CMSC 240
PRINCIPLES OF COMPUTER ORGANIZATION

Deepak Kumar

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CMSC 240_{10} (11110000_2) (360_8) ($F0_{16}$)
PRINCIPLES OF COMPUTER ORGANIZATION

Pre-requisites: CMSC B 151 or H106 or H107 and CMSC B231

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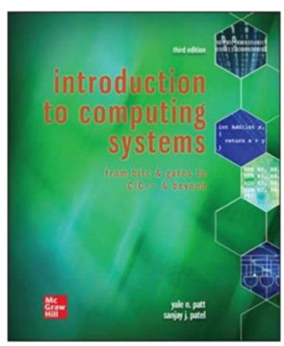
ADMINISTRIVIA

Instructor: Deepak Kumar
Office: Room 202 PSB
Office Hours: TBA

Lectures: Tue-Thu 1:10p to 2:30p
Lecture Room: 337 Park Science Building
Labs: Wednesdays from 2:40p to 4:00p (starts next week)
Lab Room: 230 Park Science Building

Class Website: https://cs.brynmawr.edu/Courses/cs240/Spring2025/

TEXT & SOFTWARE



Main Text
Introduction to Computing Systems: From Bits & Bytes to C/C++ and Beyond, **Third Edition**, McGraw Hill 2019.

Software
LC3 Simulator (Windows/MacOS/Linux)

LEARNING OUTCOMES

- Describe the major components of a modern computer (CPU, Memory, I/O) and how they are implemented and interact in hardware.
- Understand how programs and data are represented in hardware, how instructions are executed, and how data is stored in and retrieved from memory.
- Design circuits to implement Boolean functions and basic storage/memory constructs using digital logic.
- The von Neumann Model
- Relate the behavior of high-level languages like C or Java to the underlying low-level assembly language.

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TOPICS

- What is a Computer?
- Instruction Set Architecture (ISA)
- Bits, Data Types, and Operations
- The von Neumann Model
- The LC3 ISA
- Programming in Assembly using LC3 ISA
- Subroutines and the Stack
- I/O Operations: Service Routines, Traps and Interrupts
- Memory Hierarchy & Caching
- Non-von Neumann Architectures

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MY ROLE

- Create educational opportunities for you to achieve the learning outcomes.
- Assess your progress and provide timely feedback
- Provide support so you can successfully complete the course.

YOUR RESPONSIBILITIES

- Put in the effort
- Attend all classes and labs (let me know if you are going to miss any)
- Follow the rules and guidelines in the class website
- Stay connected
  - Check the class website for schedule, updates, readings, and assignments
  - Do the readings as and when they are assigned. This is a key to success.
  - Be familiar with the main concepts before every class meeting
  - Ask for help when you need it!

IMPORTANT DATES & EVALUATION

Important Dates	Activity
January 21	First Class Meeting
February 18	Exam 1
April 1	Exam 2
May 1	Exam 3

Assessments	Weight
Exam 1	20%
Exam 2	20%
Exam 3	20%
Assignments	30%
Labs	10%

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WHAT IS A COMPUTER?

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WHAT IS A COMPUTER?

A device with

- A processor (CPU – Central Processing Unit)
- Storage/Memory (RAM, Disk, USB Stick)
- A keyboard
- A mouse
- A Monitor
- A printer

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THESE ARE ALL COMPUTERS

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THIS IS ALSO A COMPUTER

El Capitan

World's Fastest Computer (2024)

Lawrence Livermore National Labs, CA

Over 1 million Processors

Size of two tennis courts

Costs $600 million

Can execute ~3 ExaFLOP (10^{18} FLOPS)

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WHAT WAS THE FIRST COMPUTER?

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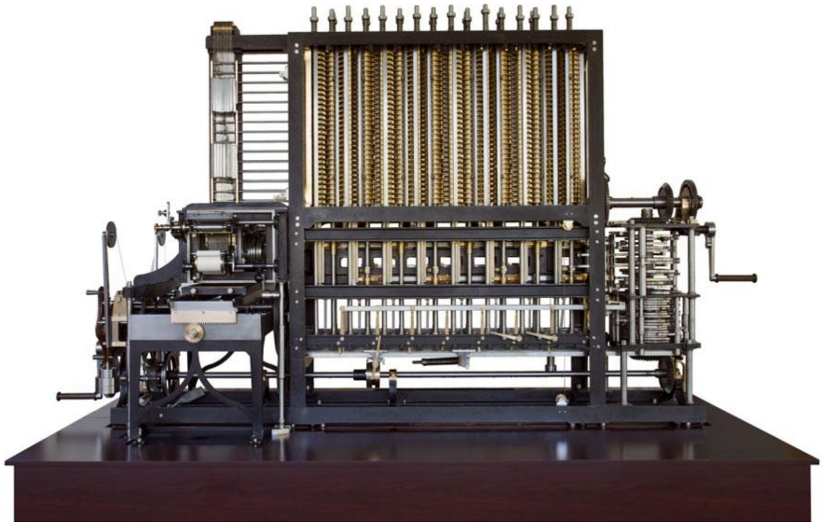
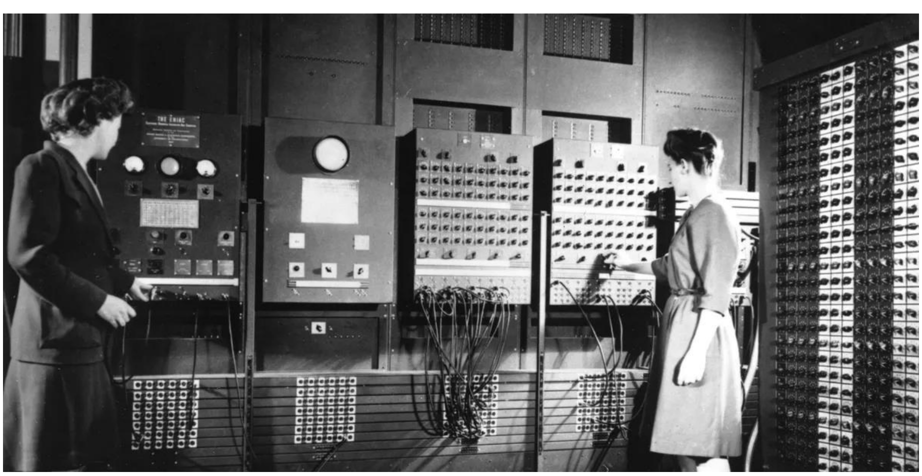
BABBAGE'S DIFFERENCE ENGINE#2 (1832, 2002)

See video at: https://youtu.be/XSkGY6LchJs?si=GzWuDh9yPtsW9DBL



ENIAC FEBRUARY 16, 1946 (U. PENN)

See video at: https://youtu.be/XSkGY6LchJs?si=GzWuDh9yPtsW9DBL



See at: Moore School Building, Corner of 34th & Walnut, Philadelphia.

WHAT IS THE DIFFERENCE BETWEEN THE ENIAC, IPHONE, AND EL CAPITAN?

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WHAT IS THE DIFFERENCE BETWEEN THE ENIAC, IPHONE, AND EL CAPITAN?

NOTHING!

Besides the size, cost, the speed of the processor(s), and amount of memory.

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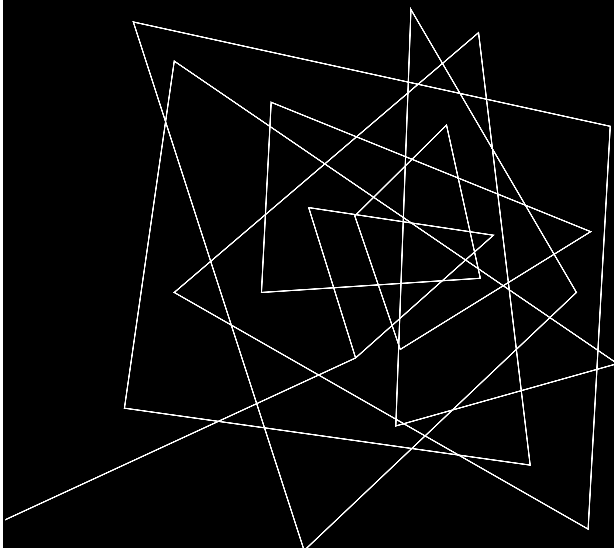

BUT REALLY, WHAT IS A COMPUTER?

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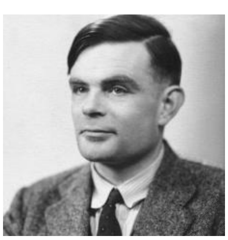
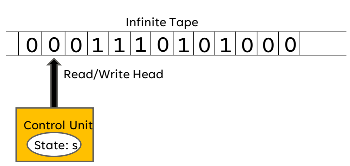
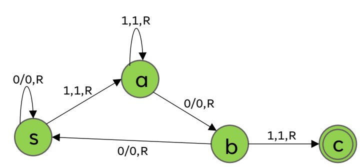
TURING MACHINE: AN IDEALIZED COMPUTER







	0	1
s	0,R, s	1,R, a
a	0,R, b	1,R, a
b	0,R s	1,R c

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TURING MACHINES FOR ADDING & MULTIPLYING

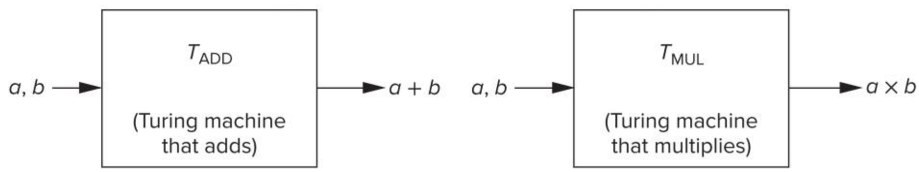

Figure 1.7 Black box models of Turing Machines

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CHURCH-TURING THESIS* (1936)

EVERY COMPUTATION CAN BE PERFORMED BY SOME TURING MACHINE.

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UNIVERSAL TURING MACHINES

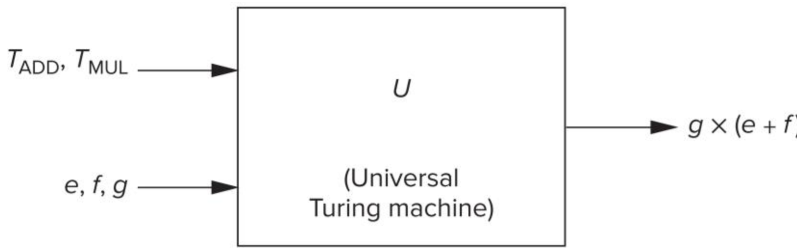

Figure 1.8 Black box model of a universal Turing Machine

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UNIVERSAL TURING MACHINE = PROGRAMMABLE COMPUTER

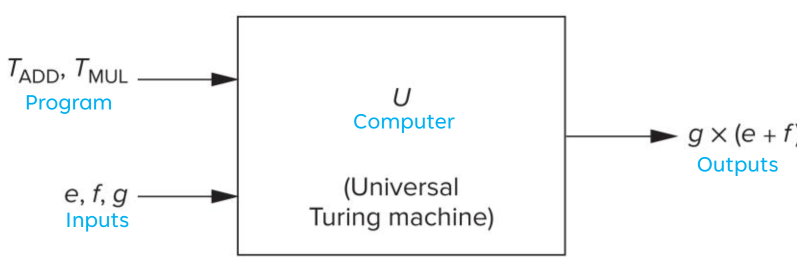

Figure 1.8 Black box model of a universal Turing Machine

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KEY IDEA

A COMPUTER IS ESSENTIALLY A UNIVERSAL TURING MACHINE.

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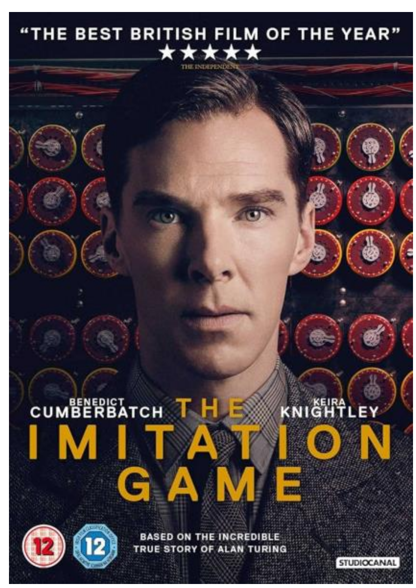
PUT THIS ON YOUR WATCH LIST



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OK, SO…

HOW DO WE ACTUALLY BUILD A UNIVERSAL TURING MACHINE (COMPUTER)???

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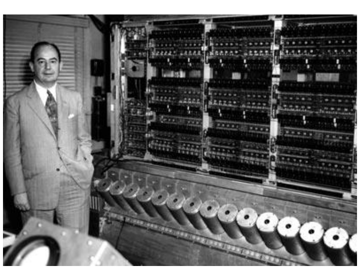
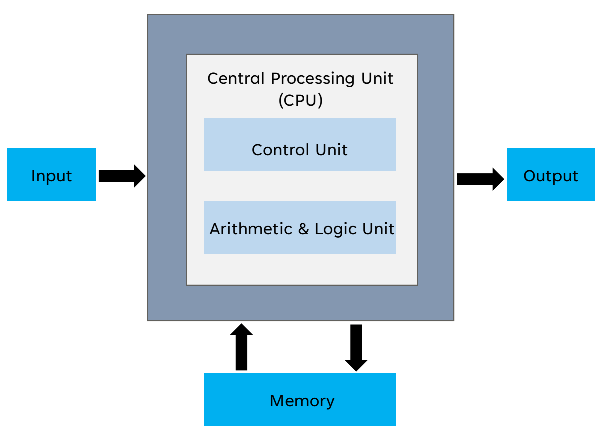
VON NEUMAN ARCHITECTURE (1945)





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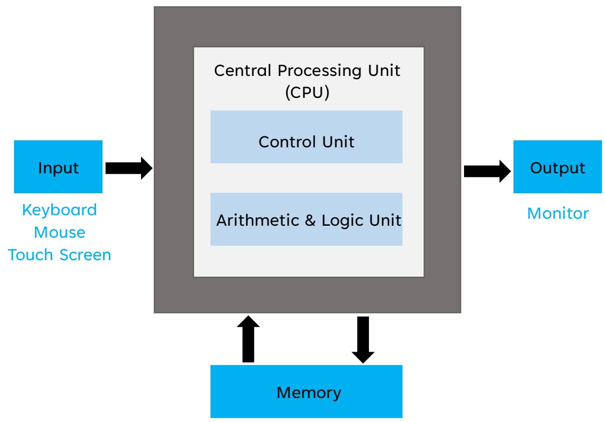
VON NEUMAN ARCHITECTURE



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Problems

Algorithms

Language

Machine (ISA) Architecture

Microarchitecture

Circuits

Devices

NON-VON NEUMANN COMPUTERS

Technically, most of today's computers are non-von Neumann computers.

In what way?

To understand/answer this, we will first need to learn what von Neumann computers are.

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HOW DO WE GET THE COMPUTER TO WORK???

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LEVELS OF TRANSFORMATION

Problems

Algorithms

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LEVELS OF TRANSFORMATION

Problems

Algorithms

Language

Software

Machine (ISA) Architecture

Hardware

Microarchitecture

Circuits

Devices

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Problems

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LEVELS OF TRANSFORMATION: EXAMPLE

PROBLEM

Compute the square root of a given number, a.

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Problems
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Microarchitecture
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Devices

LEVELS OF TRANSFORMATION

PROBLEM

Compute the square root of a given number, a.

A SOLUTION

To compute the square root $x = \sqrt{a}$ do the following:

1. Start with some guess $x_1 > 0$
2. Compute a sequence of guesses x_1, x_2, ..., x_n using the equation

$$x_{n+1} = \frac{1}{2}\left(x_n + \frac{a}{x_n}\right)$$

until the numbers produced converge.

Problems
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LEVELS OF TRANSFORMATION

ALGORITHM

1. To compute $\sqrt{a}$
2. Start with some guess $x_i = 1$. This is our initial guess.
3. Compute the next guess $x_{i+1} = \frac{1}{2}\left(x_i + \frac{a}{x_i}\right)$
4. If $x_{i+1} \neq x_i$
   Set x_i to be same as x_{i+1}
   And then repeat from Step 3.

   Otherwise, because $x_{i+1} = x_i$, they have converged.
   Therefore, $\sqrt{a} = x_{i+1}$

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ALGORITHM

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   Otherwise because $x_{i+1} = x_i$, they have converged.
   Therefore, $\sqrt{a} = x_{i+1}$

Definition:
An algorithm is a *precise*, *unambiguous*, and *effective* procedure.

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LEVELS OF TRANSFORMATION

PROGRAM

```
double sqrt (double a) {
   if (a <= 0) return 0;

   double x0 = 1;
   double x1 = (x0 + a/x0)/2.0;

   while (x0 != x1) {
      x0 = x1;
      x1 = (x1 + (a/x1))/2.0;
   }
   return x1;
} // sqrt()
```

Problems

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LEVELS OF TRANSFORMATION

ASSEMBLY PROGRAM (ISA)

```
        .globl sqrt
sqrt:
.LFB0:
        .cfi_startproc
        pushq %rbp
        .cfi_def_cfa_offset 16
        .cfi_offset 6, -16
        movq %rsp, %rbp
        .cfi_def_cfa_register 6
        movsd %xmm0, -24(%rbp)
        pxor %xmm0, %xmm0
        comisd -24(%rbp), %xmm0
        jb .L8
        pxor %xmm0, %xmm0
        jmp .L4
.L8:
        movsd .LC1(%rip), %xmm0
        movsd %xmm0, -16(%rbp)
        movsd -24(%rbp), %xmm0
        divsd -16(%rbp), %xmm0
        addsd -16(%rbp), %xmm0
        movsd .LC2(%rip), %xmm1
        divsd %xmm1, %xmm0
        movsd %xmm0, -8(%rbp)
        jmp .L5
.L6:
        movsd -8(%rbp), %xmm0
        movsd %xmm0, -16(%rbp)
        movsd -24(%rbp), %xmm0
        divsd -8(%rbp), %xmm0
        addsd -8(%rbp), %xmm0
        movsd .LC2(%rip), %xmm1
        divsd %xmm1, %xmm0
        movsd %xmm0, -8(%rbp)
.L5:
        movsd -16(%rbp), %xmm0
        jp .L6
        movsd -16(%rbp), %xmm0
        ucomisd -8(%rbp), %xmm0
        jne .L6
        movsd -8(%rbp), %xmm0
.L4:
        popq %rbp
        .cfi_def_cfa 7, 8
        ret
        .cfi_endproc
.LFE0:
        .size sqrt, .-sqrt
        .section .rodata
        .align 8
.LC1:
        .long 0
        .long 1072693248
        .align 8
.LC2:
        .long 0
        .long 1073741824
```


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Problems

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Java Program → compiler → Assembly Program

LEVELS OF TRANSFORMATION

ASSEMBLY PROGRAM (ISA)

Instruction Set Architecture (e.g. x86, ARM, LC3, etc.)

opcode: divsd — operands: -16(%rbp), %xmm0

```
        .globl sqrt
sqrt:
.LFB0:
        .cfi_startproc
        pushq %rbp
        .cfi_def_cfa_offset 16
        .cfi_offset 6, -16
        movq %rsp, %rbp
        .cfi_def_cfa_register 6
        movsd %xmm0, -24(%rbp)
        pxor %xmm0, %xmm0
        comisd -24(%rbp), %xmm0
        jb .L8
        pxor %xmm0, %xmm0
        jmp .L4
.L8:
        movsd .LC1(%rip), %xmm0
        movsd %xmm0, -16(%rbp)
        movsd -24(%rbp), %xmm0
        divsd -16(%rbp), %xmm0
        addsd -16(%rbp), %xmm0
        movsd .LC2(%rip), %xmm1
        divsd %xmm1, %xmm0
        movsd %xmm0, -8(%rbp)
        jmp .L5
.L6:
        movsd -8(%rbp), %xmm0
        movsd %xmm0, -16(%rbp)
        movsd -24(%rbp), %xmm0
        divsd -8(%rbp), %xmm0
        addsd -8(%rbp), %xmm0
        movsd .LC2(%rip), %xmm1
        divsd %xmm1, %xmm0
        movsd %xmm0, -8(%rbp)
.L5:
        movsd -16(%rbp), %xmm0
        jp .L6
        movsd -16(%rbp), %xmm0
        ucomisd -8(%rbp), %xmm0
        jne .L6
        movsd -8(%rbp), %xmm0
.L4:
        popq %rbp
        .cfi_def_cfa 7, 8
        ret
        .cfi_endproc
.LFE0:
        .size sqrt, .-sqrt
        .section .rodata
        .align 8
.LC1:
        .long 0
        .long 1072693248
        .align 8
.LC2:
        .long 0
        .long 1073741824
```


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LEVELS OF TRANSFORMATION

MACHINE LANGUAGE PROGRAM

0101000000100000	0001010010000001	0110010100000000
0001000000100001	0000010000000101	0000001111111010
0101001001100000	0001100100100001	0101000000100000
0001001001111011	0001011011111111	1111000000100101
0101011011100000	0110010100000000	0011000100000000
0001011011101010	0000001111111010	0101000000100000
0010100000001001	0101000000100000	0001000000100001
0110010100000000	1111000000100101	0101001001100000
0001010010000001	0011000100000000	0001001001111011
0000010000000101	0101000000100000	0101011011100000
0001100100100001	0001000000100001	0001011011101010
0001011011111111	0101001001100000	0010100000001001
0110010100000000	0001001001111011	0110010100000000
0000001111111010	0101011011100000	0001010010000001
0101000000100000	0001011011101010	0000010000000101
1111000000100101	0010100000001001	0001100100100001
0011000100000000	0110010100000000	0001011011111111
		...

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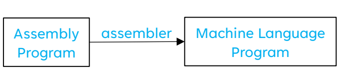

LEVELS OF TRANSFORMATION

MACHINE LANGUAGE PROGRAM

Binary representation of assembly program

0101000000100000	0001010010000001	0110010100000000
0001000000100001	0000010000000101	0000001111111010
0101001001100000	0001100100100001	0101000000100000
0001001001111011	0001011011111111	1111000000100101
0101011011100000	0110010100000000	0011000100000000
0001011011101010	0000001111111010	0101000000100000
0010100000001001	0101000000100000	0001000000100001
0110010100000000	1111000000100101	0101001001100000
0001010010000001	0011000100000000	0001001001111011
0000010000000101	0101000000100000	0101011011100000
0001100100100001	0001000000100001	0001011011101010
0001011011111111	0101001001100000	0010100000001001
0110010100000000	0001001001111011	0110010100000000
0000001111111010	0101011011100000	0001010010000001
0101000000100000	0001011011101010	0000010000000101
1111000000100101	0010100000001001	0001100100100001
0011000100000000	0110010100000000	0001011011111111
		...

What the CPU does:

```
do forever
   fetch the next instruction
   decode it
   carry it out
```

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LEVELS OF TRANSFORMATION

Problems — compute $\sqrt{a}$

Algorithms — 1. 2. 3. …

Language — Java Program

Machine (ISA) Architecture — Machine Code (LC3)

Microarchitecture

Circuits

Devices ← We will start here!

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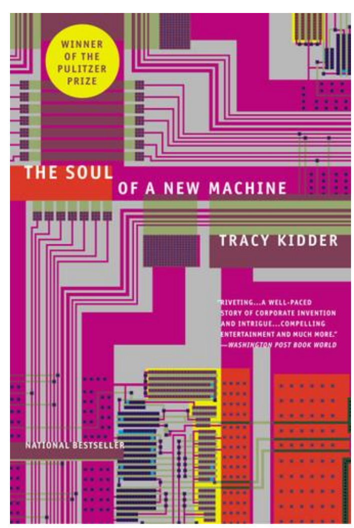
PUT THIS ON YOUR READING LIST



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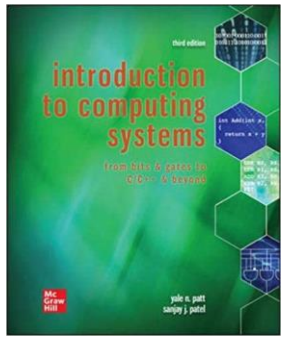

Read
Chapter 1 and Sections 2.1 and 2.2 from your text.

FOR NEXT CLASS…

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THANK YOU

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