COMP1001

Computer Systems

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Outline

- Von Neumann architecture
- What is the CPU?
- How CPU works?
  - Arithmetic Logic Unit (ALU)
  - Control Unit (CU)
  - Bus
  - Memory
  - Registers
  - Clock
- Memory Hierarchy
- Secondary Memory

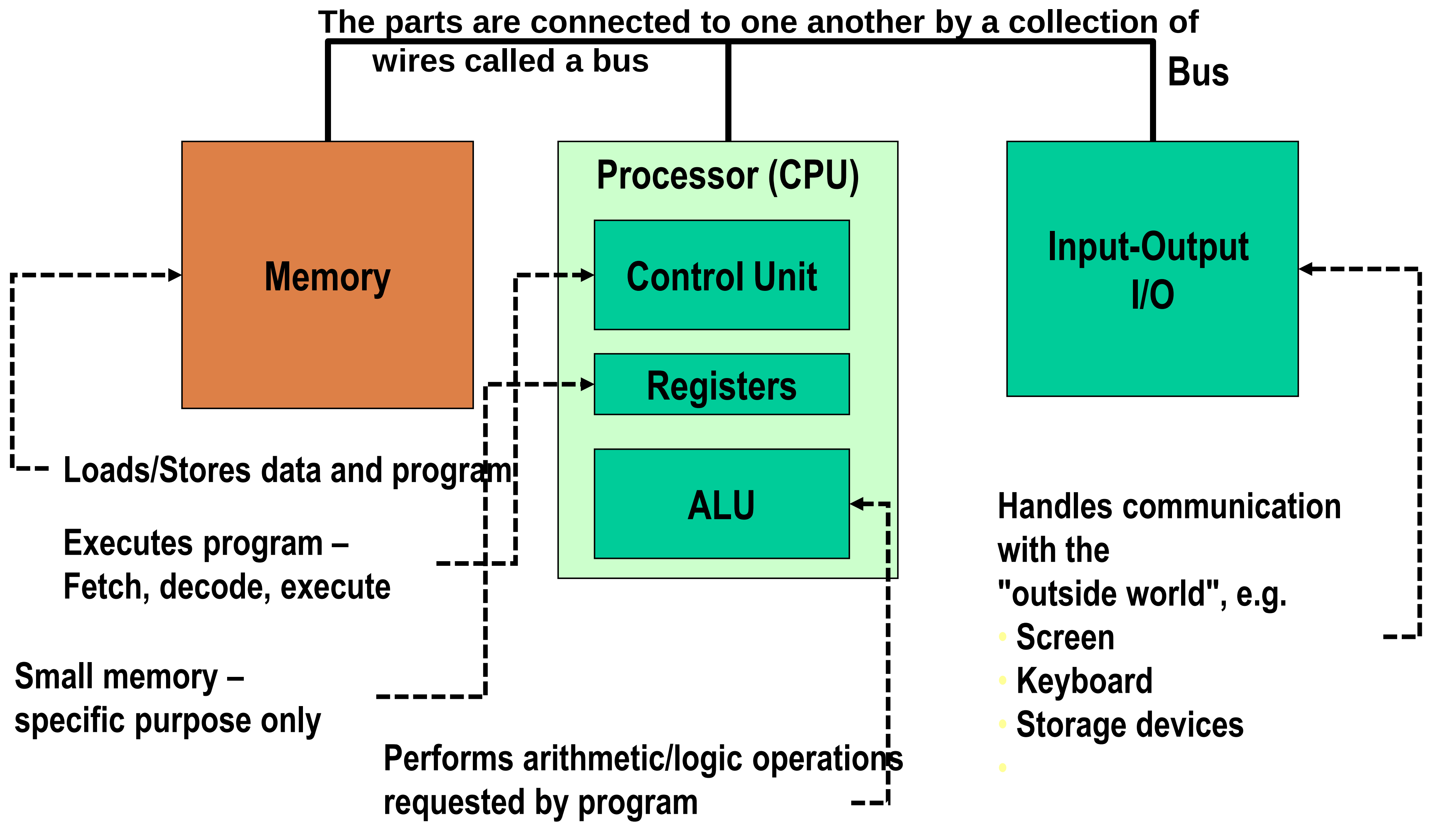
The Von Neumann Architecture

- All computers more or less based on the same basic design, the **Von Neumann architecture**
- It is a Model for designing and building computers, based on the following three characteristics:
  1. The computer consists of four main sub-systems:
     - Memory
     - ALU (Arithmetic/Logic Unit)
     - Control Unit
     - Input/Output System (I/O)
  2. Program is stored in memory during execution
  3. Program instructions are executed sequentially

✓ The architecture is named after the mathematician, John Von Neumann

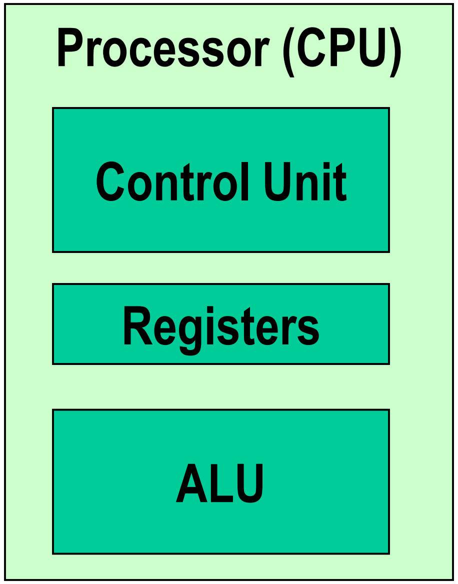
✓ A variation of this architecture is the **Harvard** architecture which separates data and instructions into two pathways

The Von Neumann Architecture



Central Processing Unit (CPU)

- CPU is responsible for **fetching** program instructions, **decoding** each instruction that is fetched, and **executing** the indicated sequence of operations **on the correct data**
- **The key parts of the CPU are**
  1. **Arithmetic Logic Unit (ALU)**
  2. **Control Unit (CU)**
  3. **Registers**
  4. **Clock**

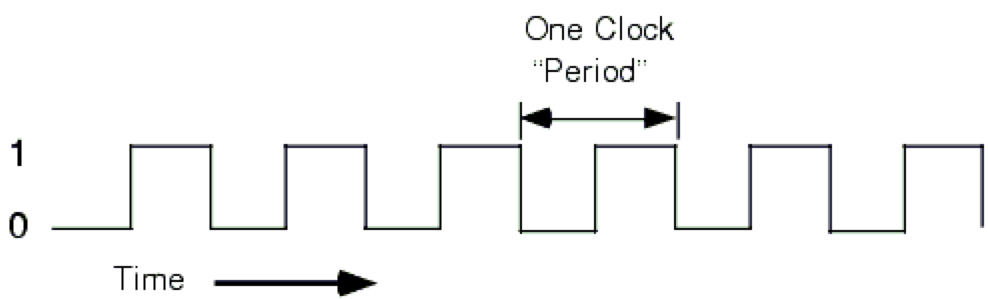


Central Processing Unit (CPU)

- Carries out the program's instructions!
- Operates on data it finds in the computer's memory
  - Includes all binary circuits that carry out arithmetic & logic operations- reduced to a single Integrated Circuit
- **CPU has four key parts that we will examine: Control Unit, Arithmetic & Logic Unit, Registers, Clock**
- CPUs support a set of very simple instructions that typically fall into the following categories:
  - Data movement (load, store, copy…)
  - Arithmetic/logical (add, subtract, compare..)
  - Program control (branch, jump…)
- Very primitive commands (operations) executed by the CPU
- These commands are implemented as electronic binary circuits which can transform the 0s and 1s.

CPU Clock (1)

- **Every computer contains an internal clock that regulates the rate at which instructions are executed and synchronizes all the various computer components**
- All CPU and bus operations are synchronized to the clock
- Clock speeds are expressed in megahertz (MHz) or gigahertz ((GHz)
  - the beginning of each cycle is when the clock signal goes from “0” to “1”
  - e.g. CPU frequency 2 GHz -> clock cycle 0.5 ns
  - In the computer, all timings are measured in terms of clock cycles, e.g., an addition needs 2 cycles



CPU.Freq.=1 / clock.period

CPU Clock (2)

- The faster the clock, the more instructions the CPU can execute per second
- But, to think that clock and performance is the same thing is the most common misconception about processors

- CPU frequency is not necessarily indicative of the execution speed; e.g. complex operations, cache misses etc
  - FLOPS: floating operations per second, a useful measure for (super)computers dedicated to extensive computations
- A typical modern PC now has either four or five different clocks, running at different (but related) speeds, e.g., system (memory) bus, L2 cache bus, PCI bus
- The entire system is tied to the speed of the system clock.
  - Normally, the processor spends a significant amount of time waiting on data and signals from much slower devices, e.g., memory

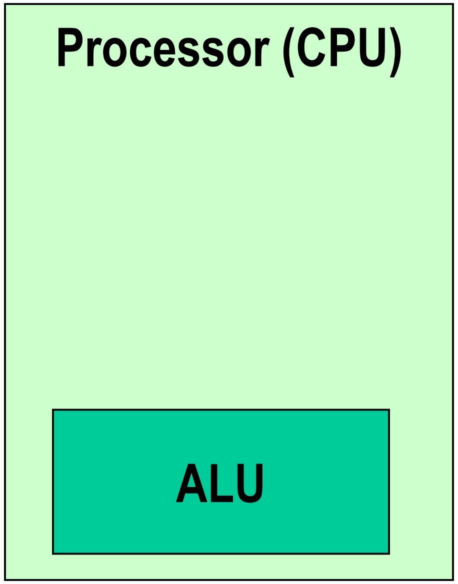
Registers

- In a computer, a register is the fastest memory
- Registers are fast stand-alone storage locations that hold data temporarily

- Multiple registers are needed to facilitate the operation of the CPU
- The main registers are:
  - The Instruction Register (IR)
  - The Program Counter (PC) or Instruction Pointer (IP)
  - Data registers

ALU (1)

- The arithmetic logic unit (ALU) carries out the **logic operations** (such as comparisons) and **arithmetic operations** (add, shift, multiply) required during the program execution
- **The ALU must know**
  1. Which operation to perform
  2. Where are the input data
  3. Where to store the output data
  - All the above are provided by the CU
- **The ALU performs**
  1. **Integer** arithmetic operations
     - Add, subtract, increment, decrement
  2. Bitwise logical operations
     - AND, OR, XOR, NOT, Arithmetic shift, logical shift, rotate



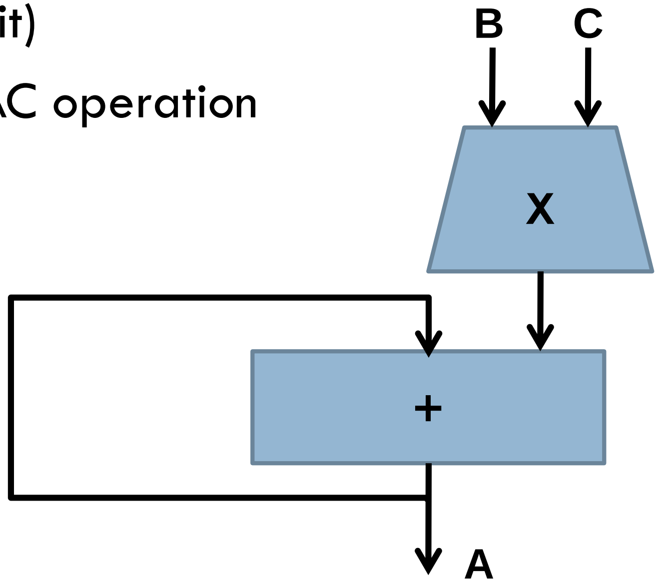
ALU (2)

- ALUs often handle the multiplication of two integers, since the result is also an integer
- ALUs typically **do not perform division operations,** since the result may be a fraction, or a "floating point" number
- **The floating-point unit (FPU)** performs operations on floating point numbers
- Modern CPUs have separate unit to perform multiplication faster
- **Processors include a coprocessor hardware unit which is used to perform more complex mathematical operations such as arcsine, cosine, floating-point division, etc**

ALU (3)

- **The multiply-accumulate operation is a common step that computes the product of two numbers and adds that product to an accumulator**
- It speeds up many computations that involve the accumulation of products, e.g., Matrix-matrix Multiplication
  - The hardware unit that performs the operation is known as a Multiplier Accumulator unit (MAC, or MAC unit)
  - the operation is called MAC or MAC operation
  - The MAC operation performs

$$A = A + B \times C$$



ALU (4)

- **Arithmetic shift:** when shifting to the right, the leftmost bit (the vacant MSB) is filled with the value of the previous MSB (sign)
  - Ideal for signed two's complement binary numbers

- **Logical shift** : The vacant bits are filled with zero
  - the logical and arithmetic **left-shifts are exactly the same**
  - Ideal for unsigned binary numbers

- **Circular shift or bit rotation** : In this operation, the bits are "rotated" as if the left and right ends of the register were joined. The value that is shifted in on the right during a left-shift is whatever value was shifted out on the left, and vice versa
  - frequently used in digital cryptography

Control Unit (CU) (1)

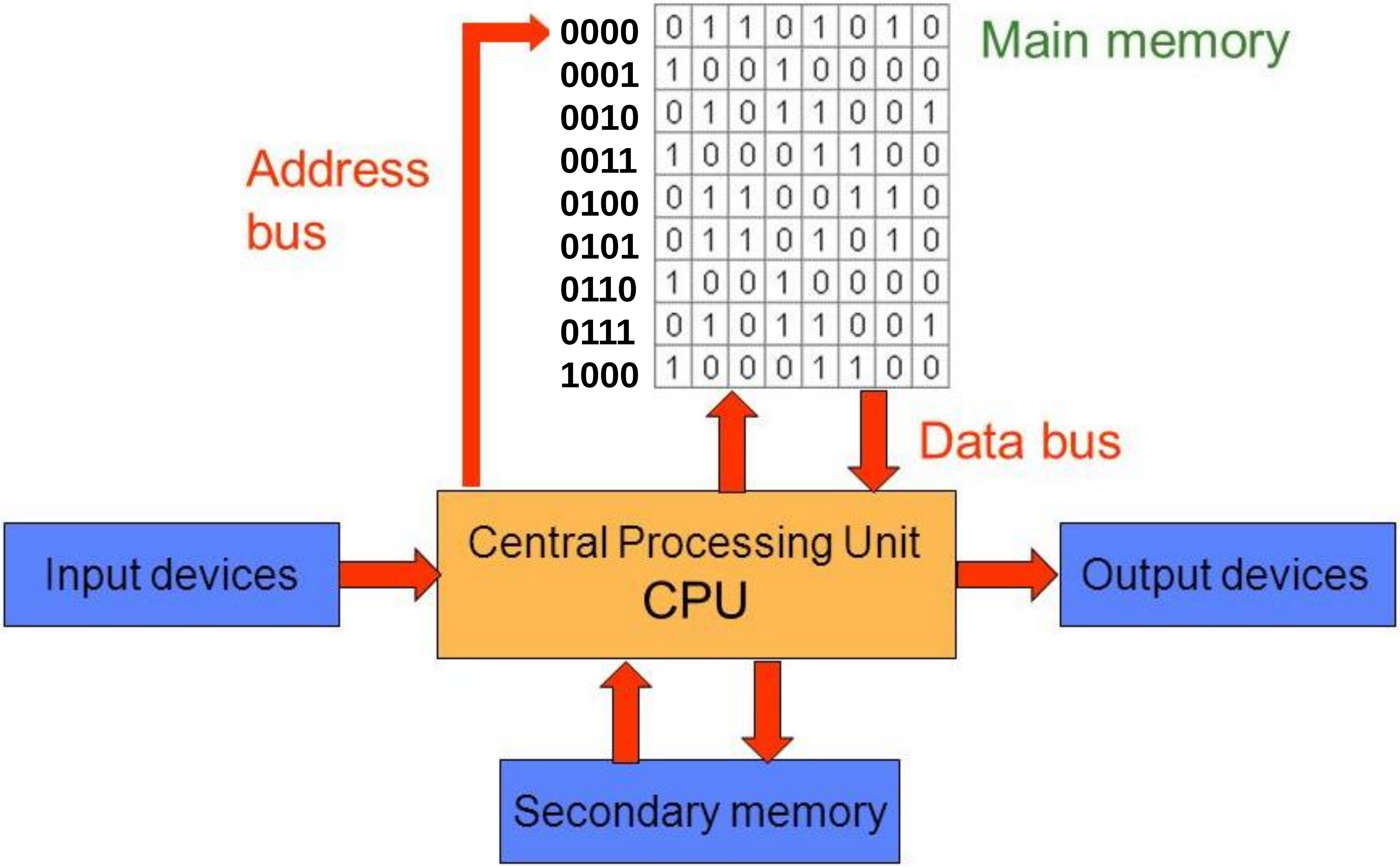
- A Control Unit is the unit that handles the central work of the computer
- **There are two registers in the control unit**
  - The **instruction register** (**IR**) contains the instruction that is being executed
  - The **program counter** (**PC**) contains the address of the next instruction to be executed

- **The CU is responsible of executing the right instruction and organizes the other function units appropriately**
- **In every clock cycle the CU:**
  - Loads from memory the next instruction to be executed – PC register contains that address
  - The instruction is stored into IR and is decoded
  - The CU sends the appropriate signals to the ALU, memory, I/O devices in order to execute the instruction
  - The CU increments PC to show next instruction

Control Unit (CU) (2)

- Program is stored in memory
  - machine language instructions are in binary format

- The task of the control unit is to execute programs by repeatedly:
  - Fetch from memory the next instruction to be executed
  - Decode it, that is, determine what is to be done
  - Execute it by issuing the appropriate signals to the ALU, memory, and I/O subsystems
  - Continues until the program terminates (HALT instruction)



Main memory
Address bus
0000
0001
0010
0011
0100
0101
0110
0111
1000
0 1 1 0 1 0 1 0
1 0 0 1 0 0 0 0
0 1 0 1 1 0 0 1
1 0 0 0 1 1 0 0
0 1 1 0 0 1 1 0
0 1 1 0 1 0 1 0
1 0 0 1 0 0 0 0
0 1 0 1 1 0 0 1
1 0 0 0 1 1 0 0
Data bus
Input devices
Central Processing Unit
CPU
Output devices
Secondary memory

Main Memory

- **Computer memory consists of a linear array of addressable storage cells that are similar to registers**
- Both program and data are stored into memory
- Load/store operations are performed on both instructions and data

- Consists of many memory cells (storage units) of a fixed size
  - **Each cell has an address associated with it**
- All accesses to memory are to a specified address
- The time it takes to fetch/store a word is the same for all words

Main Memory - Address Space

- To access a word in memory requires an identifier, e.g., *int temp*. Although programmers use a name to identify a word (or a collection of words), at the hardware level each word is identified by an address
- The total number of uniquely identifiable locations in memory is called the **address space**. For example, a memory with 1 kilobyte (2^{10}) and a word size of 1 byte has an address space that ranges from 0 to 1023

- **If memory contains N words, then $\log_2 N$ bits are needed to address all words in memory**
- **If the memory address space needs N bits, then there are 2^N words in memory**

Main Memory - Address Space (2)

Mem. Addr.	Data
00	0
01	1
10	2
11	3

Mem. Addr.	Data
000	0
001	1
010	2
011	3
100	4
101	5
110	6
111	7

- **If memory contains 4 words, then $\log_2 4 = 2$ bits are needed to address all words in memory**
- **If the memory address space needs 2 bits, then there are 2^2 words in memory**

Think Pair Share

1. A computer has 32 MB (megabytes) of memory. How many bits are needed to address any single byte in memory?

The memory address space is 32 MB, or 2^{25} bytes ($2^5 \times 2^{20}$). This means that we need $\log_2 2^{25}$, or 25 bits, to address each byte

2. If main memory is of 64Mbyte and every word is of 2 bytes how many bits do we need to address any single word in memory?

The memory address space is 64 MB, which means 2^{26} bytes. However, each word is two (2^1) bytes, which means that we have 2^{25} words. Note that (*Mem.size=number.words x word.size*)

This means that we need $\log_2 2^{25}$, or 25 bits, to address each word

Question1 in previous slide

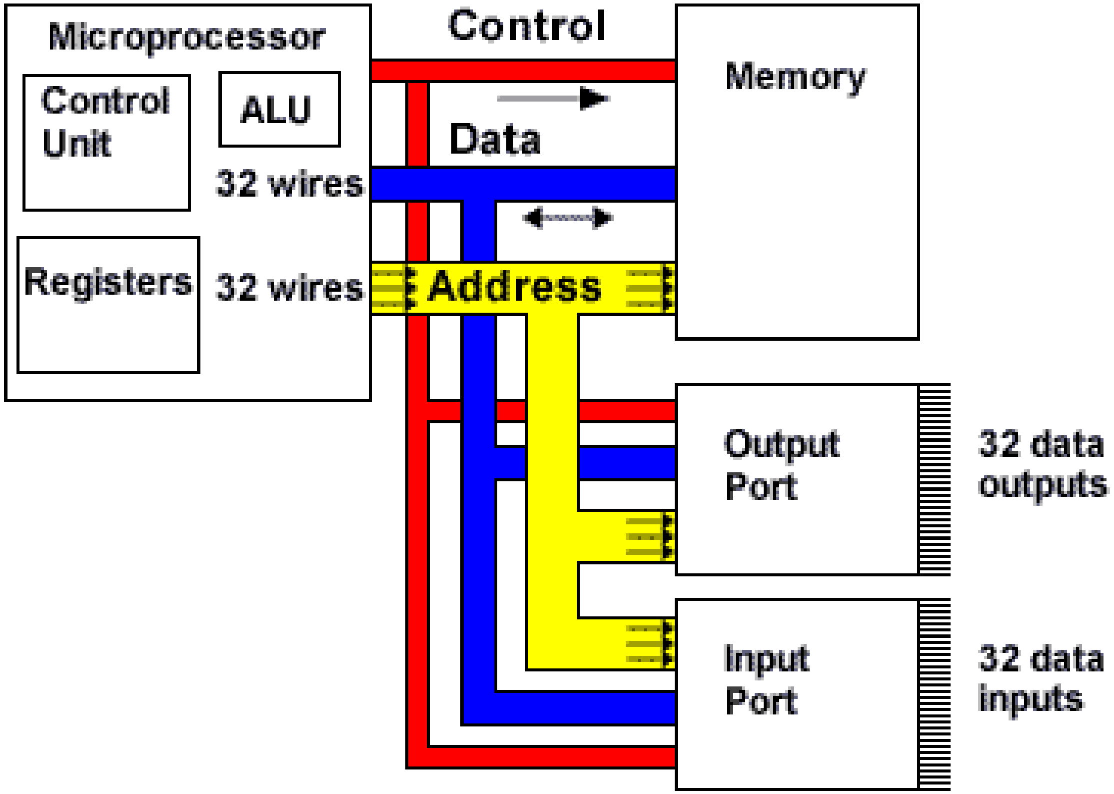
Mem. Addr.	Data
000	0
001	1
010	2
011	3
100	4
101	5
110	6
111	7

Question2 in previous slide

Mem.Addr.	Data	
00	0	1
01	2	3
10	4	5
11	6	7

How Main Memory and CPU are connected?

- Control Bus – sends appropriate signal whether store or load
- Address Bus – sends the memory address
- Data Bus – sends the data

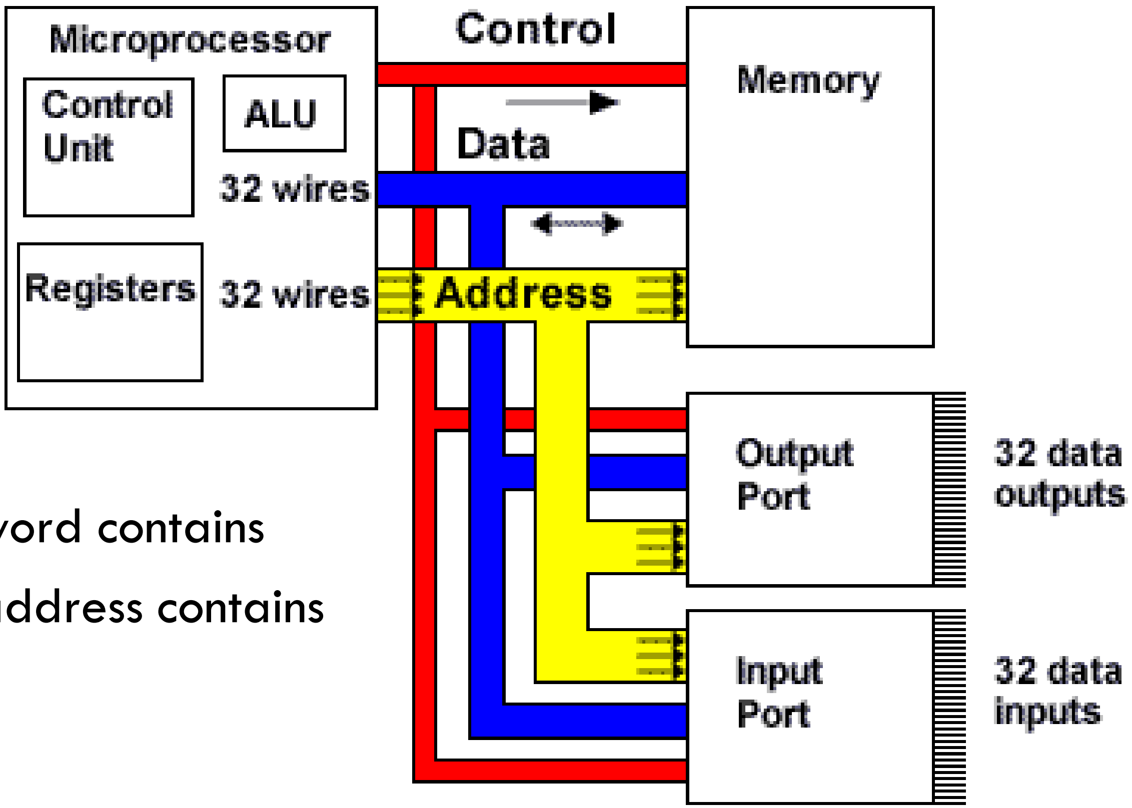


Buses (1)

- **Bus:** a group of wires that transfer data from one part to another (data, address, control)
  - ✓ **Data bus:**
    - bi-directional (read/write)
    - 8, 16, 32, 64-bit wide (same as 'word size')
  - ✓ **Address bus:**
    - specifies memory location in RAM/ROM/interface device to be accessed; monodirectional
    - address space: 16-bit wide -> 2^{16} words= $64x2^{10}$ = 64KB
    - 32-bit wide -> 2^{32} = 4GB – **this is why in 32-bit PCs we cannot use more than 4Gbyte of RAM**
  - ✓ **Control bus:**
    - carries commands from the CPU and returns status signals from the devices

Buses (2)

- How many wires needed for the?
  - A. Data bus?
  - B. Address bus?
  - C. Control Bus?



A. As many bits as the memory word contains

B. As many bits as the memory address contains

C. 1 bit is enough

Think Pair Share

Q: If main memory is of 64Kbyte and every word is of 8 bytes how many wires do we need for the address bus?

Assembly basic instructions

Depending on the target CPU, different assembly instructions exist

Instr:	Meaning:
Store 0xA2B , R1	Store R1 in $A2B_{16}$ memory location
ADD R1, R2	Add R1 and R2 and store the result in R1
SUB R1, R2, R3	R1 = R2- R3
MUL R1, R2	R1= R1 * R2
DIV R1, R2	R1= R1 / R2
INC R4	R4=R4+1
HALT	Stops program execution
CMP R1, 10	If R1==10, then set the register EQ=1, else EQ=0
JMP EQ S1	Load next instruction from memory location S1, if EQ==1

- **Assemblers** translate instructions that are comprehensible to humans into the machine language that is comprehensible to computers

Machine Language or Machine Code (1)

- A *program* consists of a sequence of instructions (in binary)
- EACH instruction specifies both:
  - The operation to perform
  - The address of the data

- Instructions are stored and processed in *machine language*--also called ***microcode***
- Like everything else (e.g. like ASCII characters) machine language consists solely of **bit patterns**

Machine Language or Machine Code (2)

- **A machine language instruction consists of:**
  - **Operation code,** specifying which operation to perform
  - **Address field(s),** specifying the memory addresses of the values on which the operation works

Opcode (8 bits)	Address 1 (16 bits)	Address 2 (16 bits)
00001001	0000000001100011	0000000001100100

- Instructions are given to the processor in the form of a program … so it knows what circuits to use, in what order; and from where the data should be read or to where it should be stored

Machine Language or Machine Code (3)

- **Machine languages consist entirely of binary numbers and are almost impossible for humans to read and write**
- **Assembly languages** have the same structure and set of commands as machine languages, but they enable a programmer to use names instead of numbers
- Each type of CPU has its own machine language and assembly language
  - an assembly language program written for one type of CPU won't run on another
- In the early days of programming, all programs were written in assembly language
- **Now, most programs are written in a high-level language** such as Java, Python, C/C++
- Programmers still use assembly language when speed is essential

High level language VS Assembly language

High Level Language (HLL)

a = x + y - z

Assembly Language (AL):

load x into r1

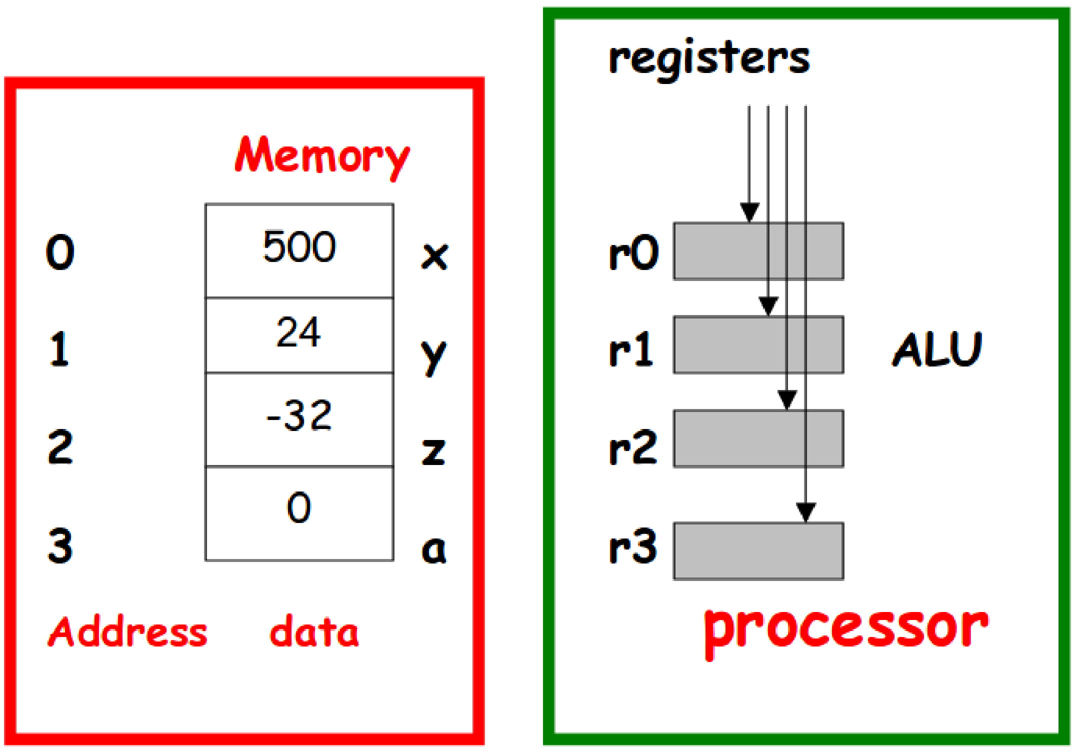
load y into r2

load z into r0

r3 ← r1 + r2

r0 ← r3 – r0

store r0 into a



- In HLL we write a=5 and we assume that it is stored somewhere – we don't care
- But the computer does not work like that – it has to store every variable in an exact memory location

- **In assembly we must specify the Hardware registers as well as the memory locations**

High level language VS Assembly language

- Easily understandable
- Portable - **run on just any computer**
- Debugging of the code is easy
- High level languages like java, C++, etc. have **one to many relationship with assembly,** i.e., one statement of java expands into many assembly language commands
- **High level language is always converted into assembly language**
- The high level language programmer doesn't need to know the HW details

- Hard to understand
- **Runs only on the target CPU only**
- Debugging is very hard
- **One to one or one to a few relationship**
- The assembly language programmer must know about the hardware such as registers, etc.
- Assembly language can control the machine code better
- **Assembly is much faster**

Program Execution

1. PC is set to the address where the first program instruction is stored in memory

2. Repeat until HALT instruction or fatal error

2a. Fetch instruction

- Fetches instruction (from memory) at address given by PC; copies it into storage register

2b. Decode instruction

- Copies op code into IR and operands into address registers
- Interprets instruction
- ALU is invoked

2c. Execute instruction

- Execution cycles vary, depending on the op code (instruction), e.g., Load copies data from memory to ALU register, ADD adds values inside the ALU

2d. Increment PC by one, now contains the memory address of the *next* instruction that will be fetched

A simplified example

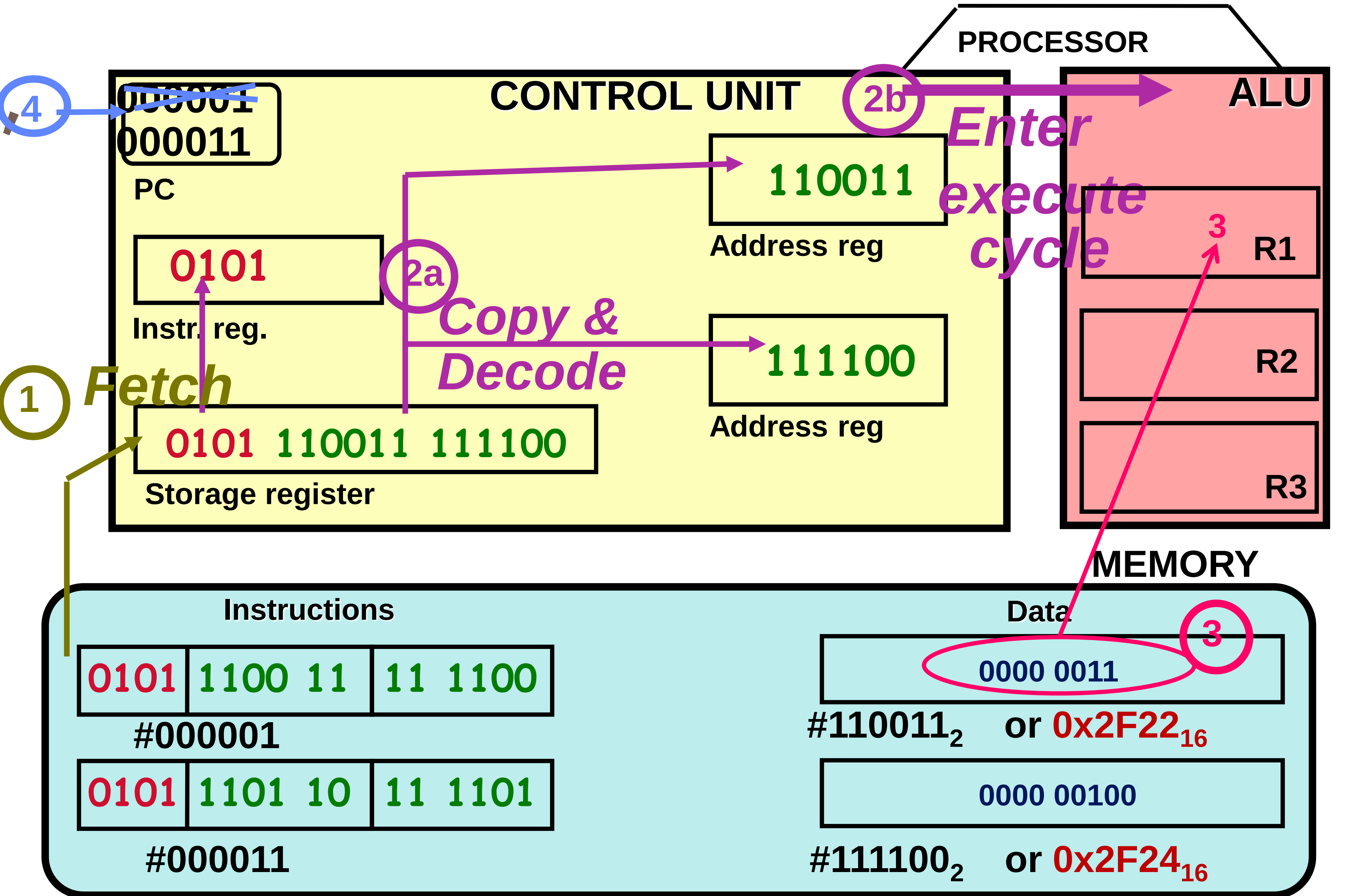
Load R1, 0x2F22

Load R2, 0x2F24

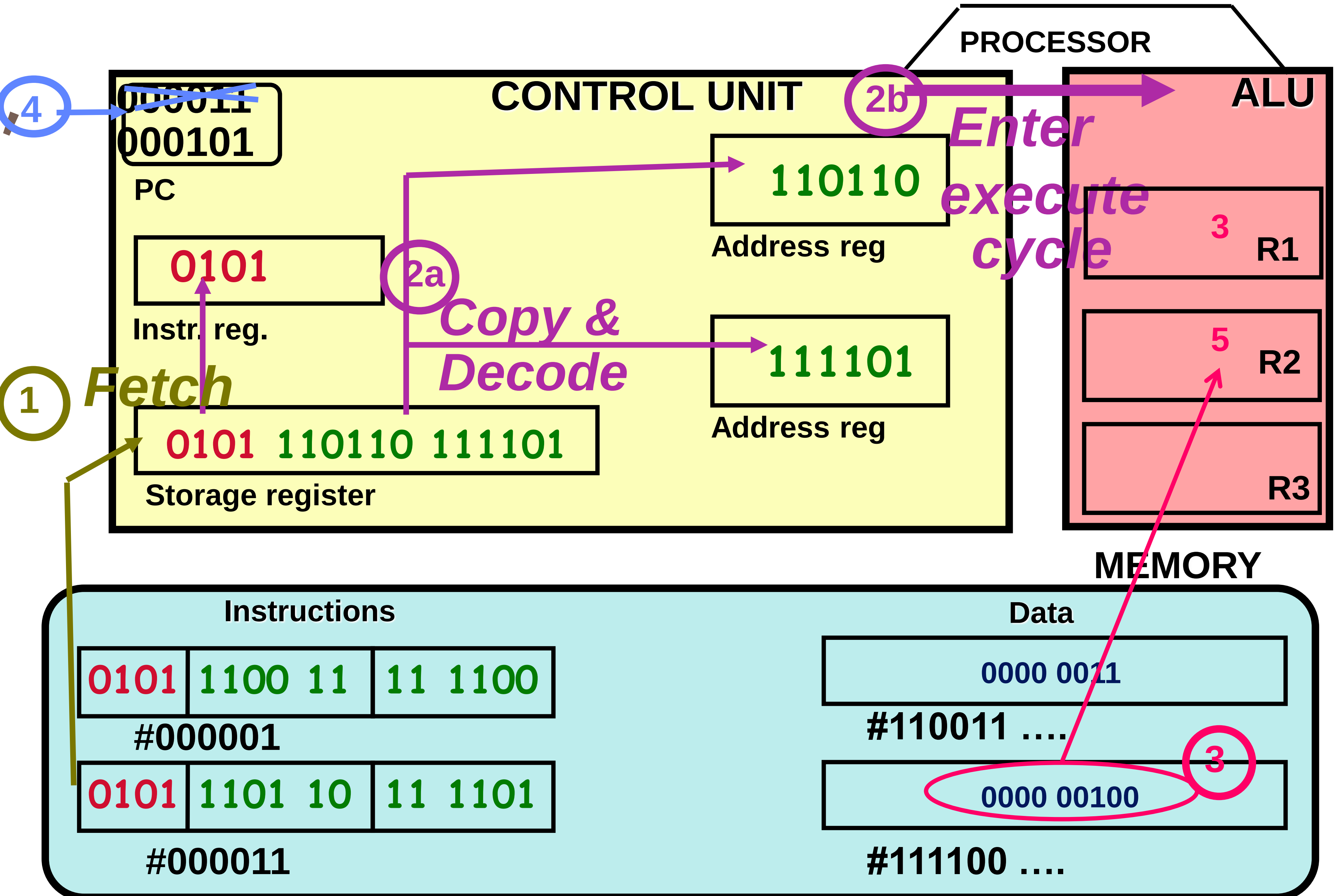
ADD R1, R2

Store 0x2F24, R1

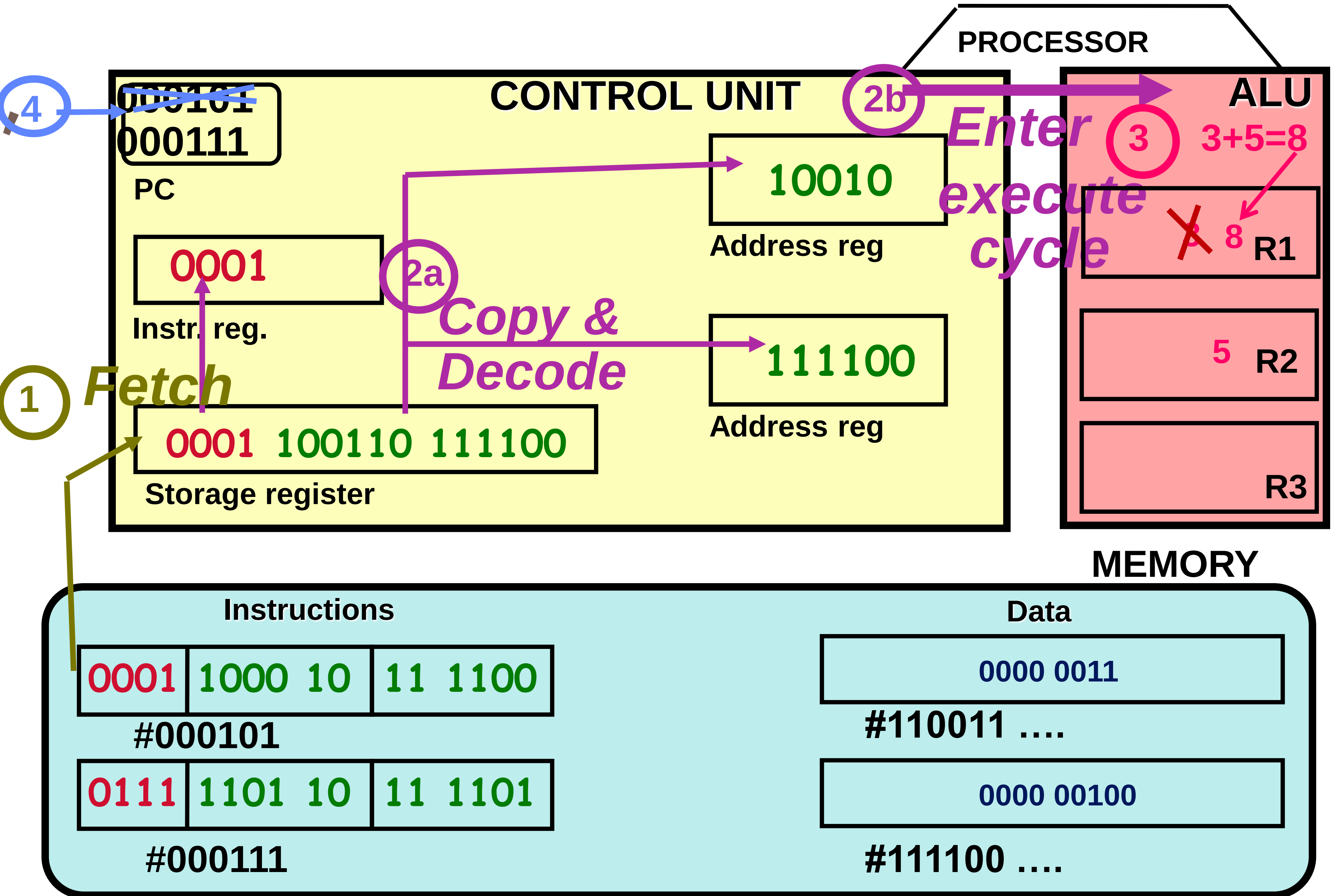
A simplified example



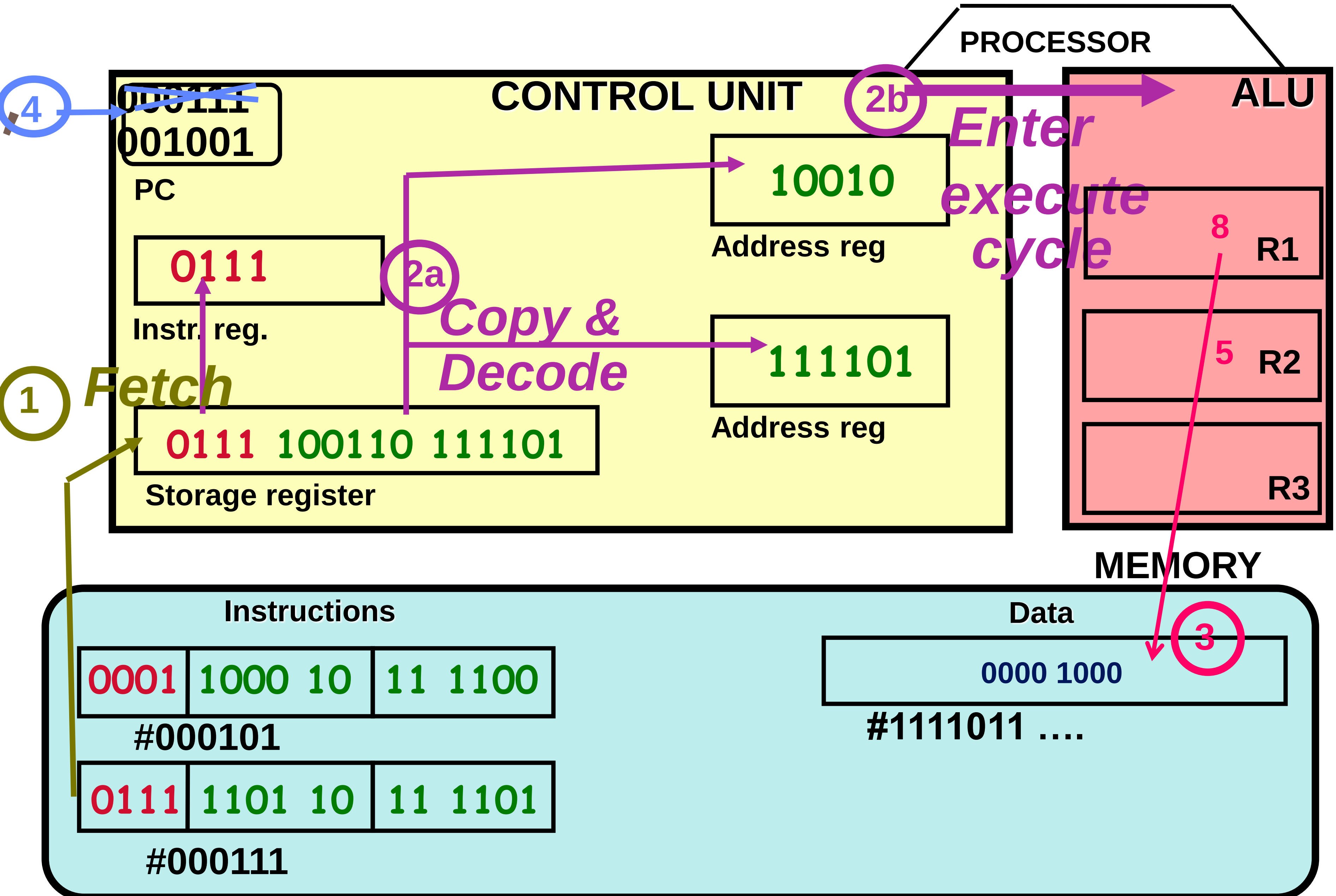
A simplified example

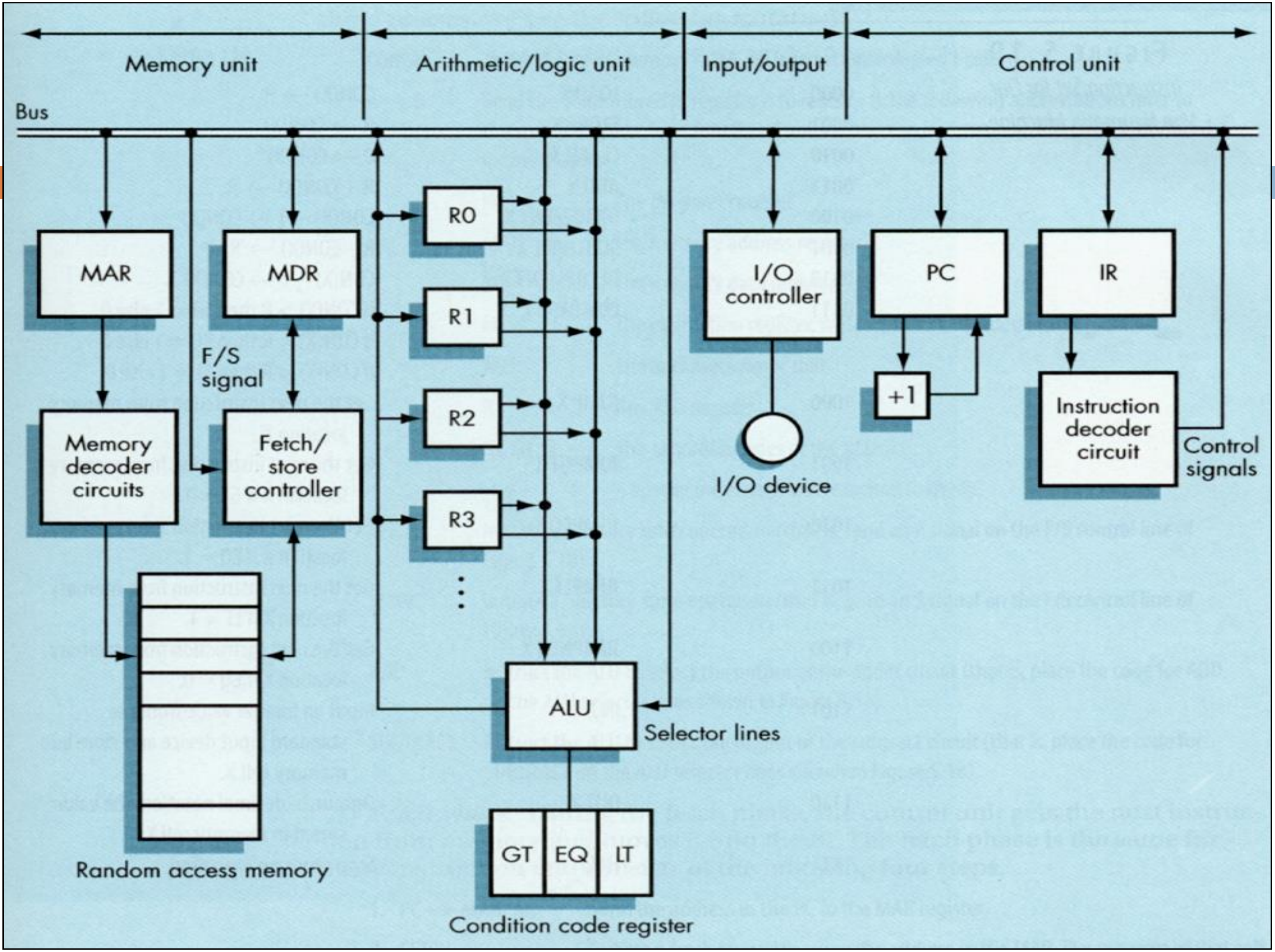


A simplified example



A simplified example



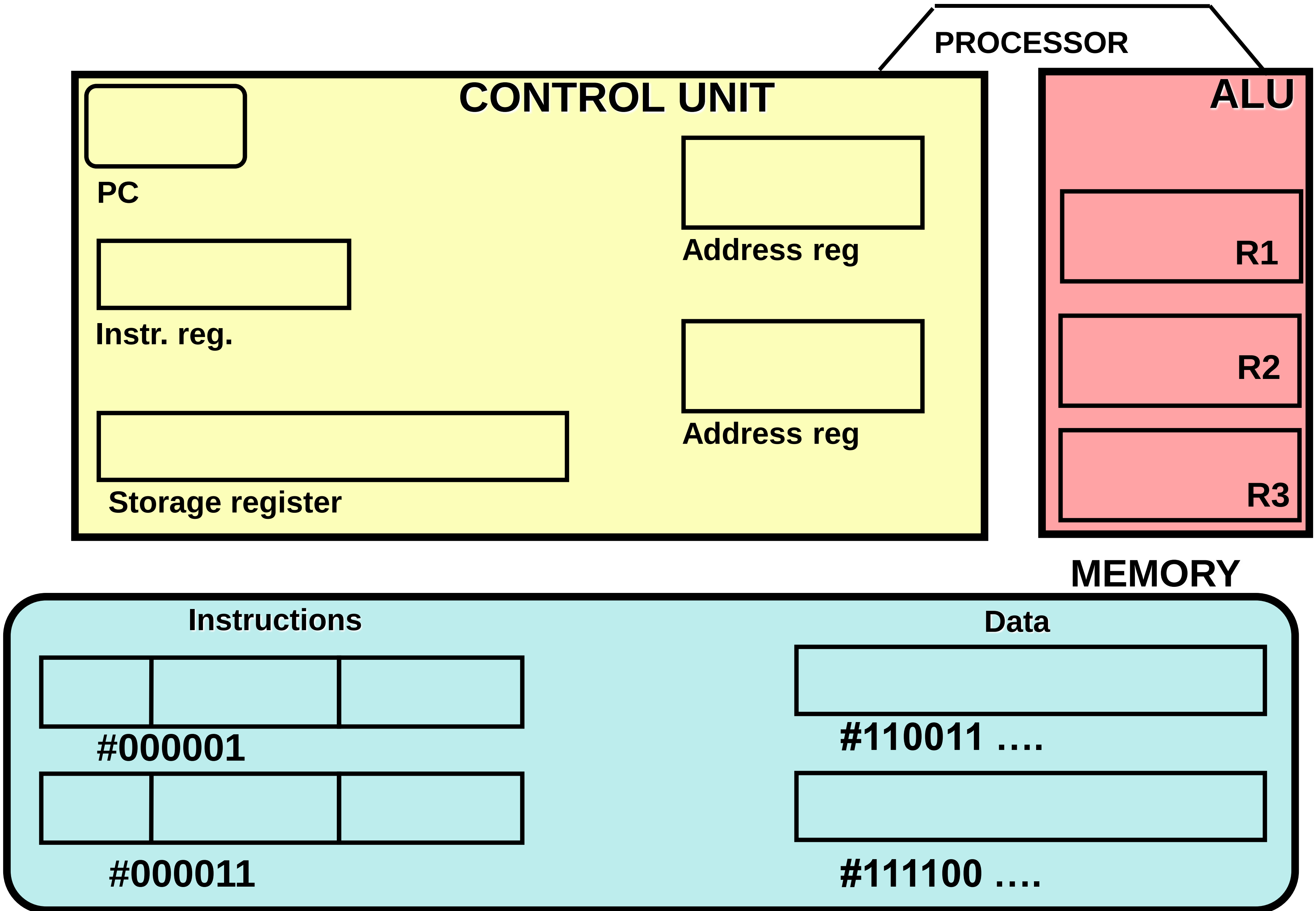

Memory unit
Arithmetic/logic unit
Input/output
Control unit
Bus
MAR
MDR
F/S signal
Memory decoder circuits
Fetch/ store controller
Random access memory
R0
R1
R2
R3
ALU
Selector lines
GT
EQ
LT
Condition code register
I/O controller
I/O device
PC
+1
IR
Instruction decoder circuit
Control signals

Think Pair Share

Given the following high level code, first translate it into assembly pseudo code and second explain the CPU steps as before. Consider that $a=0$, $x=2$, $y=3$, $z=4$.

$$a = x + y - z;$$

Think Pair Share



Memory Types (1)

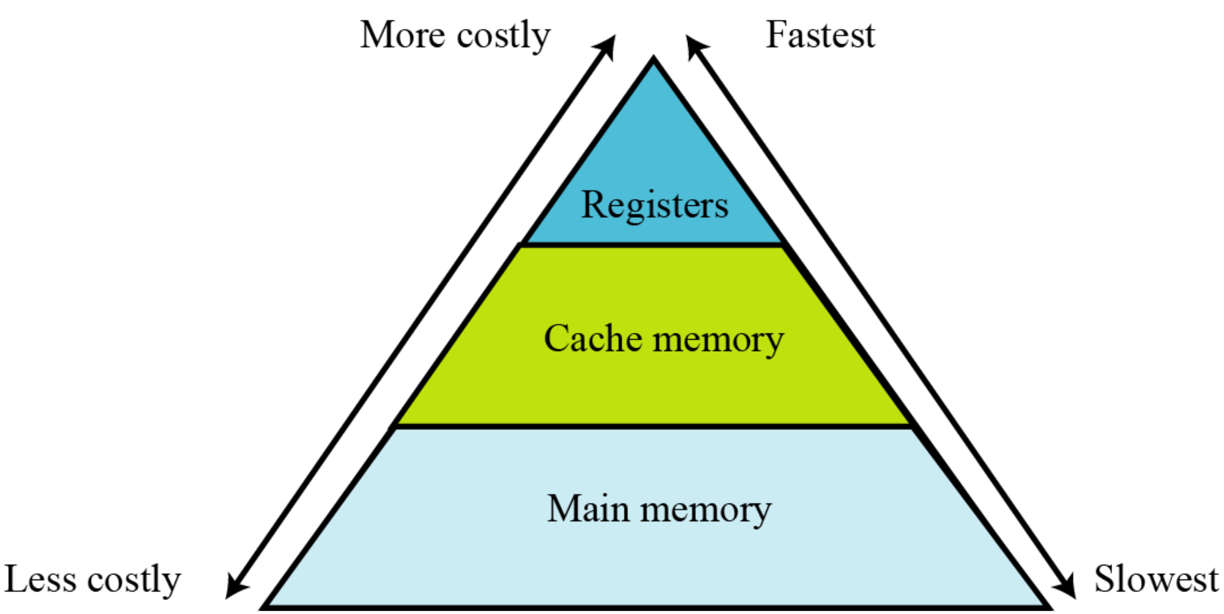
- Random Access Memory (RAM) - Alternatively **referred to as main memory**
  - Static RAM (SRAM) – fast but more expensive
  - Dynamic RAM (DRAM) – slow but cheap
  - Synchronous Dynamic RAM (SDRAM)
  - DDR SDRAM – Double Data Rate SDRAM (transferring data on both the rising and failing edges of the clock signal)
- Read Only Memory (ROM)
  - Programmable read-only memory (PROM)
  - Erasable programmable read-only memory (EPROM)
  - Electrically erasable programmable read-only memory (EEPROM)
- **RAM loses any information it is holding when the power is turned off**
- **ROM is meant for permanent storage, while RAM is for temporary storage**

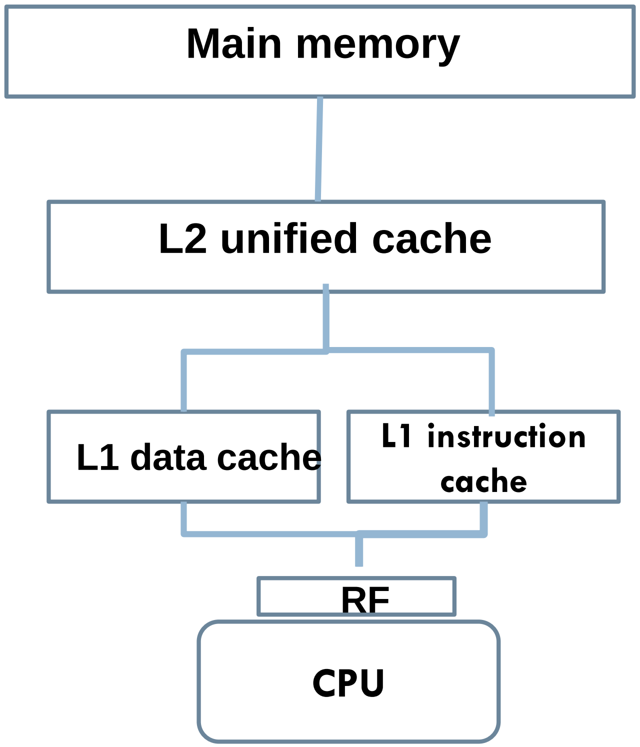
Memory Types (2)

- **ROM is used primarily in the start up process of a computer, whereas a RAM chip is used in the normal operations of a computer once the operating system has been loaded**
- A good example of ROM is the computer BIOS, a PROM chip that stores the programming needed to begin the initial computer start up process
- Writing data to a ROM chip is a much slower process than writing it to a RAM chip
- A RAM chip can store multiple gigabytes (GB) of data, ranging from 1 GB to 256 GB per chip.
- A ROM chip stores several megabytes (MB) of data, typically 4 MB or 8 MB per chip

Memory Hierarchy

- users want unlimited fast memory
- fast memory is expensive, slow memory is cheap
- cache: small, fast memory near CPU
- main memory, disk : large, slow memory





Cache Memory

- Cache is a high-speed static random access memory (SRAM) that a CPU can access more quickly than it can access regular random access memory (RAM)
- This memory is typically integrated directly into the CPU chip
- Cache memory is faster than main memory, but slower than the CPU and its registers
- Cache memory, which is normally small in size, is placed between the CPU and main memory
- **The purpose of cache memory is to store program instructions and data that are used repeatedly -** The computer processor can access this information quickly from the cache rather than having to get it from computer's main memory
- Fast access to these instructions increases the overall speed of the program

Secondary memory (1)

- **Secondary memory is where programs and data are kept on a long-term basis**
  - Common secondary storage devices are the hard disk and optical disks
- The hard disk has enormous storage capacity compared to main memory
- **The hard disk is used for long-term storage of programs and data**
- Data and programs on the hard disk are organized into files
  - A file is a collection of data on the disk that has a name

Secondary memory (1)

- **Running programs are always located in main memory**
- **When creating a new file and type something it is stored into main memory; When you "save" your document, the characters are copied to a file on the hard disk**
- **A permanent copy will also be in secondary memory on the hard disk**

Main Memory	Hard Disc
Fast	Slow
Expensive	Cheap
Low Capacity	High Capacity

Question: Do you think that data transfer from the network is slower or faster than from main memory?

Answer: Data transfers from the network are much slower than from main memory

Questions?

Further Reading

- Chapter 14 in in 'Computer Organization and architecture' available at http://home.ustc.edu.cn/~leedsong/reference_books_tools/Computer%20Organization%20and%20Architecture%2010th%20-%20William%20Stallings.pdf