is a signal sent by a device to the CPU to request its attention.
- The CPU reacts by suspending what it is doing to answer to the interrupt.
- The CPU saves information about what it is currently doing so that it can return to it afterwards.
- Then the CPU jumps to some fixed memory location and begins executing the instructions stored there.
- Those instructions correspond to the interrupt handler that does the processing necessary to respond to the interrupt.
- Once the interrupt is processed, the CPU returns to the process that was suspended.

# contents

# improving computers

- Improving the characteristics of computers, like performance, cost, reliability, energy consumption, is a concern for computer engineers and architects.
- Performance is an inescapable issue, since making computers run faster is always relevant.
- One possible approach is to exploit parallelism, which can have different forms: instruction-, data-, and processor-level.
- Instruction-level parallelism with pipelining explores individual instructions to obtain higher throughput.

# pipeline analogy



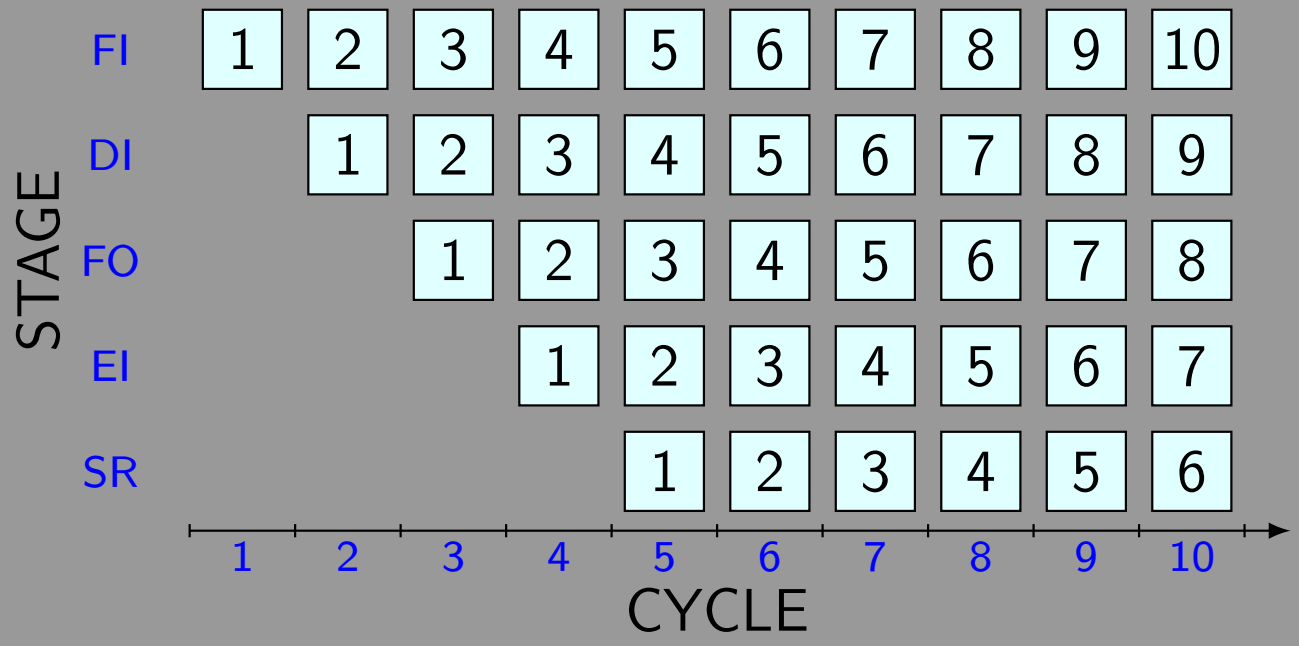

Patterson and Hennessy, Computer organization and design, 5th ed., Morgan Kaufmann, 2014.

# pipeline

- With pipelining, the process of executing instructions is divided in stages.
- Multiple instructions can be overlapped in execution.
- Each stage is responsible for a part of the process and all can run in parallel, thus speeding up the process.

# ideal operation of the pipeline

- Stages operate in parallel, which accelerates the process.
- Pipelining increases the number of instructions that are simultaneously under execution.
- Instruction throughput (number of instructions completed per time unit) is improved.
- Latency (time that is required to complete each individual instruction) is maintained.

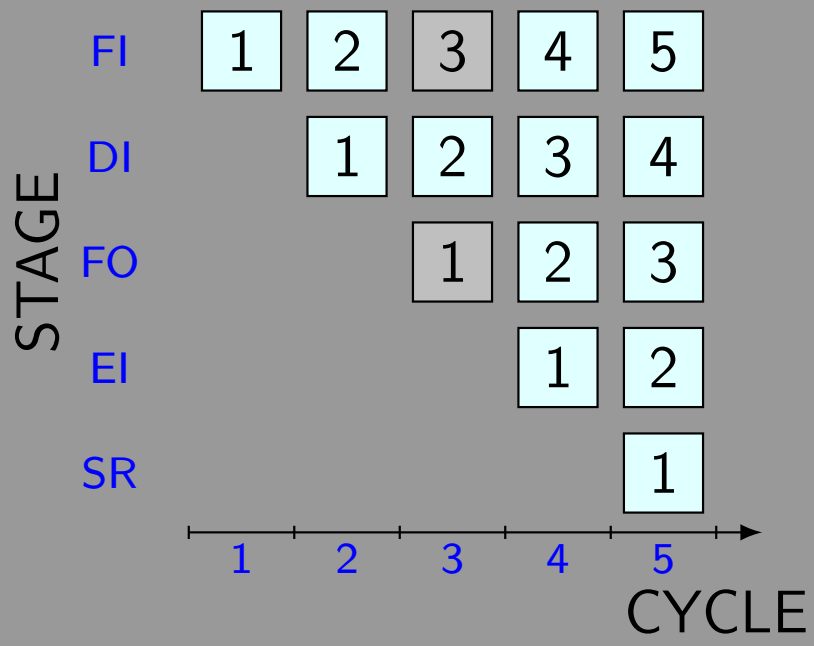


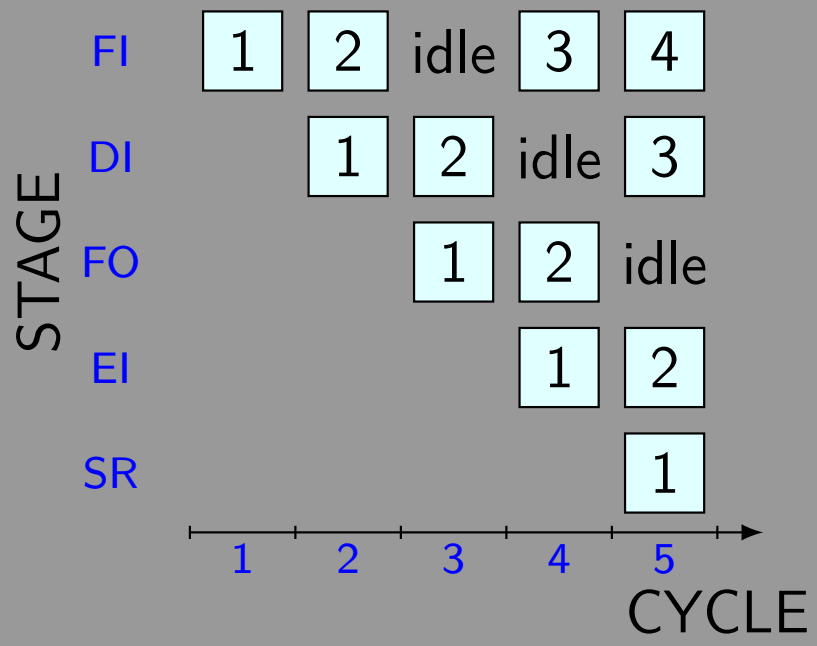
# aspects affecting pipeline

- The maximum theoretical speed up is very unlikely to occur in practice, because it is difficult to balance the time it takes to complete each stage.
- All stages must be equally balanced, otherwise the faster stages must wait for the slower ones.
- Three major aspects negatively affect the theoretical speed up:
  1. resource conflicts,
  2. data dependencies,
  3. conditional branch statements.

# Resource conflicts

- A resource conflict occurs whenever two pipeline stages need to simultaneously access the same resource (e.g., memory).



# data dependency

- A data dependency occurs whenever the result of one instruction, not yet available, is also the operand of a subsequent instruction.
- Some solutions exist to handle these conflicts.
- By inserting a delay (e.g., a `nop` instruction) into the pipeline, sufficient time passes and the conflict disappears.
- Some architectures assume that this problem is solved by the compiler, which must reorder instructions.

# branch instruction

- Problems in the pipeline may also be caused by a branch instruction that modifies the normal flow of a program.
- If the conditional branch is taken, the subsequent instructions must not be executed and the pipeline must be emptied.
- Some architectures predict the outcome of a conditional branch to try to identify the instructions that will be executed next.
- In some cases, compilers try to solve branching issues by rearranging the machine code to cause a delayed branch.
- Another alternative is to initiate fetches on both paths of the branch. When the branch is actually executed, the correct path is identified and the pipeline can be safely continued.