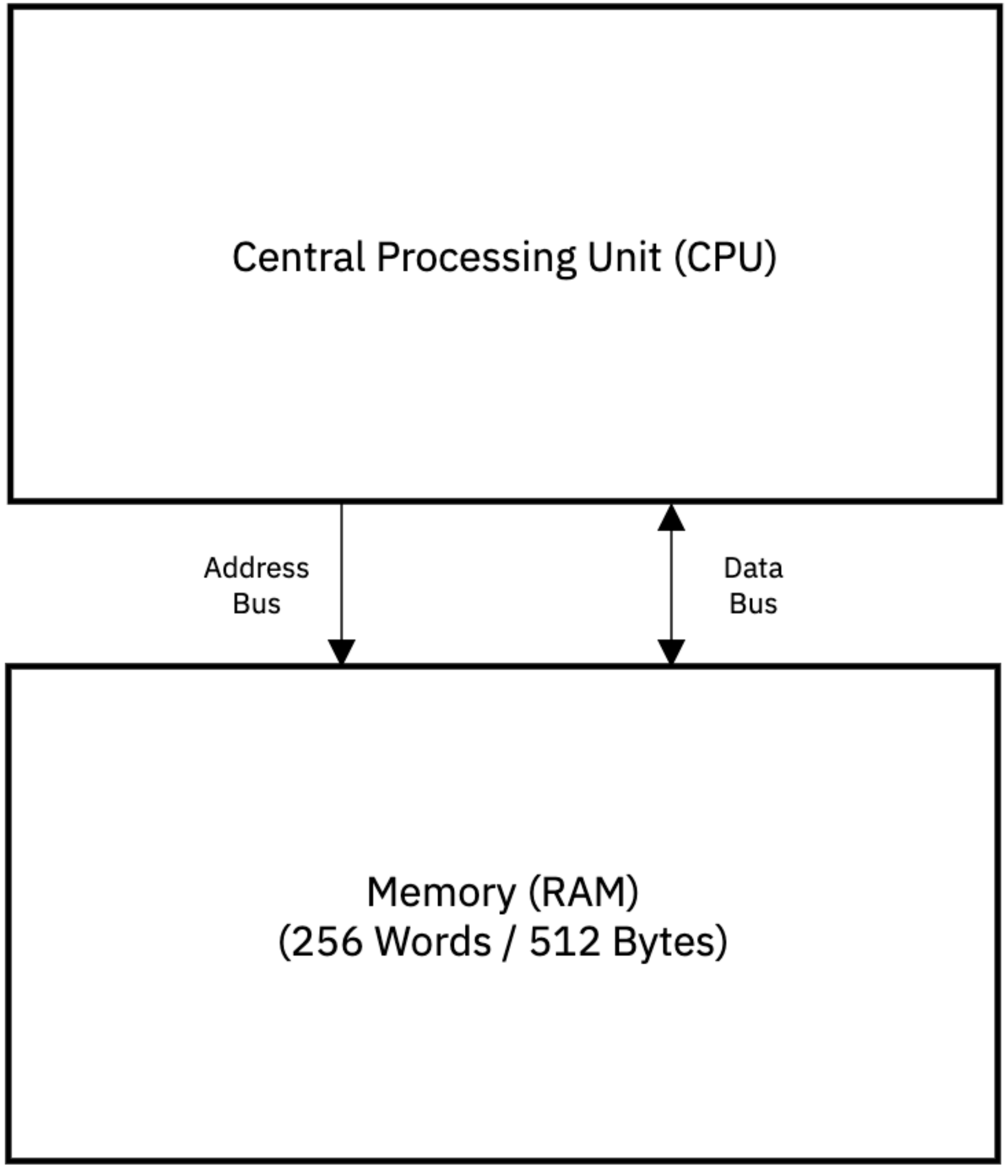
Toy Computer Architecture

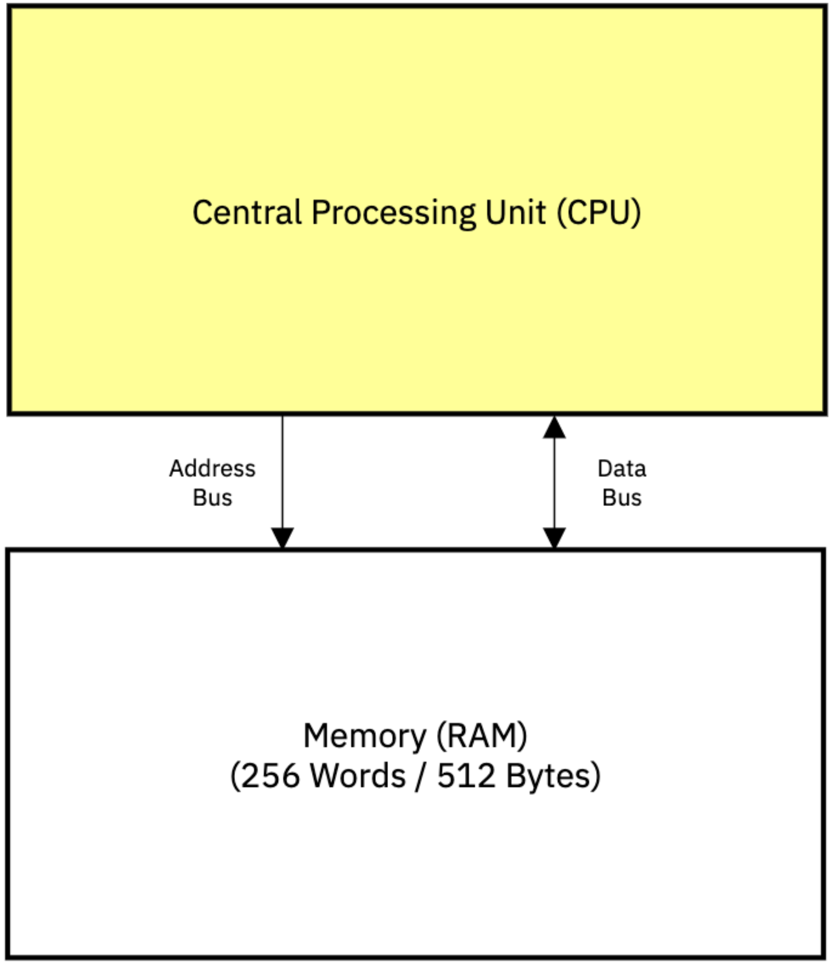
Toy Computer Adapted from:

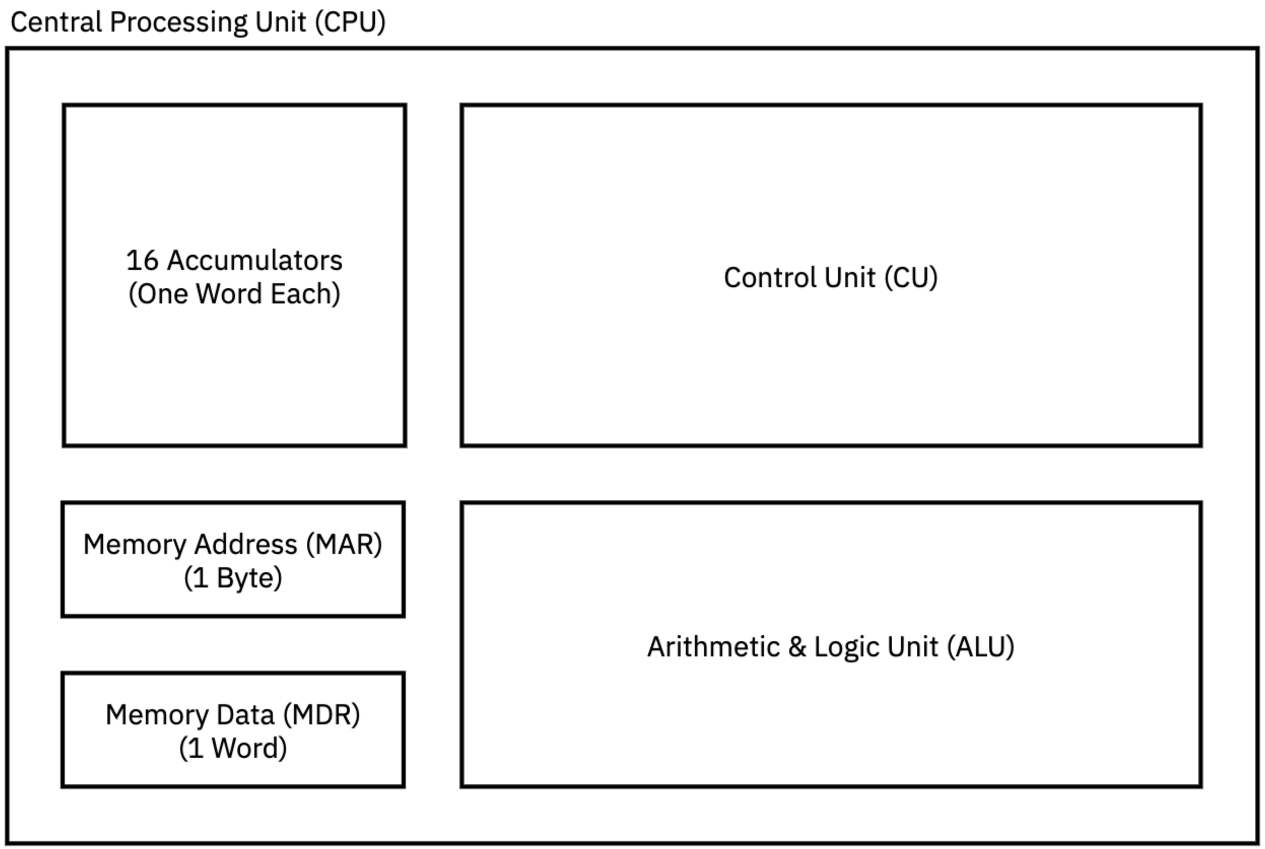
Sedgewick, R. & Wayne, K. (2017)

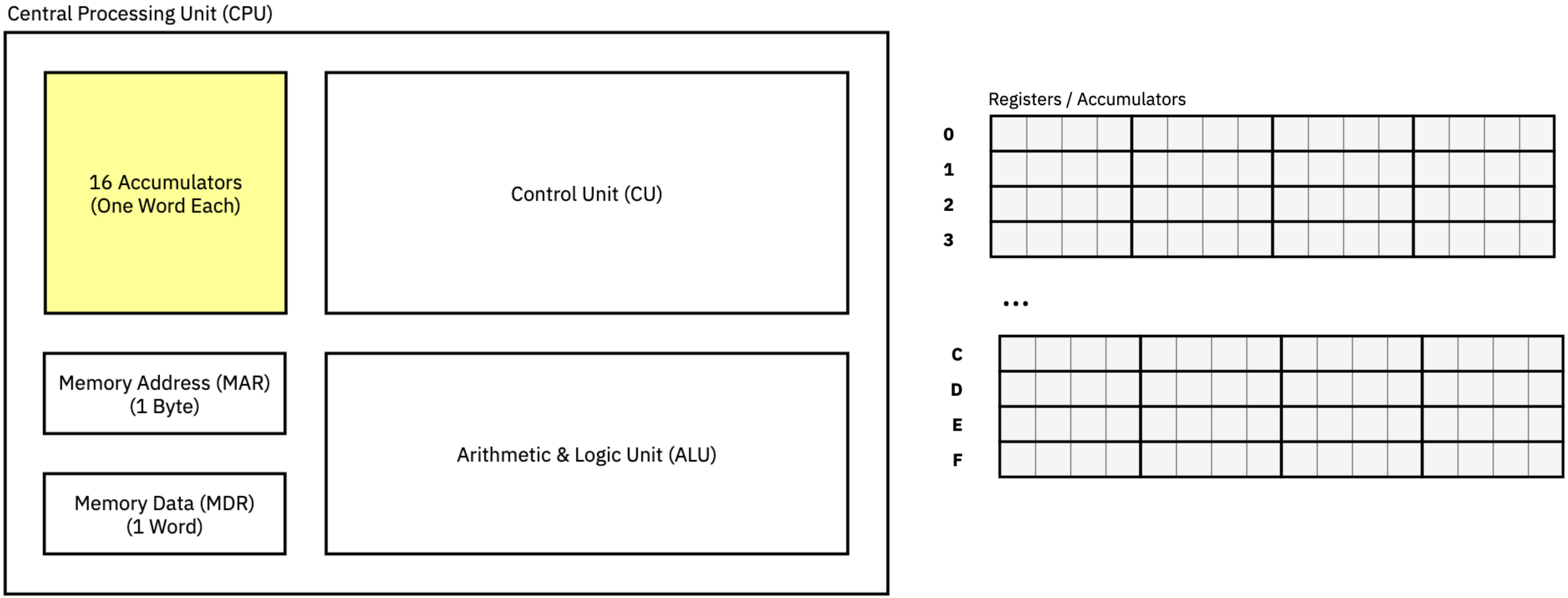
Computer Science: An Interdisciplinary Approach.

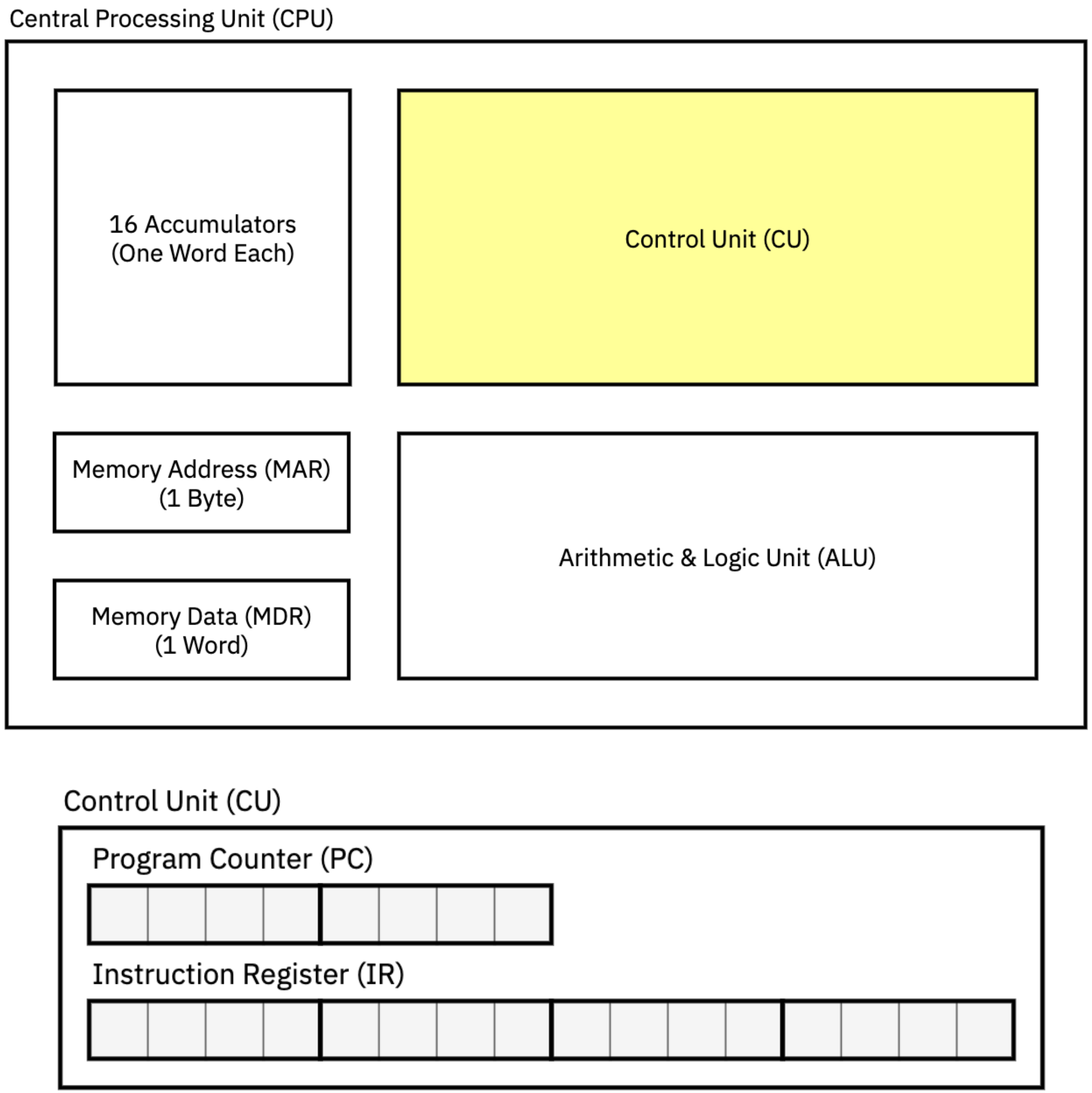
Pearson Education


Central Processing Unit (CPU)
Address
Bus
Data
Bus
Memory (RAM)
(256 Words / 512 Bytes)

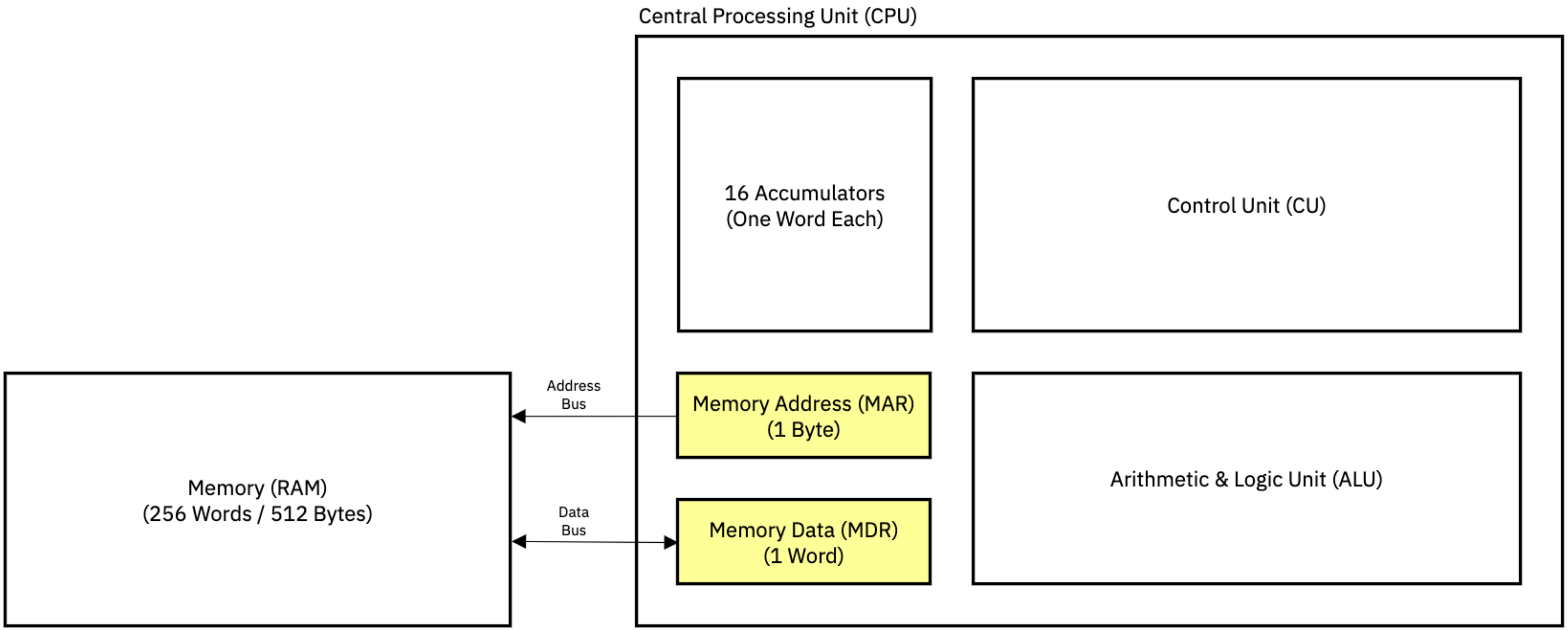

Central Processing Unit (CPU)
Address Bus
Data Bus
Memory (RAM)
(256 Words / 512 Bytes)


Central Processing Unit (CPU)
16 Accumulators
(One Word Each)
Control Unit (CU)
Memory Address (MAR)
(1 Byte)
Memory Data (MDR)
(1 Word)
Arithmetic & Logic Unit (ALU)


Central Processing Unit (CPU)
16 Accumulators
(One Word Each)
Control Unit (CU)
Memory Address (MAR)
(1 Byte)
Memory Data (MDR)
(1 Word)
Arithmetic & Logic Unit (ALU)
Registers / Accumulators
0
1
2
3
...
C
D
E
F



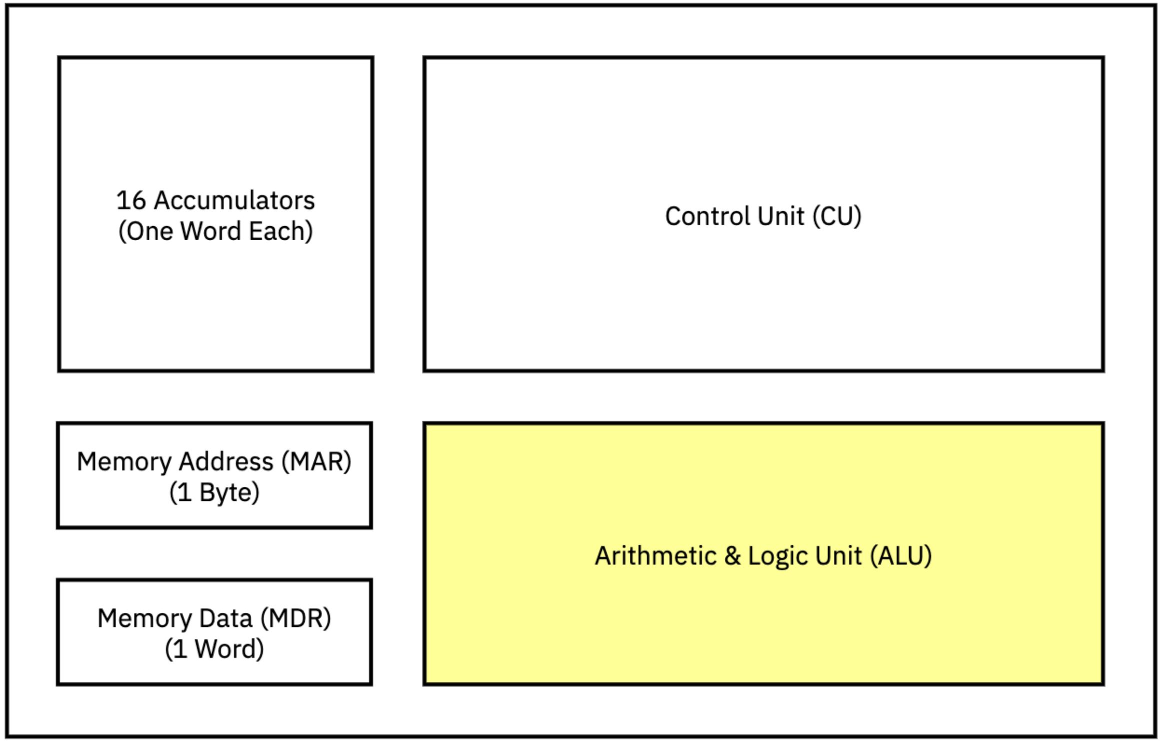
Central Processing Unit (CPU)
16 Accumulators
(One Word Each)
Control Unit (CU)
Memory Address (MAR)
(1 Byte)
Arithmetic & Logic Unit (ALU)
Memory Data (MDR)
(1 Word)
Control Unit (CU)
Program Counter (PC)
Instruction Register (IR)



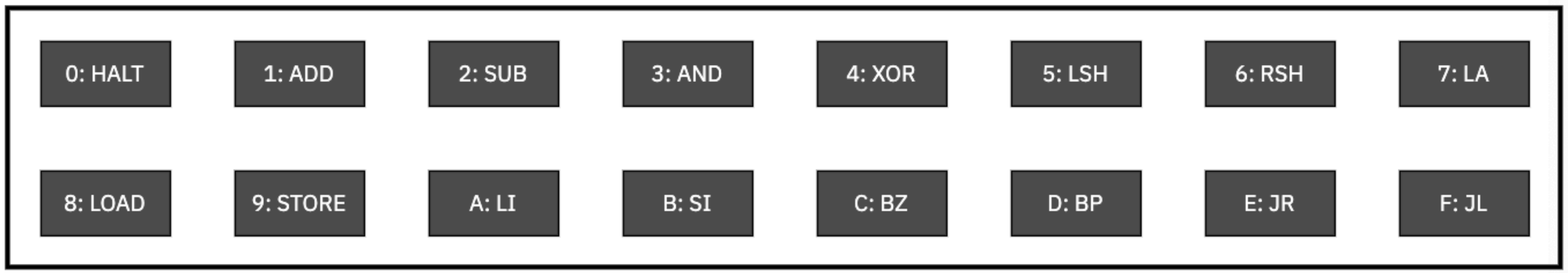
Memory Address Register (MAR)

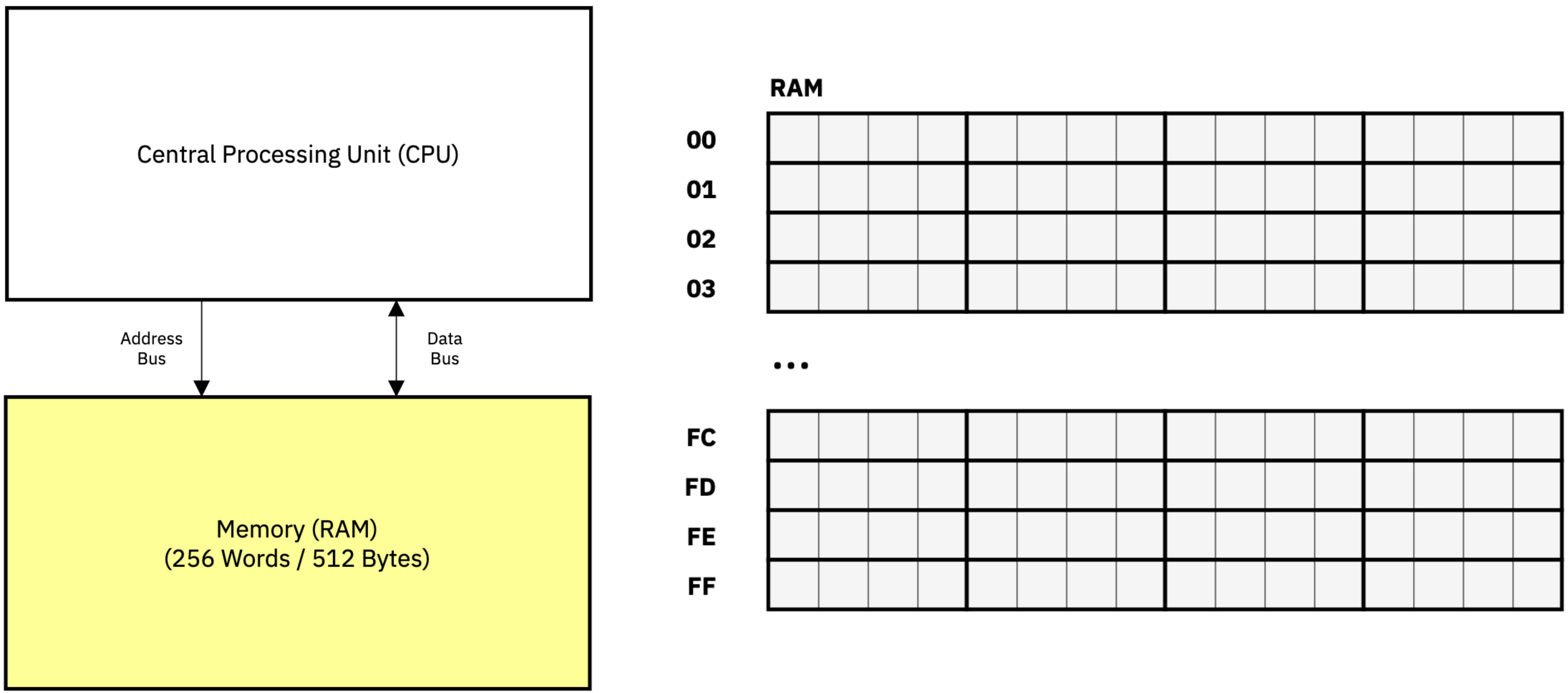
Memory Data Register (MDR)

Central Processing Unit (CPU)

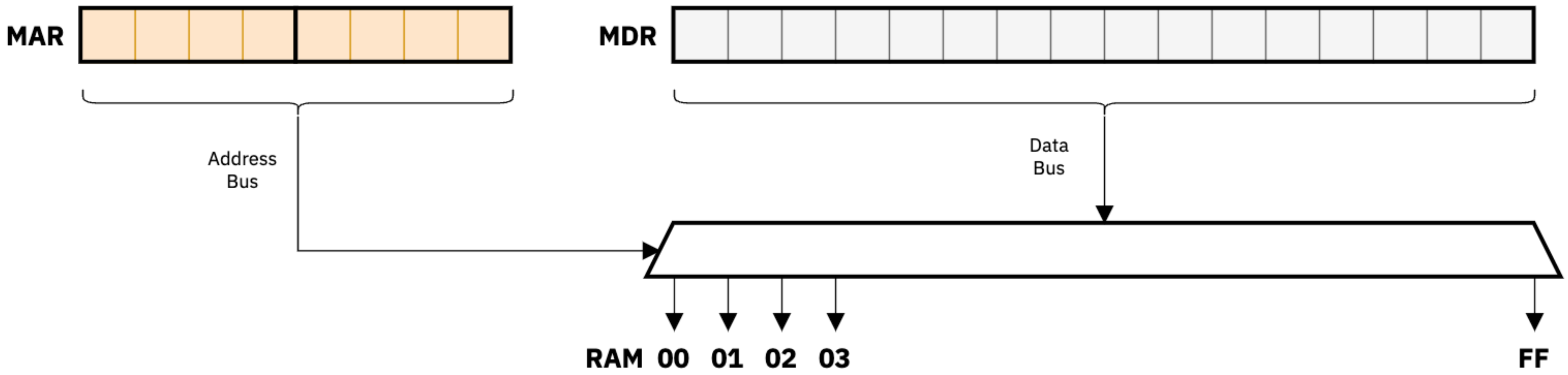


Arithmetic & Logic Unit (ALU)

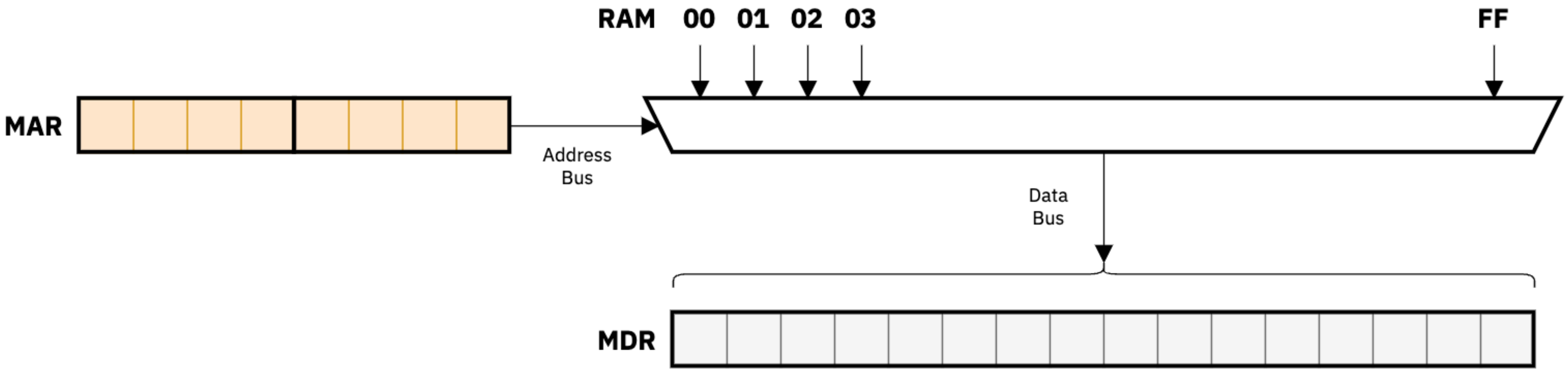



Central Processing Unit (CPU)
Address Bus
Data Bus
Memory (RAM)
(256 Words / 512 Bytes)
RAM
00
01
02
03
...
FC
FD
FE
FF

Storing to RAM



Loading from RAM

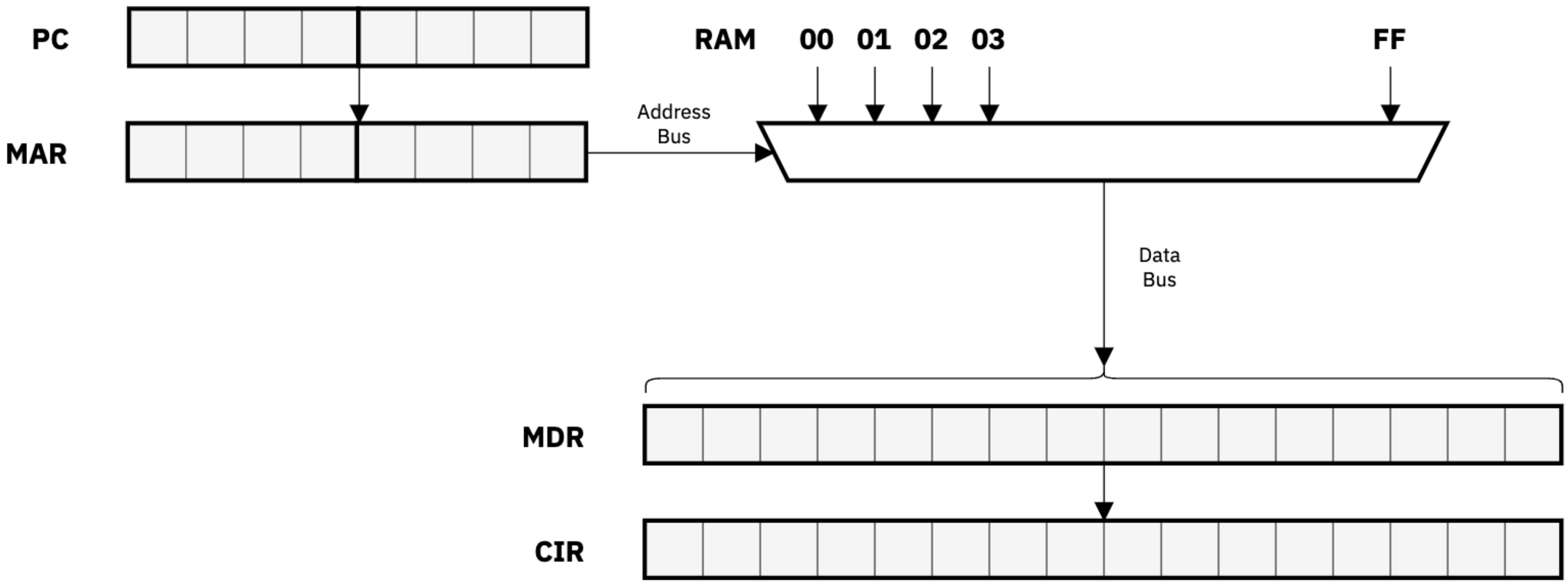


How are programs executed?

Machine Instruction Cycle

1. Fetch
2. Decode
3. Execute

1. Fetch



1. Fetch

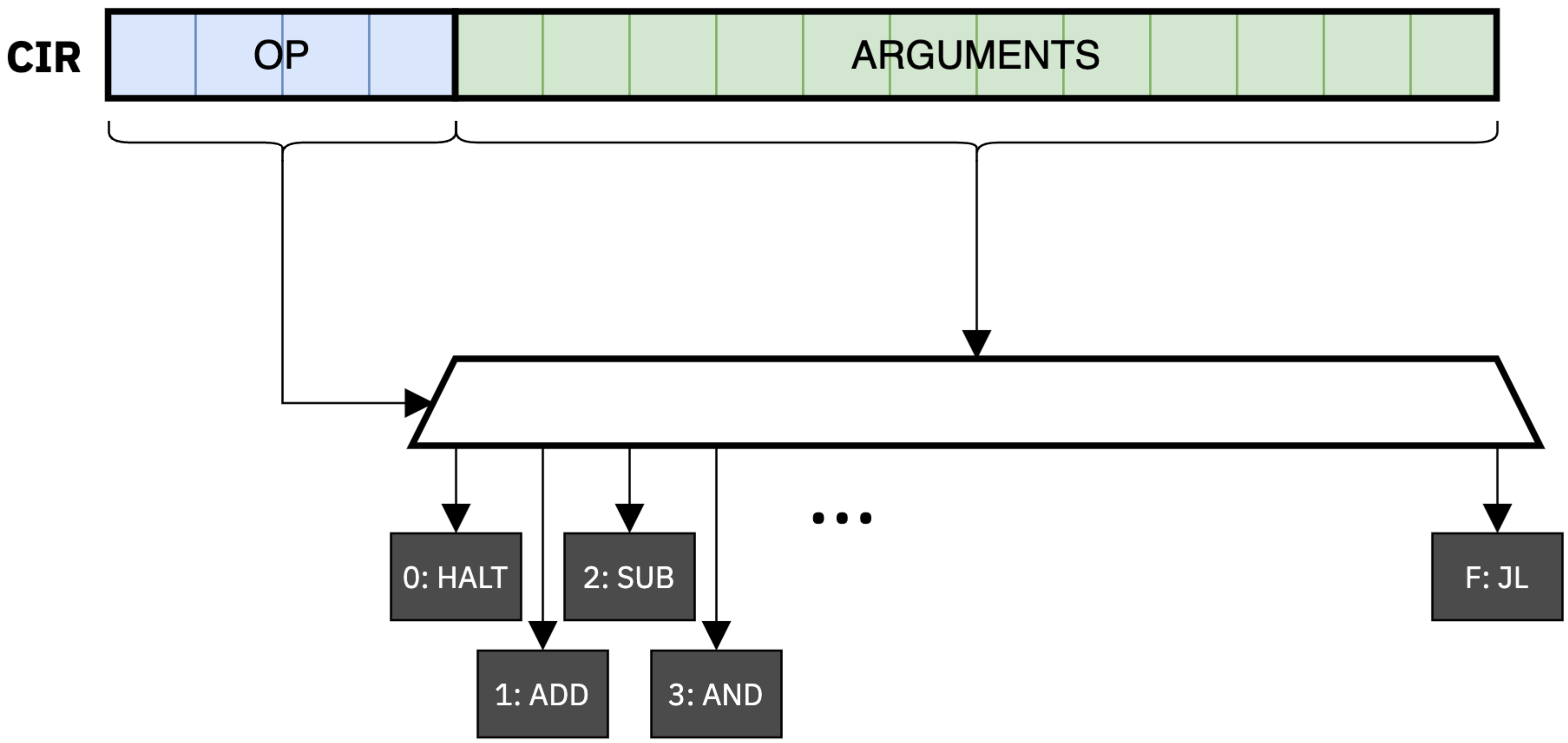
(i) Address copied from PC to MAR.

(ii) Data at address in MAR copied to MDR.

(iii) Data in MDR copied to CIR.

(iv) Value in PC incremented.

2. Decode

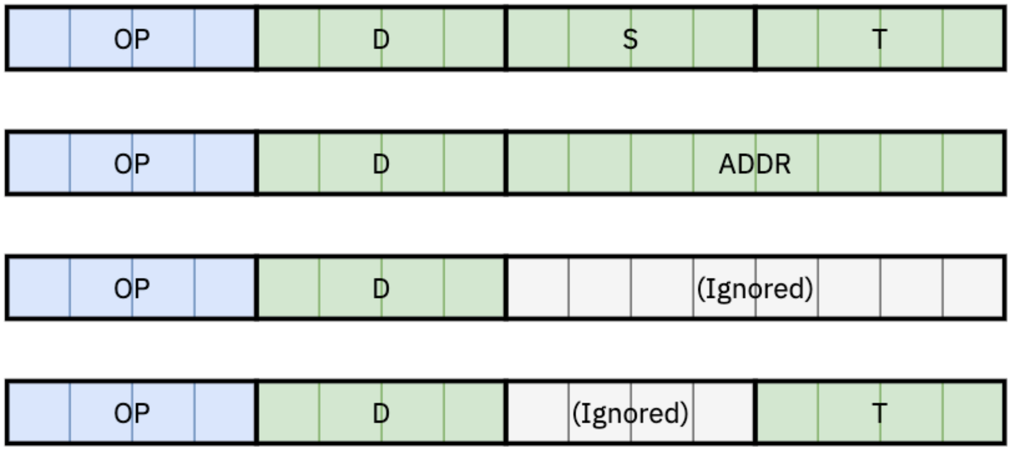


2. Decode

Part of the data in CIR determines which circuit in the ALU the rest of the data in the CIR is sent to.

3. Execute

CIR




```
0 Halt             -
1 Add              R[D] <- R[S] + R[T]
2 Subtract         R[D] <- R[S] - R[T]
3 Bitwise And      R[D] <- R[S] & R[T]
4 Bitwise Xor      R[D] <- R[S] ^ R[T]
5 Left Shift       R[D] <- R[S] << R[T]
6 Right Shift      R[D] <- R[S] >> R[T]
7 Load Address     R[D] <- ADDR
8 Load             R[D] <- M[ADDR]
9 Store            M[ADDR] <- R[D]
A Load Indirect    R[D] <- M[R[T]]
B Store Indirect   M[R[T]] <- R[D]
C Branch Zero      if R[D] == 0 PC <- ADDR
D Branch Positive  if R[D] > 0 PC <- ADDR
E Jump Register    PC <- R[D]
F Jump & Link      R[D] <- PC; PC <- ADDR
```

3. Execute

Helpful calculations or effects are achieved through the hardwired circuits in the ALU.

Some of the instructions involve interactions with the MAR and MDR to **load** data from memory to registers or to **store** data from registers to memory.

```
0 Halt             -
1 Add              R[D] <- R[S] + R[T]
2 Subtract         R[D] <- R[S] - R[T]
3 Bitwise And      R[D] <- R[S] & R[T]
4 Bitwise Xor      R[D] <- R[S] ^ R[T]
5 Left Shift       R[D] <- R[S] << R[T]
6 Right Shift      R[D] <- R[S] >> R[T]
7 Load Address     R[D] <- ADDR
8 Load             R[D] <- M[ADDR]
9 Store            M[ADDR] <- R[D]
A Load Indirect    R[D] <- M[R[T]]
B Store Indirect   M[R[T]] <- R[D]
C Branch Zero      if R[D] == 0 PC <- ADDR
D Branch Positive  if R[D] > 0 PC <- ADDR
E Jump Register    PC <- R[D]
F Jump & Link      R[D] <- PC; PC <- ADDR
```

Input / Output

Most computers have an additional bus to interact with input / output devices — like keyboards, mice, touch screens, printers, hard drives and networks.

Toy Computer performs “magic” I/O via interactions with special memory addresses.

Special Load Addresses

8	Load	R[D] <- M[ADDR]
A	Load Indirect	R[D] <- M[R[T]]

ADDR / R[T]	**Loads**
F0	User Input
FA	Random Word

Special Store Addresses

```
9 Store          M[ADDR] <- R[D]
B Store Indirect M[R[T]] <- R[D]
```

ADDR / R[T]	**Outputs**
F1	R[D] in binary
F2	R[D] in octal
F3	R[D] in hexadecimal
F4	R[D] in denary
F5	R[D] as ascii character
F6	A new line
F7	R[D] as binary pattern
F8	Computer State
F9	Computer State as Machine Code

Machine Language

Machine language allows us to specify what data should be saved and where in the computer's memory the data should be saved.

Toy Machine Language uses hexadecimal and has only got two instructions:

- PC: *addr* (Sets the value stored to the PC)
- *addr*: *data* (Stores *data* to address *addr*)

Example

Write a Toy Machine Language program that inputs two integers from the user and outputs the sum of the two integers.

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Write a Toy Machine Language program that inputs two integers from the user and outputs the sum of the two integers.

1. Load the first value into a register, say R[0].
2. Load the second value into a register, say R[1]
3. Perform the addition and store the result into a register, say R[2].
4. Output the result.

Example

Write a Toy Machine Language program that inputs two integers from the user and outputs the sum of the two integers.

Address	Data
PC:	00
00:	80F0
01:	81F0
02:	1201
03:	92F4
04:	0000

Example

Write a Toy Machine Language program that inputs two integers from the user and outputs the sum of the two integers.

Address	Data	
PC:	00	Sets PC to zero.
00:	80F0	R[0] ← M[F0] (Reads user input)
01:	81F0	R[1] ← M[F0] (Reads user input)
02:	1201	R[2] ← R[0] + R[1]
03:	92F4	M[F4] ← R[2] (Outputs as denary)
04:	0000	Halts

Problem 1

Write a program in Toy Machine Language that inputs a value from the user and then outputs the value in binary, octal, denary and hexadecimal, each on a new line.

Problem 2

Notice that Toy Computer does not have a machine instruction for *multiplication*.

Write a machine language program that inputs two integers from the user and outputs the product of the two integers. (Hint: treat multiplication as repeated addition.)

Problem 2: Hints

One way we could get the computer to perform multiplication is as follows:

A. Input value 1 to register 1.
B. Input value 2 to register 2.
C. Load 0 to register 3, to represent the product.
D. If value in register 1 is zero, jump to step H.
E. Add value in register 2 to register 3.
F. Subtract 1 from value in register 1. (This involves storing the literal value 1 to some register first.)
G. Jump to step D.
H. Output value in register 3.

Problem 3

What does this machine language program do?

Address	Data
PC:	00
00:	7001
01:	8AF0
02:	7B00
03:	7C01
04:	9BF4
05:	9BF6
06:	1DBC
07:	7B00
08:	1BBC
09:	7C00
0A:	1CCD
0B:	2AA0
0C:	DA04
0D:	0000

Problem 4

(a) Write a program in machine language that inputs three values from the user. The first number represents a first term, the second number represents a common difference and the third number represents how many terms are desired. The program should then output that many terms of the arithmetic sequence thus described.

(b) Repeat part (a), but this time, instead of outputting the terms in the sequence, the program should store the terms in the computer's memory starting at address B0.

Problem 5

This machine language program consists of data meant to be interpreted as ascii characters in addresses 00 to 0d, and data meant to be interpreted as program instructions in addresses 0e to 17.

What does this program do?

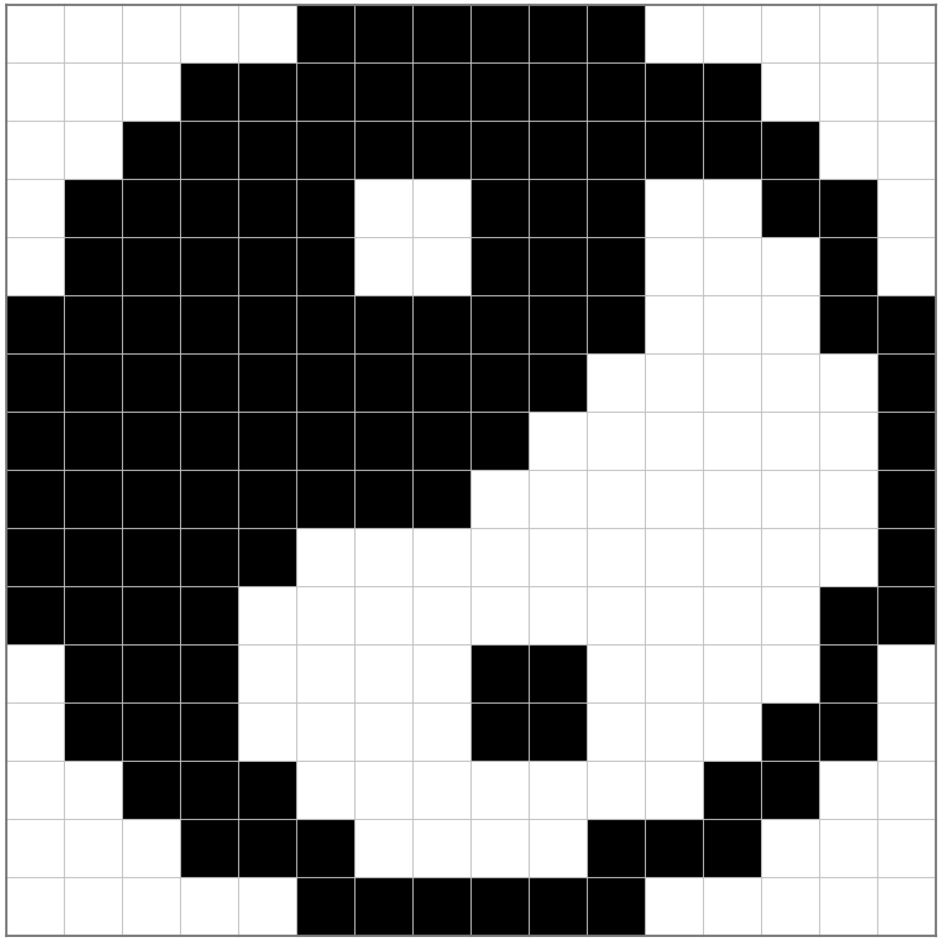
Address	Data
PC:	0e
00:	0048
01:	0065
02:	006c
03:	006c
04:	006f
05:	002c
06:	0020
07:	0077
08:	006f
09:	0072
0a:	006c
0b:	0064
0c:	0021
0d:	0000

0e:	7a00
0f:	ab0a
10:	cb16
11:	9bf5
12:	7f01
13:	1aaf
14:	7f0f
15:	ef00
16:	90f6
17:	0000

Problem 6

Write a program in machine language that outputs the yin yang symbol on the right to the terminal.

(Hint: consider organizing your memory similarly to the way it was organized in problem 5.)

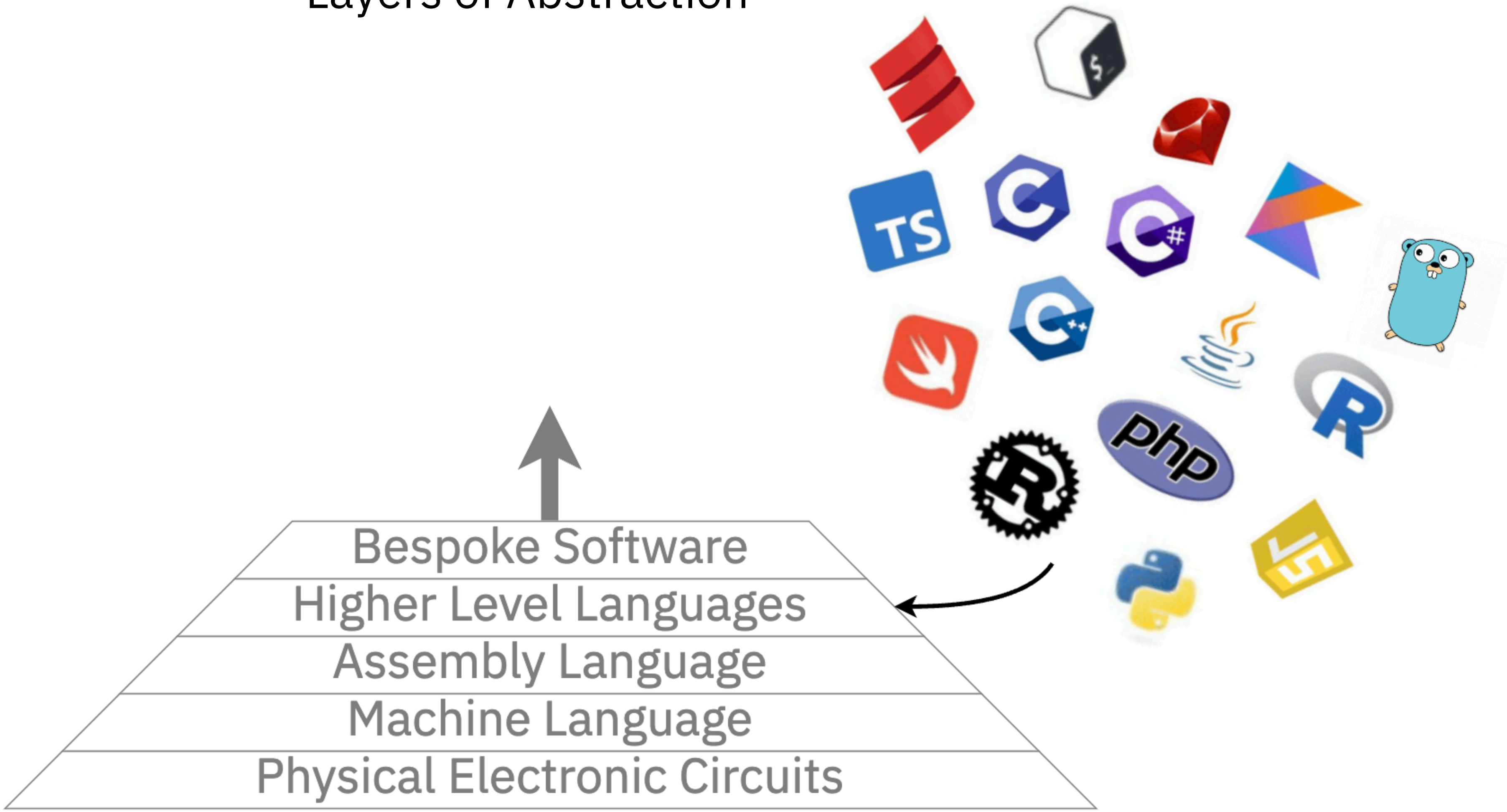


Toy Assembly

Layers of Abstraction

What is abstraction, and how is abstraction central to computational thinking?

Layers of Abstraction



Assembly Language

- Uses *mnemonics*, such as **ld** (for load) and **st** (for store), instead of explicitly specifying the underlying architecture that instructions are referencing.

- Allows us to give important memory addresses *labels* so that we can refer to these addresses without using explicit address values. (This also means we don't need to worry about updating memory addresses in our code when we insert or edit!)

- Each assembly instruction is directly translated to a sequence (one or more) of machine instructions.

Toy Assembly

Program Control

By default, the address in the PC is incremented as part of the fetch-decode-execute cycle. *Program control* instructions can conditionally or unconditionally change the address in the PC. They are:

- *halt*
- *jz*
- *jp*
- *jmp*
- *call*
- *ret*

Toy Assembly

Moving Data

Some instructions **load** data to registers, **store** data to memory or **move** data between registers:

- *ld*
- *st*
- *mv*

Toy Assembly

Operations

Special purpose circuits in the ALU perform operations on data:

- **Arithmetic:**

  add, sub

- **Logic:**

  and, or, xor, not

- **Bit Shifting:**

  lsh, rsh

Toy Assembly

Labels

Labels allow us to give addresses mnemonic names.

In Toy Assembly, the special name **.main** labels the starting position of the PC.

Toy Assembly

Input

In Toy Computer, input is loaded to registers from special memory addresses; in Toy Assembly, we use the mnemonics:

- *.rand*
- *.input*
- *.string*

Toy Assembly

Output

In Toy Computer, output is stored to special memory addresses; in Toy Assembly, we use the mnemonics:

- *.char*
- *.bin*
- *.oct*
- *.den*
- *.hex*

Toy Assembly

Data

Special data instructions include:

- *.data*
- *.ascii*

Example

Here is an assembly *Hello World!* program:

```
greet: .ascii "Hello, world!"
       .main
       ld %0 greet
loop:  ld %1 [%0]
       jz %1 done
       .char %1
       add %0 1
       jmp loop
done:  .line
       halt
```

Example

Here is an assembly *Hello World!* program:

```
greet: .ascii "Hello, world!"
       .main
       ld %0 greet
loop:  ld %1 [%0]
       jz %1 done
       .char %1
       add %0 1
       jmp loop
done:  .line
       halt
```

```
PC: 0e
00: 0048;    72    'H'    0e: 7000; R[0] <- 0  (*)
01: 0065;   101    'e'    0f: a100; R[1] <- M[R[0]]
02: 006c;   108    'l'    10: c116; if (R[1] == 0) PC <- 16
03: 006c;   108    'l'    11: 91f5; M[f5] <- R[1]
04: 006f;   111    'o'    12: 7e01; R[e] <- 1
05: 002c;    44    ','    13: 100e; R[0] <- R[0] + R[e]
06: 0020;    32    ' '    14: 7f0f; R[f] <- f
07: 0077;   119    'w'    15: ef00; PC <- R[f]
08: 006f;   111    'o'    16: 90f6; M[f6] <- R[0]
09: 0072;   114    'r'    17: 0000
0a: 006c;   108    'l'
0b: 0064;   100    'd'
0c: 0021;    33    '!'
0d: 0000
```

Problem 7

Compile the following assembly code and examine the machine code generated.

```
ld %0 0xFF
halt
```

(a) Which machine instruction was used to load the constant value 0xFF to register 0?

Recompile the assembly, but with the value 0x100 instead of 0xFF.

(b) Outline the machine instructions made use of in this case, and explain why a different set of machine instructions was necessary.

(c) Explain how the ld instruction has added a layer of abstraction over using machine instructions directly.

Problem 8

Let's explore how it is possible for Toy Assembly to have **or** instructions, even though Toy Computer does not have an **or** machine instruction circuit in the ALU.

Compile the following assembly and examine the machine code generated.

```
ld %0 5
ld %1 9
or %2 %0 %1
.bin %2
.line
halt
```

(a) Outline how the assembly **or** instruction has been implemented.

(b) Similarly, write and compile an appropriate assembly program to help you outline how the assembly **not** instruction has been implemented.

Project

Choose one of the following Toy Assembly programs and create a poster that contains (i) a fun illustration, (ii) the assembly code, (iii) the compiled machine code, (iv) a sample run, and (v) a brief analysis of how one or two of the aspects of the program works in terms of the underlying machine instructions.

- *smiley.asm*
- *guess.asm*
- *hurkle.asm*
- *hello.asm*
- *wumpus.asm*
- *rule90.asm*