CSCI 476: Computer Security

Lecture 2: Computer Systems Review

Reese Pearsall

Fall 2022

*all images are stolen from the internet

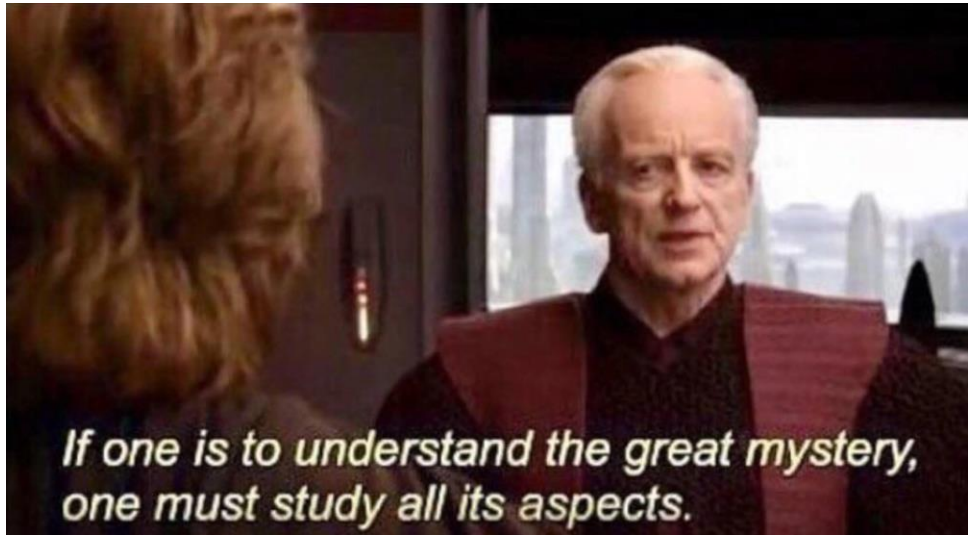
Announcements

TA
- **Gerard Fuhnwi**
- gerardfuhnwi@yahoo.com
- Office Hours: TBD
- Location: Barnard 259

Lab 0 posted→ Due **Sunday** January 29th
- I am still waiting to hear back on M1/M2 Apple chip issues

Computer Systems Review

To understand the technical aspects of security, we must have a good understanding of how computers work



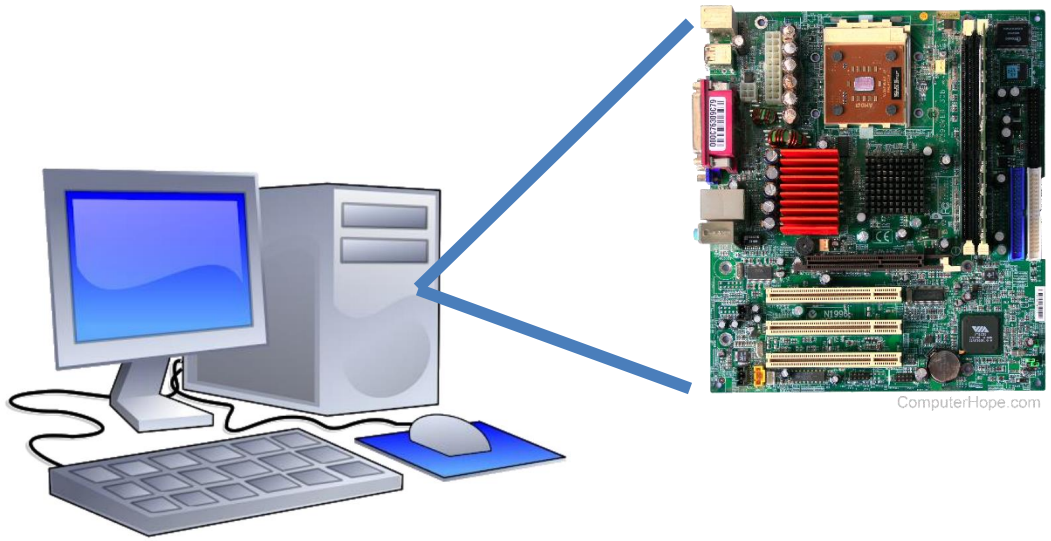
What is a computer?

What is a computer?

A magical box that does stuff

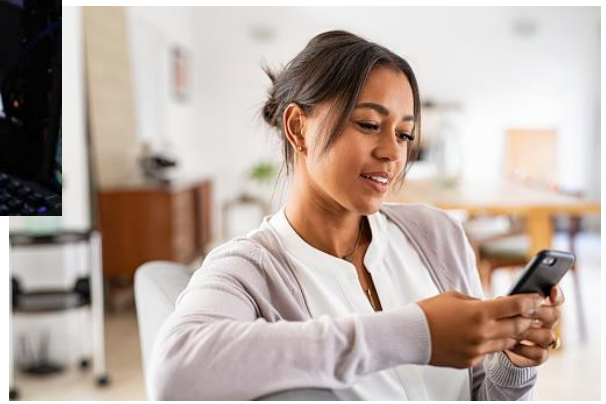
What is a computer?

A **semi-**magical box that ~~does stuff~~ **executes instructions**



What is so magical about a computer?

We use computers every day for many different things



What is so magical about a computer?

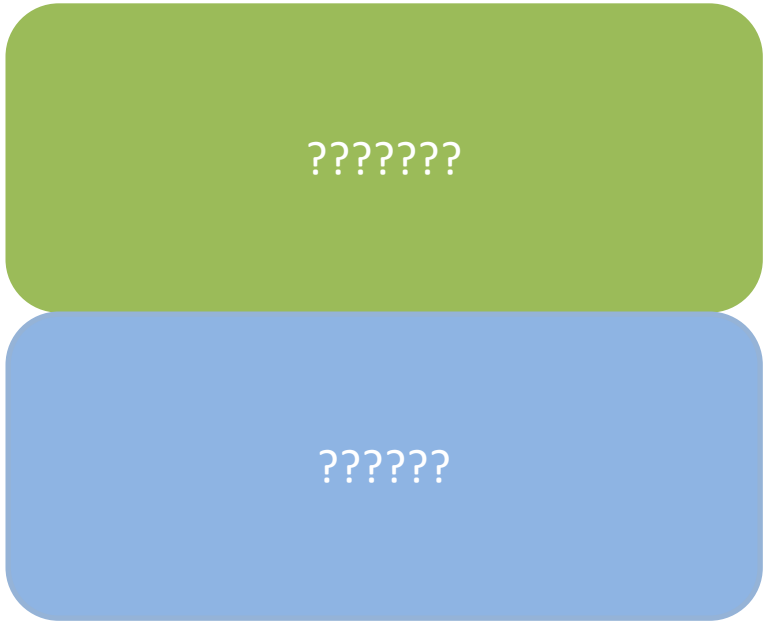
Big Idea

Computers only understand instructions in the form of 0s and 1s (binary)

~~Welcome to CSCI 476~~ 

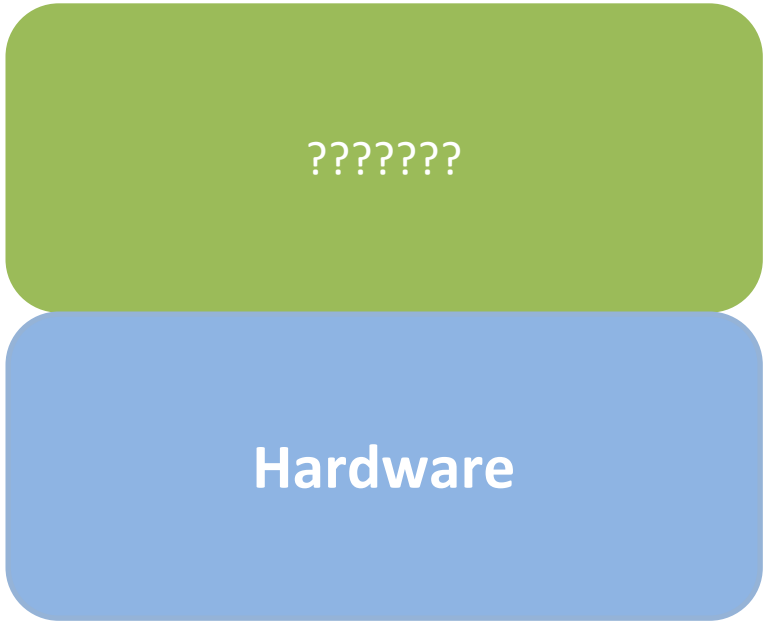
01010111 01100101 01101100 01100011 01101111
01101101 01100101 00100000 01110100 01101111
00100000 01000011 01010011 01000011 01001001
00100000 00110100 00110111 00110110

How does this happen?



From a high level, we will divide a computer system into two parts

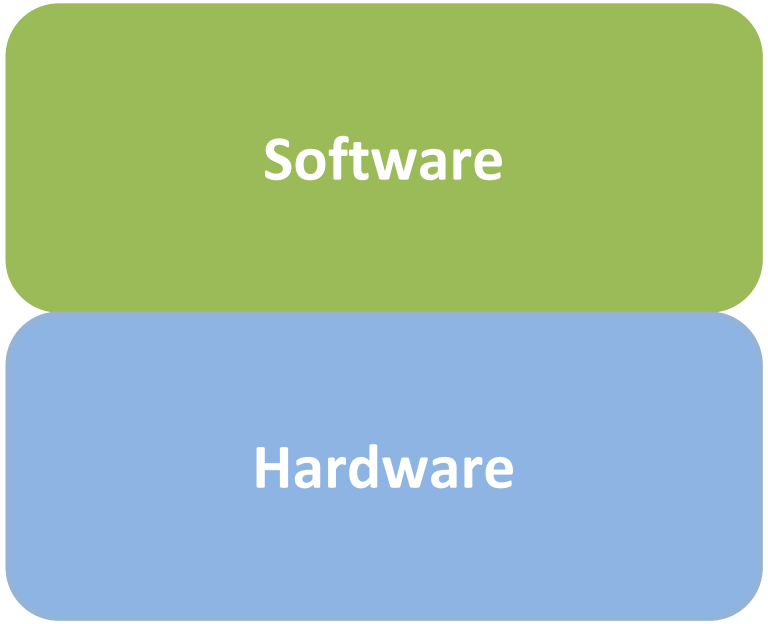
How does this happen?



From a high level, we will divide a computer system into two parts

I. Hardware

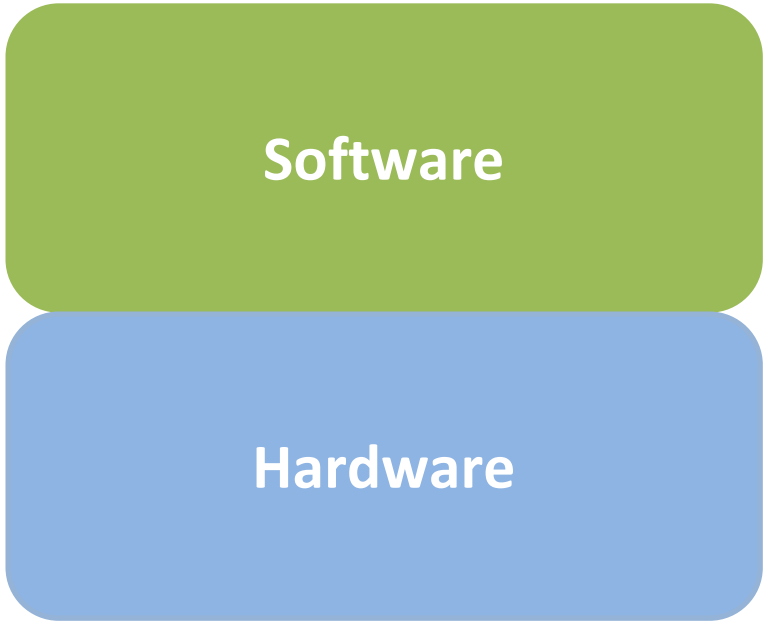
How does this happen?



From a high level, we will divide a computer system into two parts

I. **Hardware**
II. **Software**

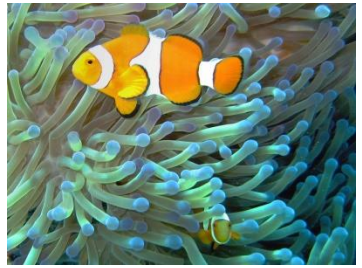
How does this happen?



From a high level, we will divide a computer system into two parts

I. **Hardware**
II. **Software**

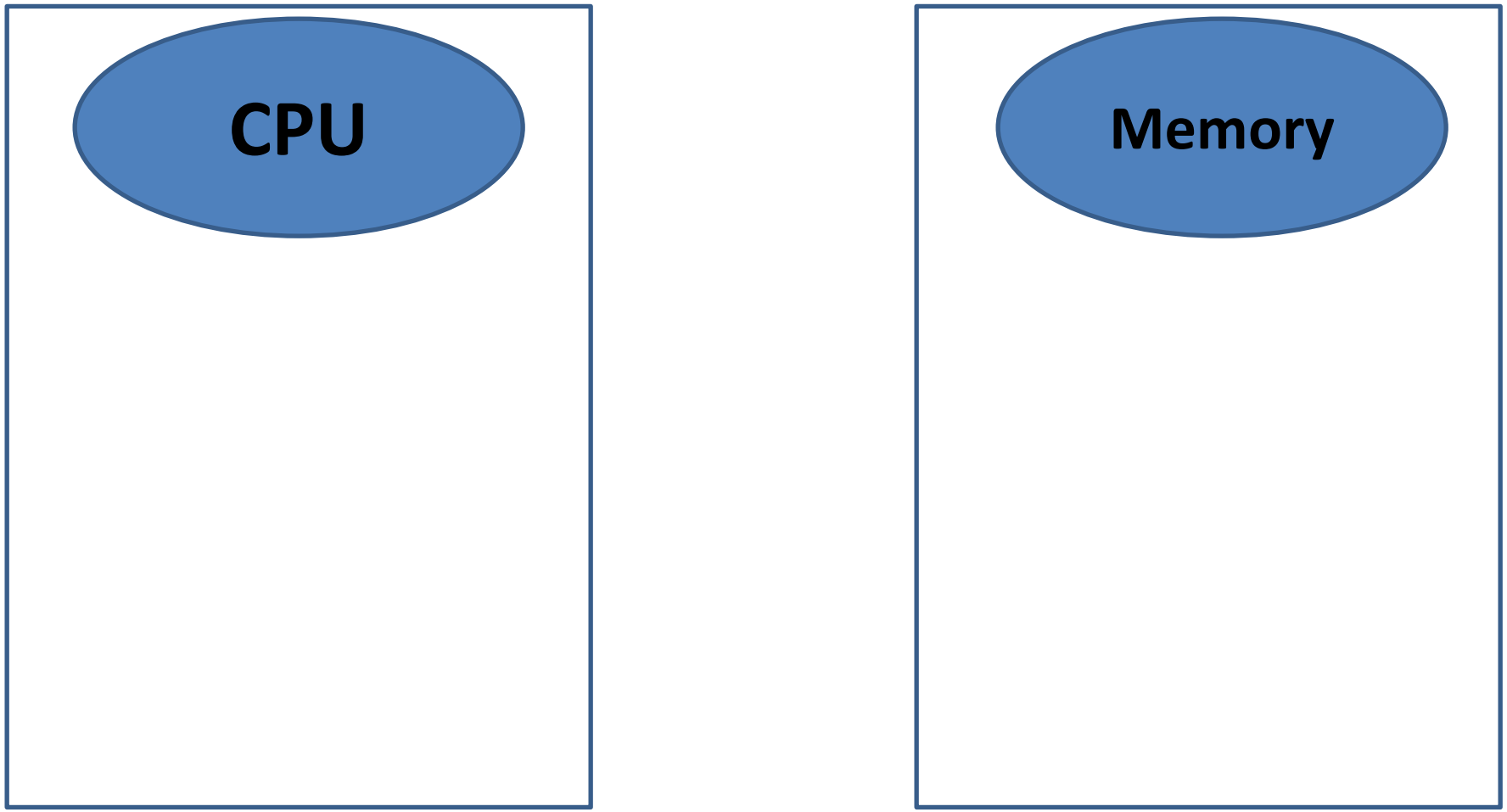
Symbiotic relationship



I. Hardware

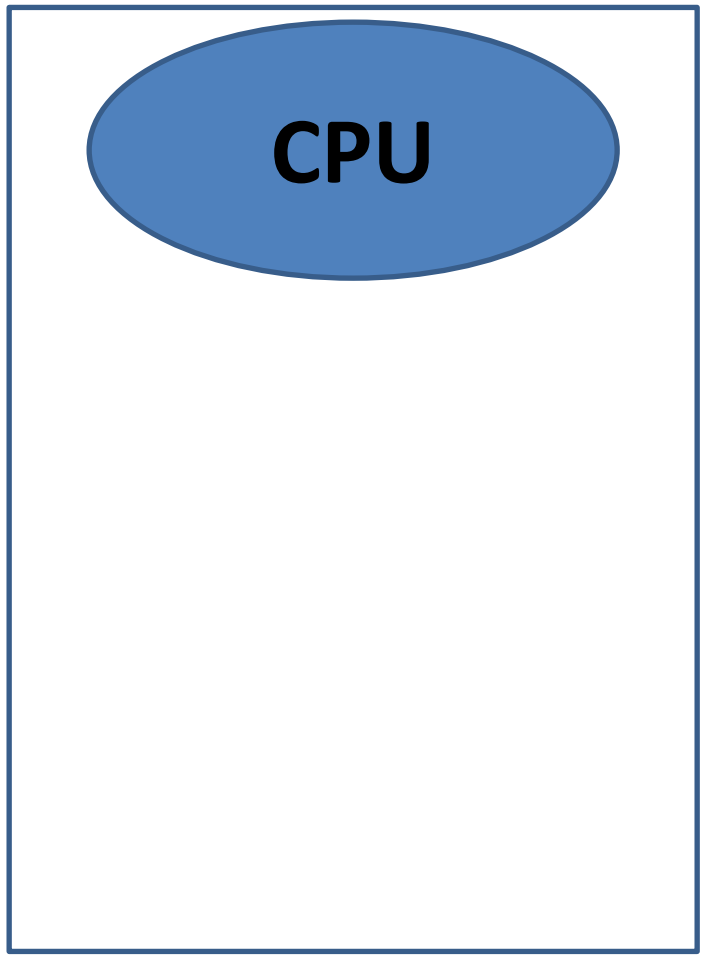
The **physical** parts of a computer

I. Hardware

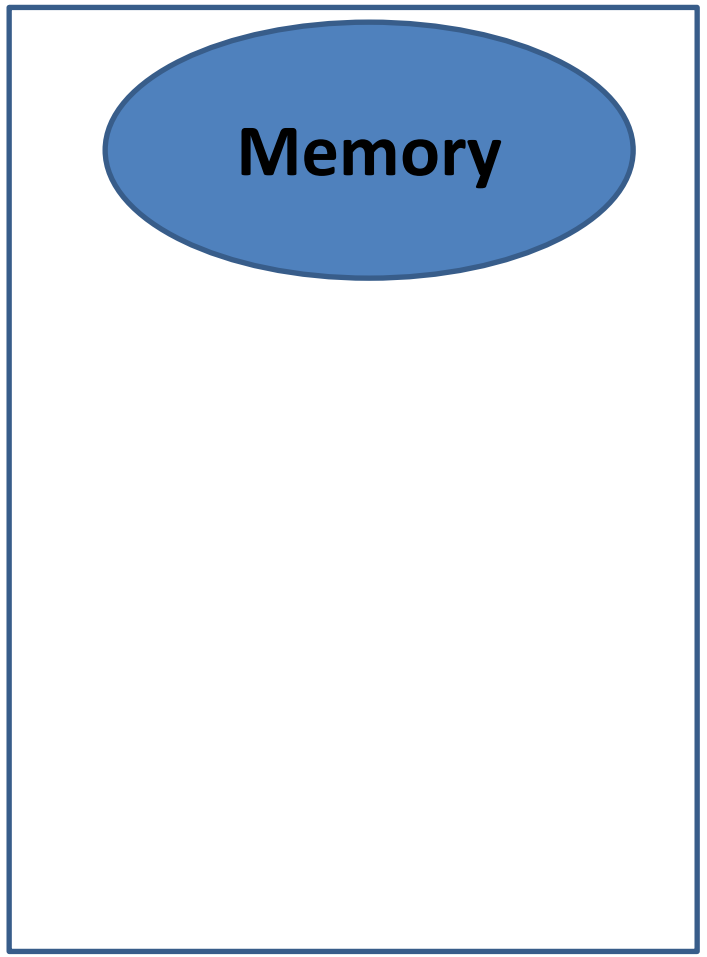


I. Hardware

Brain with no short-term memory



Scratch Pad



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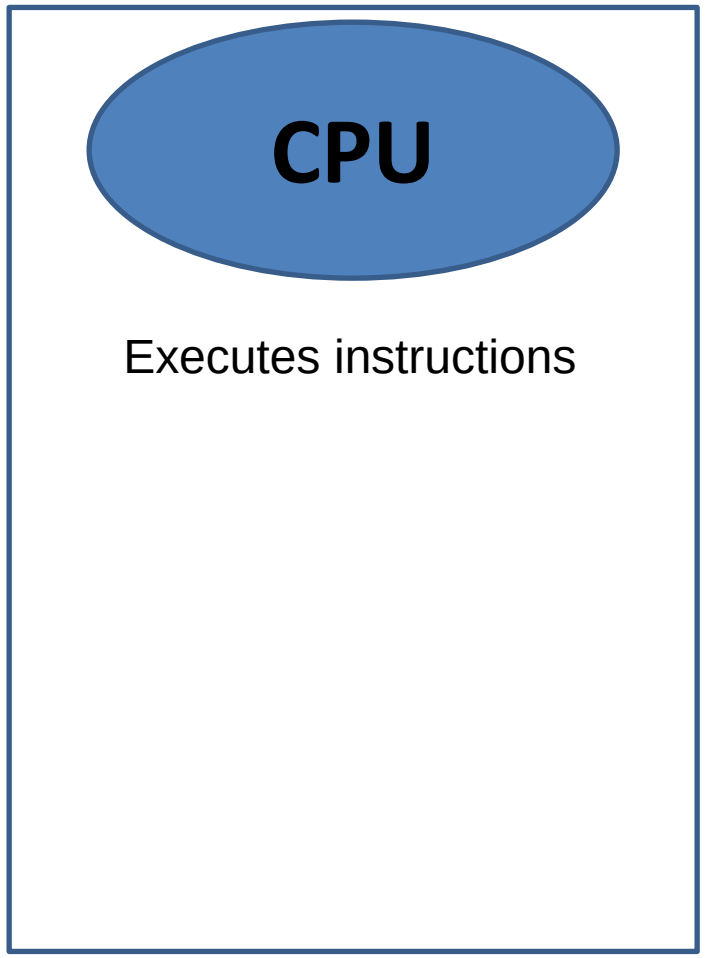

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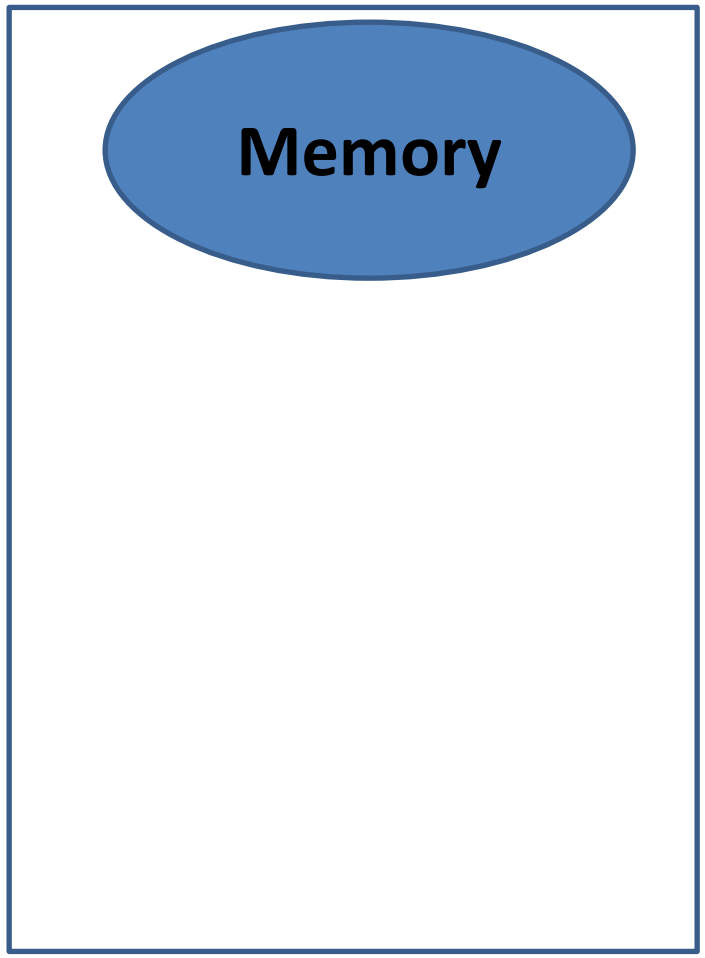

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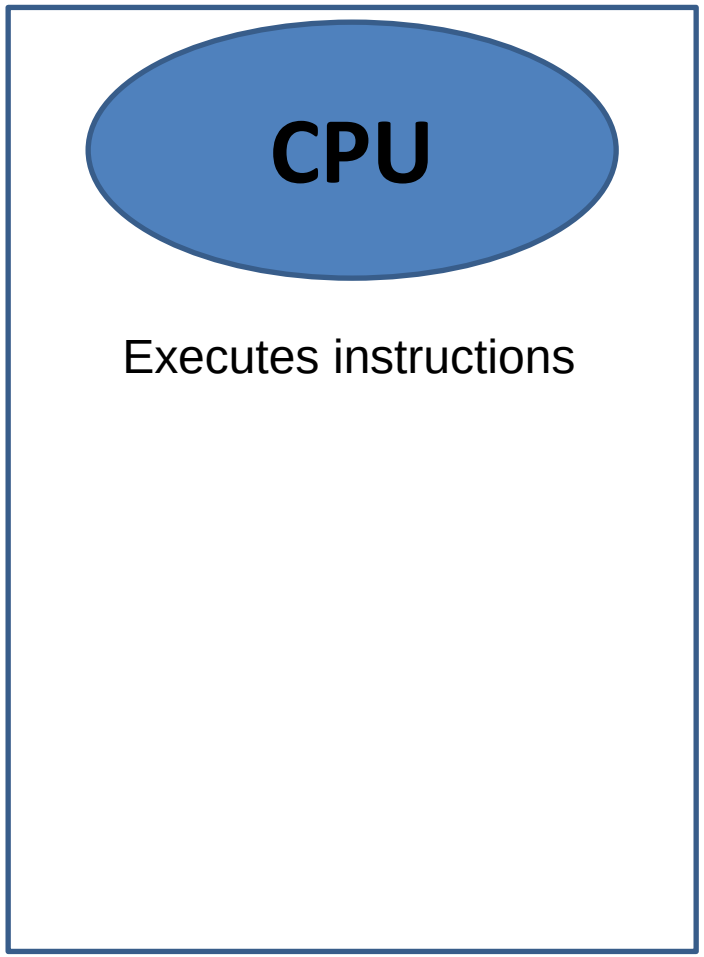
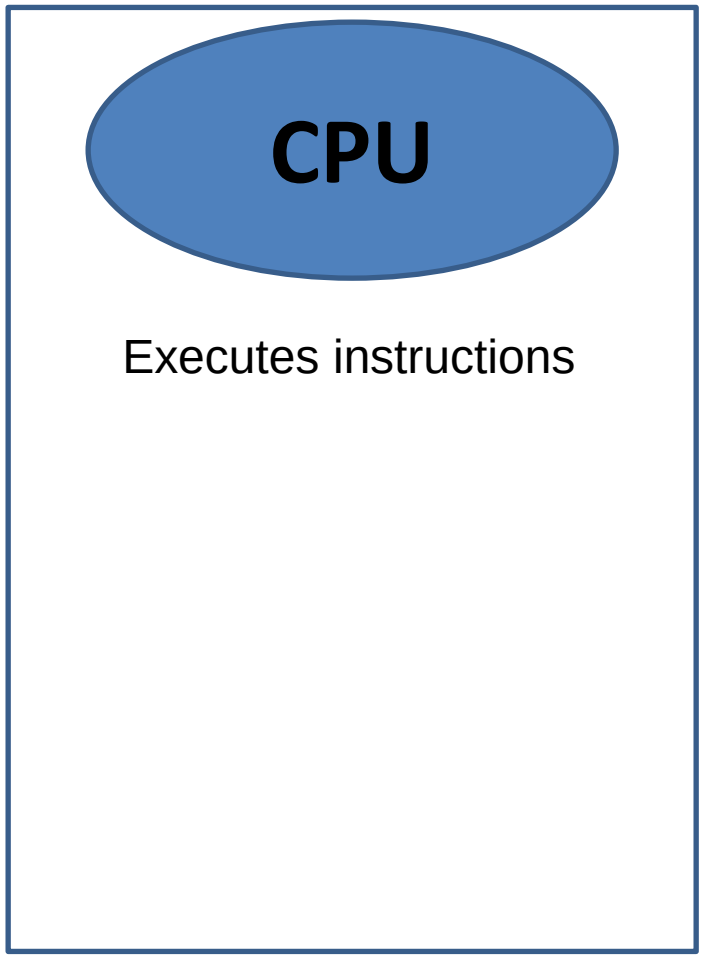


How does it “execute” instructions?

It is sent instructions from another part of the computer

I. Hardware

Brain with no short-term memory



How does it "execute" instructions?

It is sent instructions from another part of the computer

01001100000000110100011100001010

I. Hardware

Brain with no short-term memory

CPU

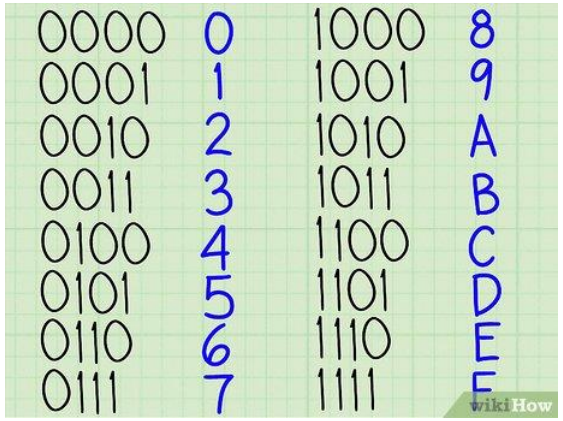
Executes instructions

How does it "execute" instructions?

It is sent instructions from *another part of the computer*

00000000101000010001100000100000 → 00 A1 18 20

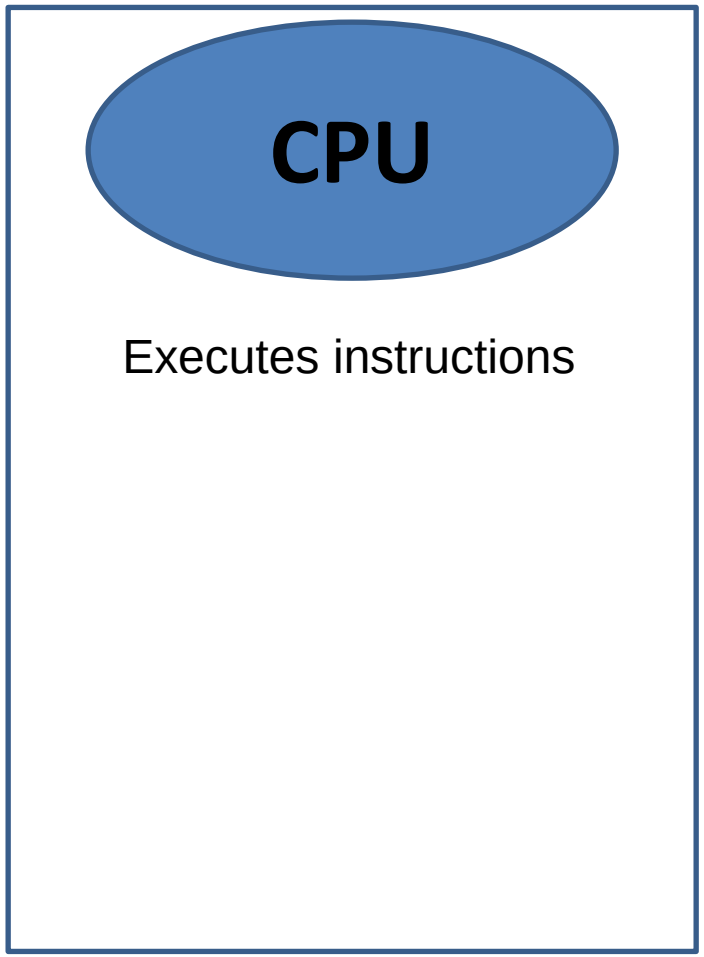
00 A1 18 20



Hex(hexadecimal) is a common representation for binary

I. Hardware

Brain with no short-term memory



How does it "execute" instructions?

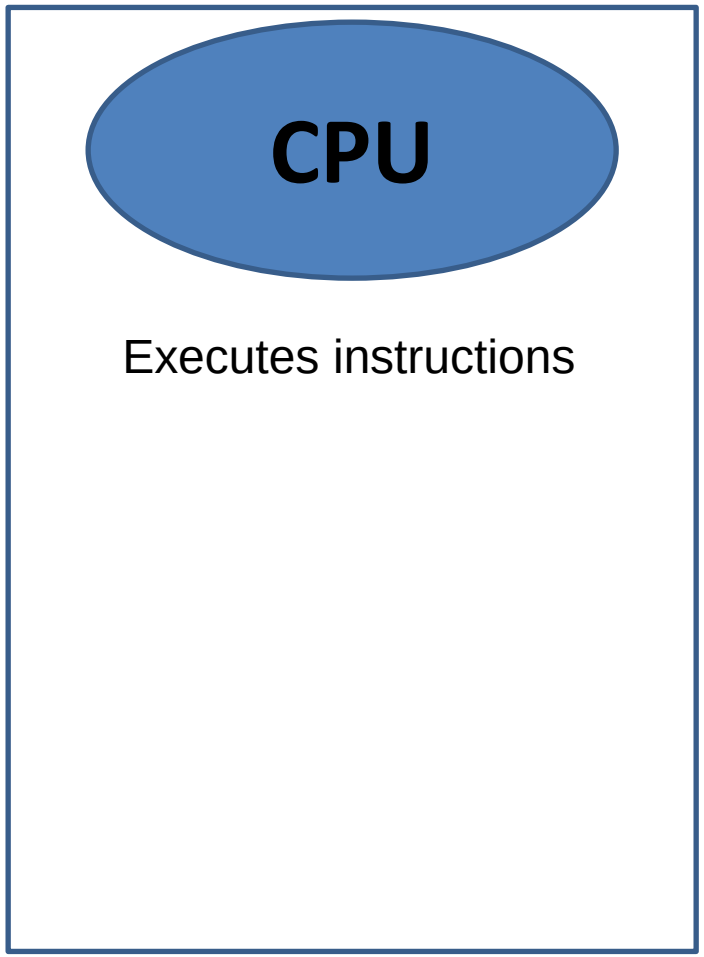
It is sent instructions from another part of the computer

00000000101000100011000001000000

What does this instruction do?????

I. Hardware

Brain with no short-term memory



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It is sent instructions from another part of the computer

00000000101000010001100000100000

Opcode

Common MIPS instructions

Notes: *op, funct, rd, rs, rt, imm, address, shamt* refer to fields in the instruction format
PC is assumed to point to the next instruction, **Mem** is the byte addressed main memory

Assembly Instruction	Instr Format	op op/funct	Meaning	Comments
add *$rd, $rs, $rt*	R	0/32	*$rd = $rs + $rt*	Add contents of two registers
sub *$rd, $rs, $rt*	R	0/34	*$rd = $rs - $rt*	Subtract contents of two registers
addi *$rt, $rs, imm*	I	8	*$rt = $rs + imm*	Add signed constant
addu *$rd, $rs, $rt*	R	0/33	*$rd = $rs + $rt*	Unsigned, no overflow
subu *$rd, $rs, $rt*	R	0/35	*$rd = $rs - $rt*	Unsigned, no overflow
addiu *$rt, $rs, imm*	I	9	*$rt = $rs + imm*	Unsigned, no overflow
mfc0 *$rt, $rd*	R	16	*$rt = $rd*	*rd* = coprocessor register (e.g. epc, cause, status)
mult *$rs, $rt*	R	0/24	Hi, Lo = *$rs * $rt*	64 bit signed product in Hi and Lo
multu *$rs, $rt*	R	0/25	Hi, Lo = *$rs * $rt*	64 bit unsigned product in Hi and Lo
div *$rs, $rt*	R	0/26	Lo = *$rs / $rt*, Hi = *$rs* mod *$rt*	
divu *$rs, $rt*	R	0/27	Lo = *$rs / $rt*, Hi = *$rs* mod *$rt* (unsigned)	
mfhi *$rd*	R	0/16	*$rd* = Hi	Get value of Hi
mflo *$rd*	R	0/18	*$rd* = Lo	Get value of Lo
and *$rd, $rs, $rt*	R	0/36	*$rd = $rs & $rt*	Logical AND
or *$rd, $rs, $rt*	R	0/37	*$rd = $rs | $rt*	Logical OR
andi *$rt, $rs, imm*	I	12	*$rt = $rs & imm*	Logical AND, unsigned constant
ori *$rt, $rs, imm*	I	13	*$rt = $rs | imm*	Logical OR, unsigned constant
sll *$rd, $rs, shamt*	R	0/0	*$rd = $rs << shamt*	Shift left logical (shift in zeros)
srl *$rd, $rs, shamt*	R	0/2	*$rd = $rs >> shamt*	Shift right logical (shift in zeros)

Common MIPS instructions

Notes: *op, funct, rd, rs, rt, imm, address, shamt* refer to fields in the instruction format
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sub *$rd, $rs, $rt*	R	0/34	*$rd = $rs - $rt*	Subtract contents of two registers
addi *$rt, $rs, imm*	I	8	*$rt = $rs + imm*	Add signed constant

MIPS Instruction formats

Format	Bits 31-26	Bits 25-21	Bits 20-16	Bits 15-11	Bits 10-6	Bits 5-0
R	op	rs	rt	rd	shamt	funct
I	op	rs	rt	imm		
J	op	address				

multu *$rs, $rt*	R	0/25	Hi, Lo = *$rs* * *$rt*	64 bit unsigned product in Hi and Lo
div *$rs, $rt*	R	0/26	Lo = *$rs* / *$rt*, Hi = *$rs* mod *$rt*	
divu *$rs, $rt*	R	0/27	Lo = *$rs* / *$rt*, Hi = *$rs* mod *$rt* (unsigned)	
mfhi *$rd*	R	0/16	*$rd* = Hi	Get value of Hi
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andi *$rt, $rs, imm*	I	12	*$rt = $rs & imm*	Logical AND, unsigned constant
ori *$rt, $rs, imm*	I	13	*$rt = $rs | imm*	Logical OR, unsigned constant
sll *$rd, $rs, shamt*	R	0/0	*$rd = $rs << shamt*	Shift left logical (shift in zeros)
srl *$rd, $rs, shamt*	R	0/2	*$rd = $rs >> shamt*	Shift right logical (shift in zeros)

I. Hardware

Brain with no short-term memory

CPU

Executes instructions

Must decipher what instruction to execute

How does it “execute” instructions?

It is sent instructions from another part of the computer

00000000101000010001100000100000

Opcode

I. Hardware

Brain with no short-term memory

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00000000101000010001100000100000

Opcode $rs

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00000000101000010001100000100000

Opcode $rs $rt

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00000000101000010001100000100000

Opcode $rs $rt $rd

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Opcode $rs $rt $rd shamt

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Opcode $rs $rt $rd shamt funct

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00000000101000010001100000100000

Opcode $rs $rt $rd shamt funct

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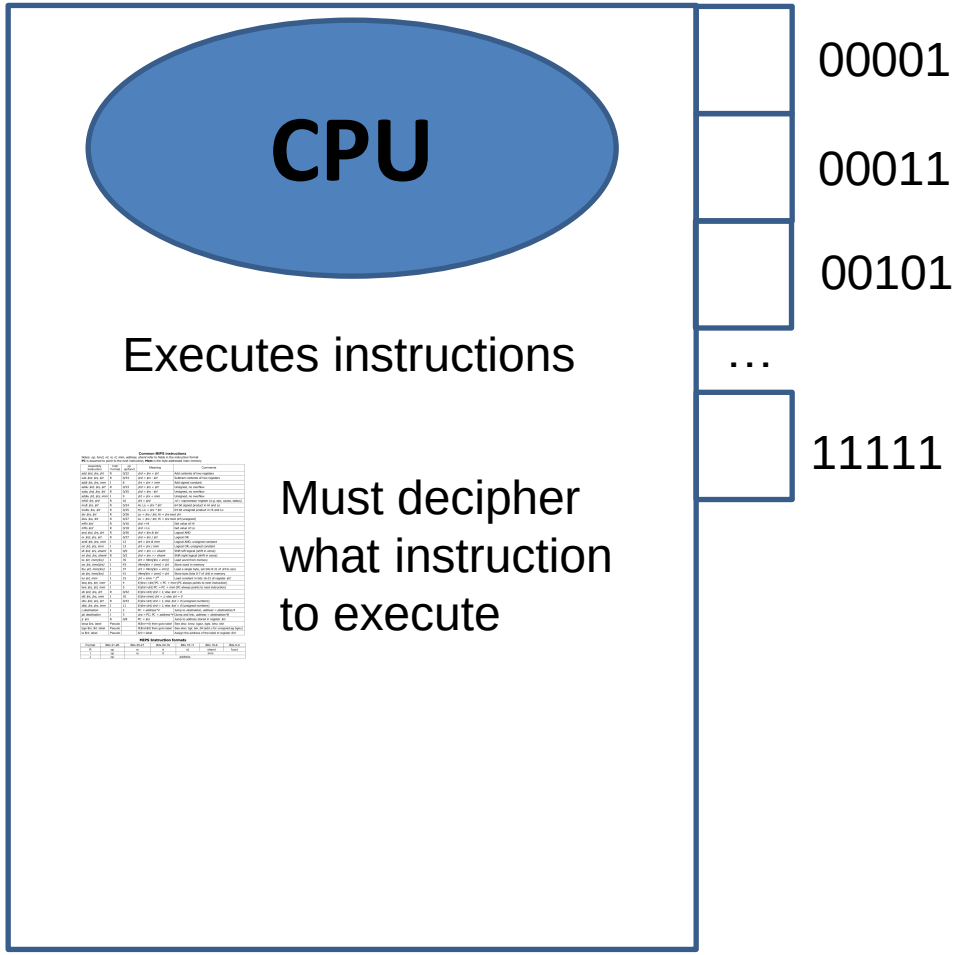


How does it "execute" instructions?

It is sent instructions from another part of the computer

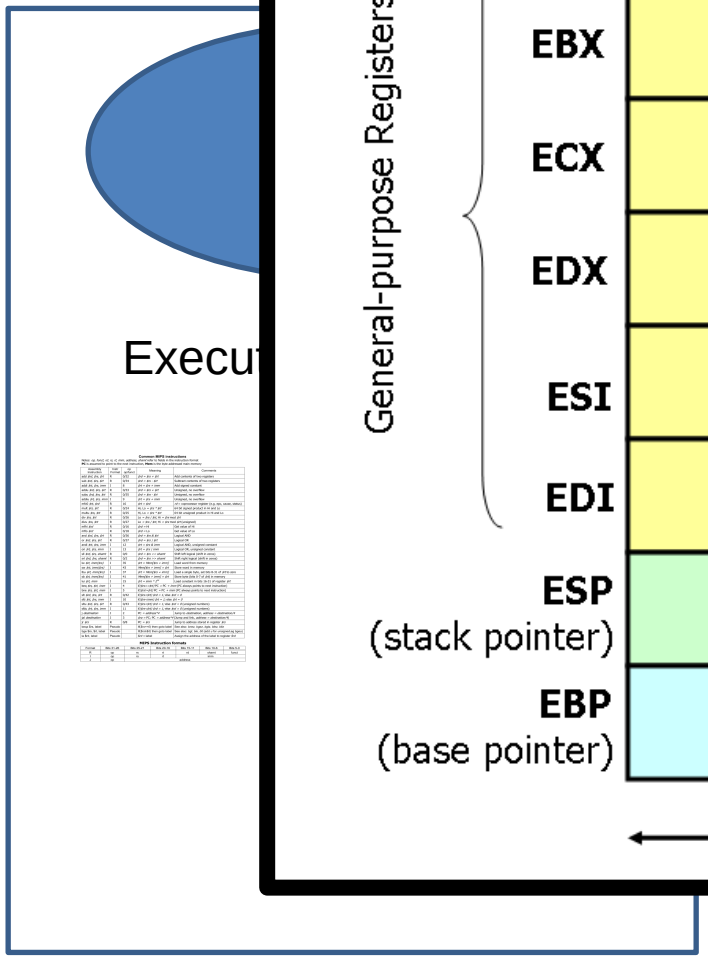
00000000101000010001100000100000

Opcode $rs $rt $rd shamt funct

$ denotes that it is a **register**

I. Hardware

Brain with nc



Execut

ructions?

rt of the computer

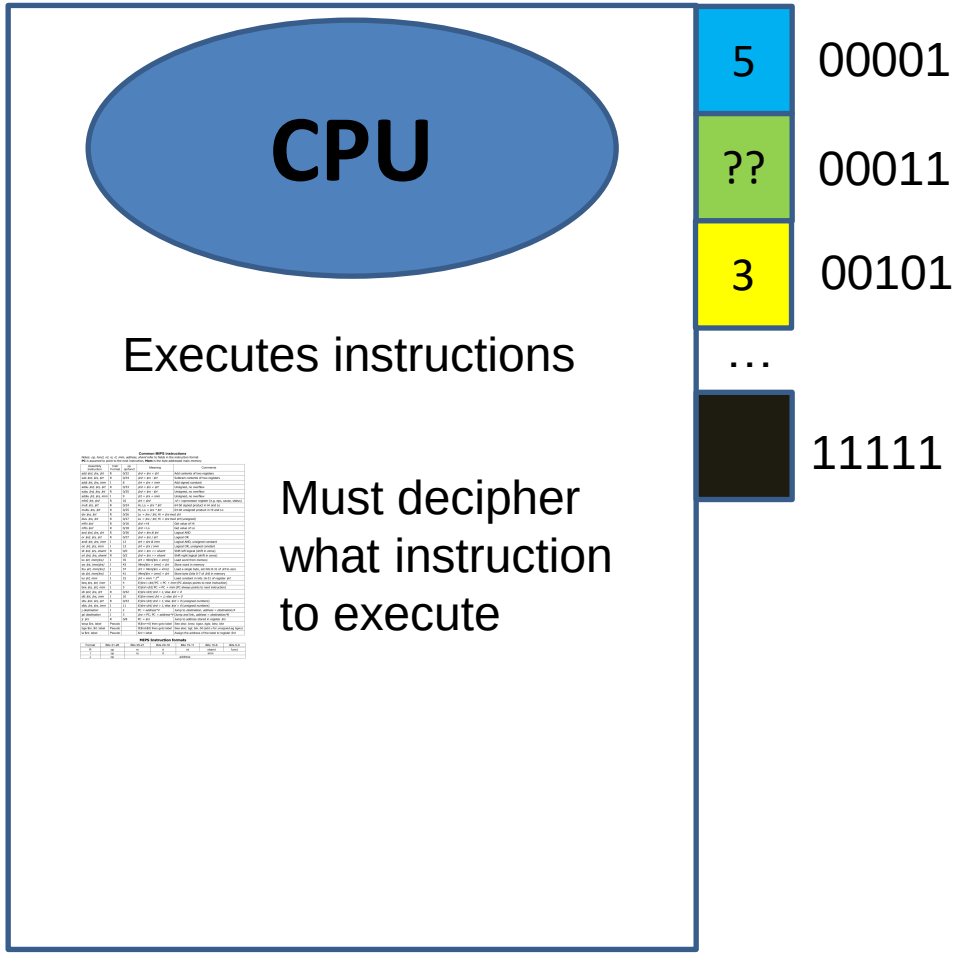
00000100000

shamt funct

er

I. Hardware

Brain with no short-term memory



How does it "execute" instructions?

It is sent instructions from another part of the computer

00000000101000010001100000100000

Opcode $rs $rt $rd shamt funct

`ADD $rs, $rt, $rd`

I. Hardware

Brain with no short-term memory

CPU

Executes instructions

Must decipher what instruction to execute

The CPU can add, subtract, logic, move stuff around

Registers

5	00001
??	00011
3	00101
…	
	11111

How does it "execute" instructions?

It is sent instructions from another part of the computer

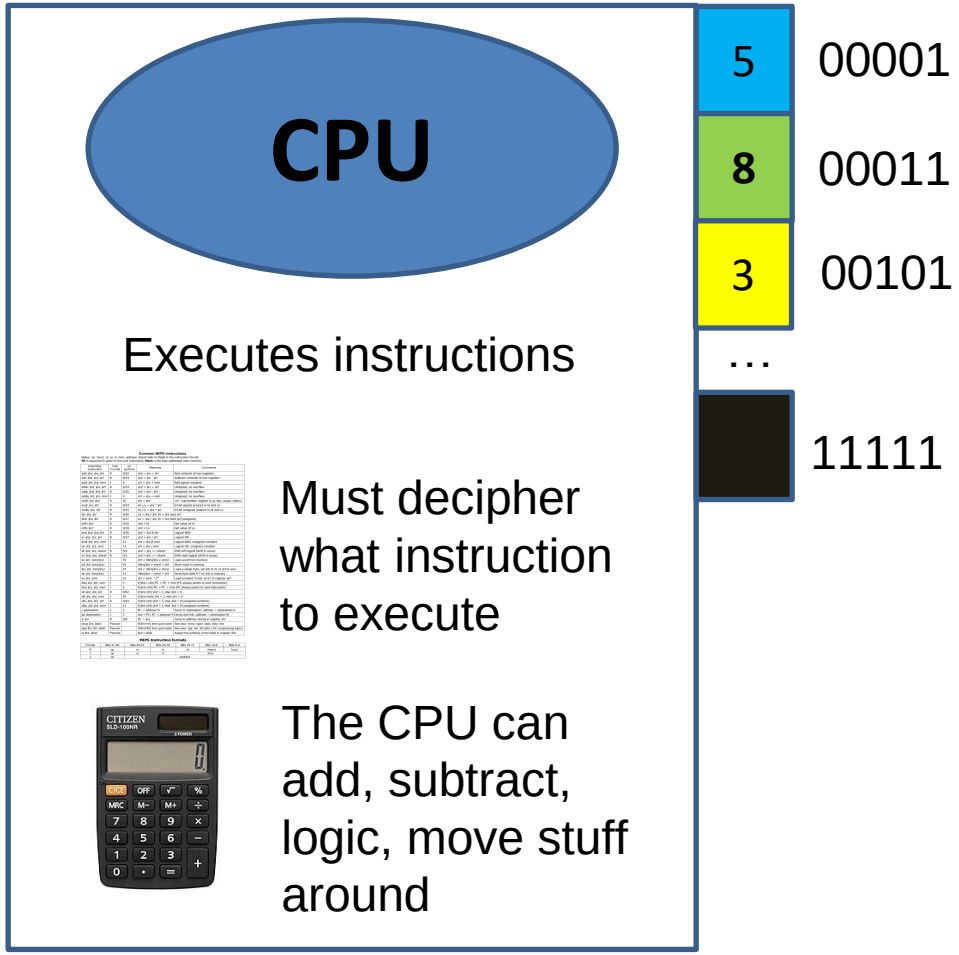
00000000101000010001100000100000

Opcode $rs $rt $rd shamt funct

```
ADD $rs, $rt, $rd
```

I. Hardware

Brain with no short-term memory



Registers

5	00001
8	00011
3	00101
…	
	11111

How does it "execute" instructions?

It is sent instructions from another part of the computer

00000000101000010001100000100000

Opcode $rs $rt $rd shamt funct

```
ADD $rs, $rt, $rd
```

I. Hardware

Brain with no short-term memory

CPU

Executes instructions

Must decipher what instruction to execute

The CPU can add, subtract, logic, move stuff around

Regis

5	0000
8	00
3	
…	
	1

CPU uses

Electricity™

I. Hardware

Brain with no short-term memory

CPU

Executes instructions

Must decipher what instruction to execute

The CPU can add, subtract, logic, move stuff around

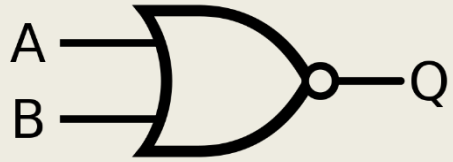
Regis

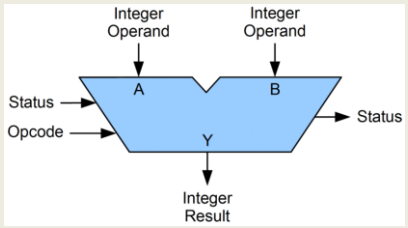
5	0000
8	00
3	
…	
	1

CPU uses

Electricity™

To decipher and execute instructions





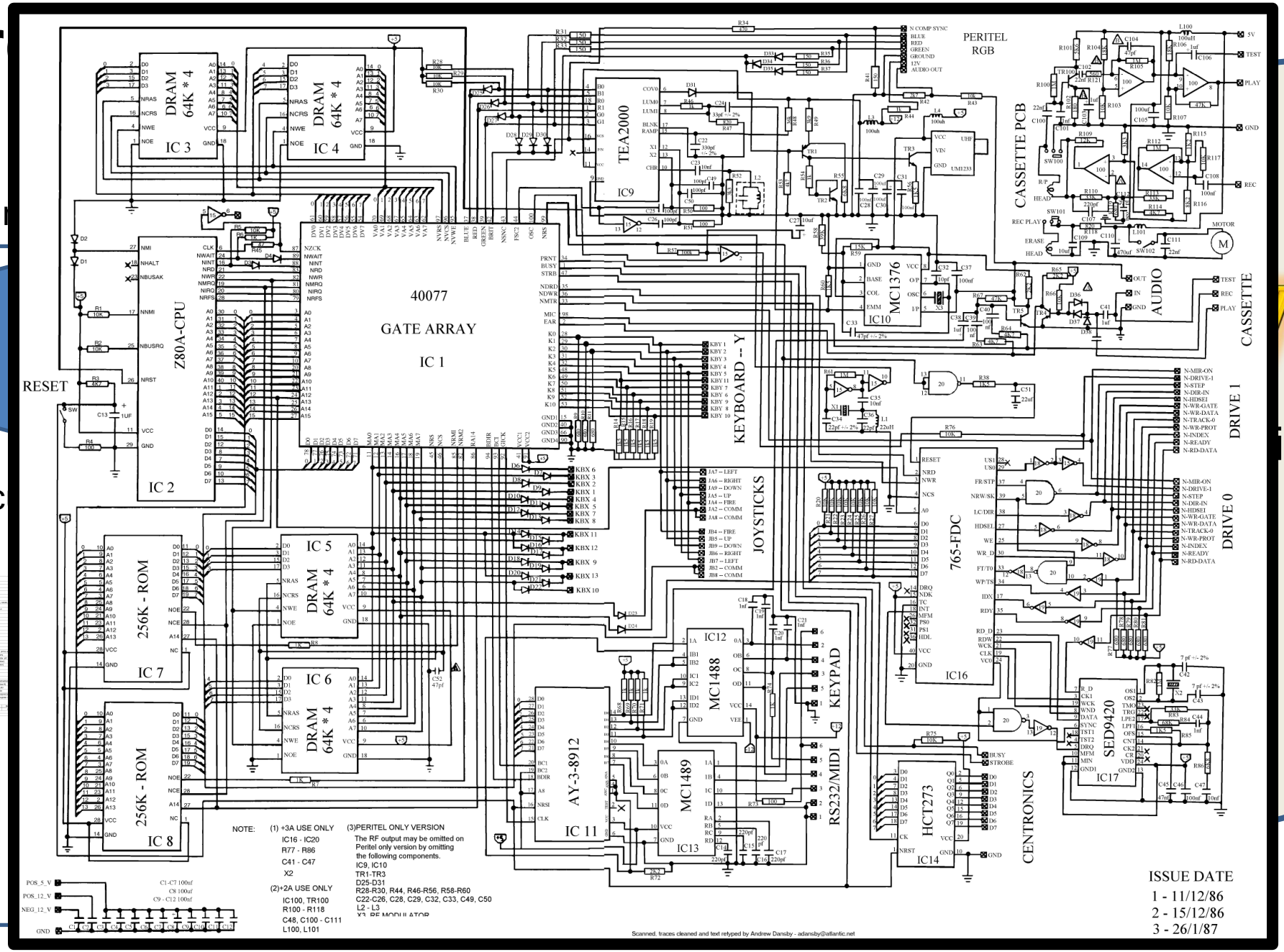
I. Har

Brain with

Exec

ions

TM



I. Hardware

Brain with no short-term memory

CPU

Executes instructions

Must decipher what instruction to execute

The CPU can add, subtract, logic, move stuff around

Regis

5	0000
8	00
3	
…	
	1

CPU uses

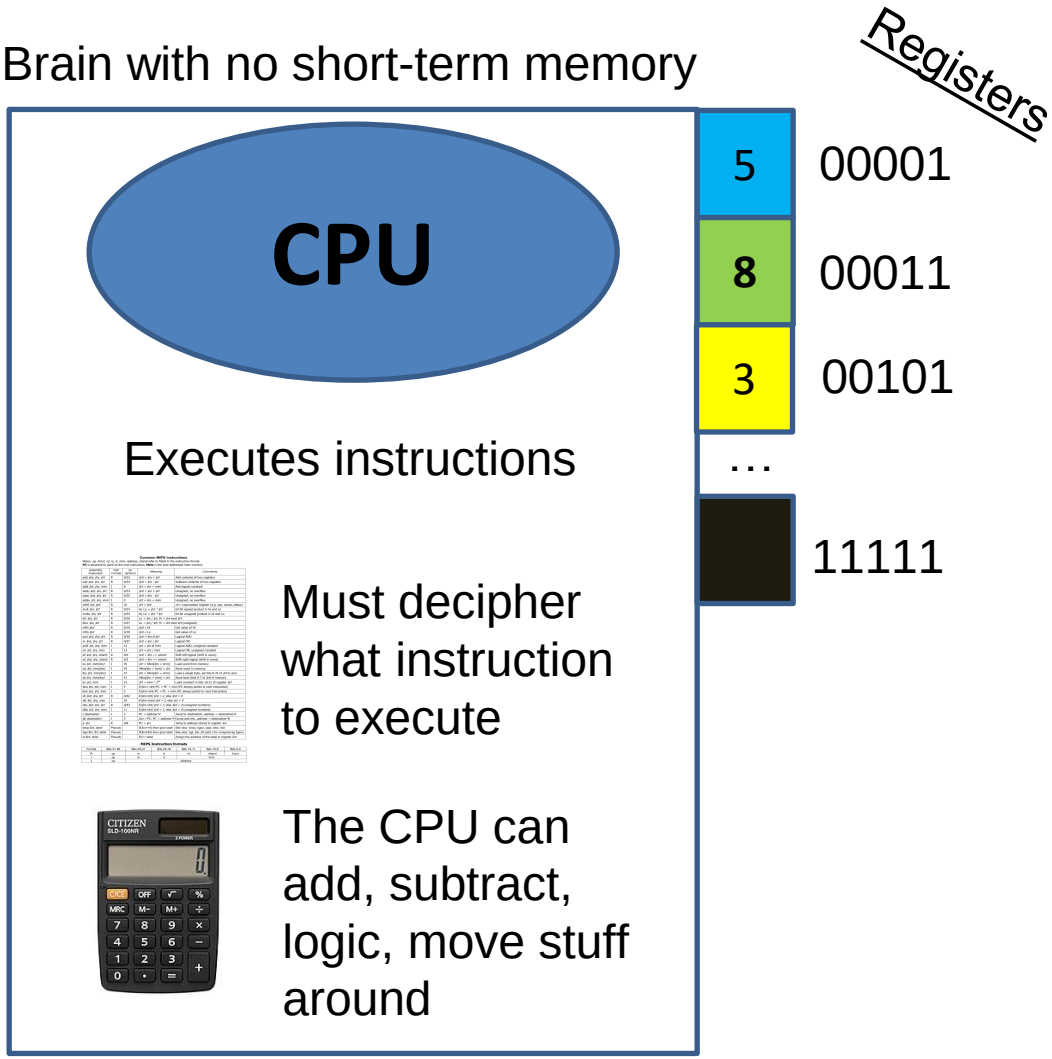
Electricity™

To decipher and execute instructions

*Everything is just **electricity on** or **electricity off***

I. Hardware

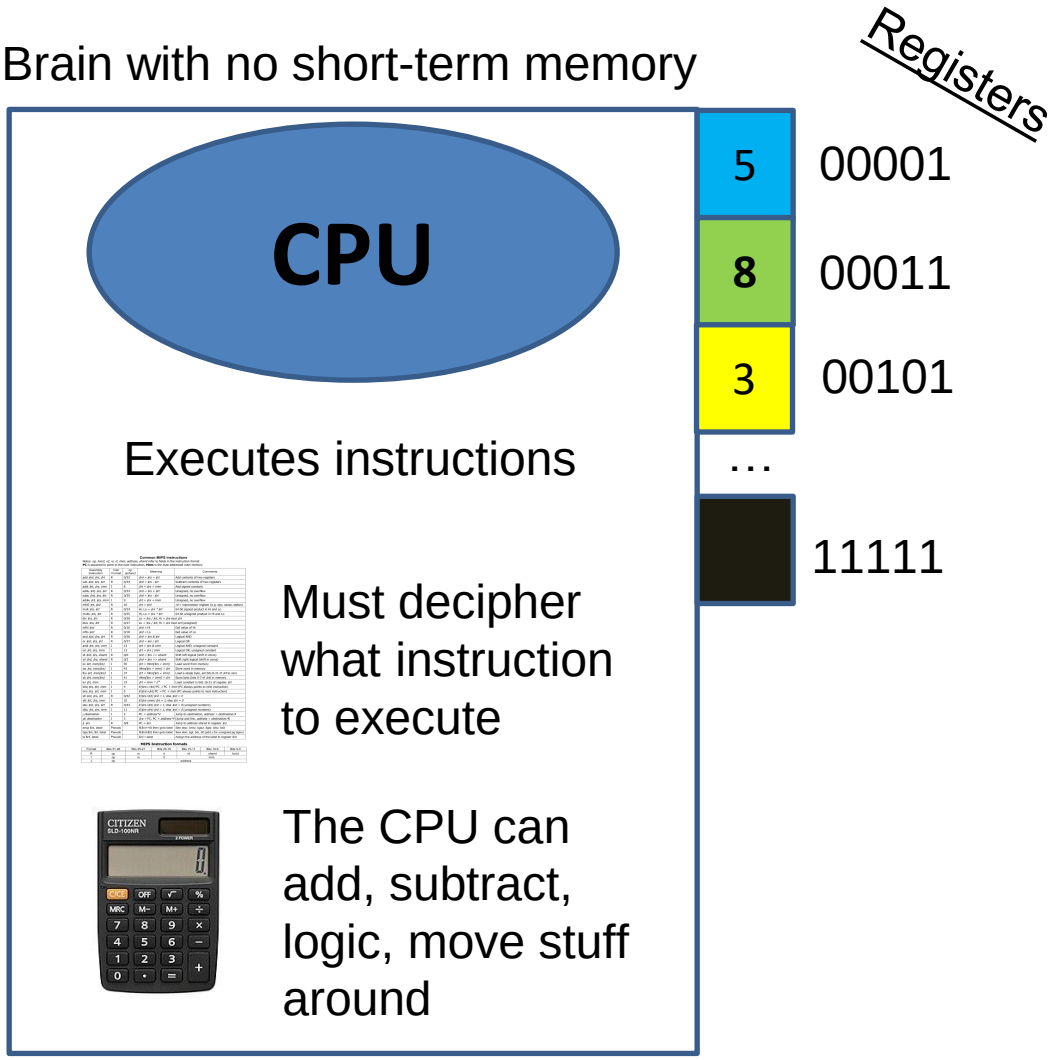
Brain with no short-term memory



32 bit vs 64 bit?

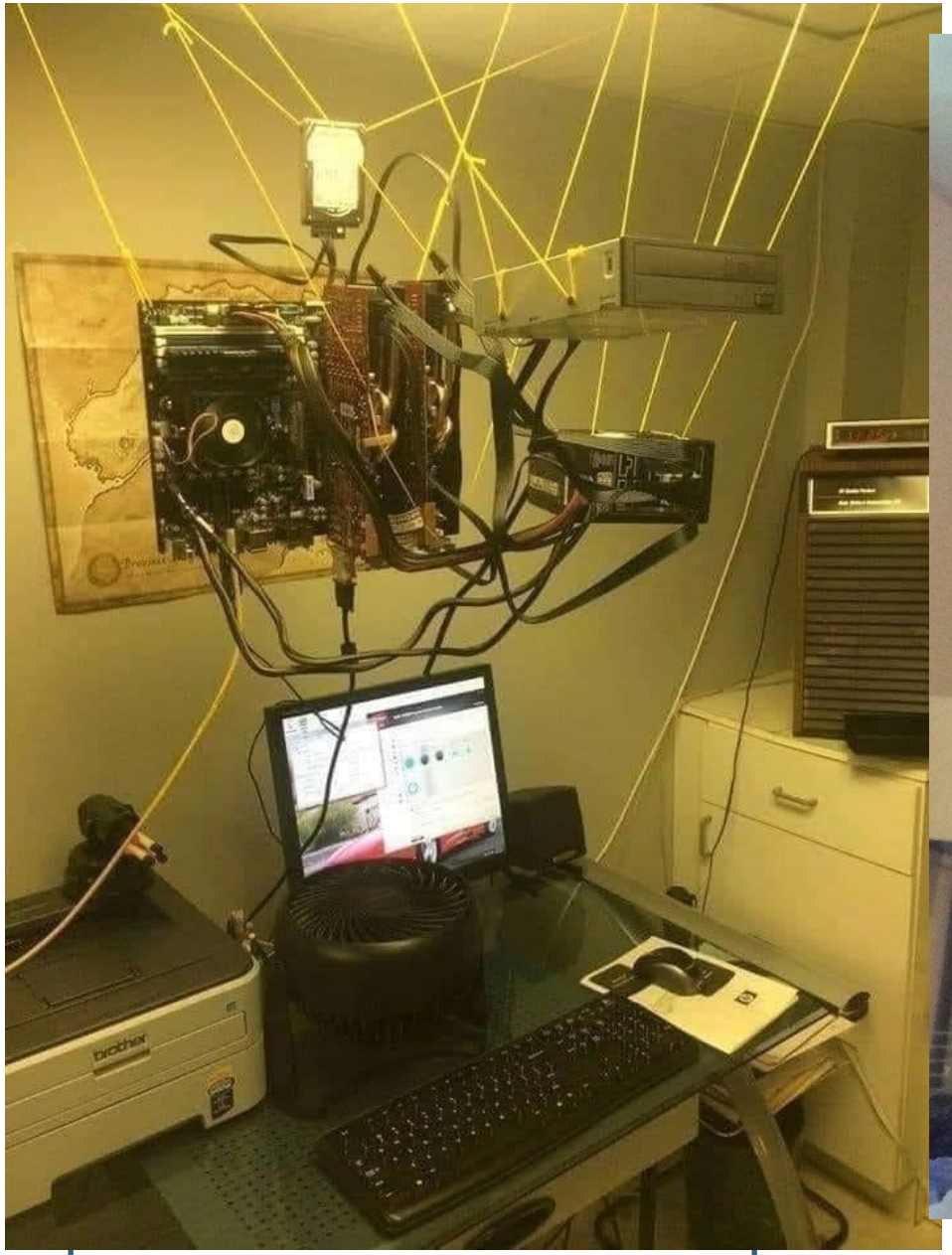
I. Hardware

Brain with no short-term memory



32 bit vs 64 bit?

Parameter	32-bit processors	64-bit processors
Addressable space	It has 4 GB addressable space	64-bit processors have 16 exabytes addressable space
Application support	64-bit applications and programs won't work	32-bit applications and programs will work
OS support	Need a 32-bit operating system.	It can run on 32 and the 64-bit operating system.
Support for multi-tasking	Not an ideal option for stress testing and multi-tasking.	Works best for performing multi-tasking and stress testing.
OS and CPU requirement	32-bit operating systems and applications require 32-bit CPUs	64-bit OS demands 64-bit CPU, and 64-bit applications require 64-bit OS and CPU.
System available	Support Windows 7, 8 Vista, XP, and, Linux.	Windows XP Professional, Windows Vista, Windows 7, Windows 8,Windows 10, Linux, and Mac OS X.


brother

I. Hardware

Brain with no short-term memory

CPU

Executes instructions

Must decipher what instruction to execute

The CPU can add, subtract, logic, move stuff around

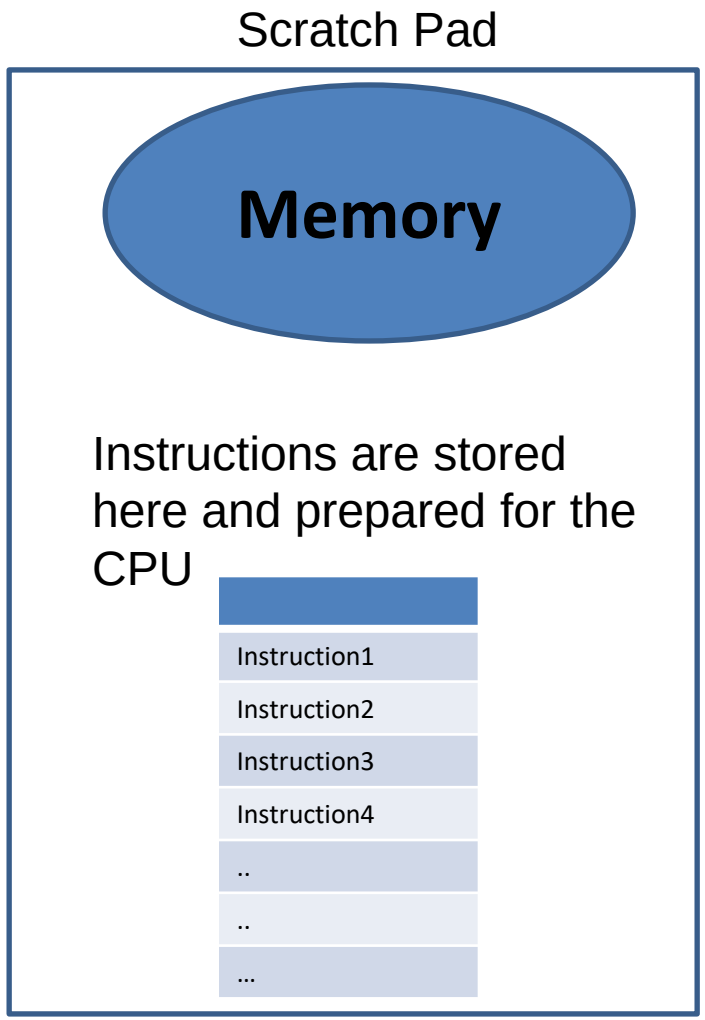
Registers

5	00001
8	00011
3	00101
…	
	11111

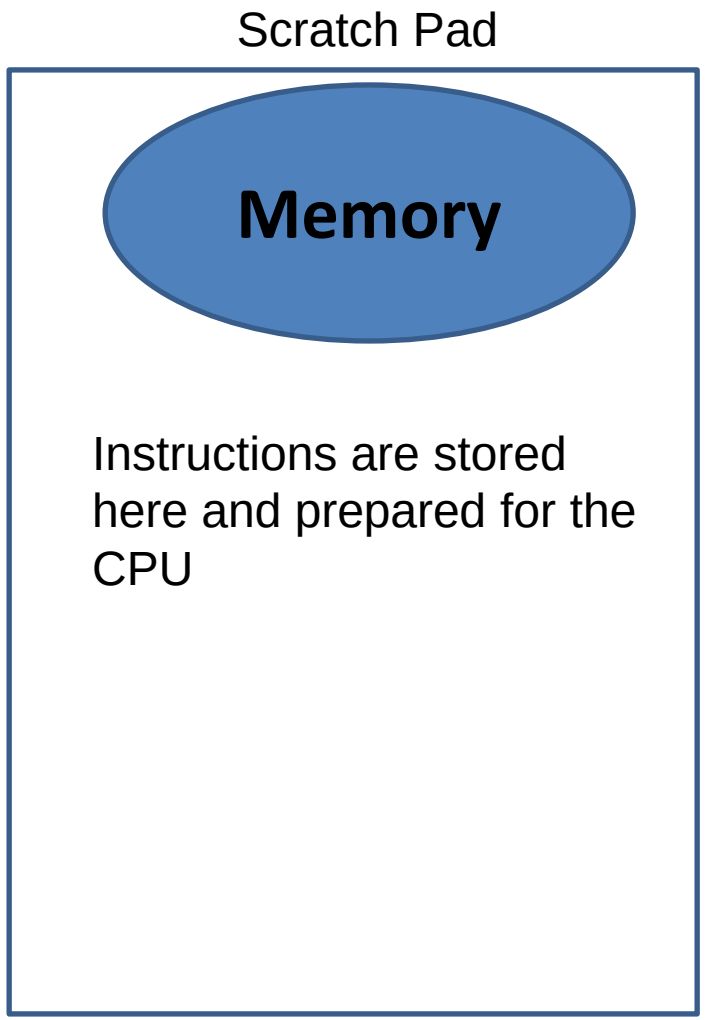
Scratch Pad

Memory

I. Hardware

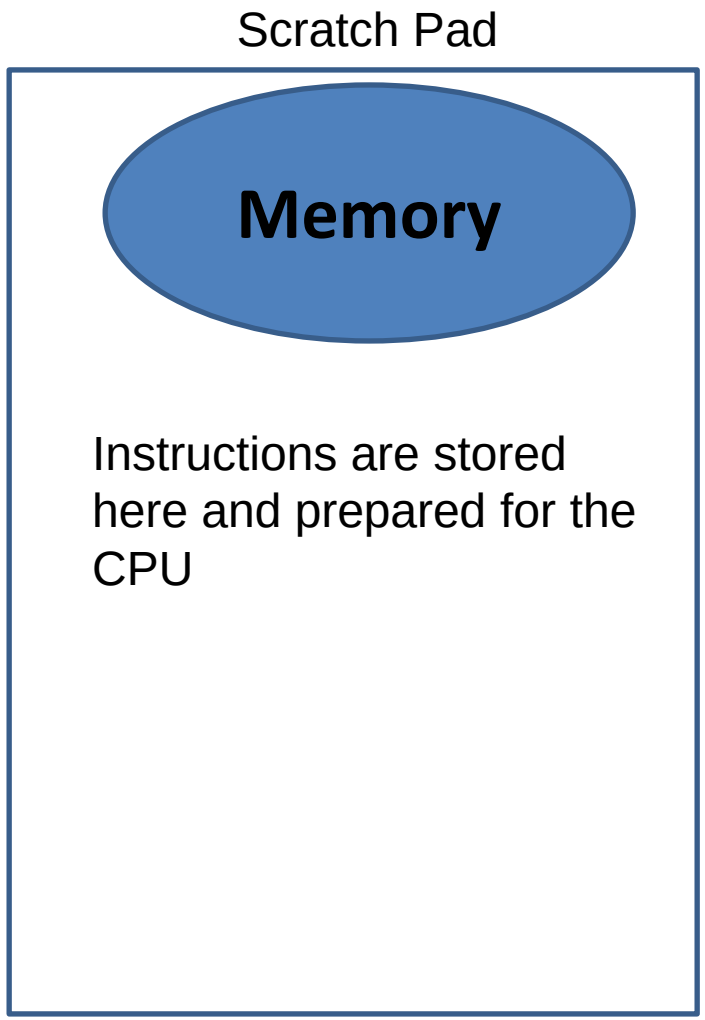

Scratch Pad
Memory
Instructions are stored here and prepared for the CPU
Instruction1
Instruction2
Instruction3
Instruction4
..
..
...

I. Hardware



When computer programs are executed, their instructions will eventually get stored in memory

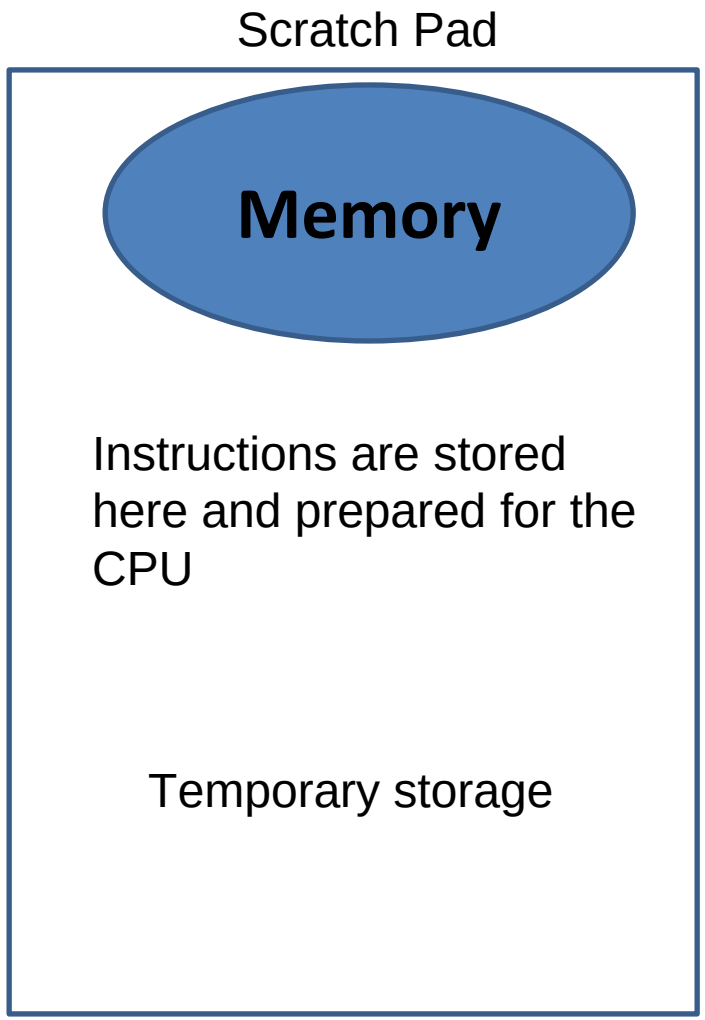
I. Hardware



When computer programs are executed, their instructions will eventually get stored in memory

Permanently?!?!

I. Hardware



When computer programs are executed, their instructions will eventually get stored in memory

Main memory is **volatile**

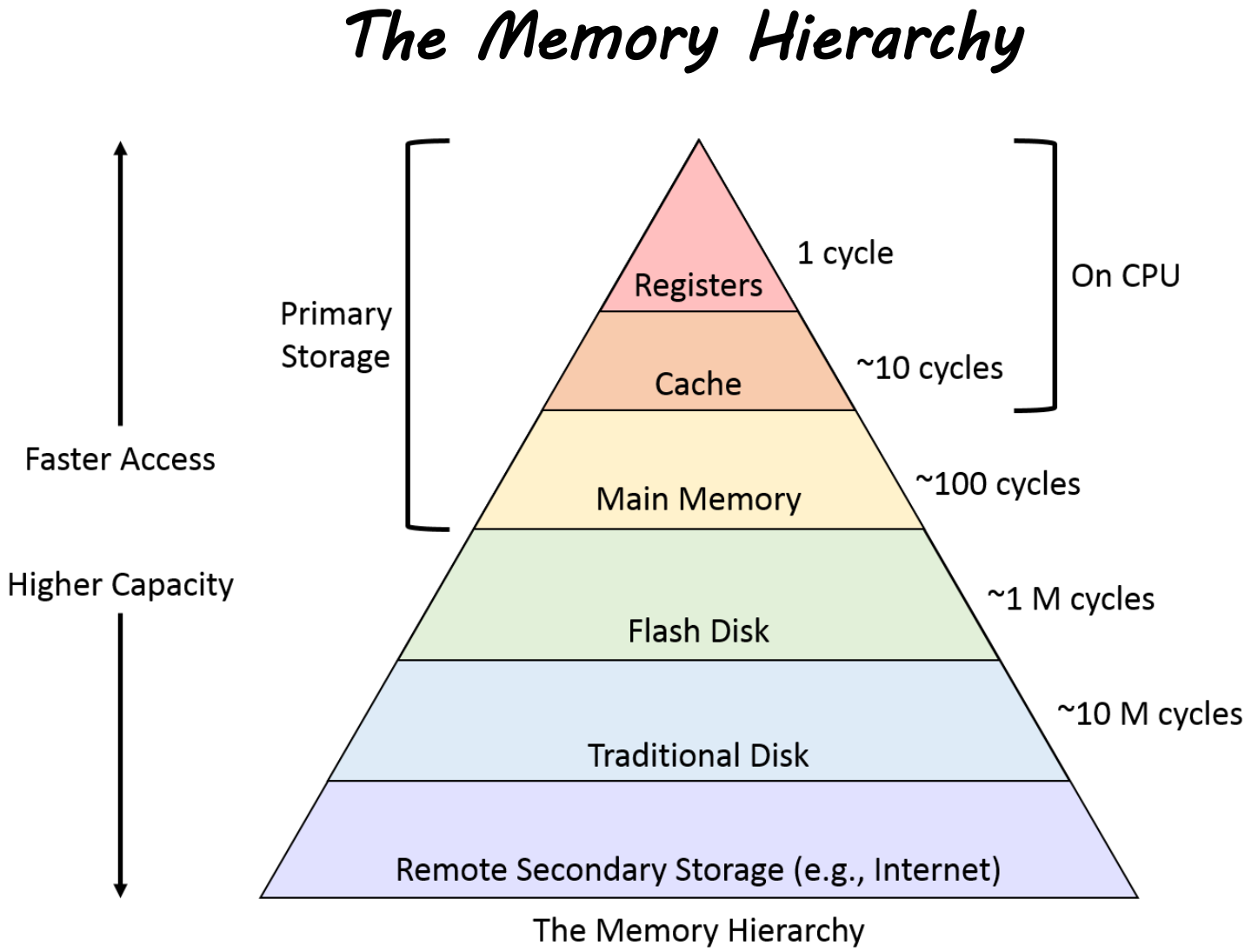
I. Hardware

Scratch Pad

Memory

Instructions are stored here and prepared for the CPU

Temporary storage



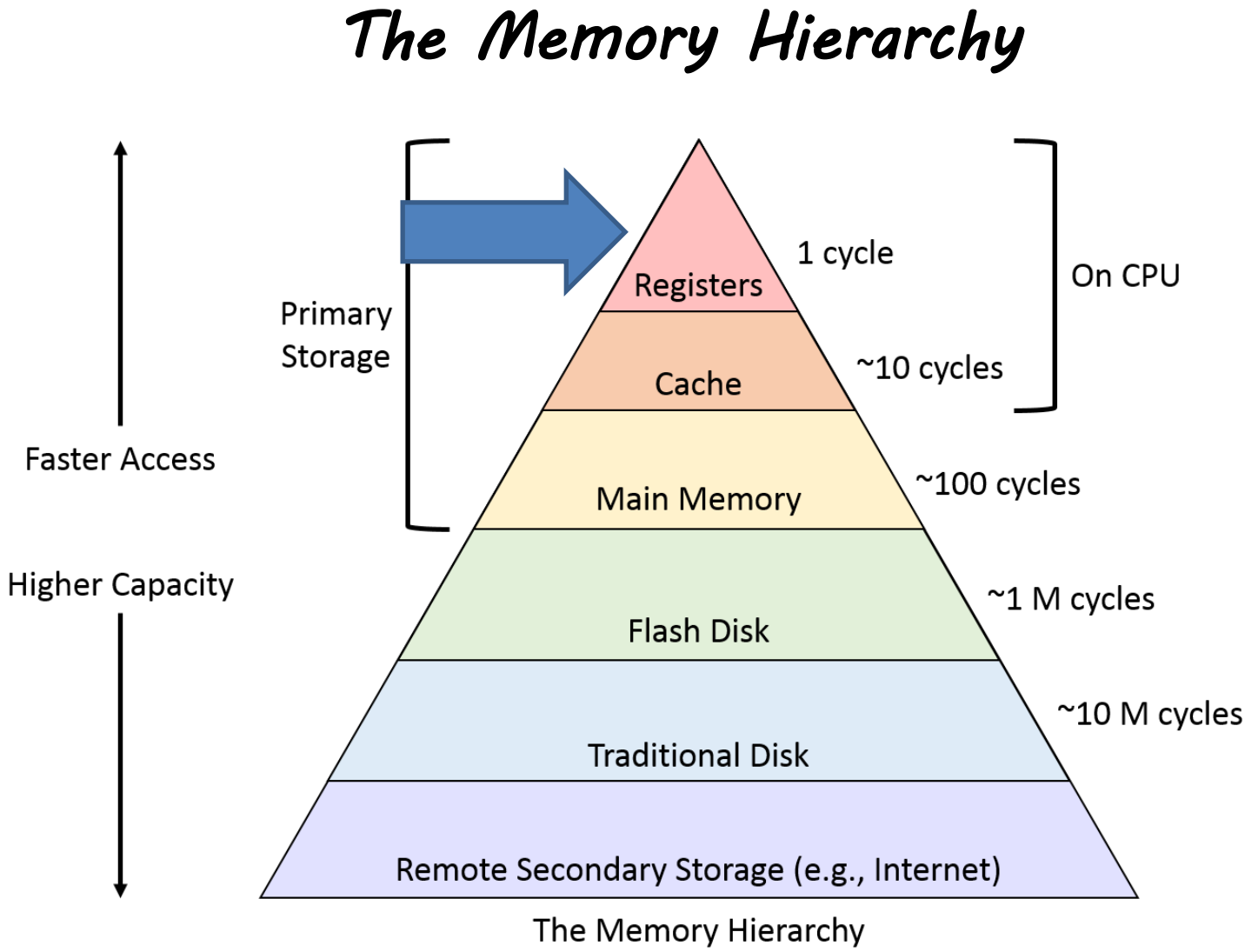
I. Hardware

Scratch Pad

Memory

Instructions are stored here and prepared for the CPU

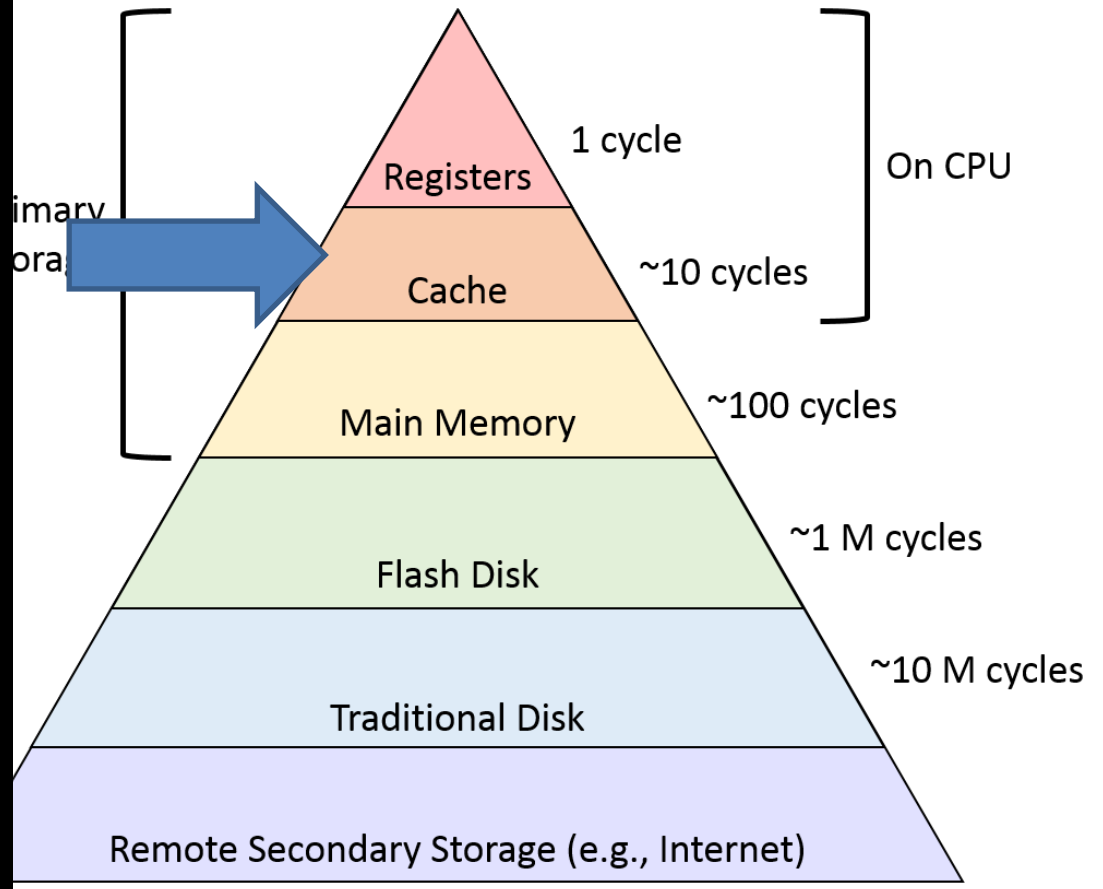
Temporary storage



I. Hardware

My CPU when the L1 cache misses

The Memory Hierarchy



The Memory Hierarchy

I. Hardware

The Memory Hierarchy

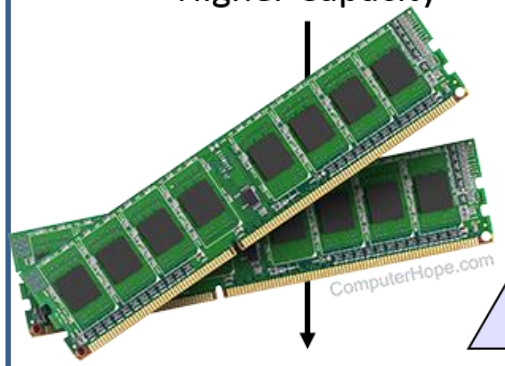
Scratch Pad

Memory

Instructions are stored

Faster Access

Higher Capacity



Primary Storage

On CPU

Registers	1 cycle
Cache	~10 cycles
RAM Main Memory	~100 cycles
Flash Disk	~1 M cycles
Traditional Disk	~10 M cycles
Remote Secondary Storage (e.g., Internet)	

The Memory Hierarchy

I. Hardware

Scratch Pad

Memory

Instructions are stored here and prepared for the CPU

Tempora

The Memory Hierarchy

The Memory Hierarchy

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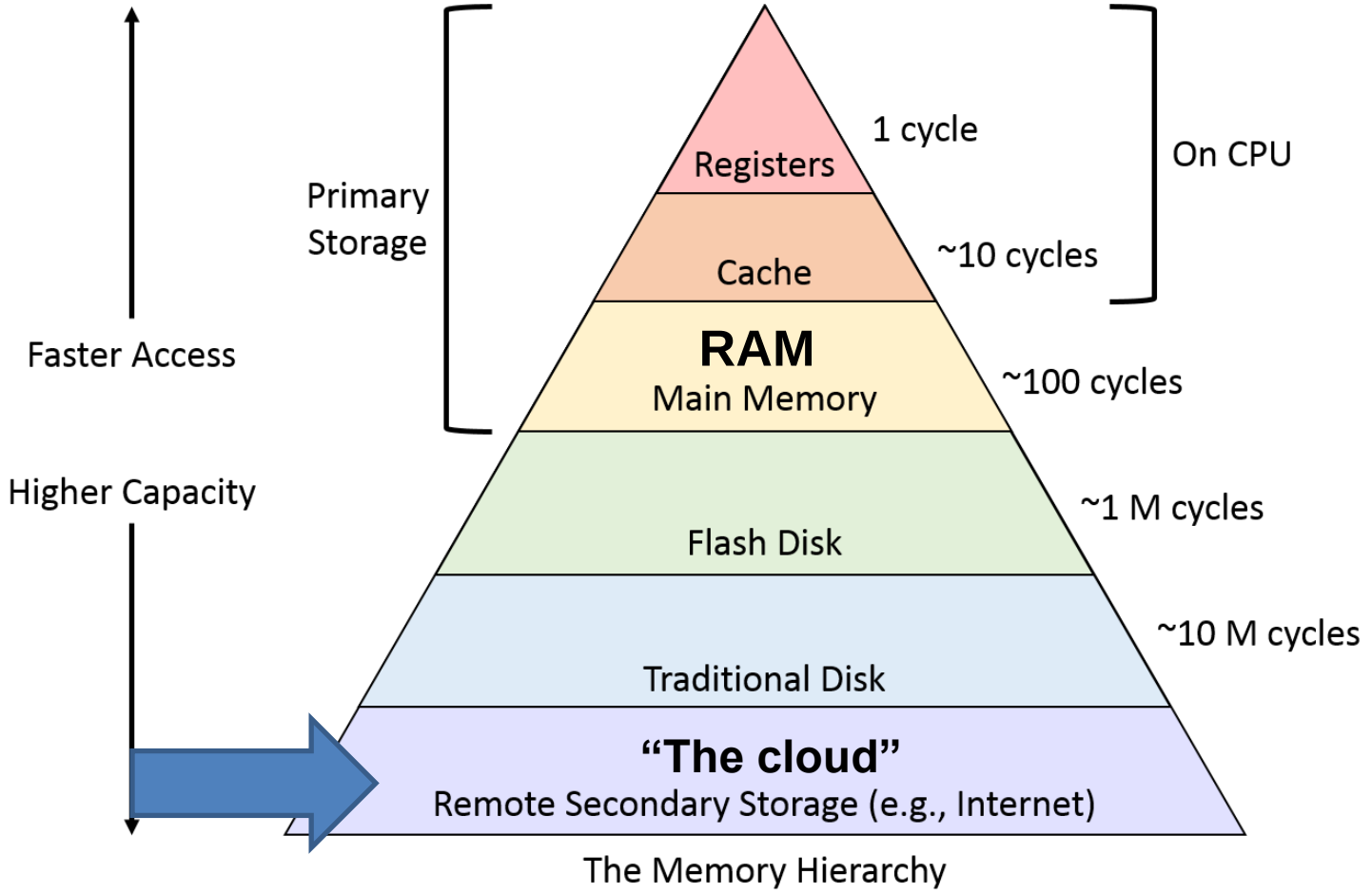
The Memory Hierarchy



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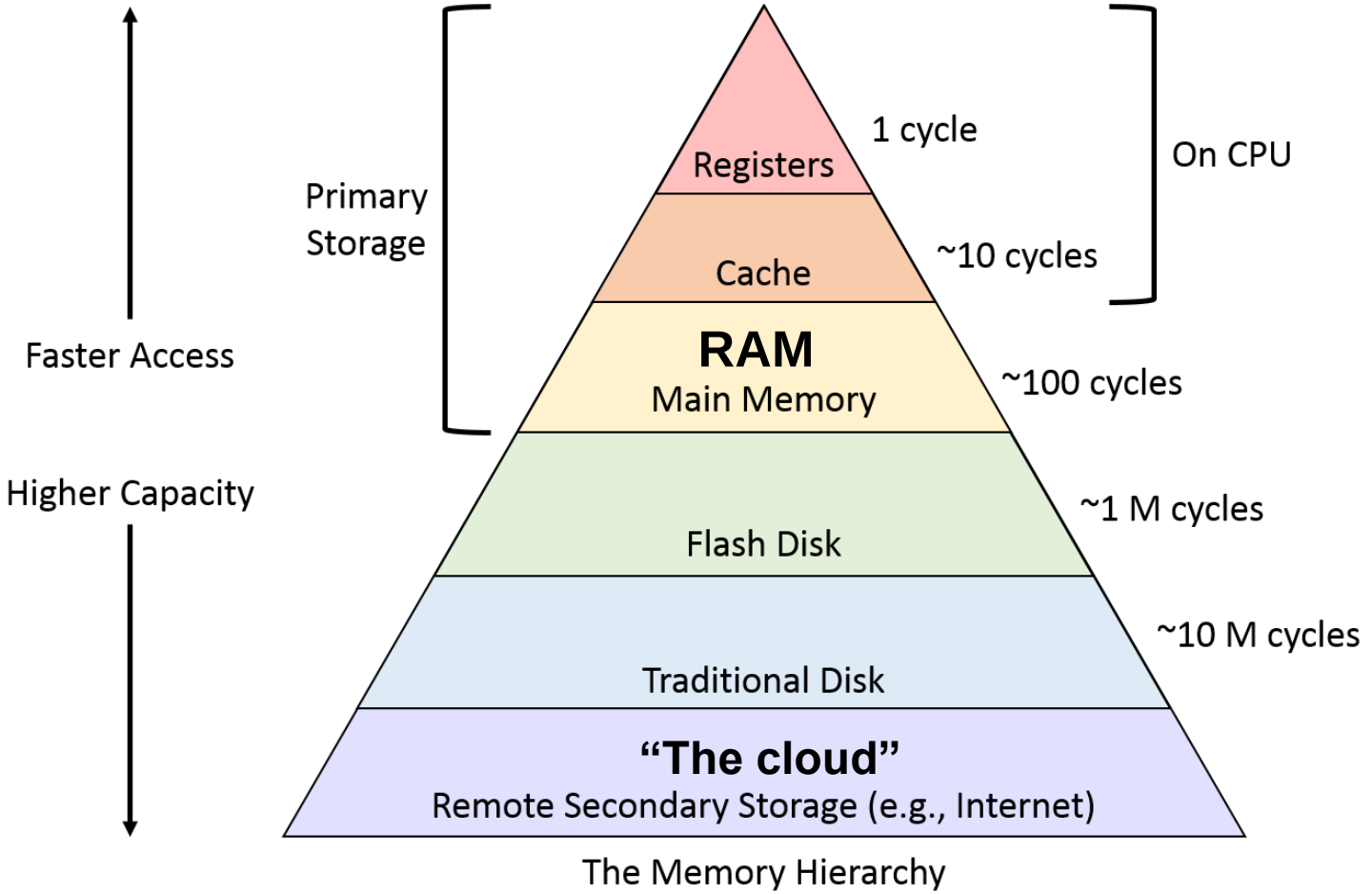
The Memory Hierarchy



The Memory Hierarchy

I. Hardware

Scratch Pad

Memory

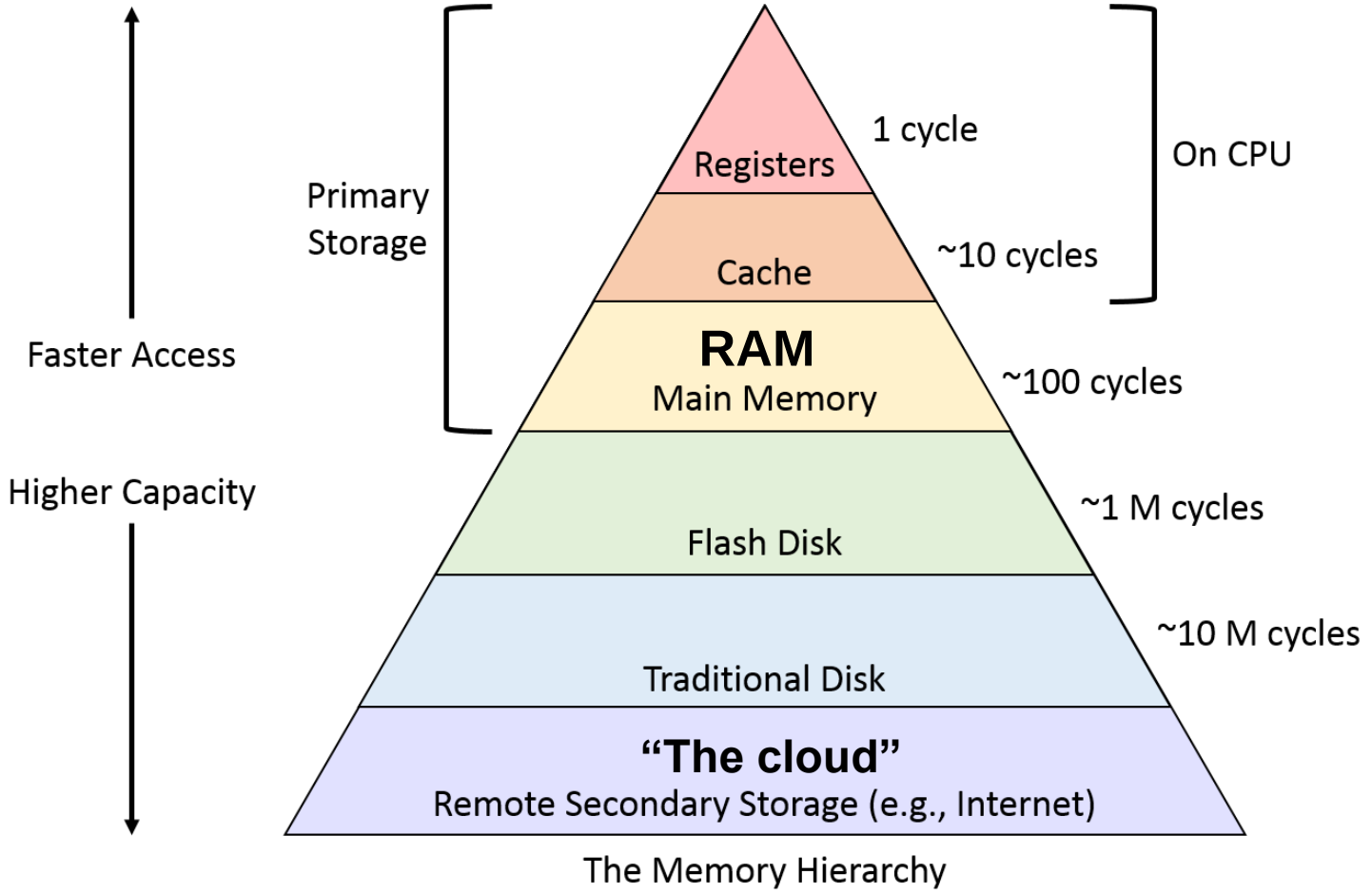
Instructions are stored here and prepared for the CPU

Temporary storage

RAM
Main Memory

Why not use memory/registers for everything??

The Memory Hierarchy



The Memory Hierarchy

I. Hardware

Brain with no short-term memory

CPU

Executes instructions

Must decipher what instruction to execute

The CPU can add, subtract, logic, move stuff around

Registers

5	00001
8	00011
3	00101
…	
	11111

Scratch Pad

Memory

Instructions are stored here and prepared for the CPU

Temporary storage

RAM
Main Memory

I. Hardware

Brain with no short-term memory

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Executes instructions

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5	00001
8	00011
3	00101
…	
	11111

1. Fetch next instruction

Scratch Pad

Memory

Instructions are stored here and prepared for the CPU

Temporary storage

RAM
Main Memory

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Brain with no short-term memory

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Executes instructions

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Registers

5	00001
8	00011
3	00101
…	
	11111

1. **Fetch next instruction**
2. **Decode Instruction**

Scratch Pad

Memory

Instructions are stored here and prepared for the CPU

Temporary storage

RAM
Main Memory

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Brain with no short-term memory

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Must decipher what instruction to execute

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Registers

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3	00101
…	
	11111

1. **Fetch next instruction**
2. **Decode Instruction**
3. **Execute Instruction**
4. **Store result***

Scratch Pad

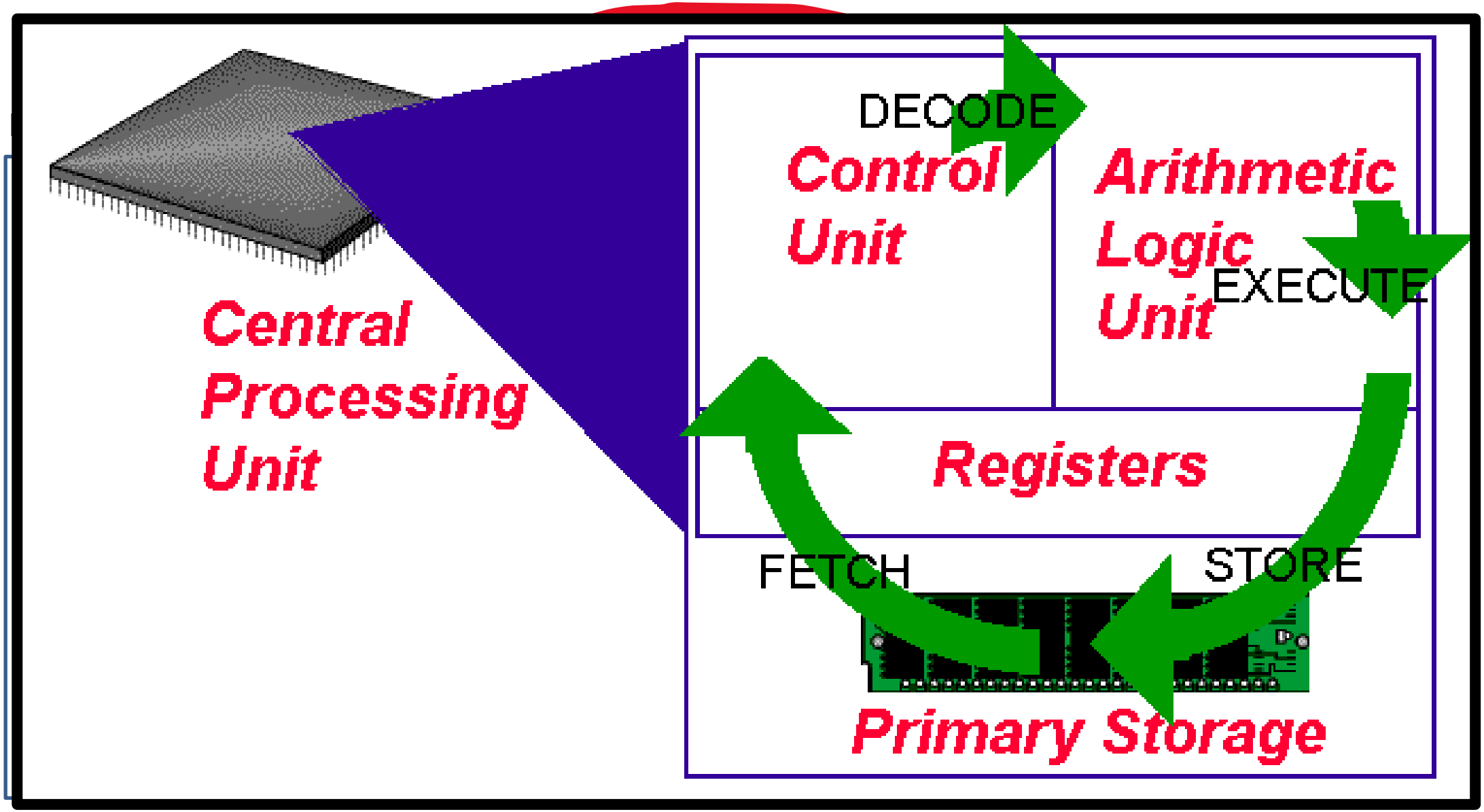
Memory

Instructions are stored here and prepared for the CPU

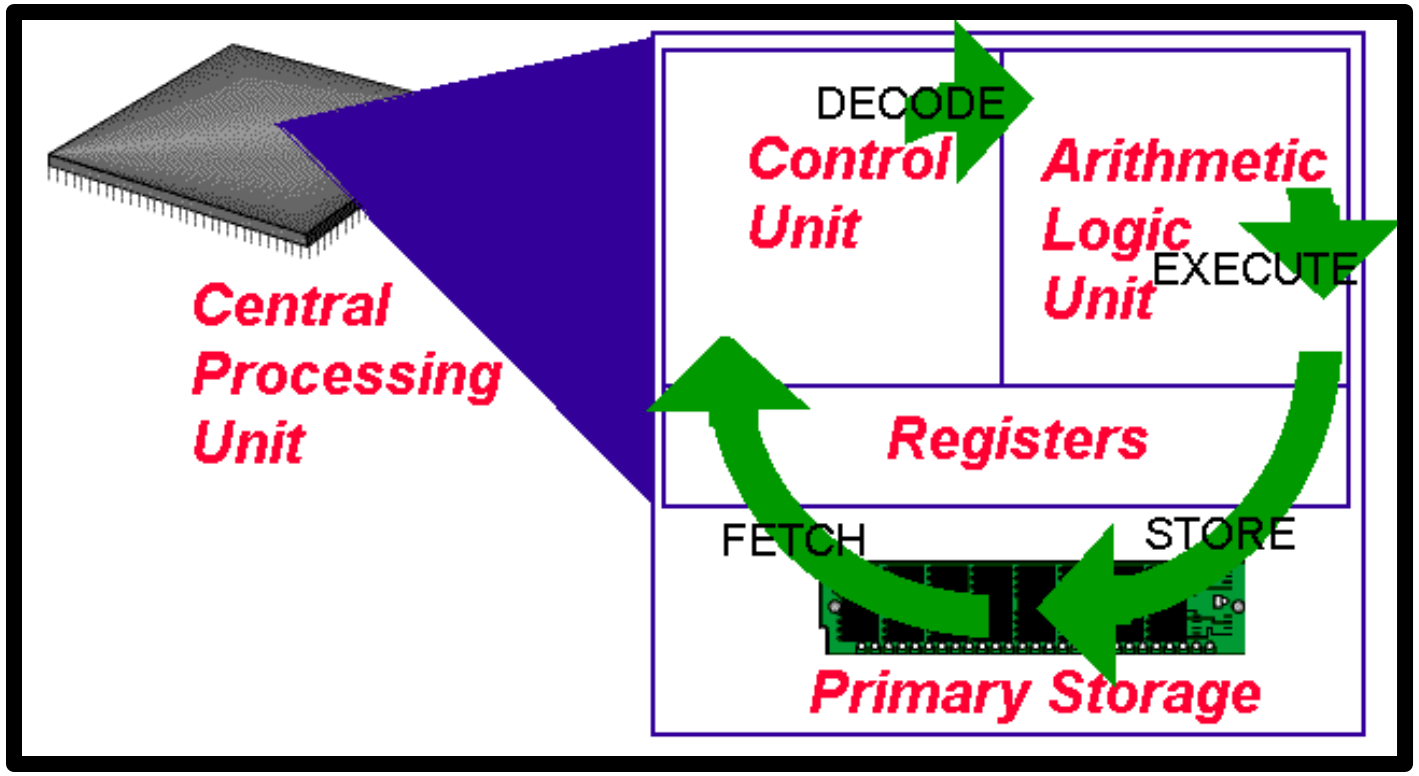
Temporary storage

RAM
Main Memory

I. Hardware

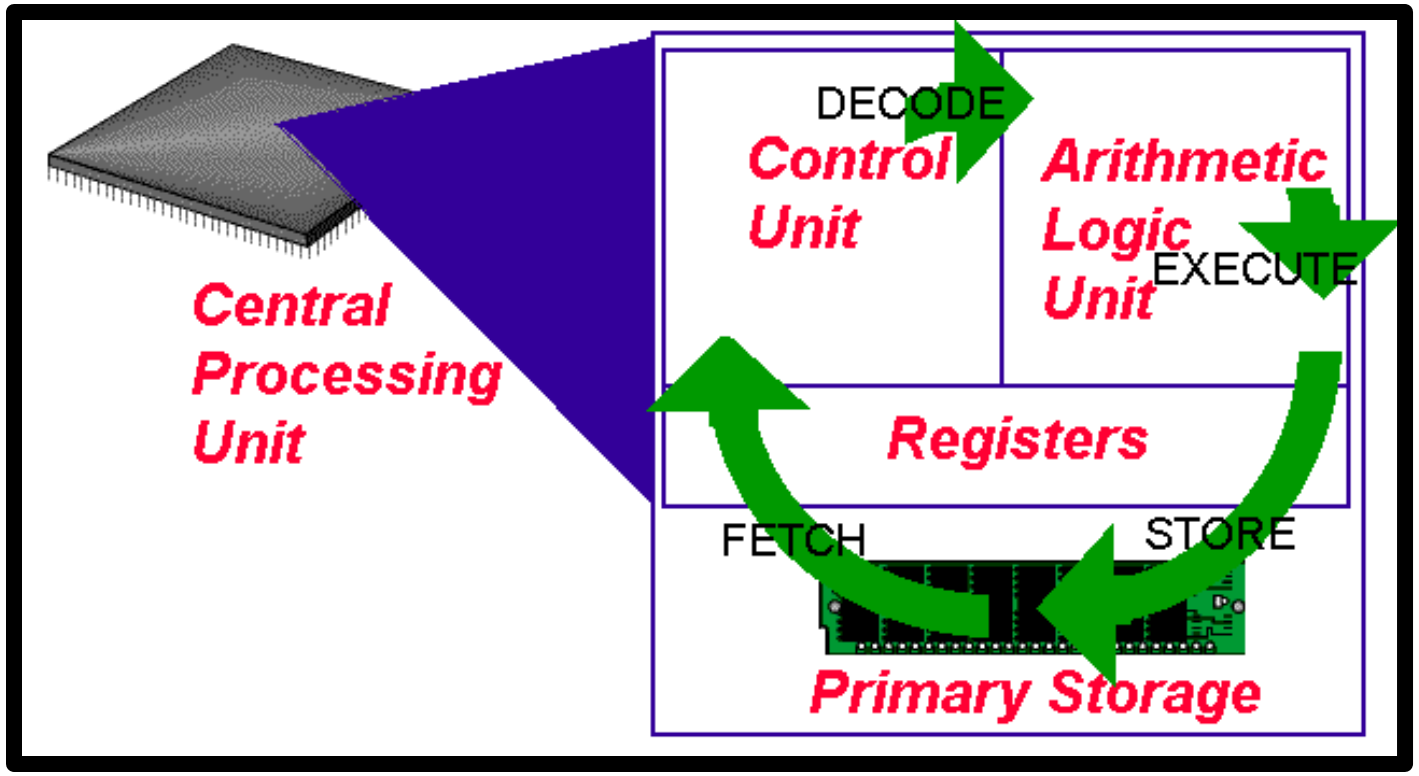

DECODE
Control Unit
Arithmetic Logic Unit
EXECUTE
Central Processing Unit
Registers
FETCH
STORE
Primary Storage

I. Hardware



This process happens really fast

I. Hardware



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… like ***really*** fast

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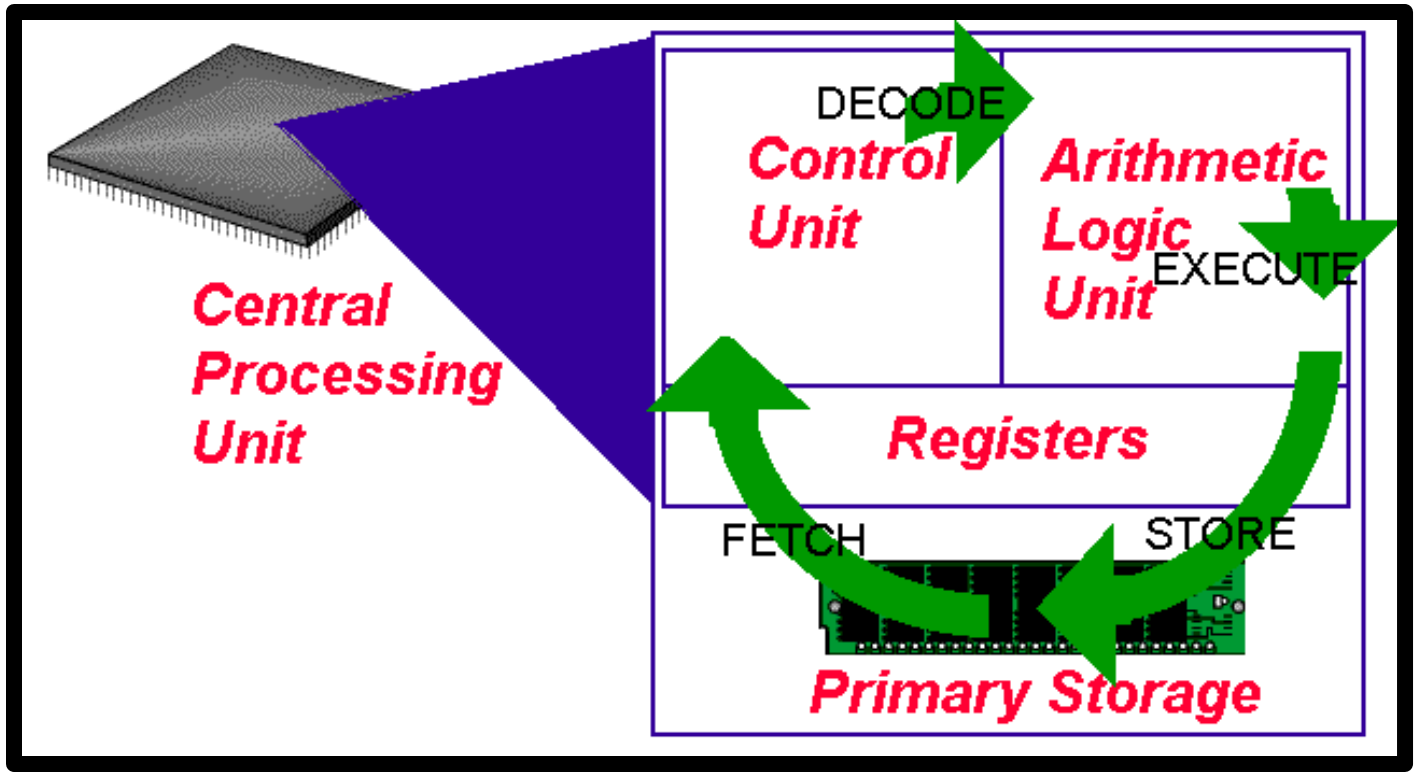

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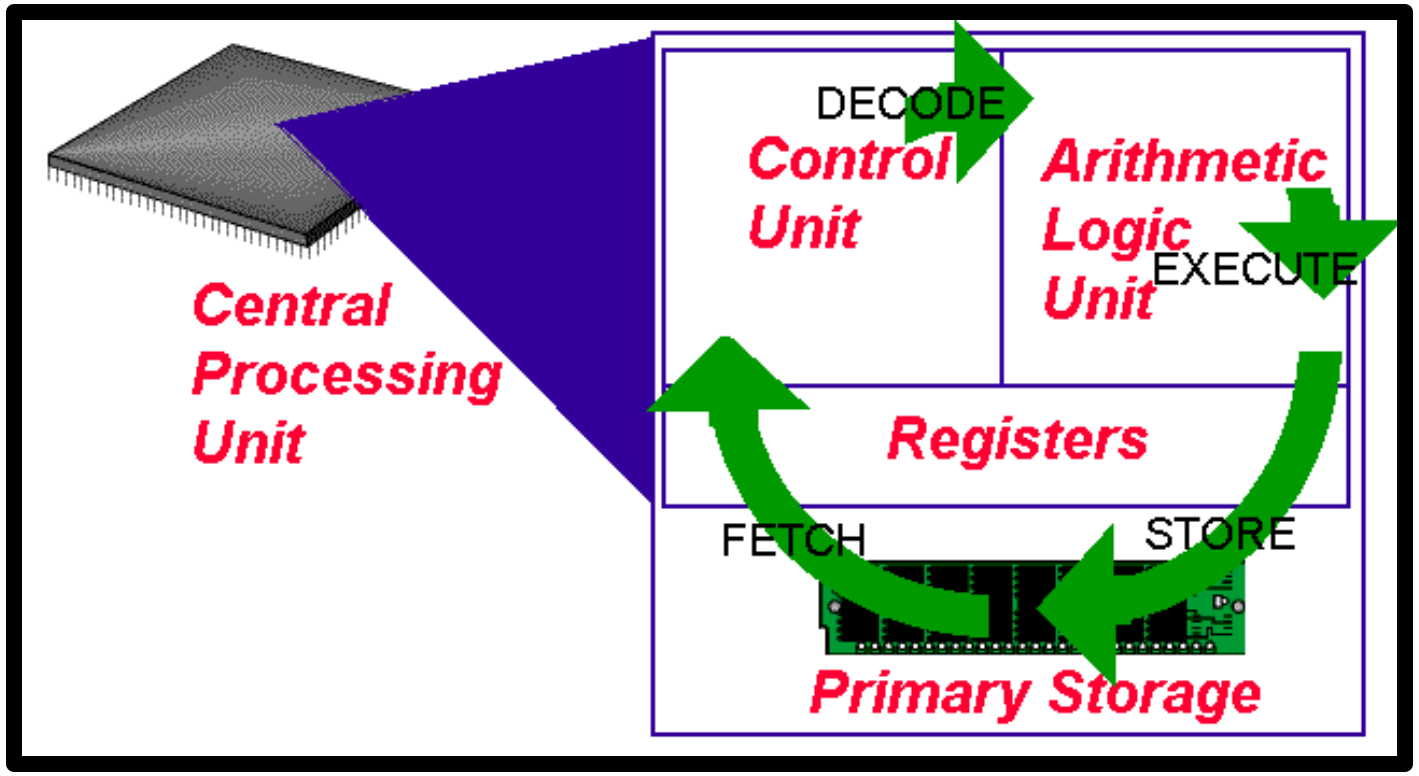
Computers can execute one or more instructions per clock cycle*

I. Hardware



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4GHz CPU speed = 4,000,000,000 clock cycles per second

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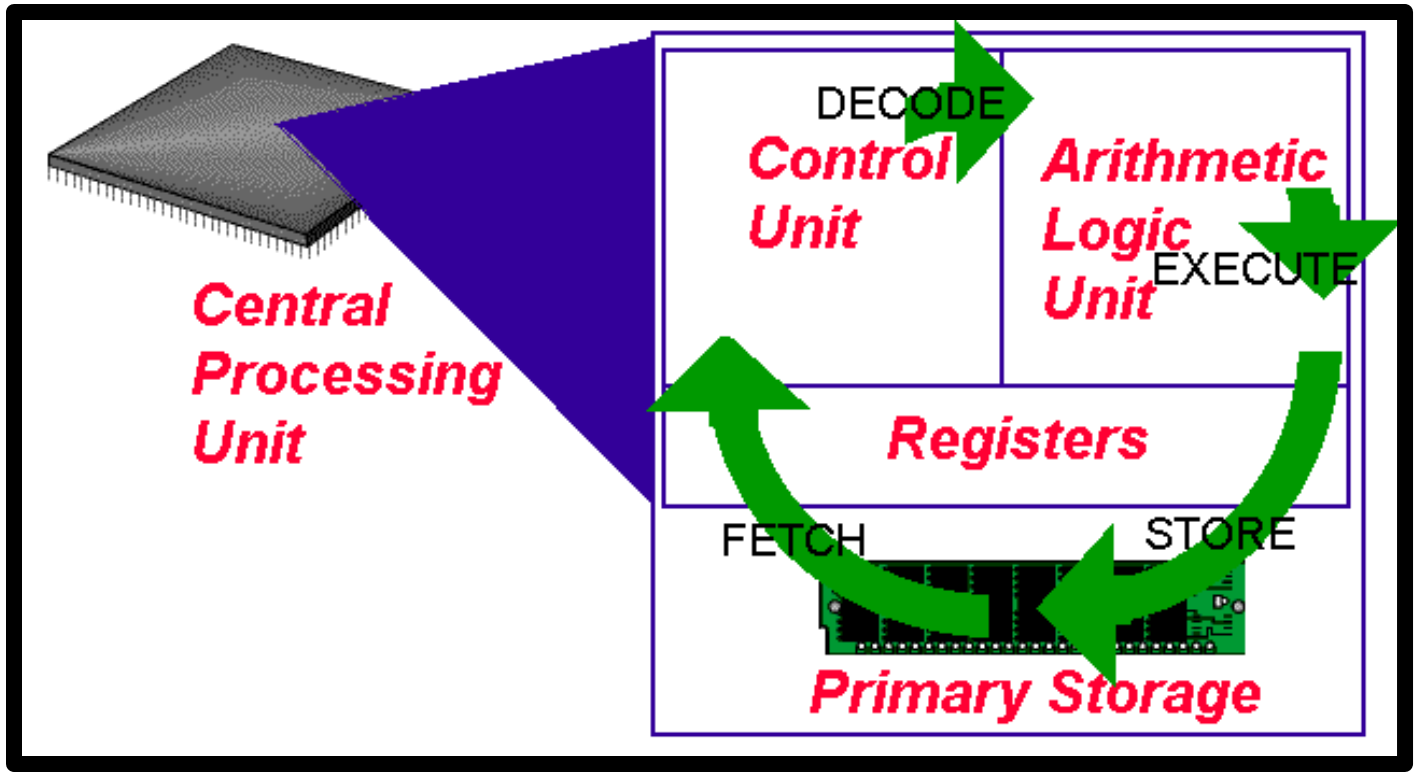

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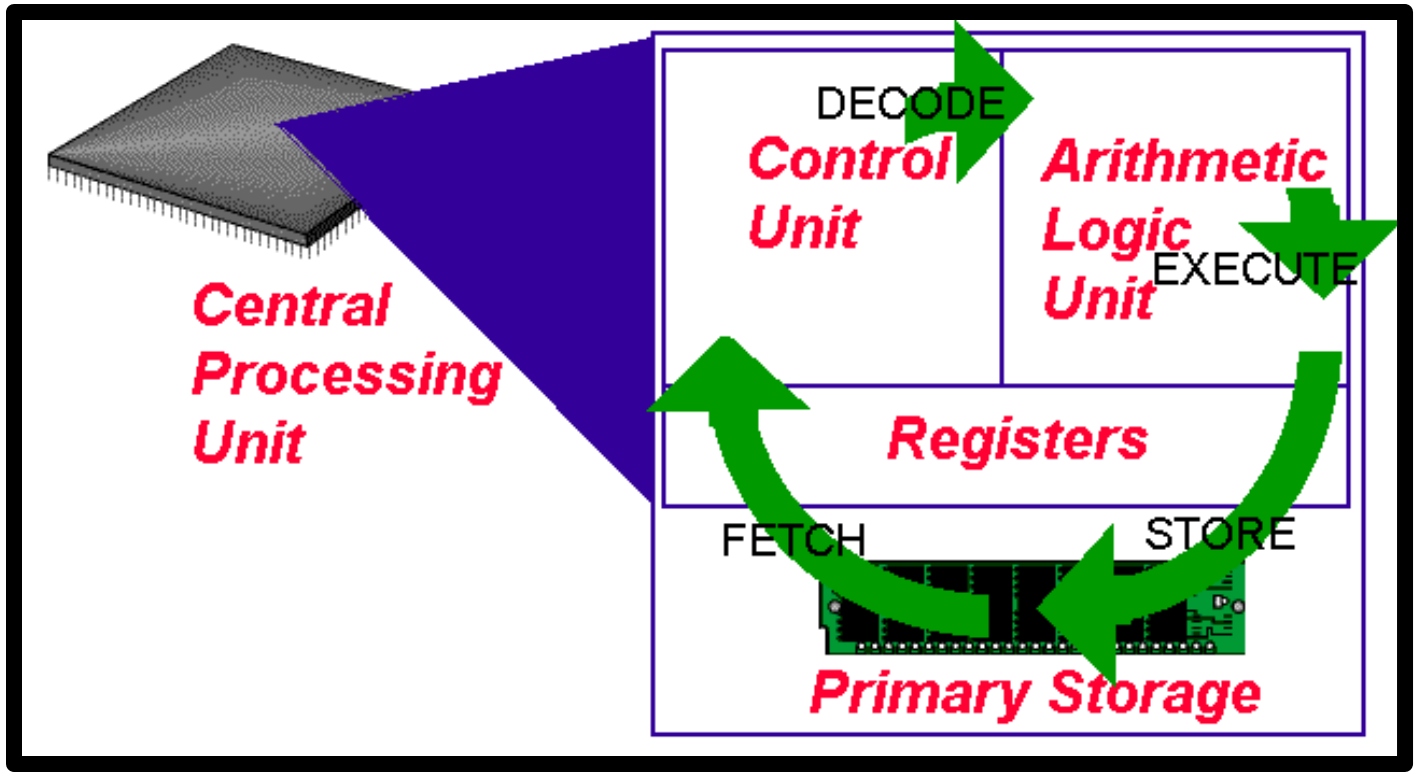

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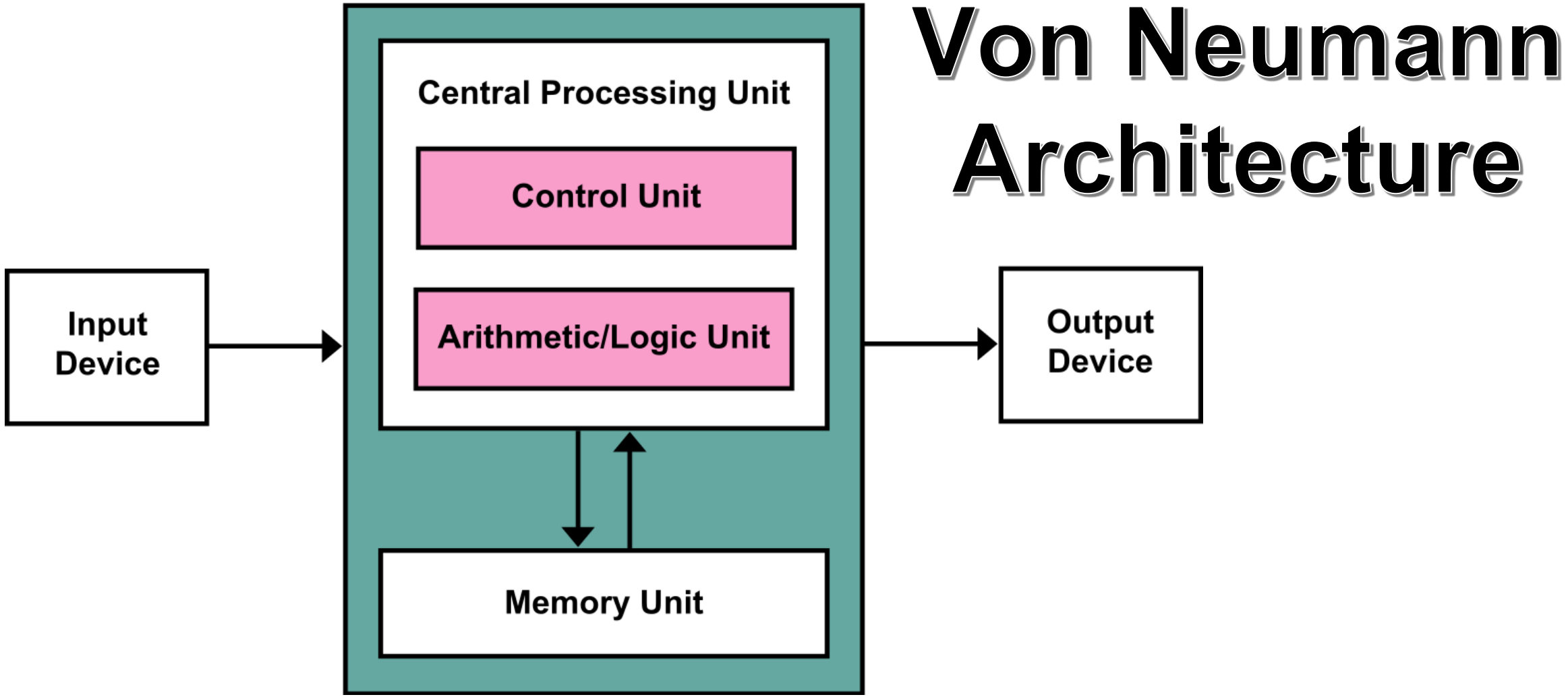
Computers can execute one or more instructions per clock cycle*

4GHz CPU speed = 4,000,000,000 clock cycles per second

Multi-core systems are even faster

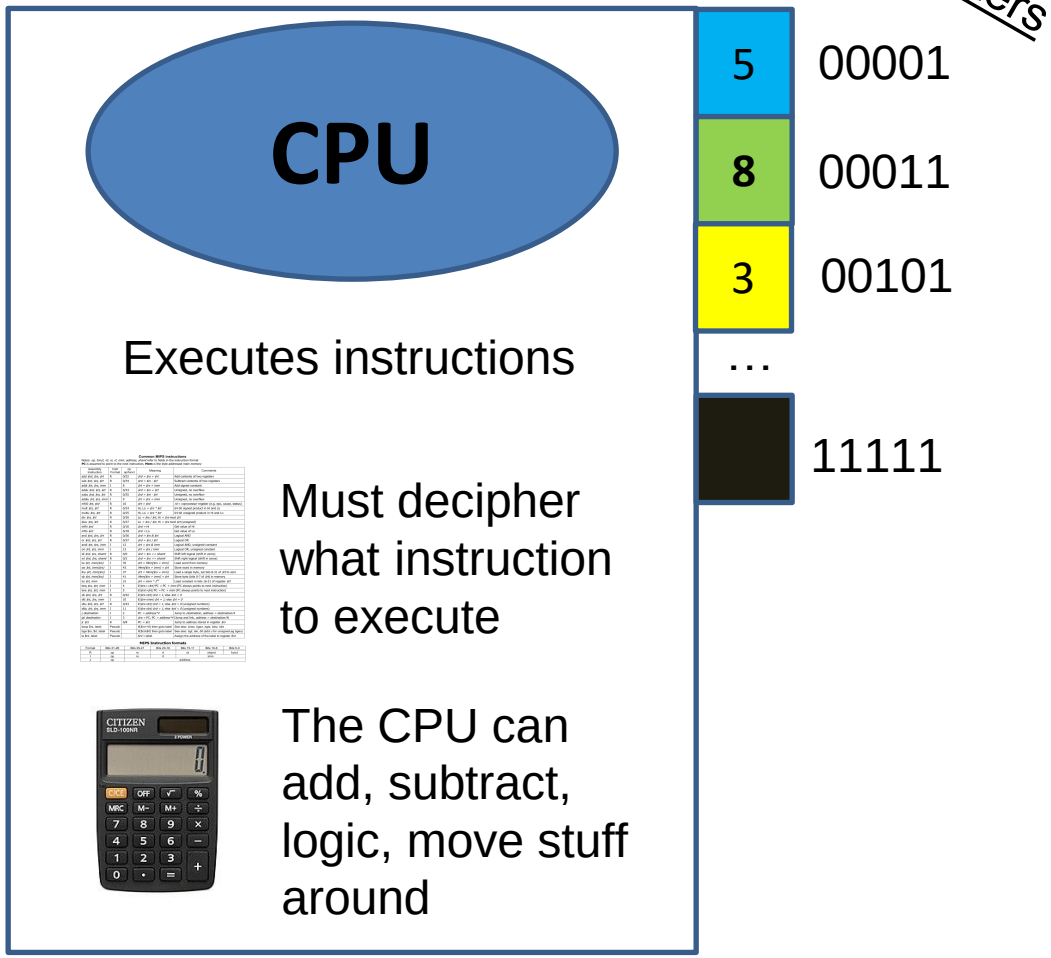
I. Hardware

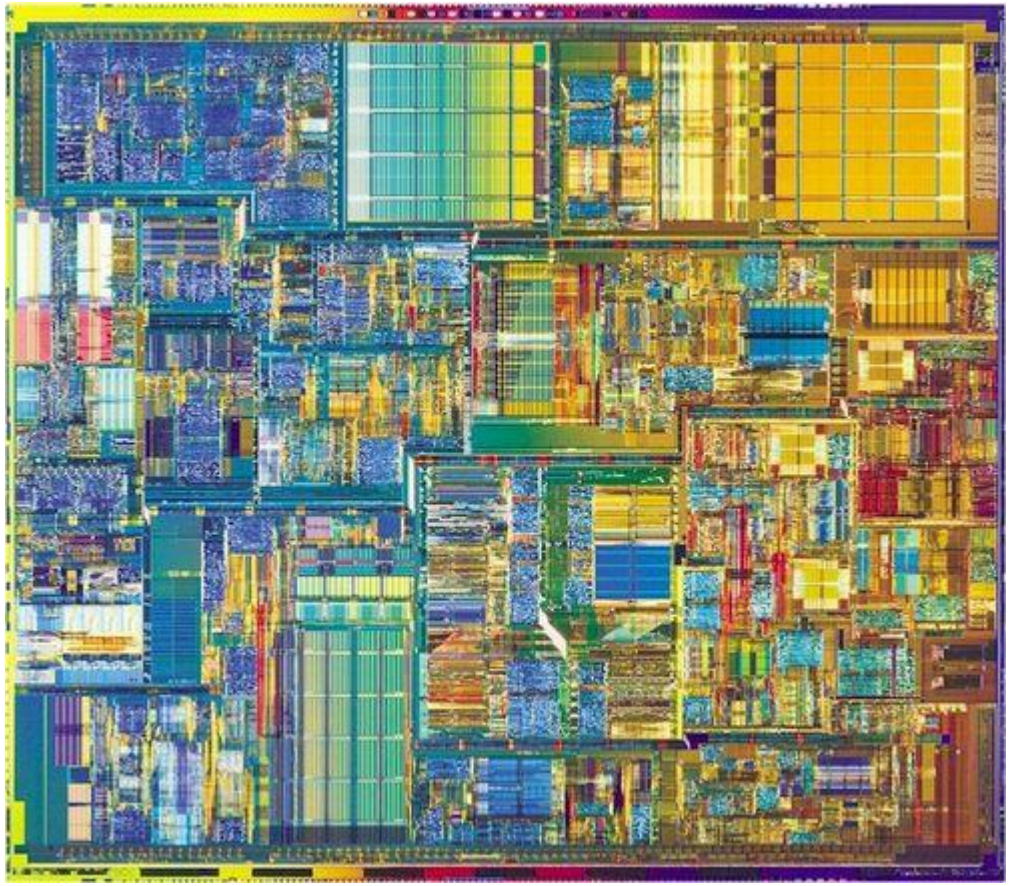
Von Neumann Architecture



I. Hardware

Brain with no short-term memory





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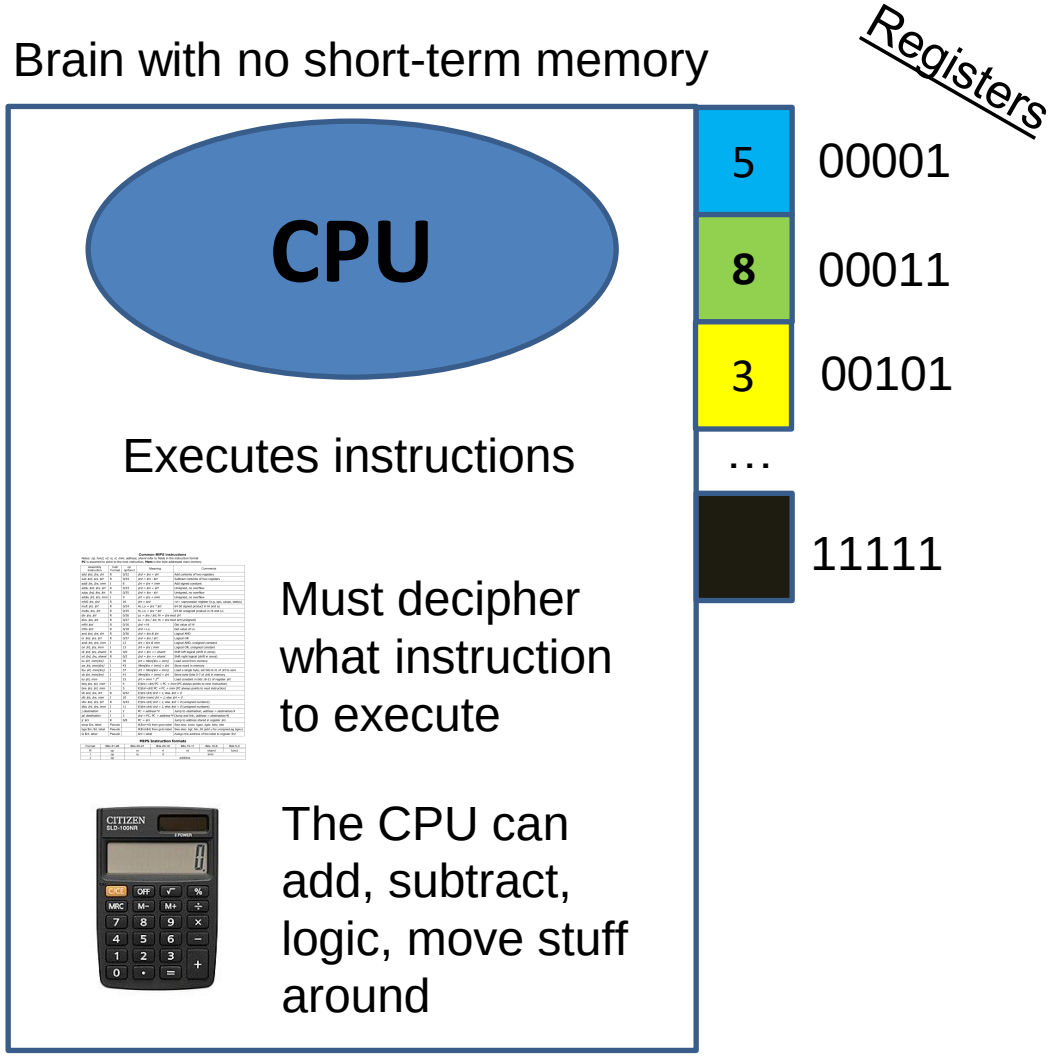
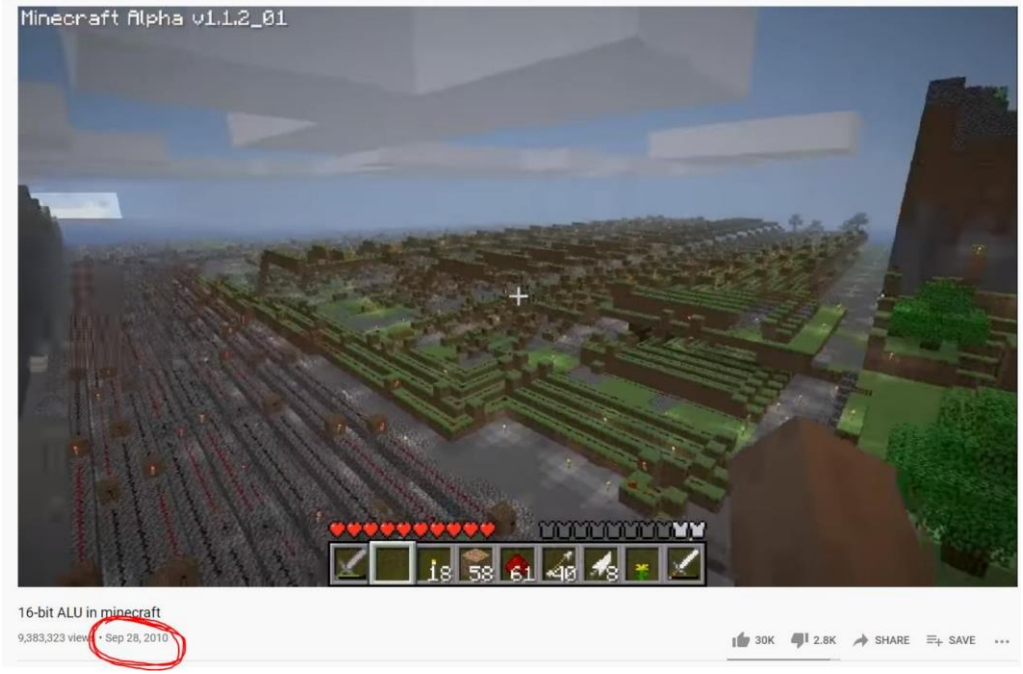




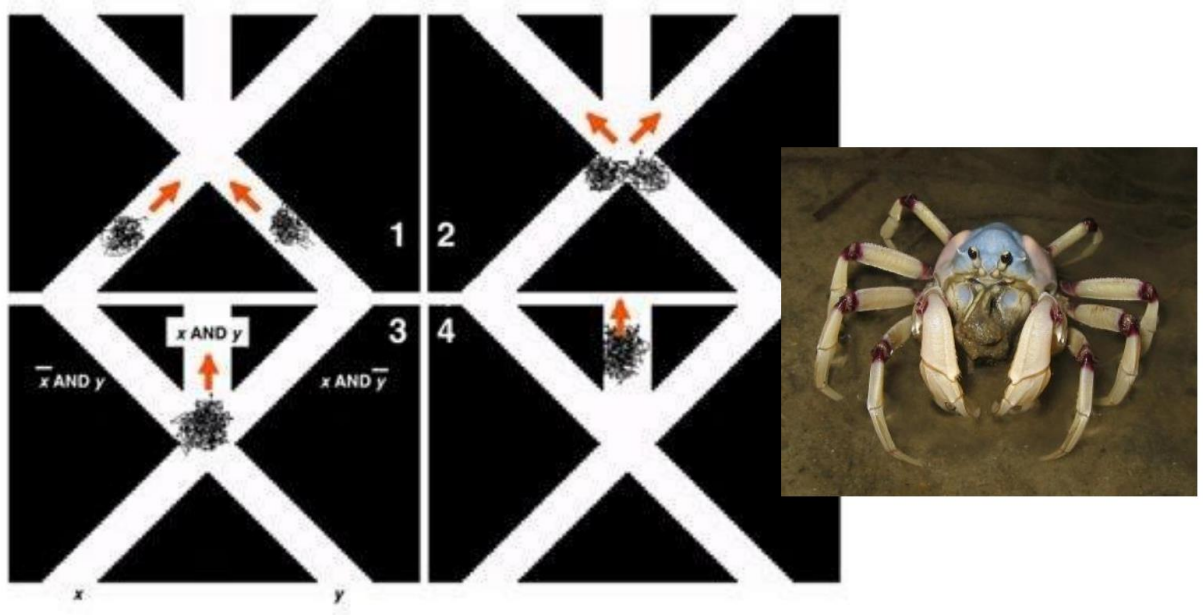
People have been able to create CPU components and fully functional, multi-core computers in games such as Minecraft

I. Hardware

WIRED STAFF BUSINESS 04.14.2012 03:20 PM

Computer Built Using Swarms Of Soldier Crabs

Computer scientists at Kobe University in Japan have built a computer that draws inspiration from the swarming behavior of soldier crabs. The computer is based on theories from the early 1980s that studies how it could be possible to build a computer out of billiard balls. Proposed by Edward Fredkin and Tommaso Toffoli, the mechanical [...]



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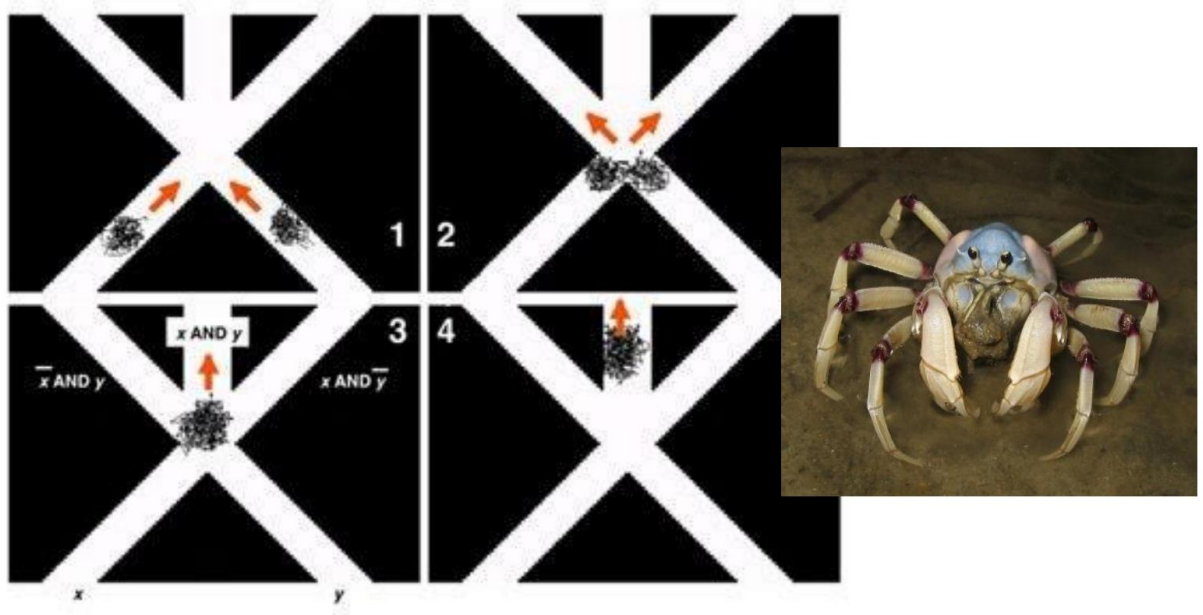

This is very real

Robust Soldier Crab Ball Gate

Yukio-Pegio Gunji
Yuta Nishiyama
Department of Earth and Planetary Sciences
Kobe University
Kobe 657-8501, Japan

Andrew Adamatzky
Unconventional Computing Centre
University of the West of England
Bristol, United Kingdom

Soldier crabs *Mictyris guinotae* exhibit pronounced swarming behavior. Swarms of the crabs are tolerant of perturbations. In computer models and laboratory experiments we demonstrate that swarms of soldier crabs can implement logical gates when placed in a geometrically constrained environment.

1. Introduction

All natural processes can be interpreted in terms of computations. To implement a logical gate in a chemical, physical, or biological spatially extended medium, Boolean variables must be assigned to disturbances, defects, or localizations traveling in the medium. These traveling patterns collide and the outcome of their collisions are converted

https://wpmedia.wolfram.com/uploads/sites/13/2018/02/20-2-2.pdf

I. Hardware

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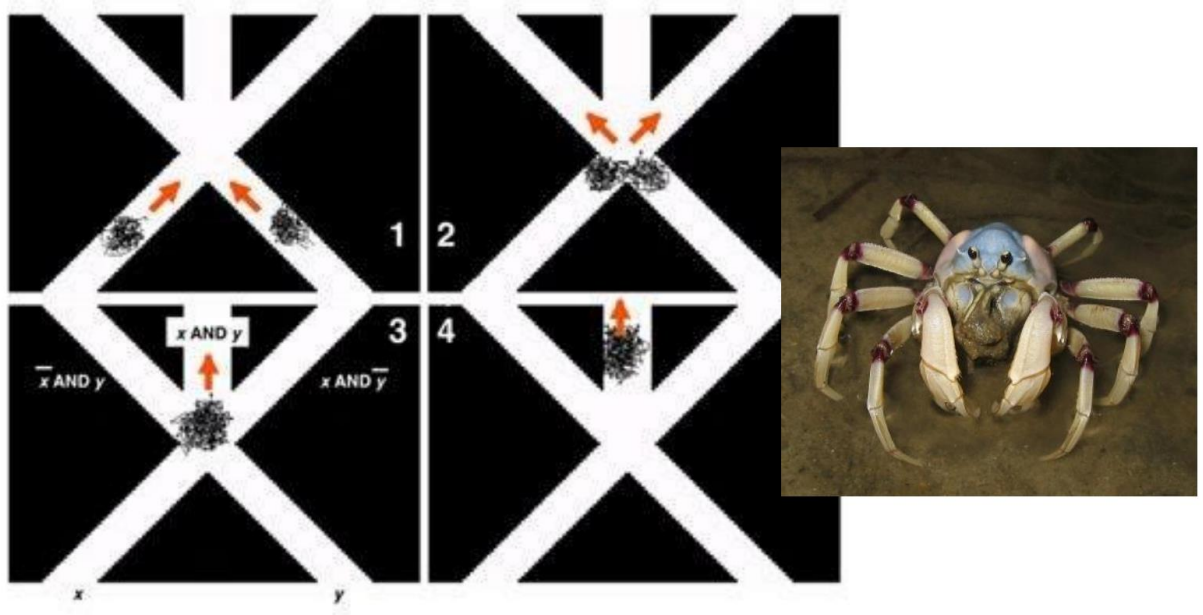
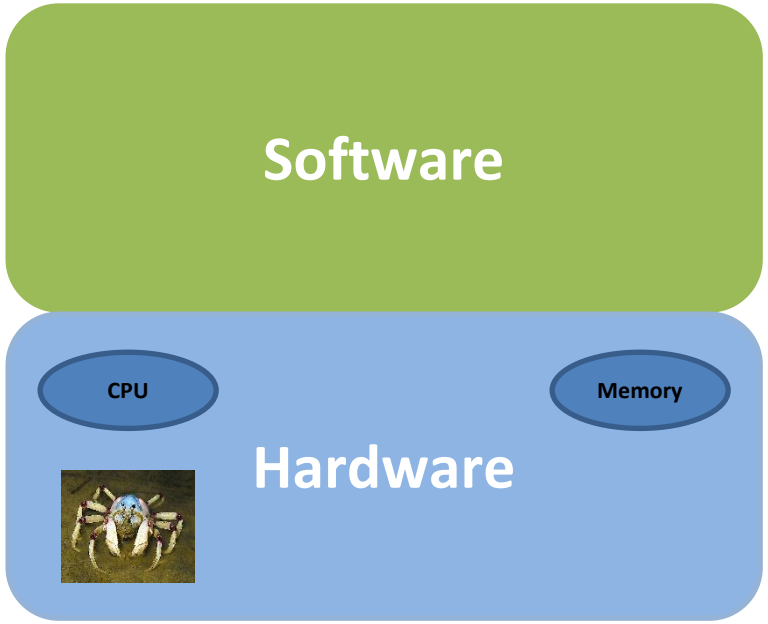


(In theory) If you wanted to play Doom (1993) using a CPU made from soldier crabs, you would need 22 million crabs

(source: twitter)

How does this happen?



From a high level, we will divide a computer system into two parts

I. **Hardware**
II. **Software**

II. Software

A sequence of instructions, or **program**,
that tells the computer how to work

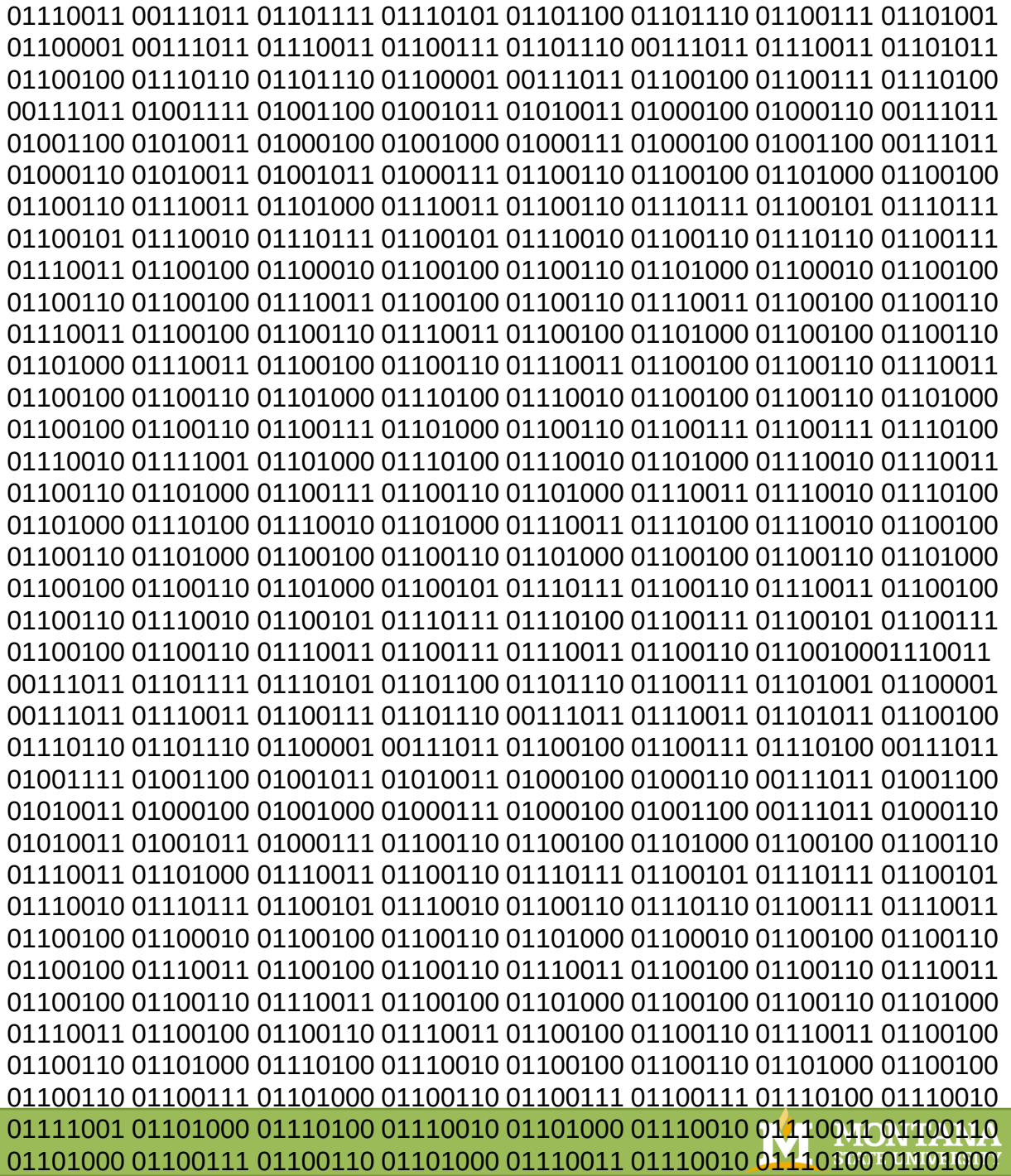





II. Software

A sequence of instructions, or **program**, that tells the computer how to work

Humans write code in binary ?



II. Software

A sequence of instructions, or **program**, that tells the computer how to work

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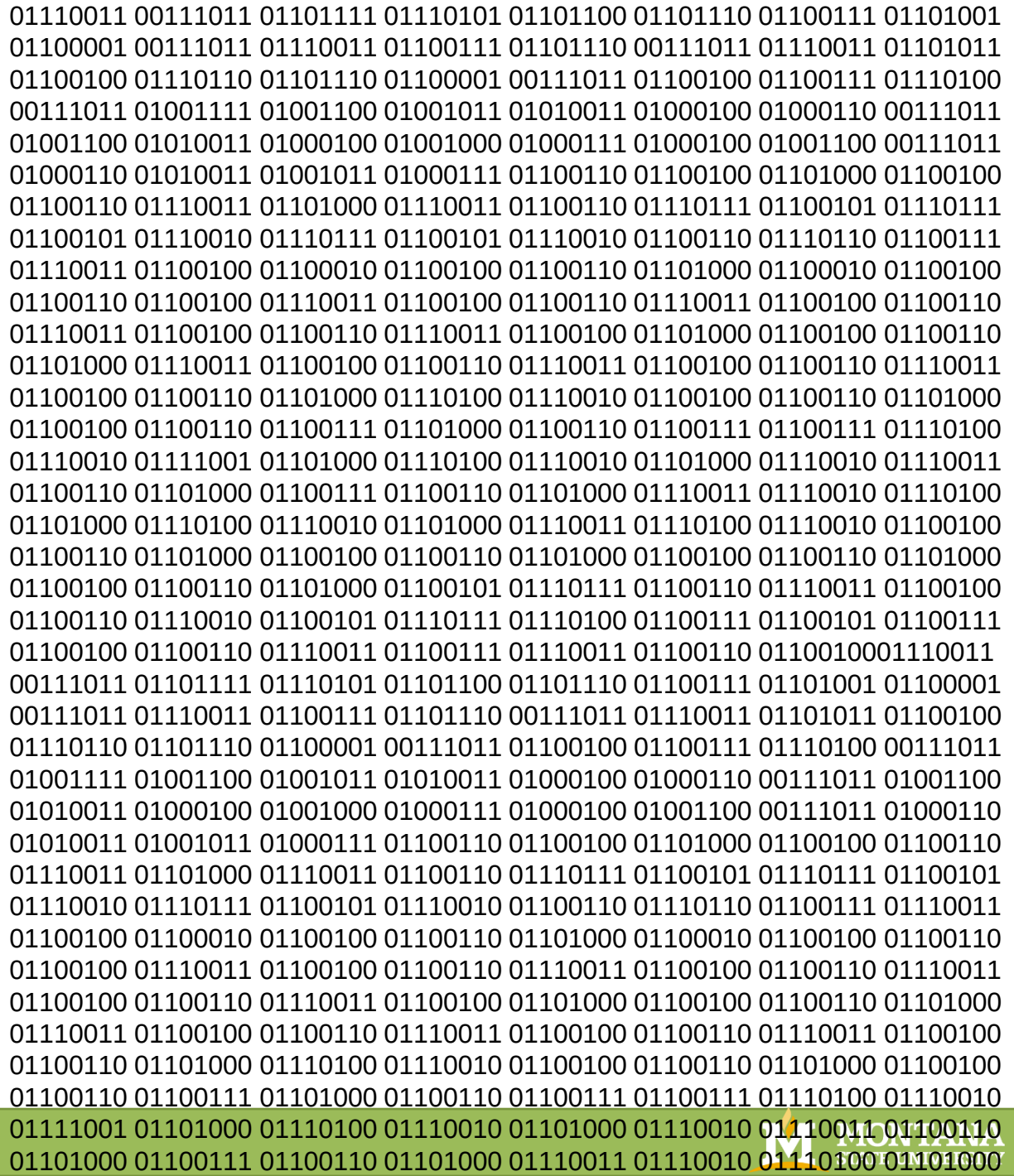
NO



II. Software

We write programs in a readable, higher-level language

```c
#include <stdio.h>

int main() {
        printf("Hello WOrld! \n");


        int x = 0;
        int y = 3;

        int z = x + y;

        printf("%d  %d  %d \n",x,y,z);
        return 0;
}
```

```python
class Person():
#method to initialize name and age attributes.
    def __init__(self,name, age):
        self.name = name
        self.age = age
#method to demonstrate what a person eats
    def eat(self):
        print(self.name.title() + "eats Matooke and rice")
        print("She is"+ str(self.age) + " years old")
    def drink(self):
        print("Drinks water")
#instantiating a class.
my_sister = Person("Haniifa", 30)
#Accessing the class method through the class object.
my_sister.eat()
```

II. Software

We need a way to convert **source** code to **binary**

```c
#include <stdio.h>

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}
```
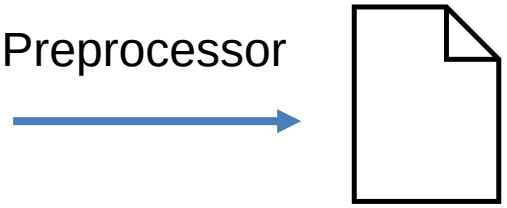

Preprocessor



- Removal of comments
- Expand Macros

**THIS PROCESS IS NOT TRUE FOR EVERY LANGUAGE

II. Software

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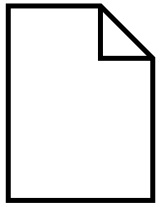
Preprocessor



- Removal of comments
- Expand Macros

Compiler

```
0000000000000000 <main>:
   0:   f3 0f 1e fa             endbr64
   4:   55                      push   %rbp
   5:   48 89 e5                mov    %rsp,%rbp
   8:   48 83 ec 10             sub    $0x10,%rsp
   c:   48 8d 3d 00 00 00 00    lea    0x0(%rip),%rdi        # 13 <main+0x13>
  13:   e8 00 00 00 00          callq  18 <main+0x18>
  18:   c7 45 f4 00 00 00 00    movl   $0x0,-0xc(%rbp)
  1f:   c7 45 f8 03 00 00 00    movl   $0x3,-0x8(%rbp)
  26:   8b 55 f4                mov    -0xc(%rbp),%edx
  29:   8b 45 f8                mov    -0x8(%rbp),%eax
  2c:   01 d0                   add    %edx,%eax
  2e:   89 45 fc                mov    %eax,-0x4(%rbp)
  31:   8b 4d fc                mov    -0x4(%rbp),%ecx
  34:   8b 55 f8                mov    -0x8(%rbp),%edx
  37:   8b 45 f4                mov    -0xc(%rbp),%eax
  3a:   89 c6                   mov    %eax,%esi
  3c:   48 8d 3d 00 00 00 00    lea    0x0(%rip),%rdi        # 43 <main+0x43>
  43:   b8 00 00 00 00          mov    $0x0,%eax
  48:   e8 00 00 00 00          callq  4d <main+0x4d>
  4d:   b8 00 00 00 00          mov    $0x0,%eax
  52:   c9                      leaveq
  53:   c3                      retq
```

- Converted to assembly code
- .s file

II. Software

We need a way to convert **source** code to **binary**

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Preprocessor

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  29:   8b 45 f8                mov    -0x8(%rbp),%eax
  2c:   01 d0                   add    %edx,%eax
  2e:   89 45 fc                mov    %eax,-0x4(%rbp)
  31:   8b 4d fc                mov    -0x4(%rbp),%ecx
  34:   8b 55 f8                mov    -0x8(%rbp),%edx
  37:   8b 45 f4                mov    -0xc(%rbp),%eax
  3a:   89 c6                   mov    %eax,%esi
  3c:   48 8d 3d 00 00 00 00    lea    0x0(%rip),%rdi        # 43 <main+0x43>
  43:   b8 00 00 00 00          mov    $0x0,%eax
  48:   e8 00 00 00 00          callq  4d <main+0x4d>
  4d:   b8 00 00 00 00          mov    $0x0,%eax
  52:   c9                      leaveq
  53:   c3                      retq
```

Assembler

- Converted to assembly code
- .s file

```
1           00000000 00000100 0000000000000000
2  01011110 00001100 11000010 0000000000000010
3           11101111 00010110 0000000000000101
4           11101111 10011110 0000000000001011
5  11111000 10101101 11011111 0000000000010010
6           01100010 11011111 0000000000010101
7  11101111 00000010 11111011 0000000000010111
8  11110100 10101101 11011111 0000000000011110
9  00000011 10100010 11011111 0000000000100001
10 11101111 00000010 11111011 0000000000100100
11 01111110 11110100 10101101
12 11111000 10101110 11000101 0000000000101011
13 00000110 10100010 11111011 0000000000110001
14 11101111 00000010 11111011 0000000000110100
15          01010000 11010100 0000000000111011
16                   00000100 0000000000111101
```

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```
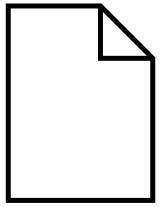

Preprocessor



- Removal of comments
- Expand Macros

Compiler

```
0000000000000000 <main>:
   0:   f3 0f 1e fa             endbr64
   4:   55                      push   %rbp
   5:   48 89 e5                mov    %rsp,%rbp
   8:   48 83 ec 10             sub    $0x10,%rsp
   c:   48 8d 3d 00 00 00 00    lea    0x0(%rip),%rdi        # 13 <main+0x13>
  13:   e8 00 00 00 00          callq  18 <main+0x18>
  18:   c7 45 f4 00 00 00 00    movl   $0x0,-0xc(%rbp)
  1f:   c7 45 f8 03 00 00 00    movl   $0x3,-0x8(%rbp)
  26:   8b 55 f4                mov    -0xc(%rbp),%edx
  29:   8b 45 f8                mov    -0x8(%rbp),%eax
  2c:   01 d0                   add    %edx,%eax
  2e:   89 45 fc                mov    %eax,-0x4(%rbp)
  31:   8b 4d fc                mov    -0x4(%rbp),%ecx
  34:   8b 55 f8                mov    -0x8(%rbp),%edx
  37:   8b 45 f4                mov    -0xc(%rbp),%eax
  3a:   89 c6                   mov    %eax,%esi
  3c:   48 8d 3d 00 00 00 00    lea    0x0(%rip),%rdi        # 43 <main+0x43>
  43:   b8 00 00 00 00          mov    $0x0,%eax
  48:   e8 00 00 00 00          callq  4d <main+0x4d>
  4d:   b8 00 00 00 00          mov    $0x0,%eax
  52:   c9                      leaveq
  53:   c3                      retq
```

- Converted to assembly code
- .s file

Assembler

```
1           00000000 00000100 0000000000000000
2  01011110 00001100 11000010 0000000000000010
3           11101111 00010110 0000000000000101
4           11101111 10011110 0000000000001011
5  11111000 10101101 11011111 0000000000010010
6           01100010 11011111 0000000000010101
7  11101111 00000010 11111011 0000000000010111
8  11110100 10101101 11011111 0000000000011110
9  00000011 10100010 11011111 0000000000100001
10 11101111 00000010 11111011 0000000000100100
11 01111110 11110100 10101101
12 11111000 10101110 11000101 0000000000101011
13 00000110 10100010 11111011 0000000000110001
14 11101111 00000010 11111011 0000000000110100
15          01010000 11010100 0000000000111011
16                   00000100 0000000000111101
```

Linker

We still need to resolve function calls
i.e. `printf, sleep, sqrt, etc`

II. Software

We need a way to convert **source** code to **binary**

```c
#include <stdio.h>

int main() {
        printf("Hello WOrld! \n");


        int x = 0;
        int y = 3;

        int z = x + y;

        printf("%d  %d  %d \n",x,y,z);
        return 0;

}
```

Preprocessor

- Removal of comments
- Expand Macros

Compiler

```
0000000000000000 <main>:
   0:   f3 0f 1e fa             endbr64
   4:   55                      push   %rbp
   5:   48 89 e5                mov    %rsp,%rbp
   8:   48 83 ec 10             sub    $0x10,%rsp
   c:   48 8d 3d 00 00 00 00    lea    0x0(%rip),%rdi        # 13 <main+0x13>
  13:   e8 00 00 00 00          callq  18 <main+0x18>
  18:   c7 45 f4 00 00 00 00    movl   $0x0,-0xc(%rbp)
  1f:   c7 45 f8 03 00 00 00    movl   $0x3,-0x8(%rbp)
  26:   8b 55 f4                mov    -0xc(%rbp),%edx
  29:   8b 45 f8                mov    -0x8(%rbp),%eax
  2c:   01 d0                   add    %edx,%eax
  2e:   89 45 fc                mov    %eax,-0x4(%rbp)
  31:   8b 4d fc                mov    -0x4(%rbp),%ecx
  34:   8b 55 f8                mov    -0x8(%rbp),%edx
  37:   8b 45 f4                mov    -0xc(%rbp),%eax
  3a:   89 c6                   mov    %eax,%esi
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  48:   e8 00 00 00 00          callq  4d <main+0x4d>
  4d:   b8 00 00 00 00          mov    $0x0,%eax
  52:   c9                      leaveq
  53:   c3                      retq
```

Assembler

- Converted to assembly code
- .s file

Two methods:

Program A

Library 1 — string.h

Library 2 — stdio.h

Linker

```
1           00000000 00000100 0000000000000000
2  01011110 00001100 11000010 0000000000000010
3           11101111 00010110 0000000000000101
4           11101111 10011110 0000000000001011
5  11111000 10101101 11011111 0000000000010010
6           01100010 11011111 0000000000010101
7  11101111 00000010 11111011 0000000000010111
8  11110100 10101101 11011111 0000000000011110
9  00000011 10100010 11011111 0000000000100001
10 11101111 00000010 11111011 0000000000100100
11 01111110 11110100 10101101
12 11111000 10101110 11000101 0000000000101011
13 00000110 10100010 11111011 0000000000110001
14 11101111 00000010 11111011 0000000000110100
15          01010000 11010100 0000000000111011
16                   00000100 0000000000111101
```

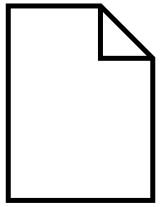
**THIS PROCESS IS NOT TRUE FOR EVERY LANGUAGE

II. Software

We need a way to convert **source** code to **binary**

```c
#include <stdio.h>

int main() {
        printf("Hello WOrld! \n");


        int x = 0;
        int y = 3;

        int z = x + y;

        printf("%d  %d  %d \n",x,y,z);
        return 0;

}
```

Preprocessor



- Removal of comments
- Expand Macros

Compiler

```
0000000000000000 <main>:
   0:   f3 0f 1e fa             endbr64
   4:   55                      push   %rbp
   5:   48 89 e5                mov    %rsp,%rbp
   8:   48 83 ec 10             sub    $0x10,%rsp
   c:   48 8d 3d 00 00 00 00    lea    0x0(%rip),%rdi        # 13 <main+0x13>
  13:   e8 00 00 00 00          callq  18 <main+0x18>
  18:   c7 45 f4 00 00 00 00    movl   $0x0,-0xc(%rbp)
  1f:   c7 45 f8 03 00 00 00    movl   $0x3,-0x8(%rbp)
  26:   8b 55 f4                mov    -0xc(%rbp),%edx
  29:   8b 45 f8                mov    -0x8(%rbp),%eax
  2c:   01 d0                   add    %edx,%eax
  2e:   89 45 fc                mov    %eax,-0x4(%rbp)
  31:   8b 4d fc                mov    -0x4(%rbp),%ecx
  34:   8b 55 f8                mov    -0x8(%rbp),%edx
  37:   8b 45 f4                mov    -0xc(%rbp),%eax
  3a:   89 c6                   mov    %eax,%esi
  3c:   48 8d 3d 00 00 00 00    lea    0x0(%rip),%rdi        # 43 <main+0x43>
  43:   b8 00 00 00 00          mov    $0x0,%eax
  48:   e8 00 00 00 00          callq  4d <main+0x4d>
  4d:   b8 00 00 00 00          mov    $0x0,%eax
  52:   c9                      leaveq
  53:   c3                      retq
```

Assembler

- Converted to assembly code
- .s file

```
1           00000000 00000100 0000000000000000
2  01011110 00001100 11000010 0000000000000010
3           11101111 00010110 0000000000000101
4           11101111 10011110 0000000000001011
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6           01100010 11011111 0000000000010101
7  11101111 00000010 11111011 0000000000010111
8  11110100 10101101 11011111 0000000000011110
9  00000011 10100010 11011111 0000000000100001
10 11101111 00000010 11111011 0000000000100100
11 01111110 11110100 10101101
12 11111000 10101110 11000101 0000000000101011
13 00000110 10100010 11111011 0000000000110001
14 11101111 00000010 11111011 0000000000110100
15          01010000 11010100 0000000000111011
16                   00000100 0000000000111101
```

Linker

.exe

Static Linking- required code and data copied into executable at compile time

II. Software

We need a way to convert **source** code to **binary**

```c
#include <stdio.h>

int main() {
        printf("Hello WOrld! \n");


        int x = 0;
        int y = 3;

        int z = x + y;

        printf("%d  %d  %d \n",x,y,z);
        return 0;

}
```

Preprocessor

- Removal of comments
- Expand Macros

Compiler

```
0000000000000000 <main>:
   0:   f3 0f 1e fa             endbr64
   4:   55                      push   %rbp
   5:   48 89 e5                mov    %rsp,%rbp
   8:   48 83 ec 10             sub    $0x10,%rsp
   c:   48 8d 3d 00 00 00 00    lea    0x0(%rip),%rdi        # 13 <main+0x13>
  13:   e8 00 00 00 00          callq  18 <main+0x18>
  18:   c7 45 f4 00 00 00 00    movl   $0x0,-0xc(%rbp)
  1f:   c7 45 f8 03 00 00 00    movl   $0x3,-0x8(%rbp)
  26:   8b 55 f4                mov    -0xc(%rbp),%edx
  29:   8b 45 f8                mov    -0x8(%rbp),%eax
  2c:   01 d0                   add    %edx,%eax
  2e:   89 45 fc                mov    %eax,-0x4(%rbp)
  31:   8b 4d fc                mov    -0x4(%rbp),%ecx
  34:   8b 55 f8                mov    -0x8(%rbp),%edx
  37:   8b 45 f4                mov    -0xc(%rbp),%eax
  3a:   89 c6                   mov    %eax,%esi
  3c:   48 8d 3d 00 00 00 00    lea    0x0(%rip),%rdi        # 43 <main+0x43>
  43:   b8 00 00 00 00          mov    $0x0,%eax
  48:   e8 00 00 00 00          callq  4d <main+0x4d>
  4d:   b8 00 00 00 00          mov    $0x0,%eax
  52:   c9                      leaveq
  53:   c3                      retq
```

Assembler

- Converted to assembly code
- .s file

Two methods:

Program A

Library 1 — string.h

Library 2 — stdio.h

Linker

```
1           00000000 00000100 0000000000000000
2  01011110 00001100 11000010 0000000000000010
3           11101111 00010110 0000000000000101
4           11101111 10011110 0000000000001011
5  11111000 10101101 11011111 0000000000010010
6           01100010 11011111 0000000000010101
7  11101111 00000010 11111011 0000000000010111
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14 11101111 00000010 11111011 0000000000110100
15          01010000 11010100 0000000000111011
16                   00000100 0000000000111101
```
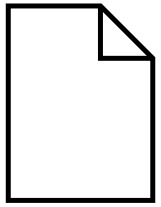

II. Software

We need a way to convert **source** code to **binary**

```c
#include <stdio.h>

int main() {
        printf("Hello WOrld! \n");


        int x = 0;
        int y = 3;

        int z = x + y;

        printf("%d  %d  %d \n",x,y,z);
        return 0;

}
```

Preprocessor



- Removal of comments
- Expand Macros

Compiler

```
0000000000000000 <main>:
   0:   f3 0f 1e fa             endbr64
   4:   55                      push   %rbp
   5:   48 89 e5                mov    %rsp,%rbp
   8:   48 83 ec 10             sub    $0x10,%rsp
   c:   48 8d 3d 00 00 00 00    lea    0x0(%rip),%rdi        # 13 <main+0x13>
  13:   e8 00 00 00 00          callq  18 <main+0x18>
  18:   c7 45 f4 00 00 00 00    movl   $0x0,-0xc(%rbp)
  1f:   c7 45 f8 03 00 00 00    movl   $0x3,-0x8(%rbp)
  26:   8b 55 f4                mov    -0xc(%rbp),%edx
  29:   8b 45 f8                mov    -0x8(%rbp),%eax
  2c:   01 d0                   add    %edx,%eax
  2e:   89 45 fc                mov    %eax,-0x4(%rbp)
  31:   8b 4d fc                mov    -0x4(%rbp),%ecx
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  4d:   b8 00 00 00 00          mov    $0x0,%eax
  52:   c9                      leaveq
  53:   c3                      retq
```

Assembler

- Converted to assembly code
- .s file

Two methods:

string.h — Library 1

stdio.h — Library 2

Program A

.exe

Linker

```
1           00000000 00000100 0000000000000000
2  01011110 00001100 11000010 0000000000000010
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5  11111000 10101101 11011111 0000000000010010
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12 11111000 10101110 11000101 0000000000101011
13 00000110 10100010 11111011 0000000000110001
14 11101111 00000010 11111011 0000000000110100
15          01010000 11010100 0000000000111011
16                   00000100 0000000000111101
```
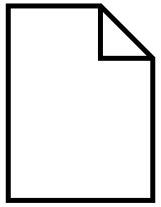

Dynamic Linking - required code and data is linked to executable at runtime

II. Software

We need a way to convert **source** code to **binary**

```c
#include <stdio.h>

int main() {
        printf("Hello WOrld! \n");


        int x = 0;
        int y = 3;

        int z = x + y;

        printf("%d  %d  %d \n",x,y,z);
        return 0;

}
```

Preprocessor



- Removal of comments
- Expand Macros

Compiler

```
0000000000000000 <main>:
   0:   f3 0f 1e fa             endbr64
   4:   55                      push   %rbp
   5:   48 89 e5                mov    %rsp,%rbp
   8:   48 83 ec 10             sub    $0x10,%rsp
   c:   48 8d 3d 00 00 00 00    lea    0x0(%rip),%rdi        # 13 <main+0x13>
  13:   e8 00 00 00 00          callq  18 <main+0x18>
  18:   c7 45 f4 00 00 00 00    movl   $0x0,-0xc(%rbp)
  1f:   c7 45 f8 03 00 00 00    movl   $0x3,-0x8(%rbp)
  26:   8b 55 f4                mov    -0xc(%rbp),%edx
  29:   8b 45 f8                mov    -0x8(%rbp),%eax
  2c:   01 d0                   add    %edx,%eax
  2e:   89 45 fc                mov    %eax,-0x4(%rbp)
  31:   8b 4d fc                mov    -0x4(%rbp),%ecx
  34:   8b 55 f8                mov    -0x8(%rbp),%edx
  37:   8b 45 f4                mov    -0xc(%rbp),%eax
  3a:   89 c6                   mov    %eax,%esi
  3c:   48 8d 3d 00 00 00 00    lea    0x0(%rip),%rdi        # 43 <main+0x43>
  43:   b8 00 00 00 00          mov    $0x0,%eax
  48:   e8 00 00 00 00          callq  4d <main+0x4d>
  4d:   b8 00 00 00 00          mov    $0x0,%eax
  52:   c9                      leaveq
  53:   c3                      retq
```

- Converted to assembly code
- .s file

Assembler

```
1           00000000 00000100 0000000000000000
2  01011110 00001100 11000010 0000000000000010
3           11101111 00010110 0000000000000101
4           11101111 10011110 0000000000001011
5  11111000 10101101 11011111 0000000000010010
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8  11110100 10101101 11011111 0000000000011110
9  00000011 10100010 11011111 0000000000100001
10 11101111 00000010 11111011 0000000000100100
11 01111110 11110100 10101101
12 11111000 10101110 11000101 0000000000101011
13 00000110 10100010 11111011 0000000000110001
14 11101111 00000010 11111011 0000000000110100
15          01010000 11010100 0000000000111011
16                   00000100 0000000000111101
```
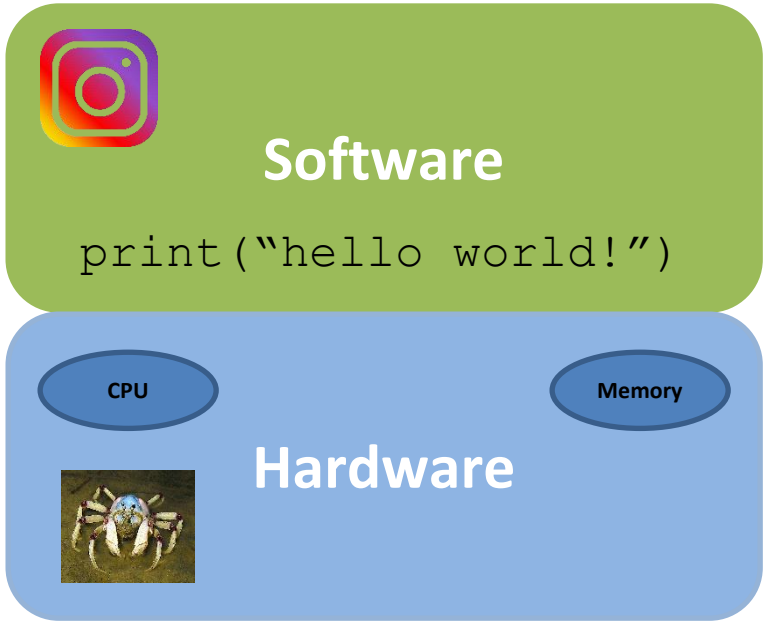

Linker

.exe

To be continued

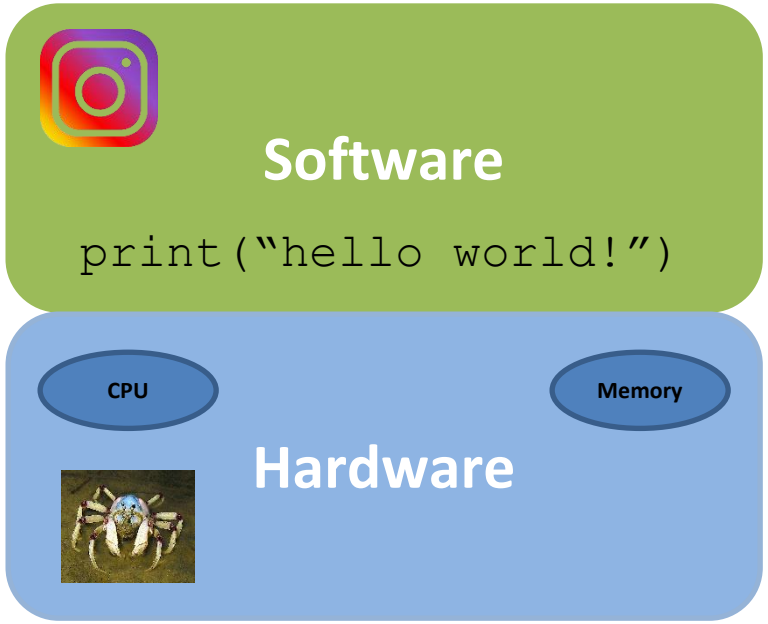
How does this happen?



From a high level, we will divide a computer system into two parts

I. **Hardware**
II. **Software**

How does this happen?

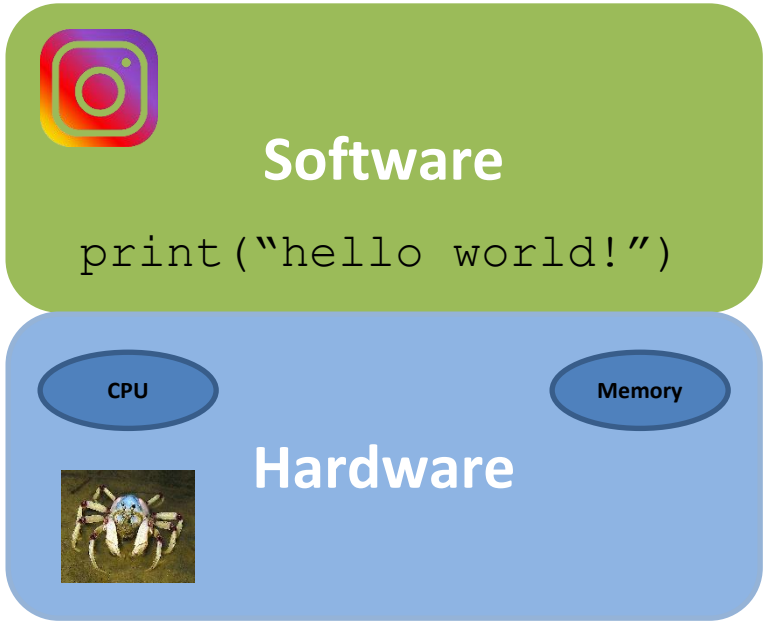


From a high level, we will divide a computer system into two parts

I. **Hardware**
II. **Software**

Software is nothing without hardware

How does this happen?

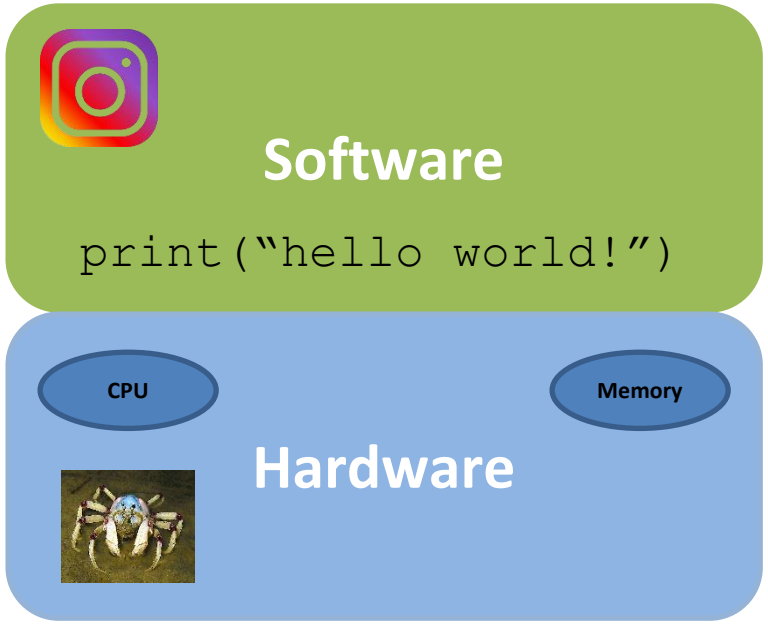


From a high level, we will divide a computer system into two parts

I. **Hardware**
II. **Software**

Hardware is *mostly* nothing without software

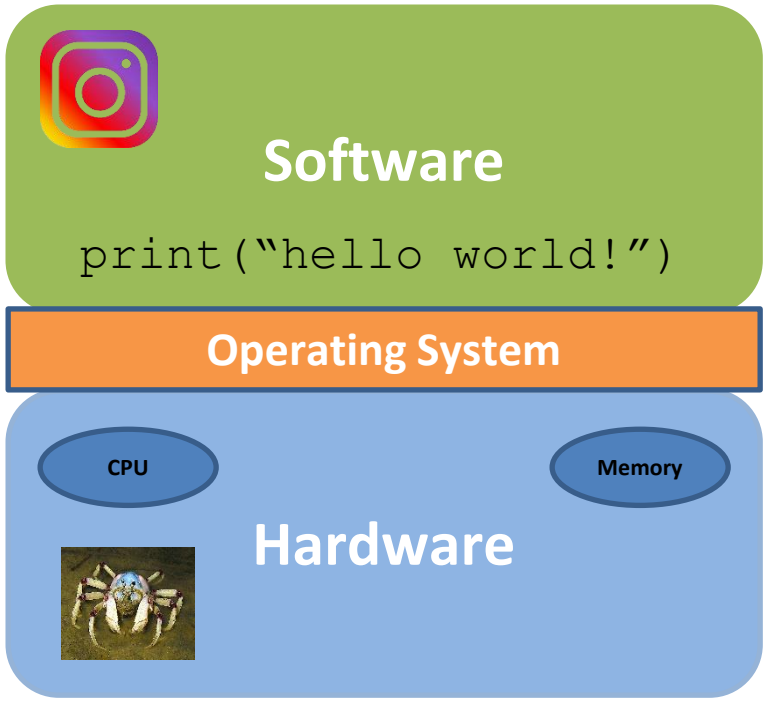
How does this happen?



From a high level, we will divide a computer system into two parts

I. **Hardware**
II. **Software**
III. **???**

How does this happen?

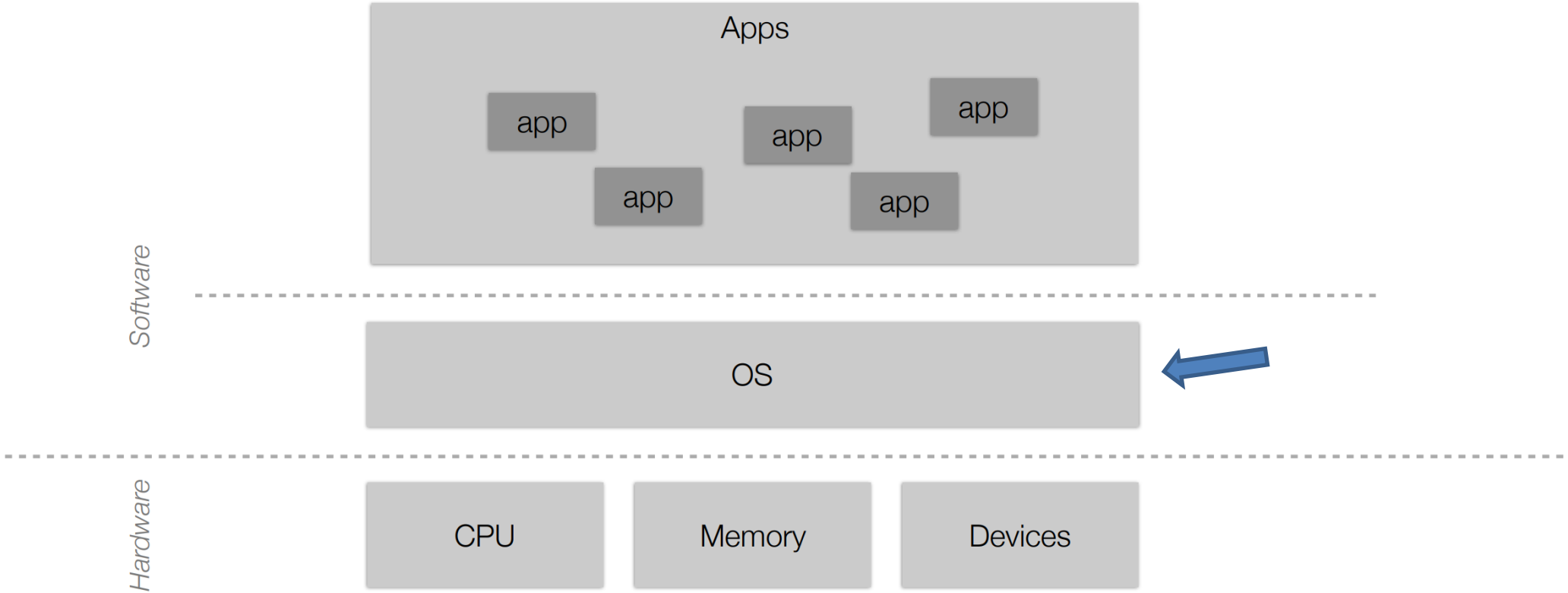


From a high level, we will divide a computer system into two parts

I. **Hardware**
II. **Software**
III. **Operating System**

Typical Layers of a Computer

The **operating system** is a vital component of a computer

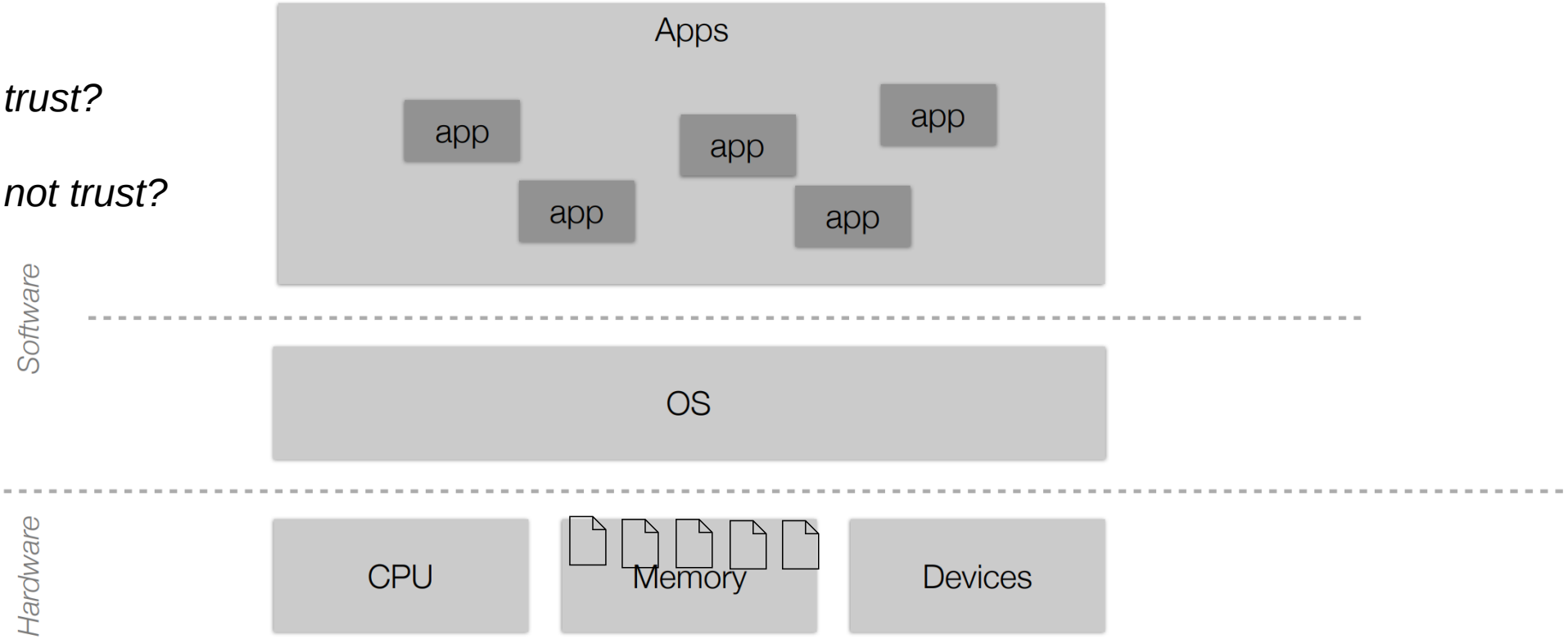


Typical Layers of a Computer

The **operating system** is a vital component of a computer

What do we trust?

What do we not trust?



Typical Layers of a Computer

The **operating system** is a vital component of a computer

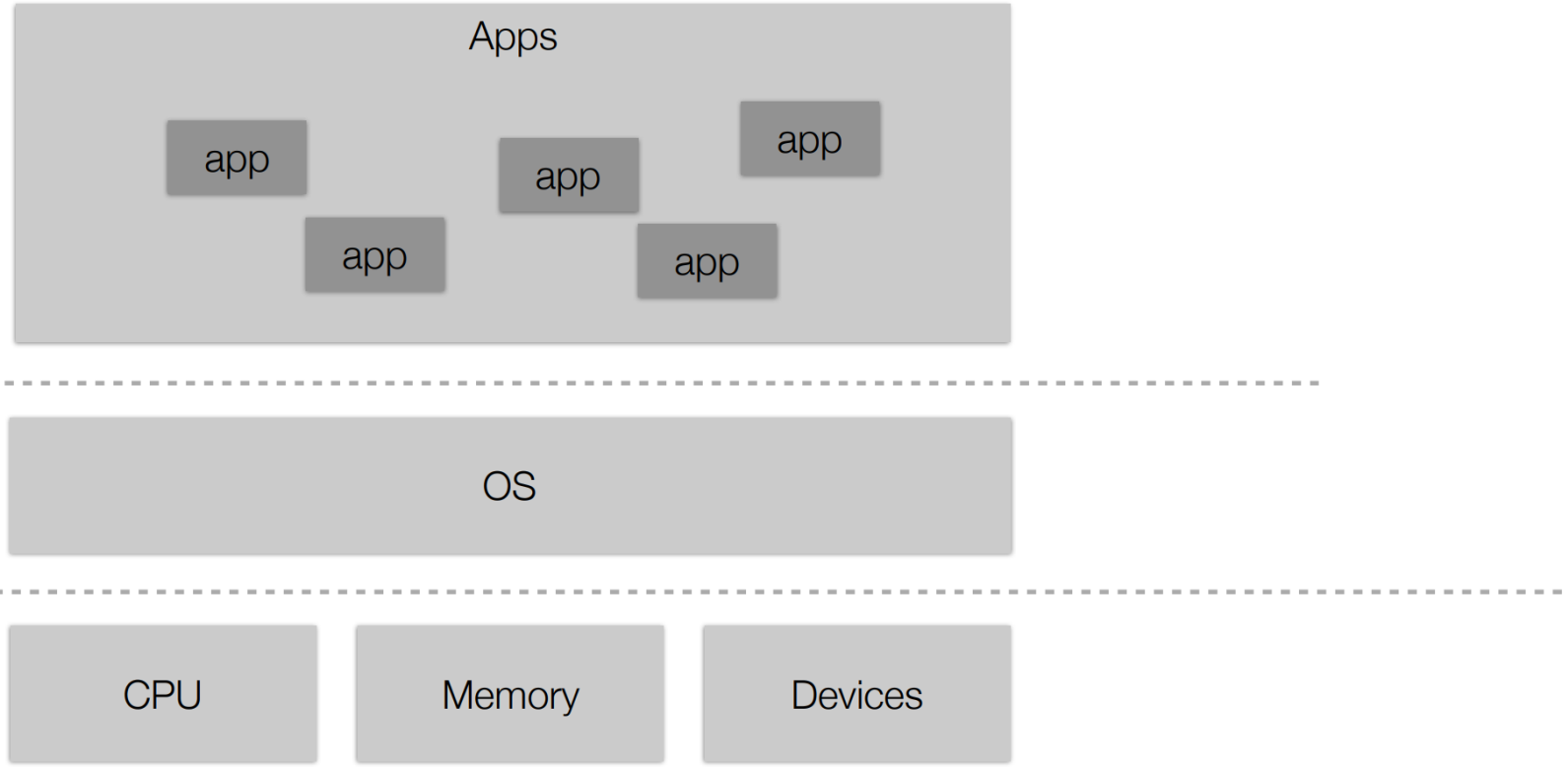
Not privileged

Privileged

Hardware

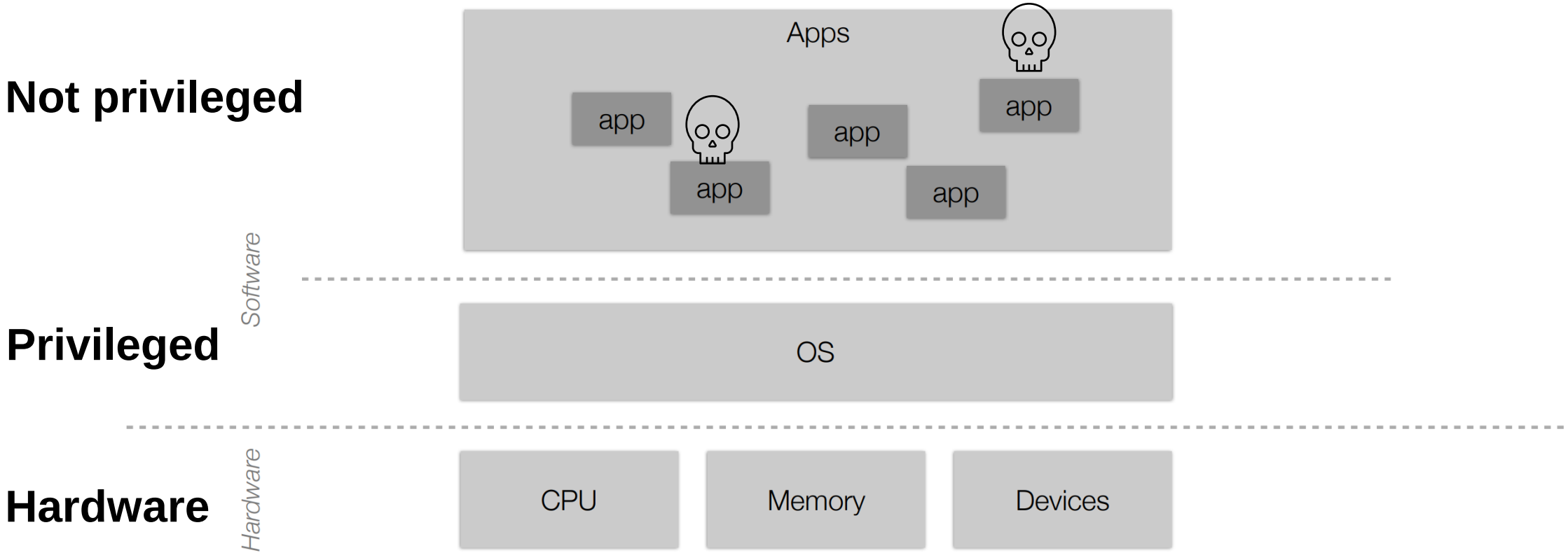
Software

Hardware



Typical Layers of a Computer

The **operating system** is a vital component of a computer



Typical Layers of a Computer

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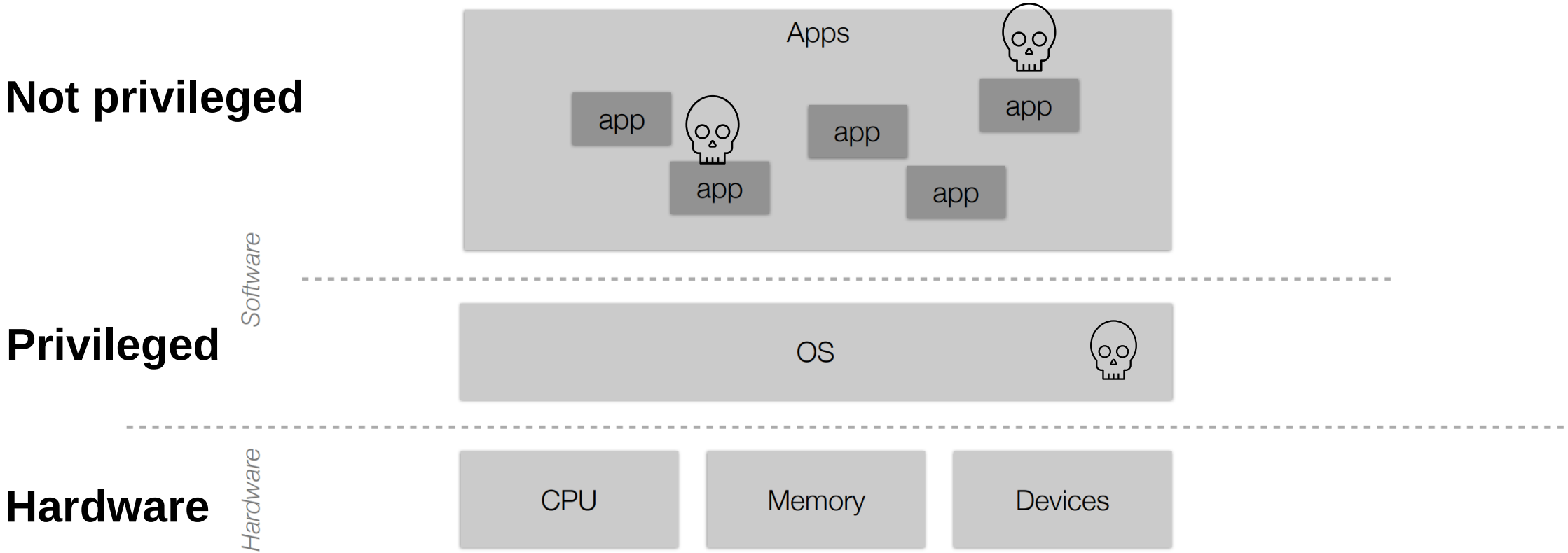

Typical Layers of a Computer

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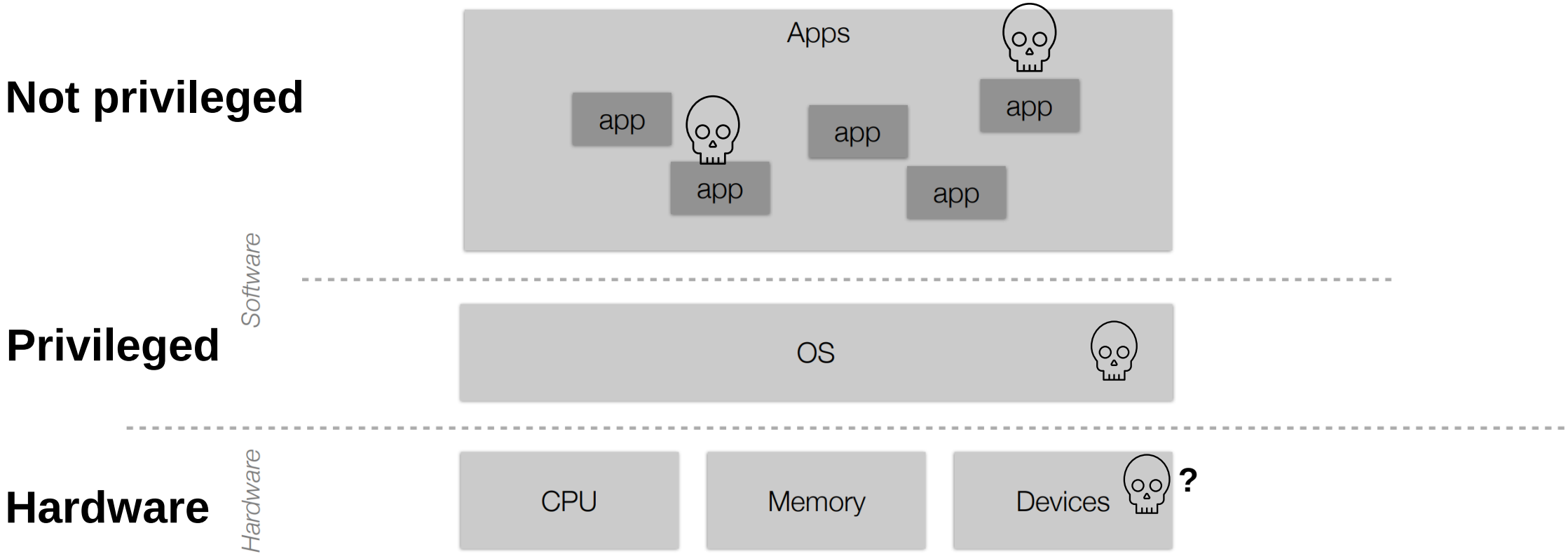

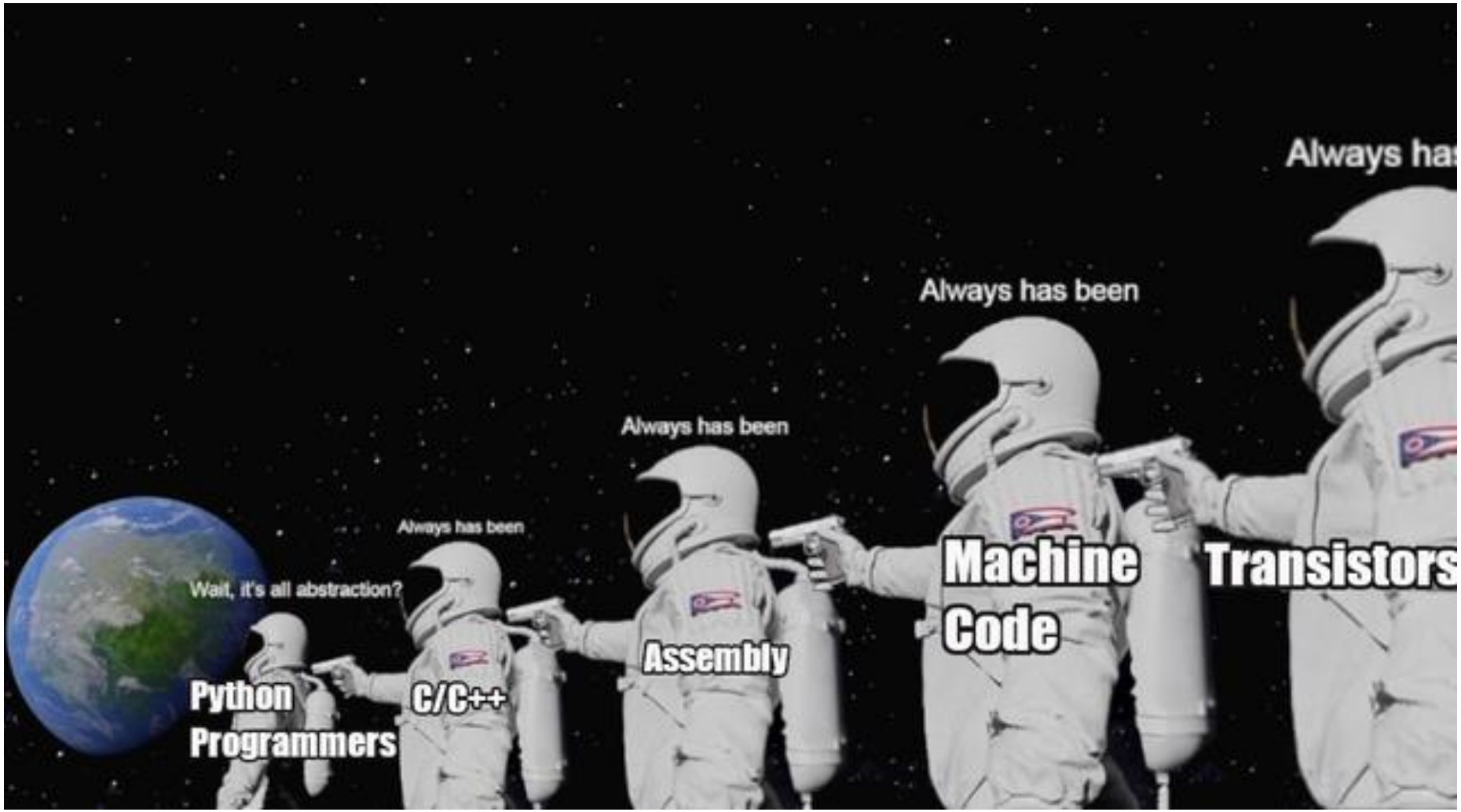

Meme credit: Carson Gross