UNIT 1
Computer Evolution and Performance

Computer Organization and Architecture

- **Computer Architecture** refers to those attributes of a system visible to a programmer or, put another way, those attributes that have a direct impact on the logical execution of a program.

- Eg. **Instruction set**, the **number of bits** used to represent various data types (e.g., numbers, characters), I/O mechanisms, and **techniques for addressing memory.**

- **Computer Organization** refers to the operational units and their interconnections that realize the architectural specifications.

- Eg. Hardware details transparent to the programmer, such as **control signals**; **Interfaces** between the computer and peripherals; and the **memory technology** used.

- Eg:
  - It is an architectural design issue whether a computer will have a multiply instructions.
  - It is an organizational issue whether that instruction will be implemented by a special multiply unit or by a mechanism that makes repeated use of the add unit of the system.

Functions and Structures

- The **hierarchical nature of complex systems** is essential to both their **design and their description**.
- The **designer need only deal with a particular level** of the system at a time.
- At **each level**, the system consists of a set of **components and their interrelationships.**

- The **behavior at each level depends only on a simplified, abstracted characterization** of the system at the next lower level.

- At each level, the designer is concerned with structure and function:

- **Structure:** The way in which the components are interrelated.

- **Function:** The operation of each individual component as part of the structure.

I. Structure

- There are four main structural components:
- **Central Processing Unit (CPU):** Controls the operation of the computer and performs its data processing functions; often simply referred to as processor.
- **Main Memory**: Stores data.
- **I/O Devices**: Moves data between the computer and its external environment.
- **System Interconnection**: Some mechanism that provides for communication among CPU, main memory, and I/O. A common example of system interconnection is by means of a **System Bus.**

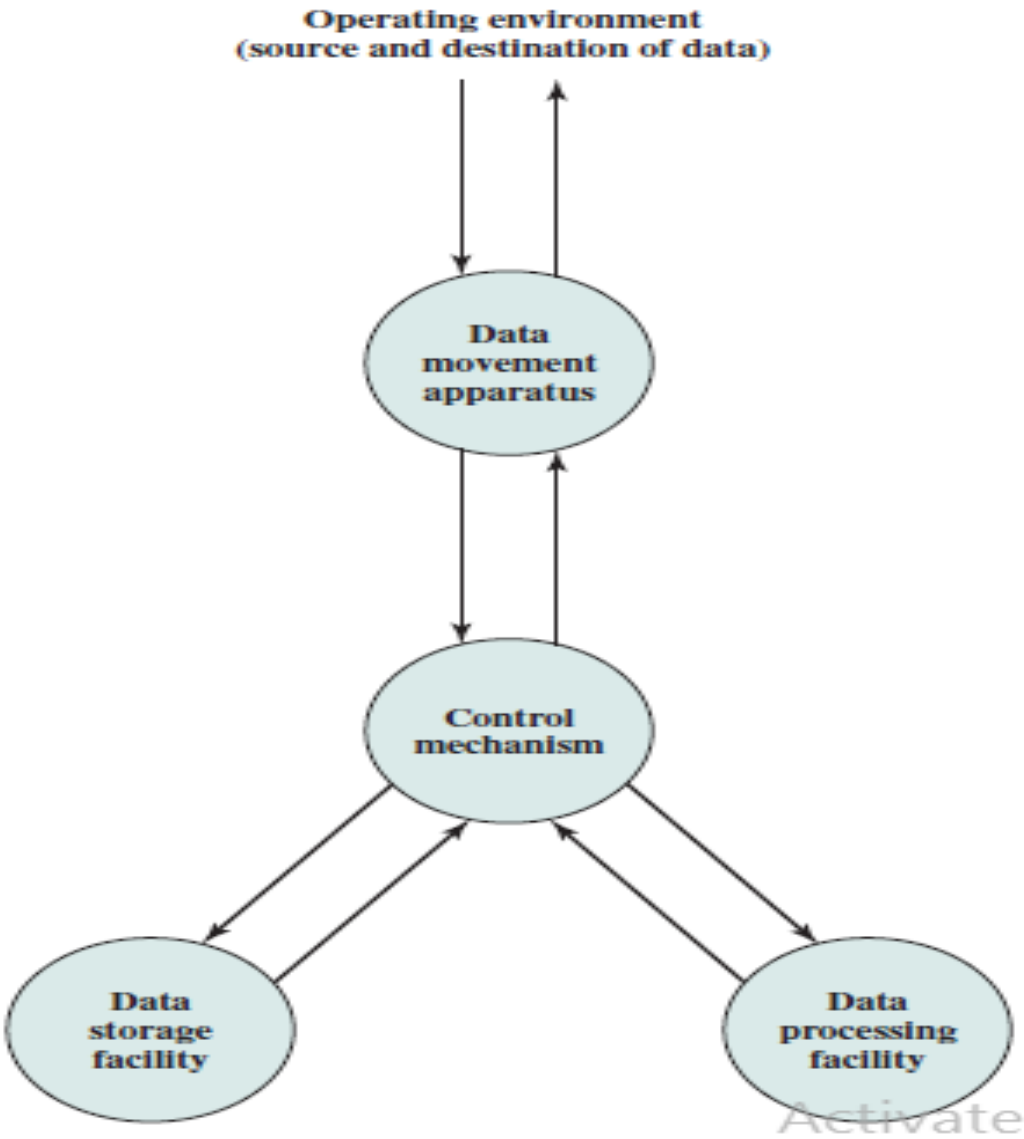
CPU

- **Control unit:** Controls the operation of the CPU and hence the computer.
- **Arithmetic and logic unit (ALU):** Performs the computer's data processing functions.
- **Registers:** Provides storage internal to the CPU.
- **CPU interconnection**: Some mechanism that provides for communication among the control unit, ALU, and registers.

II. Functions

- The operation of each individual component as part of the structure.

- There are 4 functions
  - **Data Processing**
  - **Data Storage**
  - **Data Movement**
  - **Control**


Operating environment
(source and destination of data)
Data movement apparatus
Control mechanism
Data storage facility
Data processing facility

- The computer, of course, must be able to **Process Data.** The data may take a wide variety of forms, and the range of processing requirements is broad.

- It is also essential that a computer **Store Data.** Even if the computer is processing data on the fly (i.e., data come in and get processed, and the results go out immediately), the computer must temporarily store at least those pieces of data that are being worked on at any given moment. Thus, there is at least a short-term data storage function.

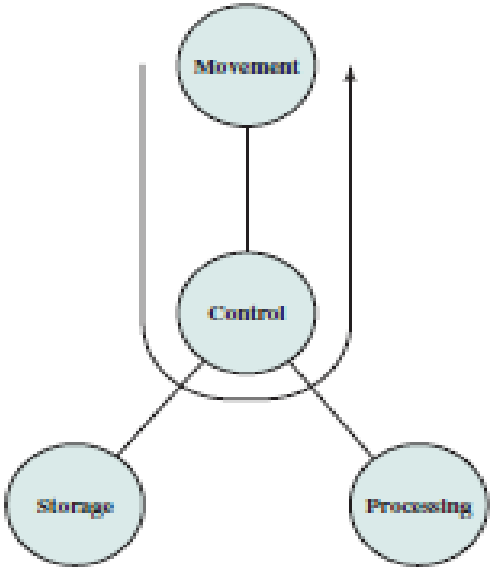
- Equally important, the computer performs a long-term data storage function. Files of data are stored on the computer for subsequent retrieval and update.

- The computer must be able to **Move Data** between itself and the outside world.

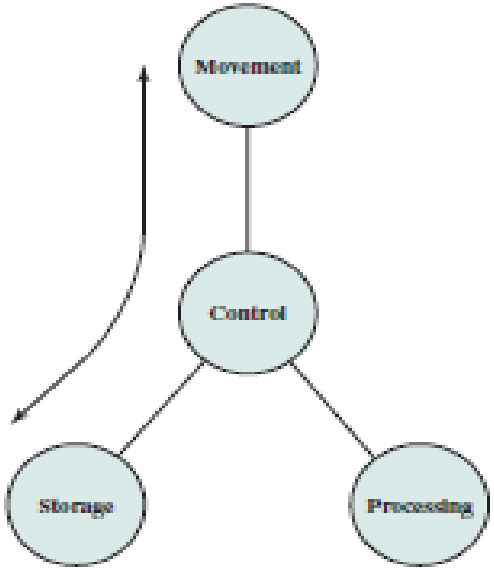
- When data are received from or delivered to a device that is directly connected to the computer, the process is known as ***Input– Output (I/O),*** and the device is referred to as a ***Peripheral.***

- *When data are moved* over longer distances, to or from a remote device, the process is known as ***Data Communications.***

- Finally, there must be **Control** of these three functions. Ultimately, this control is exercised by the individual(s) who provides the computer with instructions.



(a)



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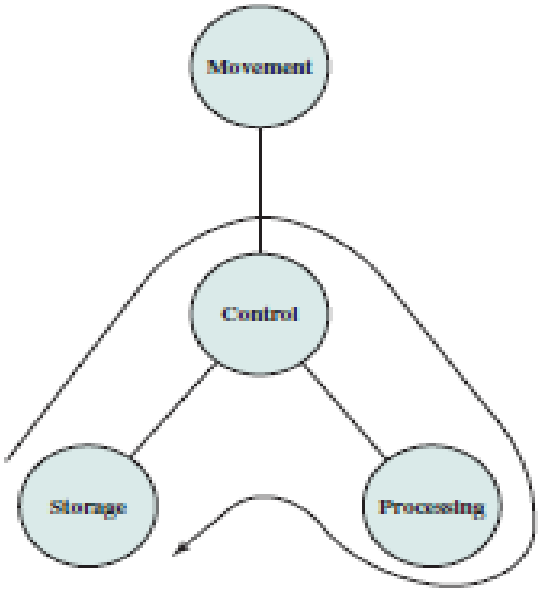

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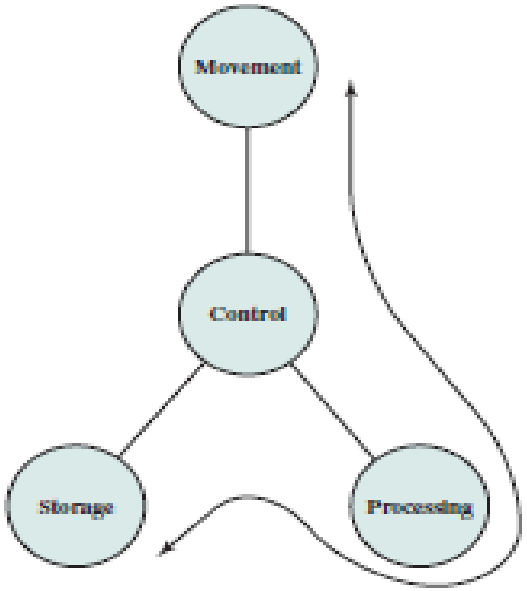


(d)

a) **Data Movement**
b) **Data Storage**
c) **Data Processing (Internal)**
d) **Data Processing (External)**

Evolution of Computers

First Generation (1940-1956) Vacuum Tubes

- The first electronic computer was designed at Iowa State between 1939-1942.
- The Atanasoff-Berry Computer used the binary system(1's and 0's).
- Contained **Vacuum Tubes** and stored numbers for calculations by burning holes in paper.

IBM Stretch - 1959

IBM Stretch - 1959

Second Generation (1956-1963) Transistors

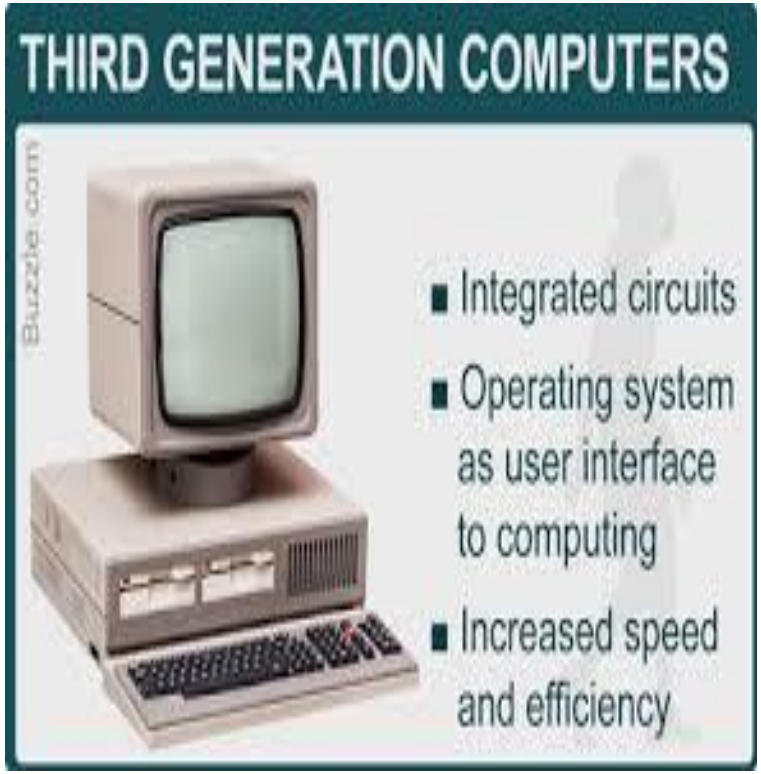
- In 1947, the **Transistor** was invented.
- The transistor made computers smaller, less expensive and increased calculating speeds.
- Second generation computers also saw a new way data was stored.
- Punch cards were replaced with magnetic tapes.
- ALP are used for computing.


SECOND GENERATION COMPUTERS
Transistors
Punched cards for input
Assembly language for computing
Buzzle.com

Third Generation (1964-1971) Integrated Circuits

- Transistors were replaced by integrated circuits(IC).
- One IC could replace hundreds of transistors.
- This made computers even smaller and faster.

- OS is used for UI.
- Keyboard entry is possible.


THIRD GENERATION COMPUTERS
Buzzle.com
Integrated circuits
Operating system as user interface to computing
Increased speed and efficiency

Fourth Generation (1971-Present) Microprocessors

- In 1970 the Intel Corporation invented the Microprocessor: an entire CPU on one chip.
- This led to microcomputers-computers on a desk.

Fifth Generation (Present and Beyond) AI

- Having features like
  - Artificial Intelligence
  - Voice Recognition
  - Parallel Processing
  - Natural Language Processing

What is Microprocessor

- A microprocessor, sometimes called a ***logic chip***, is a computer processor on a microchip.
- It is also called as **"Heart of Computer."**
- The microprocessor contains all, or most of, the **central processing unit (CPU)** functions.
- A microprocessor is designed to perform arithmetic and logic operations that make use of small number-holding areas called ***registers***.

- Typical microprocessor operations include **adding, subtracting, comparing two numbers, and fetching numbers** from one area to another.

- These operations are the result of a set of instructions that are part of the microprocessor design.

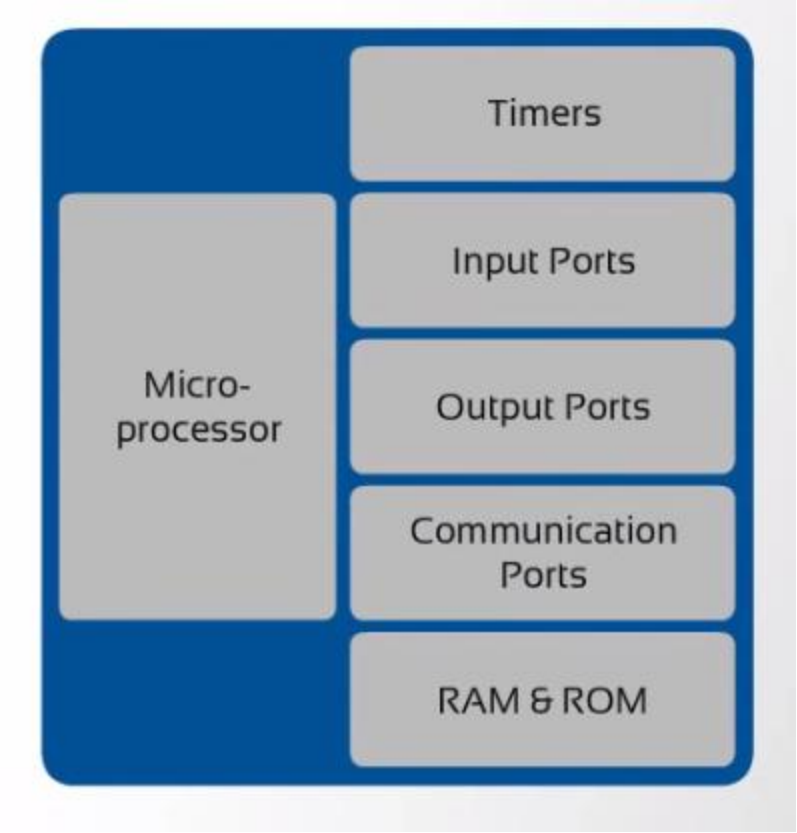
Three basic characteristics differentiate microprocessors:

- **Instruction set**: The set of instructions that the microprocessor can execute.
- **Bandwidth:** The number of bits processed in a single instruction.
- **Clock speed:** Given in megahertz (MHz), the clock speed determines how many instructions per second the processor can execute.

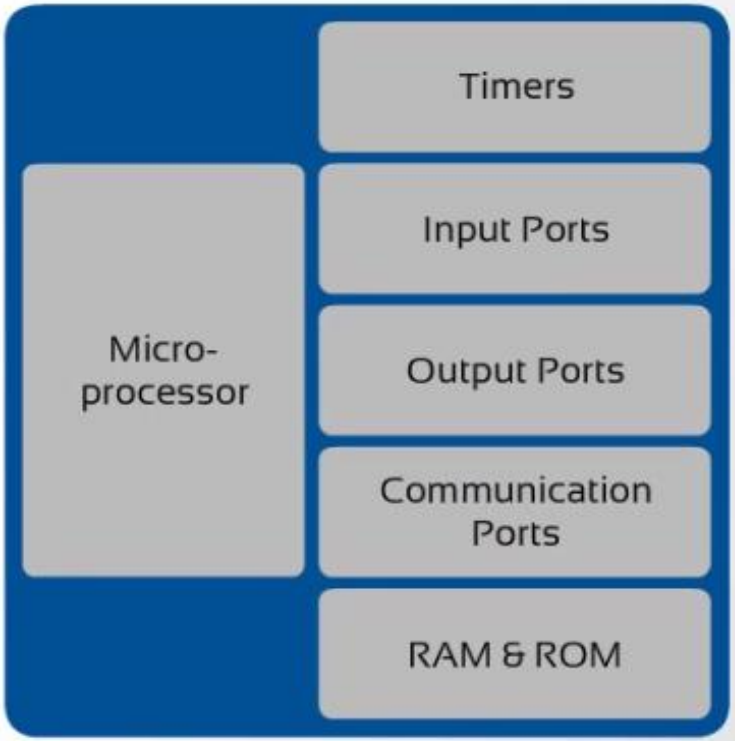
In both cases, the higher the value, the more powerful the CPU.

For example, a 32-bit microprocessor that runs at 50MHz is more powerful than a 16-bit microprocessor that runs at 25MHz.

Microprocessor Vs. Microcontroller



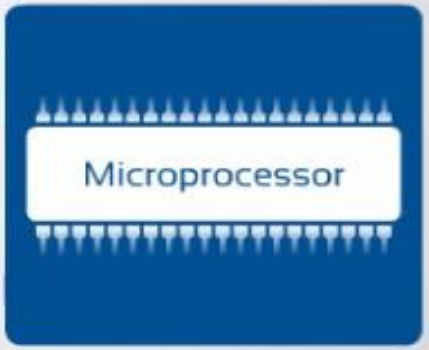
Microcontroller



Microcontroller, as an Integrated Circuit (IC), is complex than a General Purpose Processor.

Differences between a Microprocessor and a Microcontroller:

- Multipurpose
- Contains primarily the CPU
- System costs are higher
- Higher Clock speed
- Can be constantly reprogrammed as required



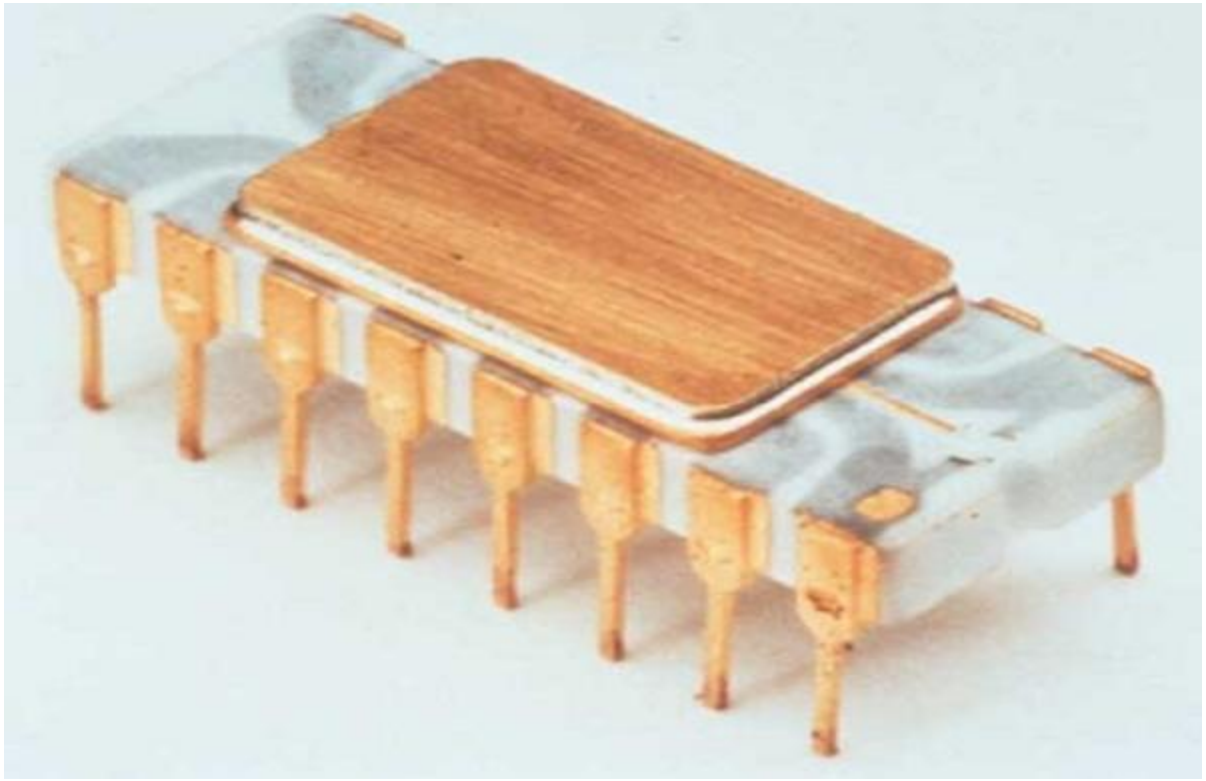
Versus

- Specific usages
- Contains the CPU and many peripheral devices
- System costs are lower
- Cannot operate at higher Clock speed
- Requires programming only once for a particular application

History of Microprocessor

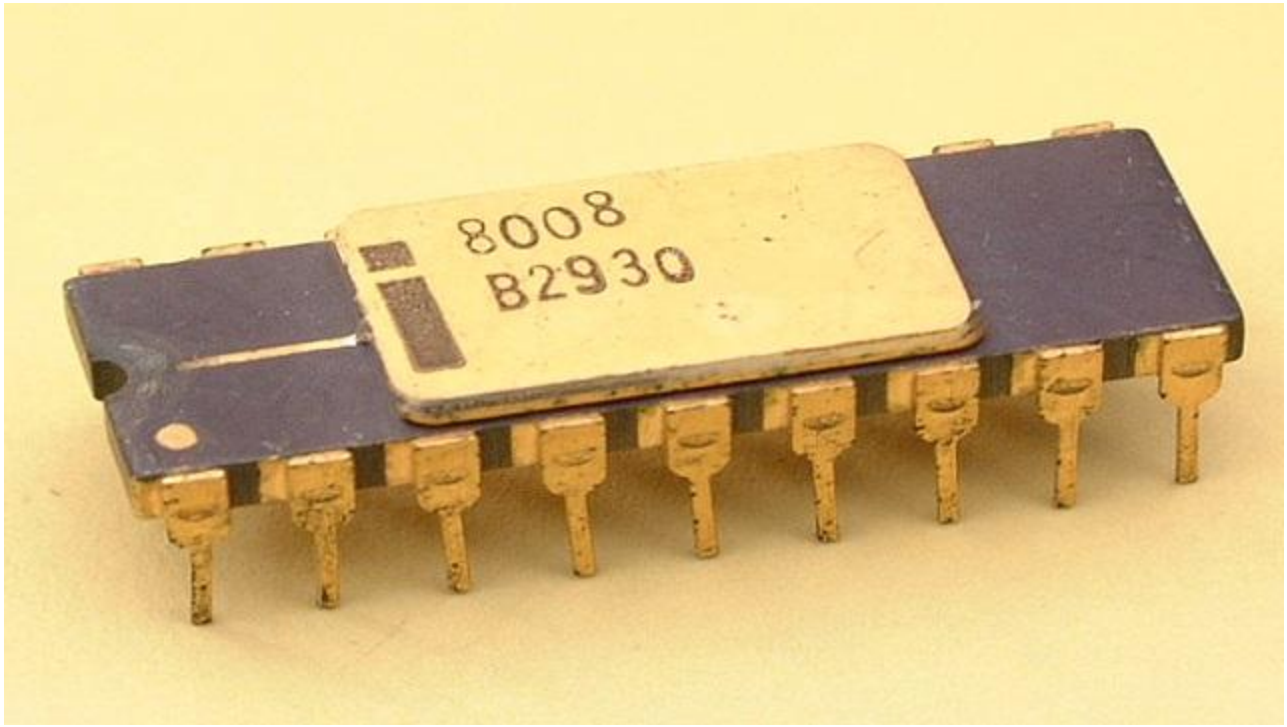
MP	Introduction	Data Bus (In Bits)	Address Bus (In Bits)
4004	1971	4	8
8008	1972	8	8
8080	1974	8	16
8085	1977	8	16
8086	1978	16	20
80186	1982	16	20
80286	1983	16	24
80386	1986	32	32
80486	1989	32	32
Pentium	1993 onwards	32	
Core solo	2006	32	
Dual Core	2006	32	
Core 2 Duo	2006	32	
Core to Quad	2008	32	
I3,i5,i7	2010	64	40

4004



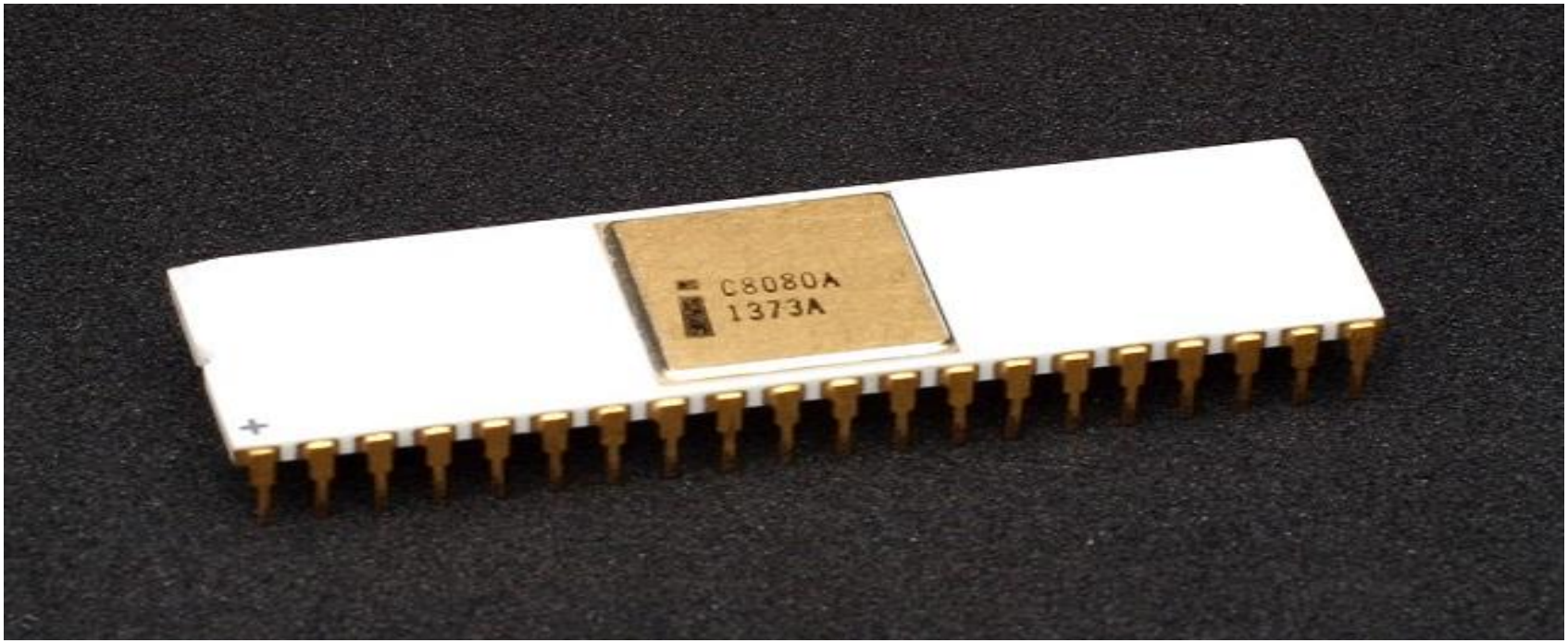
The Intel 4004 Processor was announced in **1971**. It has 2300 transistors with an initial clock speed of **108KHz**. It cost $200.

8008



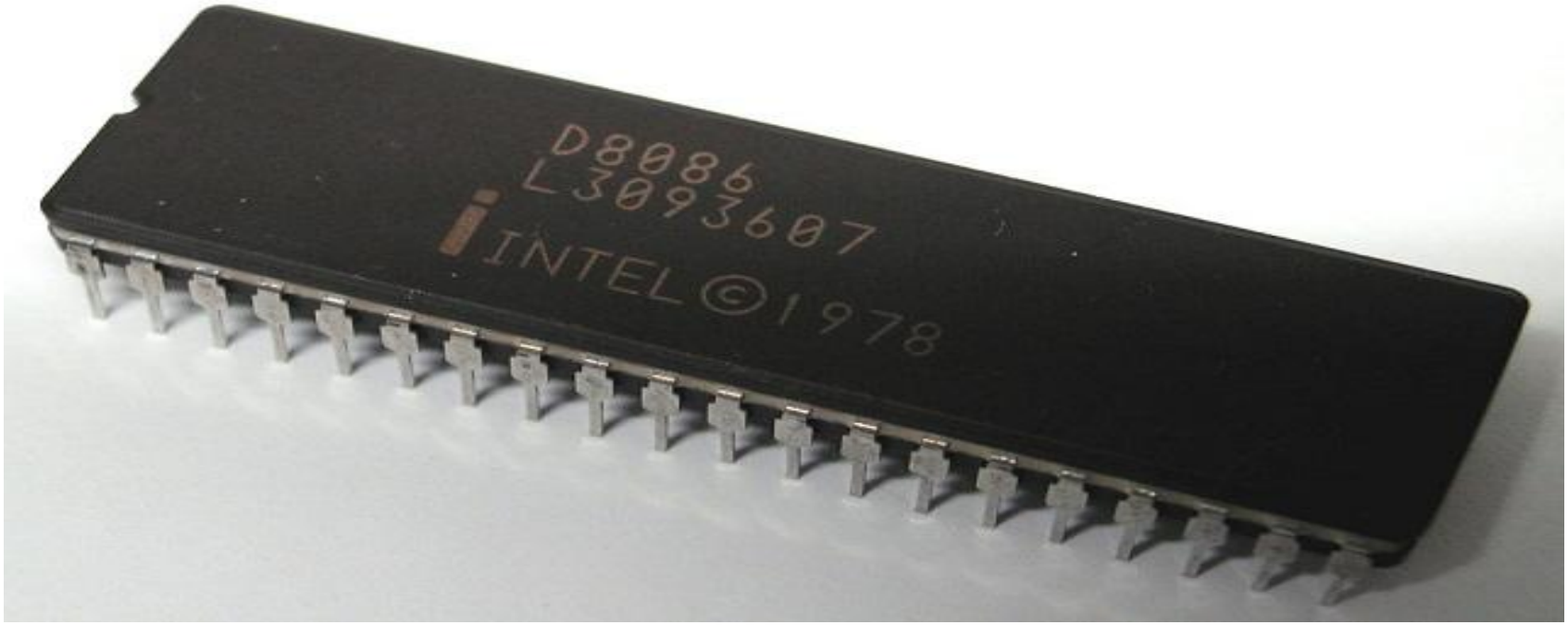
The Intel 8008 Processor was introduced in **1972**. It has 3,500 transistors with an initial clock speed of **800KHz.**

8080



The Intel 8080 Processor was introduced in **1974**. It has 4,500 transistors with an initial clock speed of **2MHz.**

8086



The Intel 8086 Processor was introduced in **1978**. It had a staggering 29,000 transistors, dwarfing the Intel 8080 processor. It has 29,000 transistors with an initial clock speed of **5MHz**.

80286

The Intel 286 Processor was introduced in **1982**. It has 134,000 transistors with an initial clock speed of **6 MHz.**

80386

The Intel 386 Processor was introduced in **1985**. It has 275,000 transistors with an initial clock speed of **16 MHz.**

80486

The Intel 486 Processor was introduced in **1989**. It has 1.2 million transistors with an initial clock speed of **25MHz.**

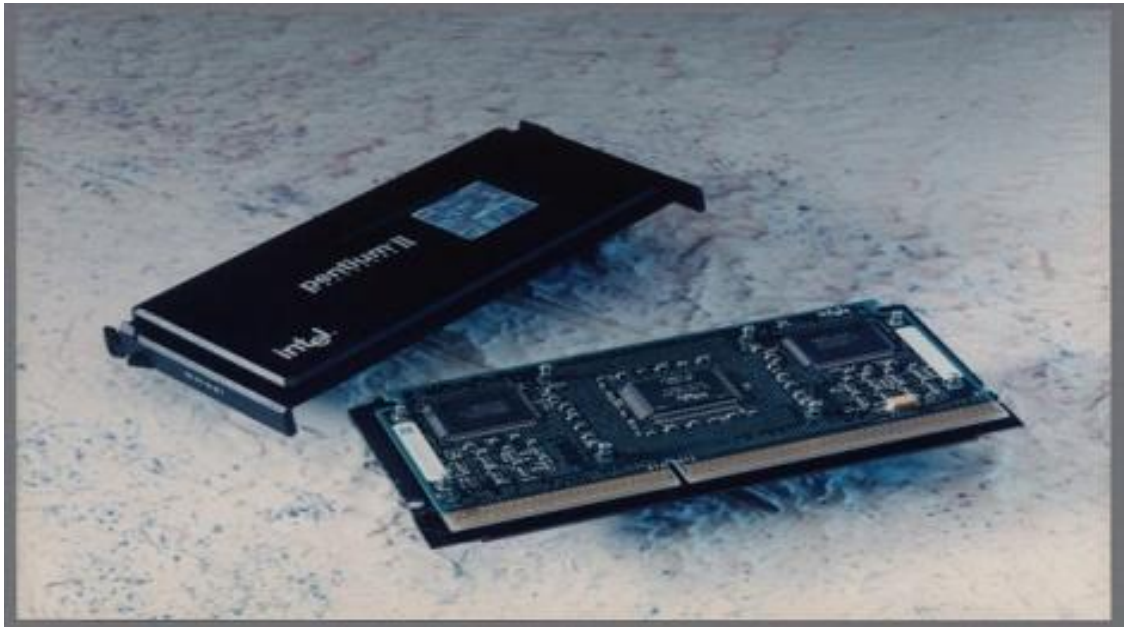
Pentium

The Intel Pentium Processor was introduced in **1993**. It has 3.1 million transistors with an initial clock speed of **66 MHz.**

Pentium-Pro

The Intel Pentium Pro Processor was introduced in **1995**. It has 5.5 million transistors with an initial clock speed of **200 MHz.**

Pentium-II



The Intel Pentium II Processor was introduced in **1997**. It has 7.5 million transistors with an initial clock speed of **300 MHz.**

Celeron

The Intel Celeron Processor was introduced in **1998**. It has 7.5 million transistors just like the Intel Pentium II but with an initial clock speed of **266 MHz.**

Pentium-III

The Intel Pentium III Processor was introduced in 1999. It has 9.5 million transistors with an initial clock speed of **600 MHz.**

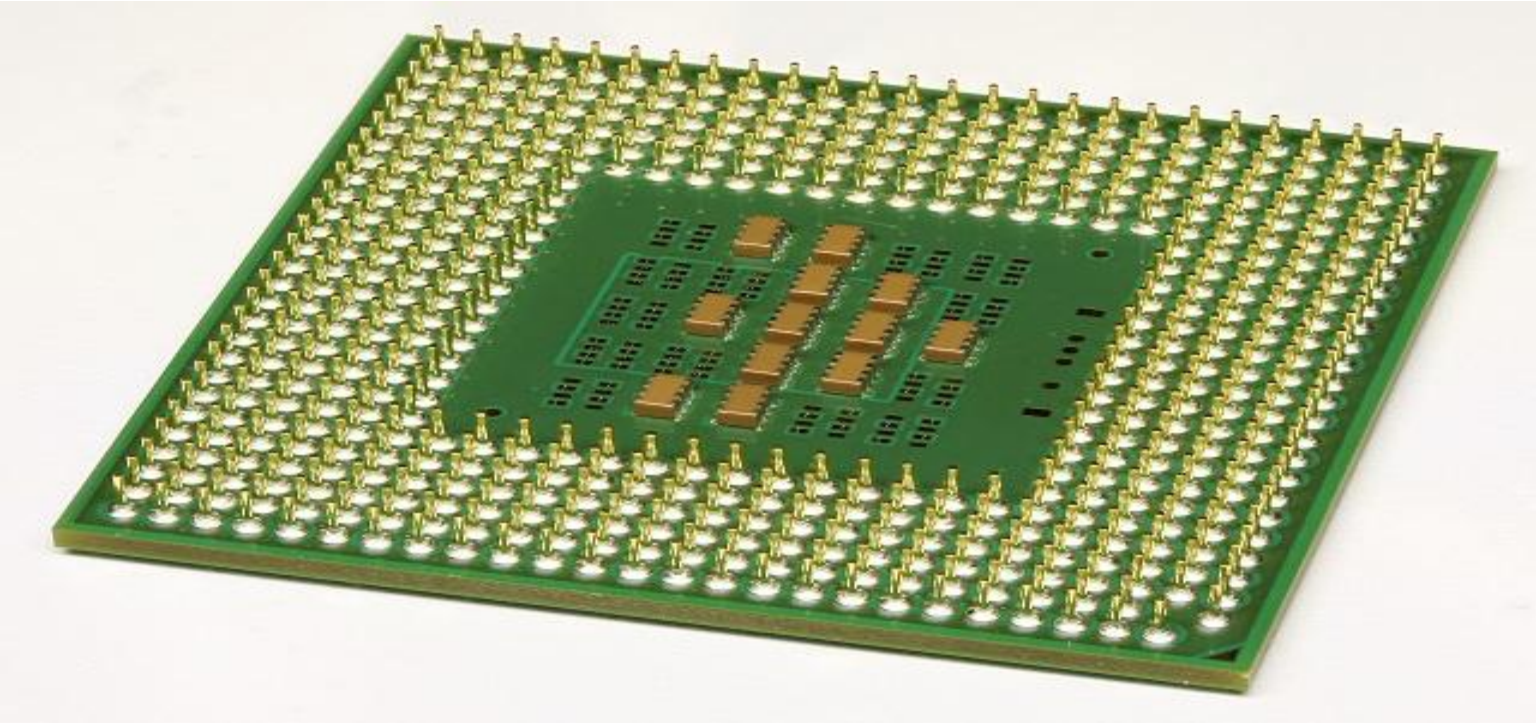
Pentium-4

The Intel Pentium 4 Processor was introduced in **2000.** It has an astonishing 42 million transistors with an initial clock speed of **1.5 GHz.**

Xeon

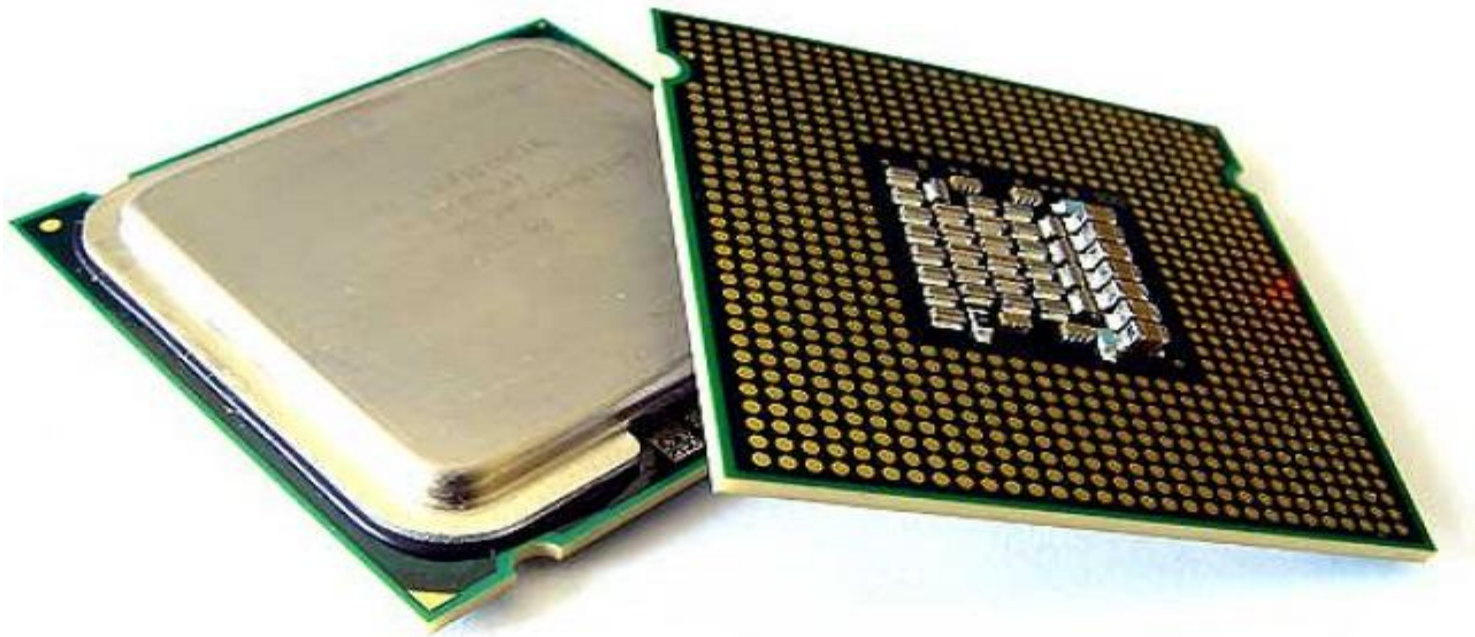
The Intel Xeon 7500 Processor was introduced in **2001**. It has 42 million transistors with an initial clock speed of **1.7 GHz.**

Pentium-M



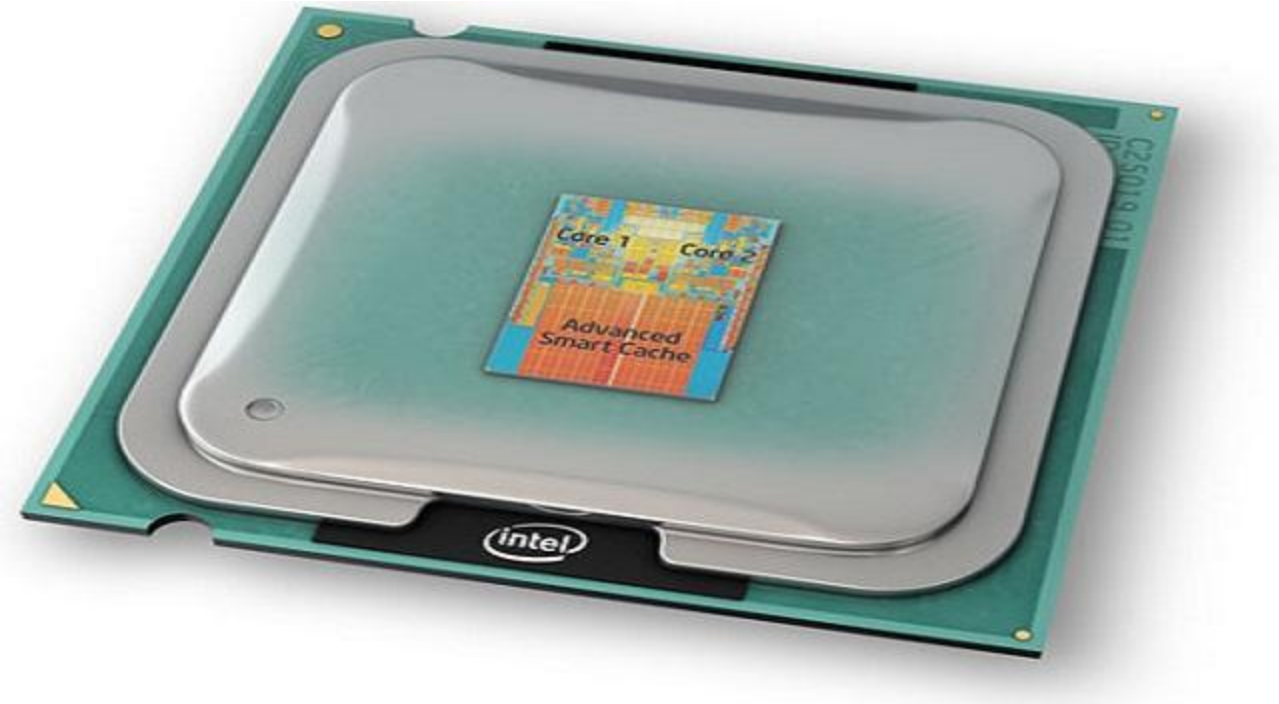
The Intel Pentium M Processor was introduced in **2003**. It has 55 million transistors with an initial clock speed of **1.7 GHz.**

Core-2



The Intel Core 2 Processor was introduced in **2006**. It has 291 million transistors with an initial clock speed of **2.66 GHz.**

Core-2-Duo



The Intel Core 2 Duo Processor was introduced in **2008**. It has 410 million transistors with an initial clock speed of **2.4 GHz.**

Atom

The Intel Atom Processor was introduced in **2008**. It has 41 million transistors with an initial clock speed of **1.86 GHz.**

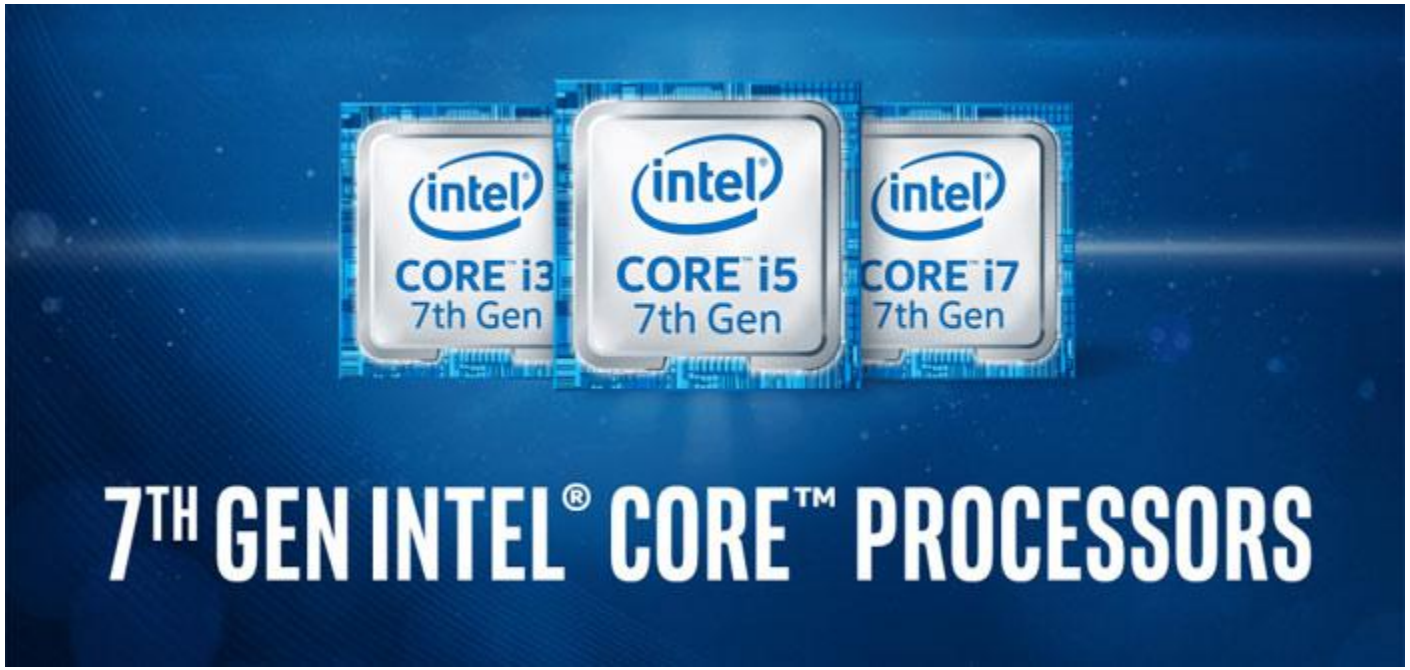
i-Series (2nd Generation)

The 2nd generation Intel Core Processor was introduced in **2010**. It is a monster with 1.16 billion transistors and an initial clock speed of **2.7 GHz.**

i-Series (3rd Generation)

The 3rd generation Intel Core Processor was introduced in **2010**. It has a staggering 1.4 billion transistors and an initial clock speed of **2.9 GHz.**

i-Series (7^{th} Generation)



- Introduced in **2015** and Clock speed can be upto **4.4 GHz**.

Designing for Performance

- **Things can be added to improve performance:**

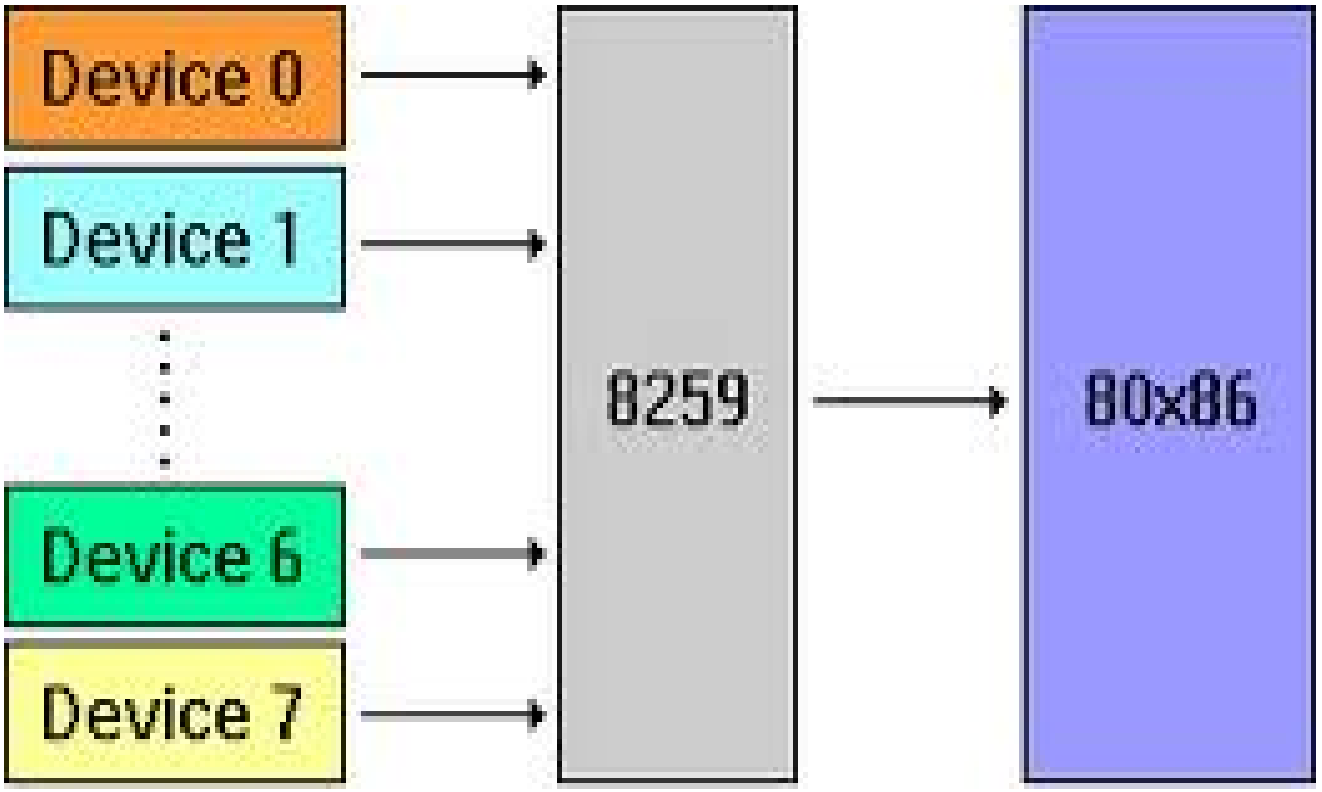
1. **Microprocessor Speed**
   - **Pipelining**
   - **Brach Prediction**
   - **Data Flow Analysis (Data Dependency)-** Data-flow analysis is a technique for gathering information about the possible set of values calculated at various points in a computer program
   - **Speculative execution** (see next slide)

Speculative Execution

- Using **Branch Prediction** and **Data Flow Analysis**, some processors execute instructions ahead of their actual appearance in the program execution, holding the results in temporary locations.

- This enables the processor to keep its execution engines as busy as possible by executing instructions that are likely to be needed.

2. Performance Balance- By increasing Hardware Requirements. (Eg. 8259 Interrupt Controller)



3. Improvements in Chip Organization and Architecture.

(Eg. Three level cache in i-Series)

Performance Assessment

- Clock Speed and Instructions Per Second
- Benchmarks
- Amdahl's Law
- Little's Law

- **Clock Speed-**

  - Operations performed by a processor, such as **Fetching an Instruction, Decoding the Instruction, Performing an Arithmetic Operation**, and so on, are governed by a system clock.

  - Typically, **all operations begin with the pulse of the clock.** Thus, at the most fundamental level, the **speed of a processor is dictated by the pulse frequency produced by the clock, measured in cycles per second, or Hertz (Hz).**

  - The rate of pulses is known as the **Clock Rate, or Clock Speed**. One increment, or pulse, of the clock is referred to as a **Clock Cycle, or A Clock Tick**. The time between pulses is the **Cycle Time**.

- **Benchmarks-**

Lists the following as desirable characteristics of a **Benchmark Program**:

- It is written in a **High-level Language**, making it portable across different machines. (Platform Independent)

- It is representative of a particular kind of **Programming Style**, such as Systems Programming, Numerical Programming, or Commercial Programming.

- It can be **Measured Easily.** (Complexities)

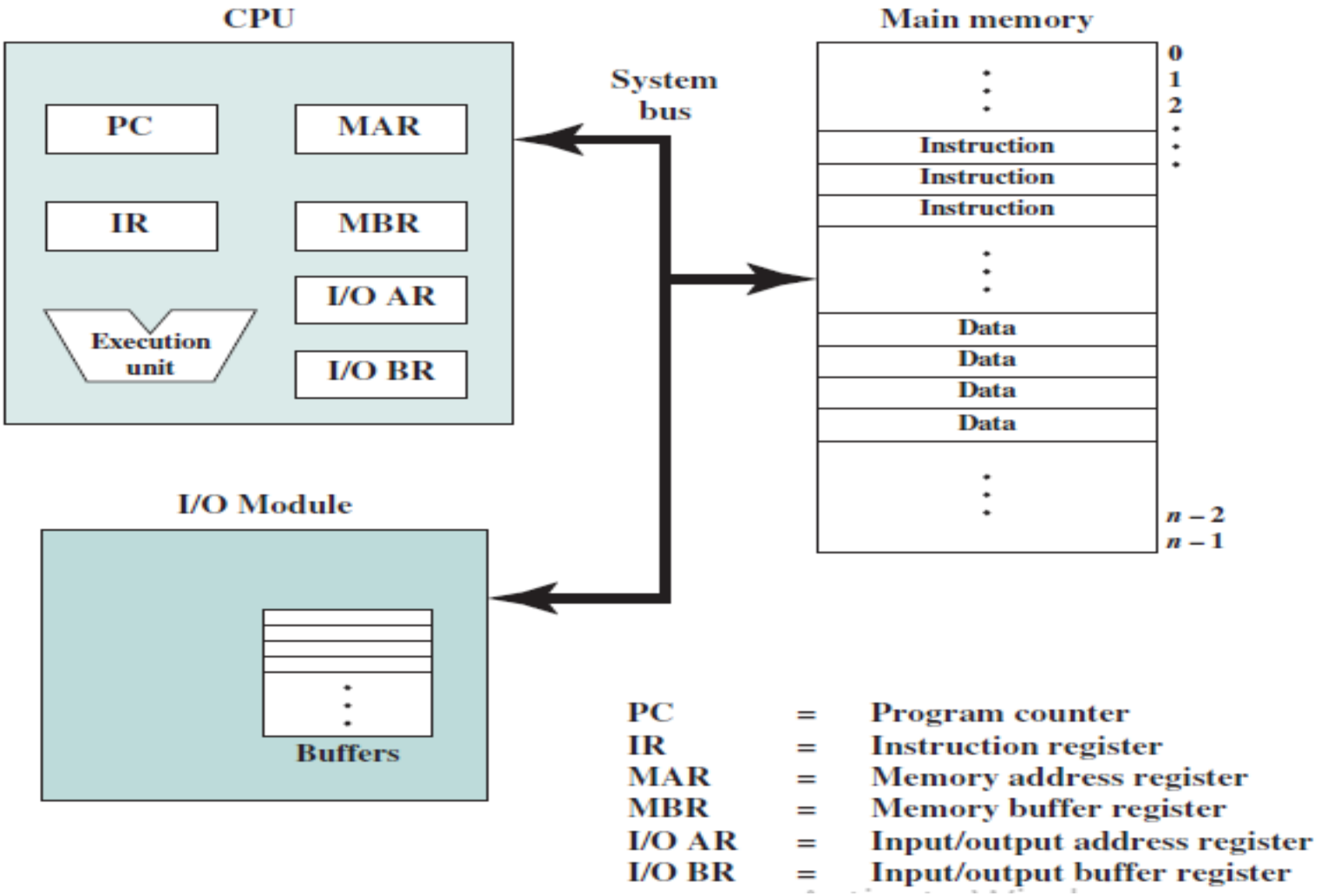
- **Amdahl's Law:**

  – Amdahl's law was first proposed by Gene Amdahl. **Deals with the potential speedup of a program using multiple processors compared to a single processor.**

$$\text{Speedup} = \frac{\text{Time to execute program on a single processor}}{\text{Time to execute program on } N \text{ parallel processors}}$$

- **Little's Law:**
  - Total number of instructions executed by the processor in a given unit time, which will tell **Processors Throughput and Response Time.**
  - Little's law can also be applied for our web / app / db servers to relate the total no of users/requests, server's throughput & the average response time.
  - **Throughput** is number of requests processed per unit time.
  - **Response time** –It includes wait time + service time.

Computer Components: Top Level View



Computer Functions

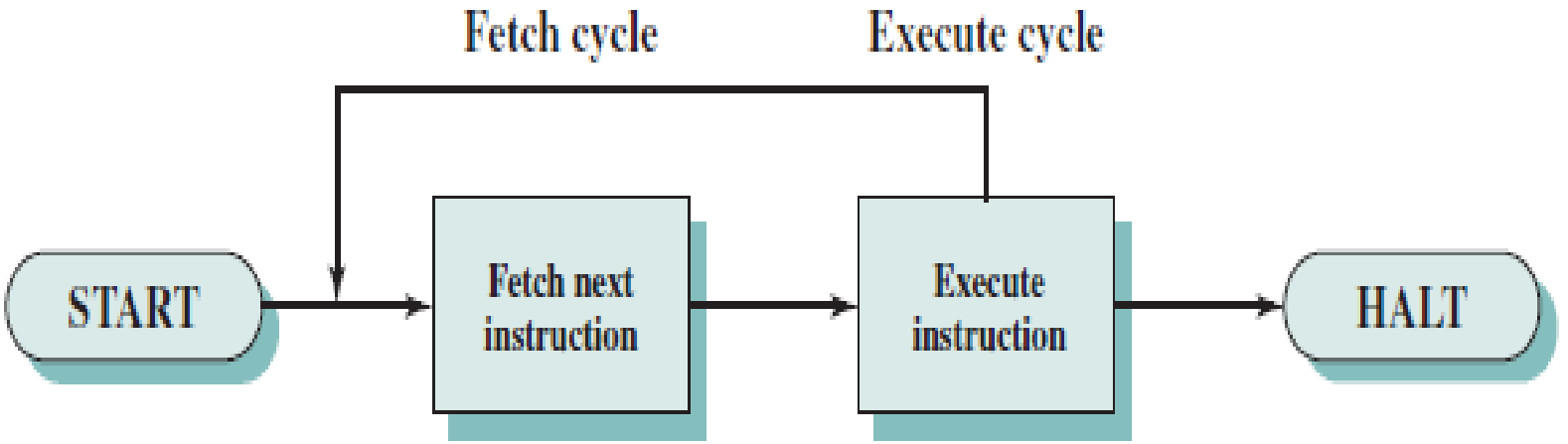
- Computer functions mainly involve
  - **Instruction Fetch and Execute**
  - **Interrupts**
  - **I/O Function**

What is a Program?

- A sequence of steps (Instructions).
- For each step, an arithmetic or logical operation is done.
- For each operation, a different set of control signals is needed.

Instruction Cycle

- Two steps:
  - **Fetch**
  - **Execute**



Fetch Cycle

- At the beginning of each instruction cycle the processor fetches an instruction from memory.

– The **Program Counter (PC) holds the address of the instruction to be fetched next.**

– The processor increments the PC after each instruction fetch so that it will fetch the next instruction in sequence.

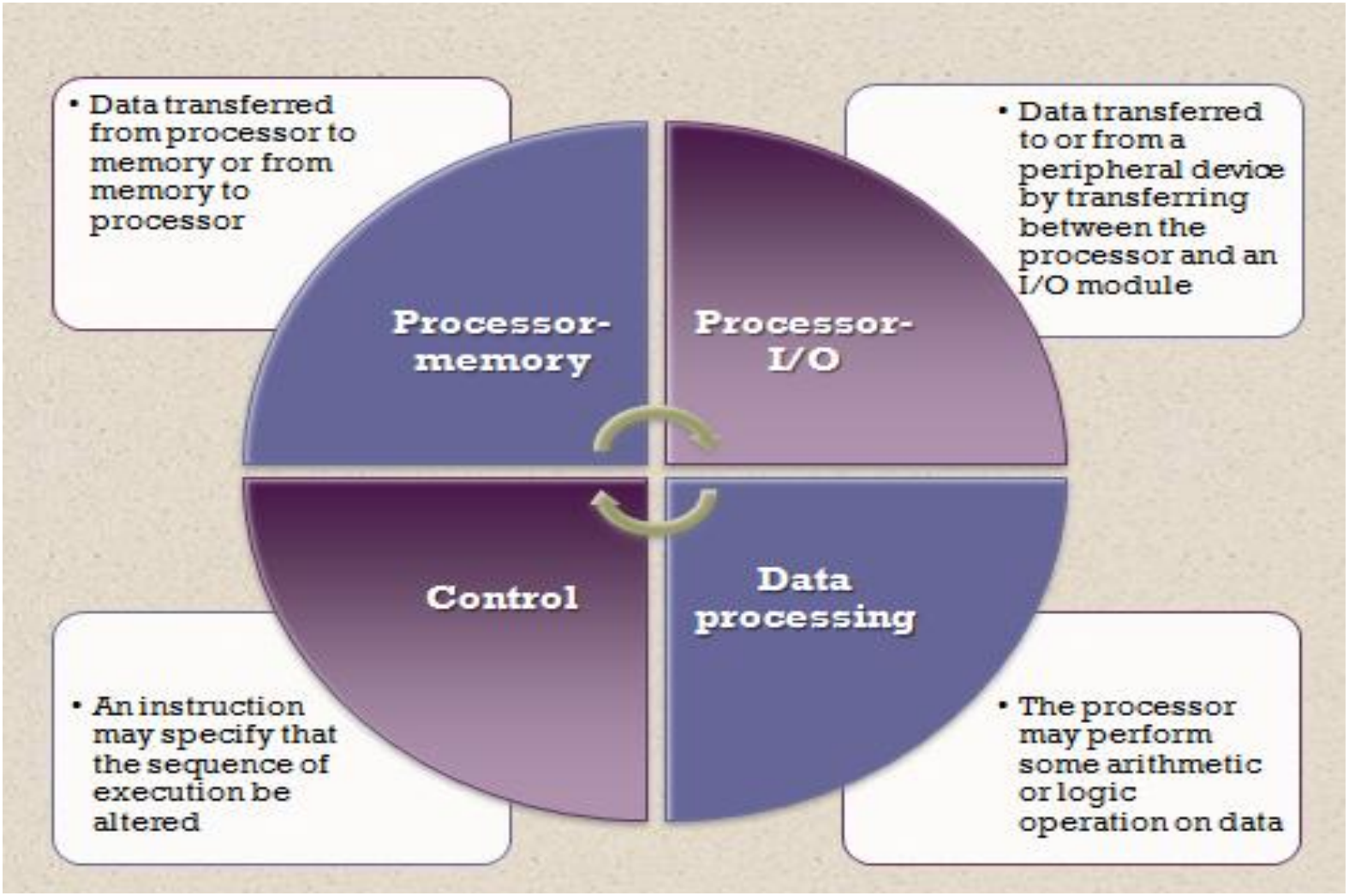
- The fetched instruction is loaded into the **Instruction Register (IR).**

– The processor interprets the instruction and performs the required action.

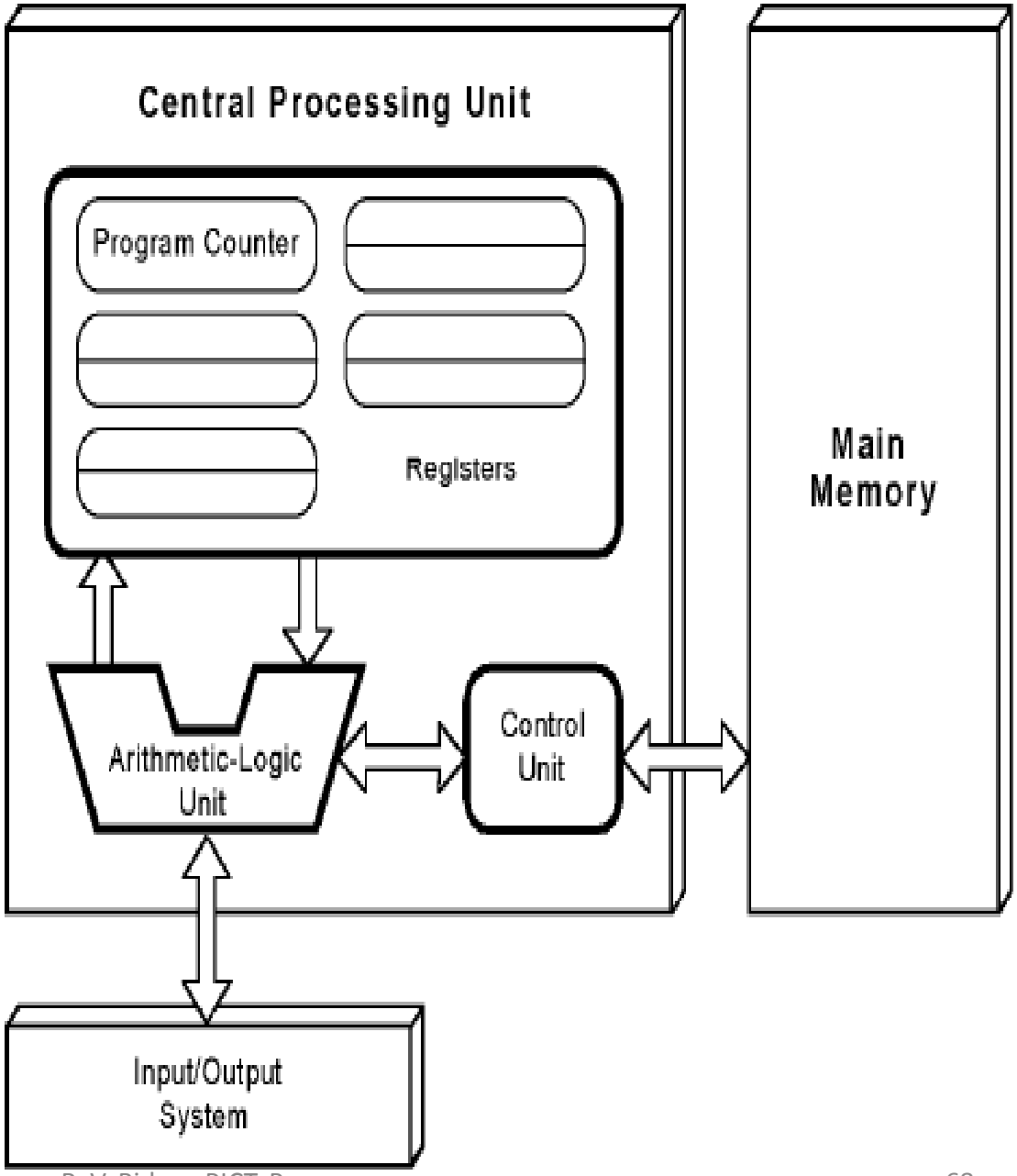
Execute Cycle

- **Processor-Memory**
  - Data transfer between CPU and main memory.
- **Processor-I/O**
  - Data transfer between CPU and I/O module.
- **Data Processing**
  - Some arithmetic or logical operation on data.
- **Control**
  - Alteration of sequence of operations.
  - e.g. Jump, Call.
- **Combination of above.**

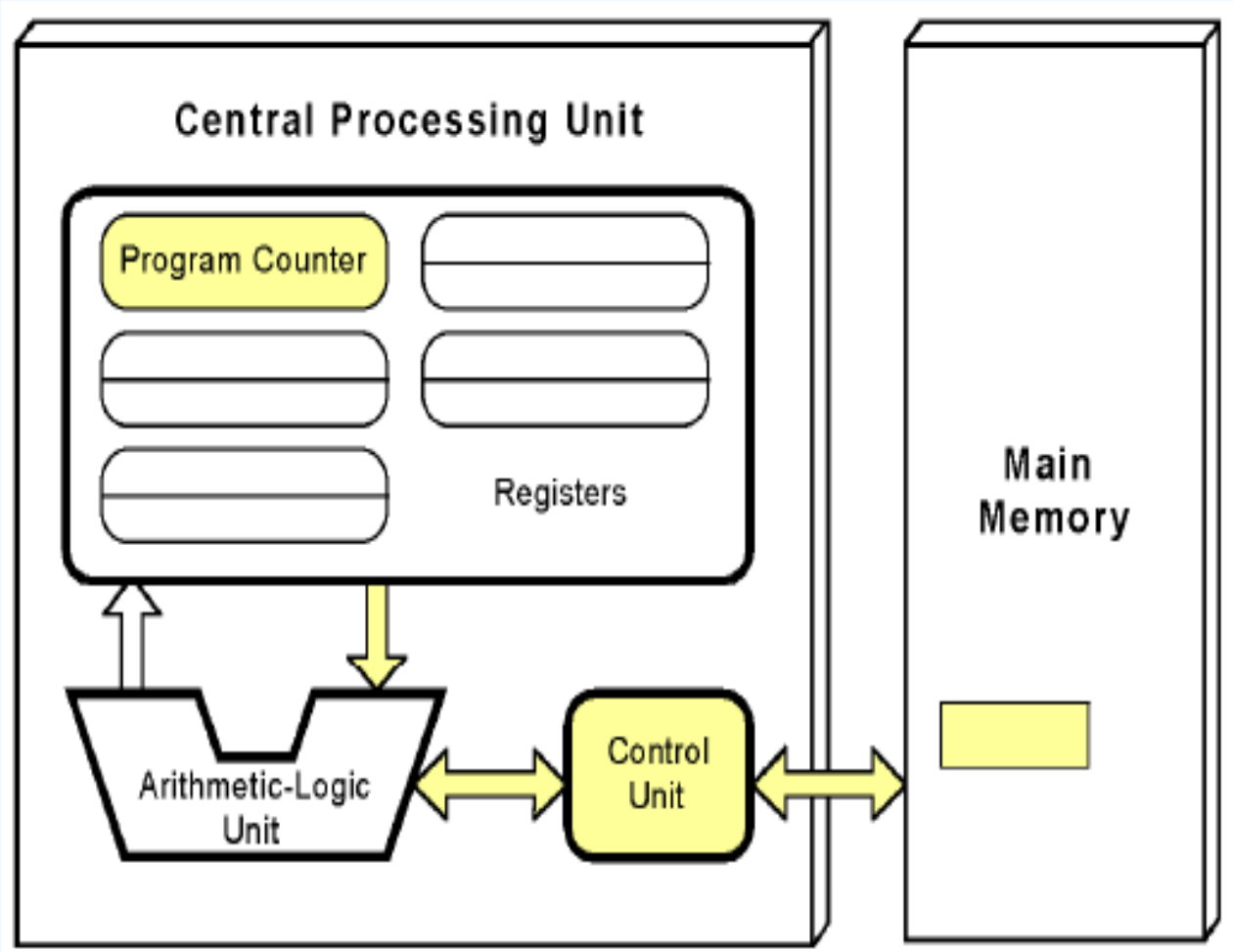
Actions Performed by Instructions



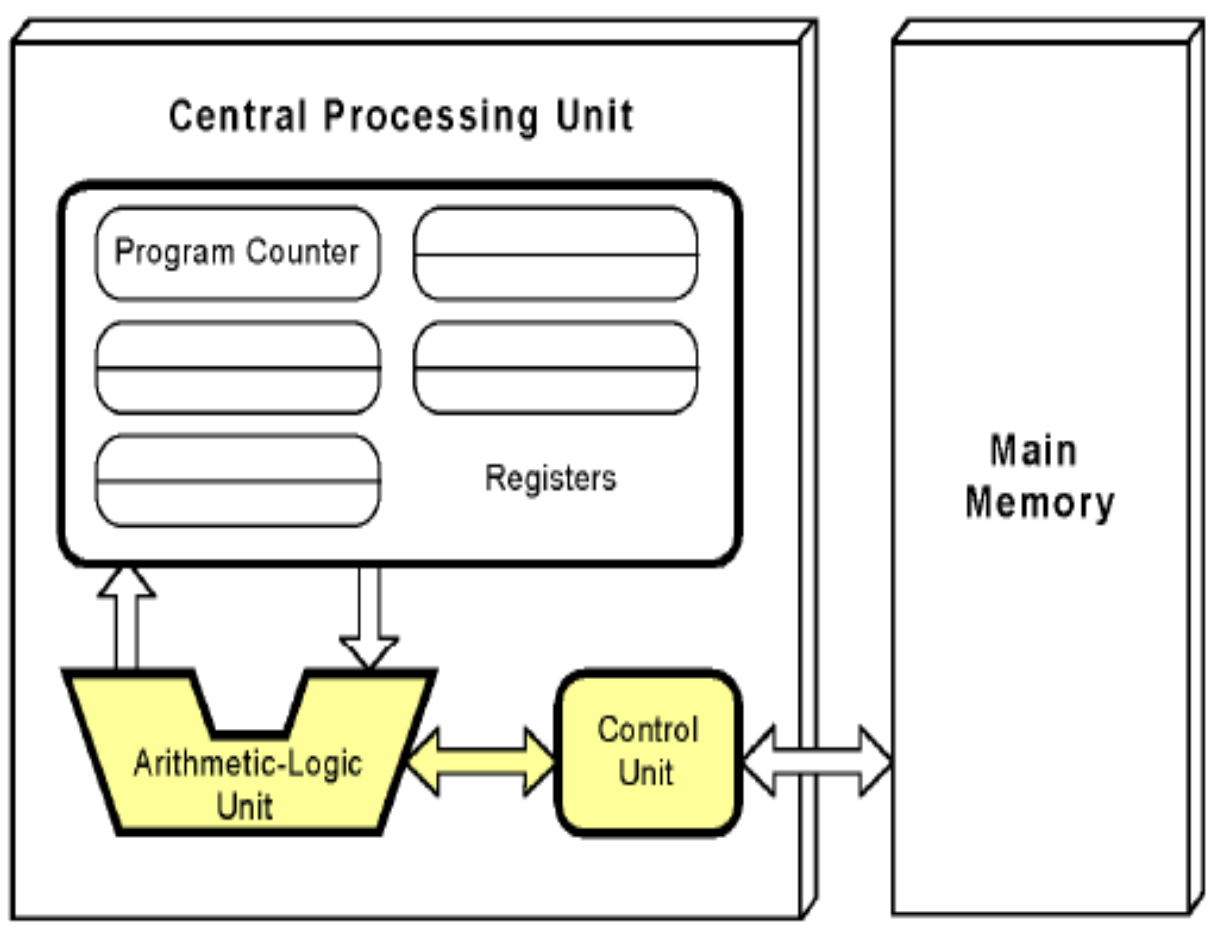
- This is a general depiction of a von Neumann system:
- These computers employ a fetch-decode-execute cycle to run programs as follows . . .



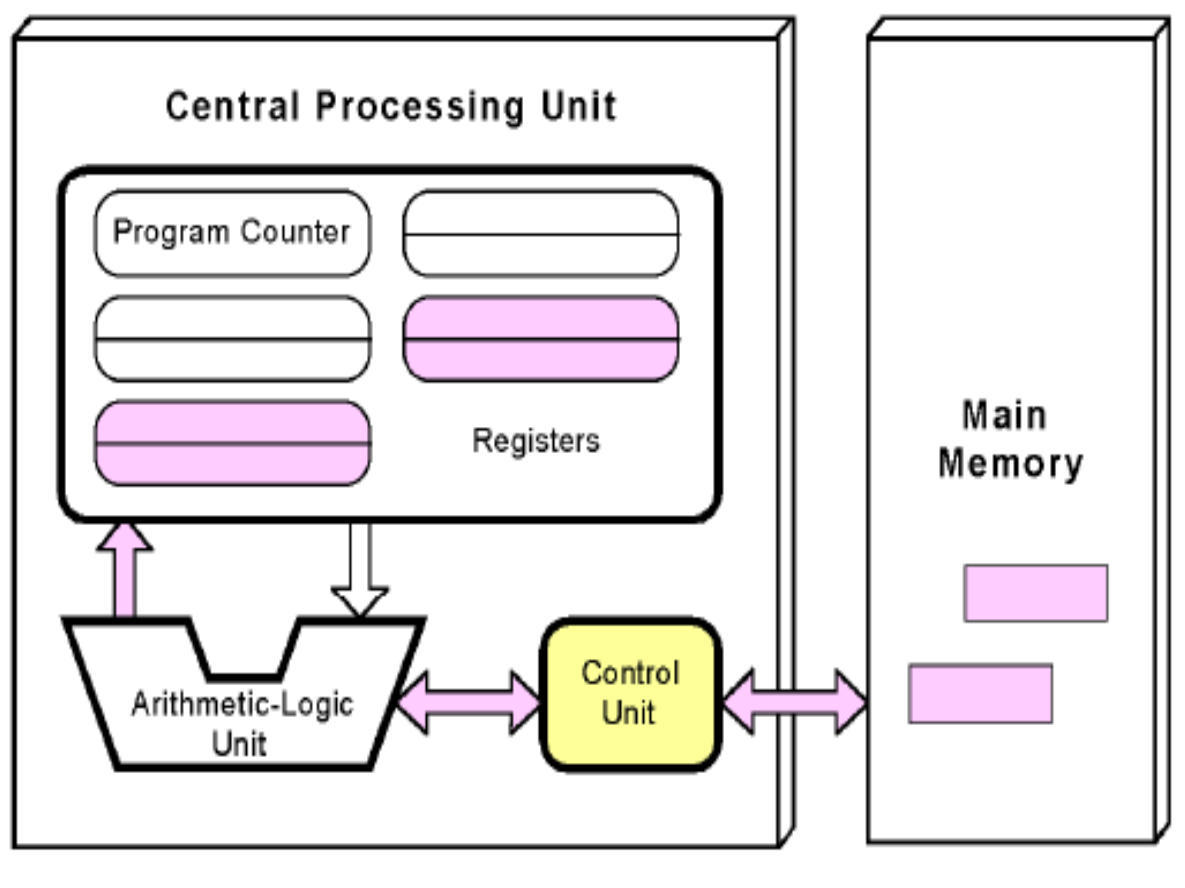
- **The control unit fetches the next instruction from memory using the program counter to determine where the instruction is located.**



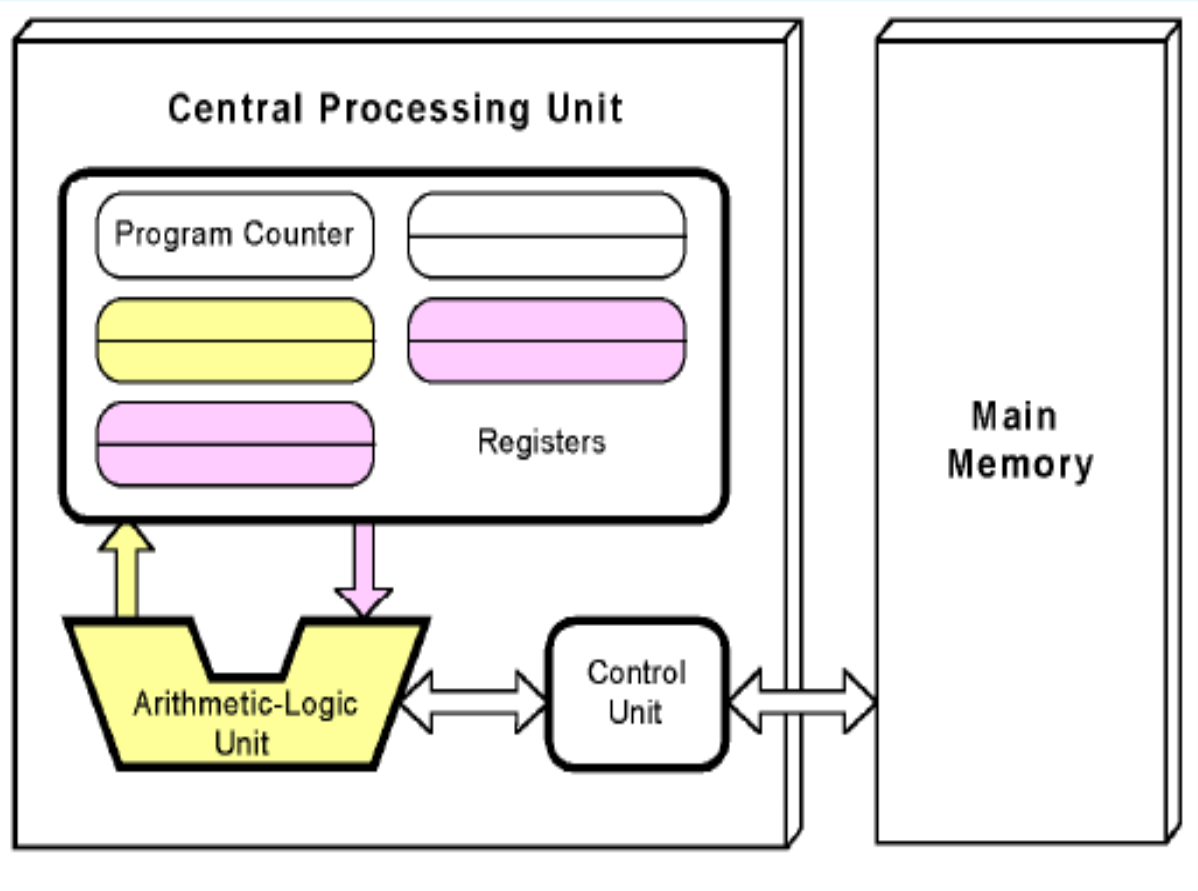
- **The instruction is decoded into a language that the ALU can understand.**

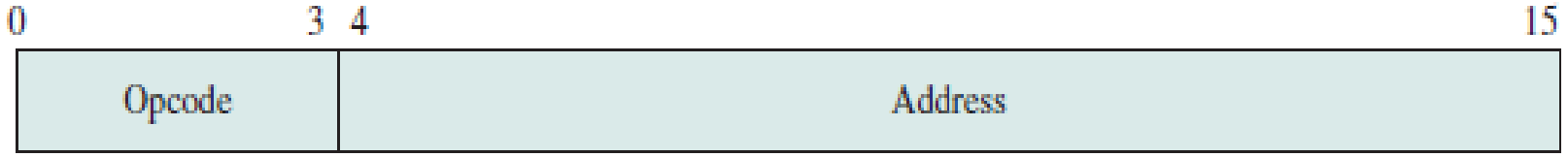


- Any data operands required to execute the instruction are fetched from memory and placed into registers within the CPU.

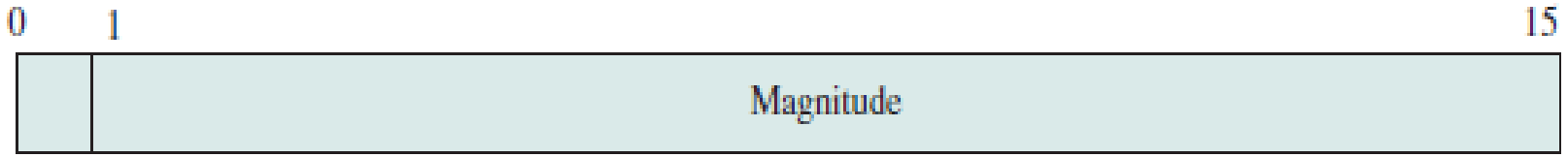


- **The ALU executes the instruction and places results in registers or memory.**





(a) Instruction format



(b) Integer format

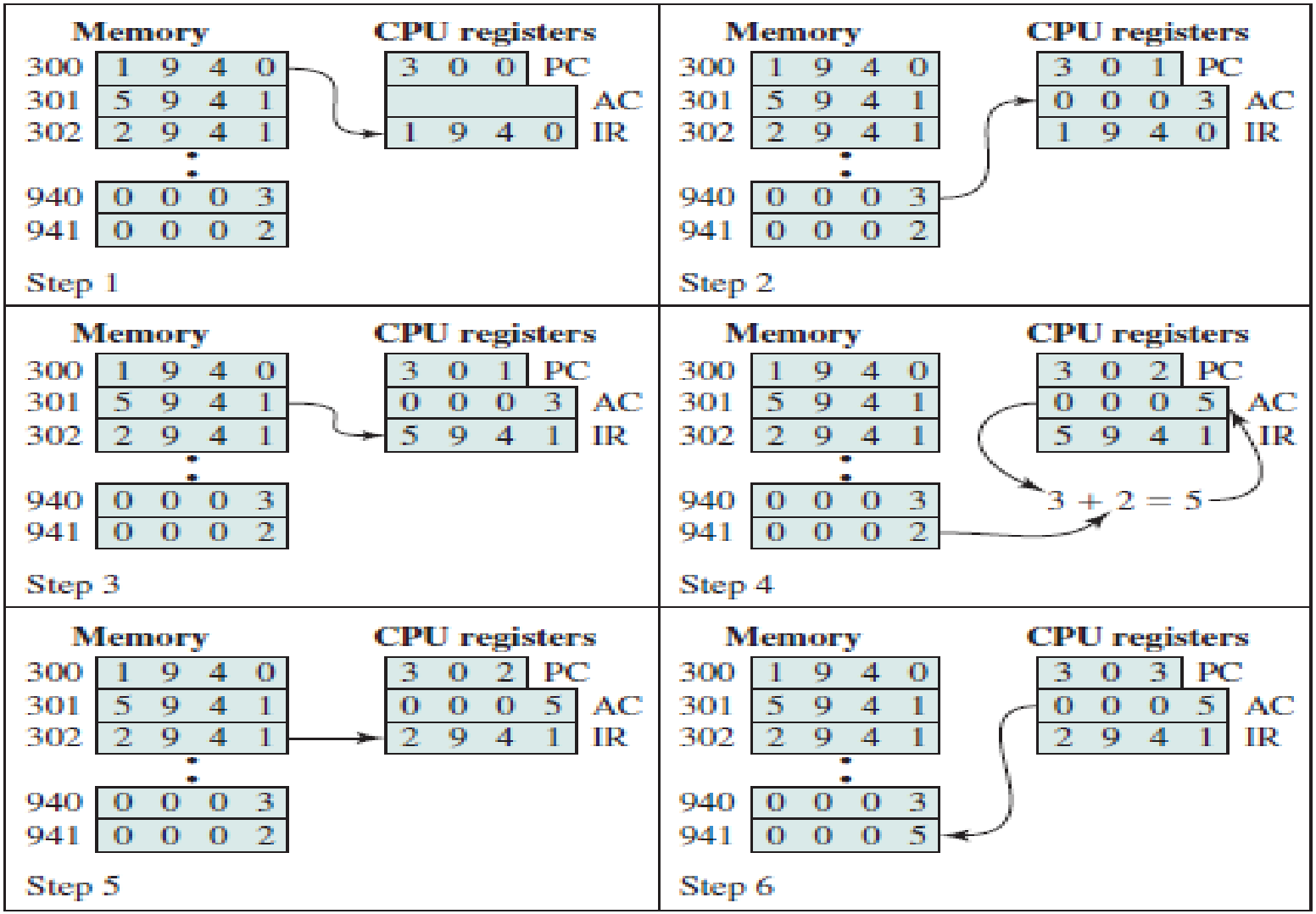
Program counter (PC) = Address of instruction
Instruction register (IR) = Instruction being executed
Accumulator (AC) = Temporary storage

(c) Internal CPU registers

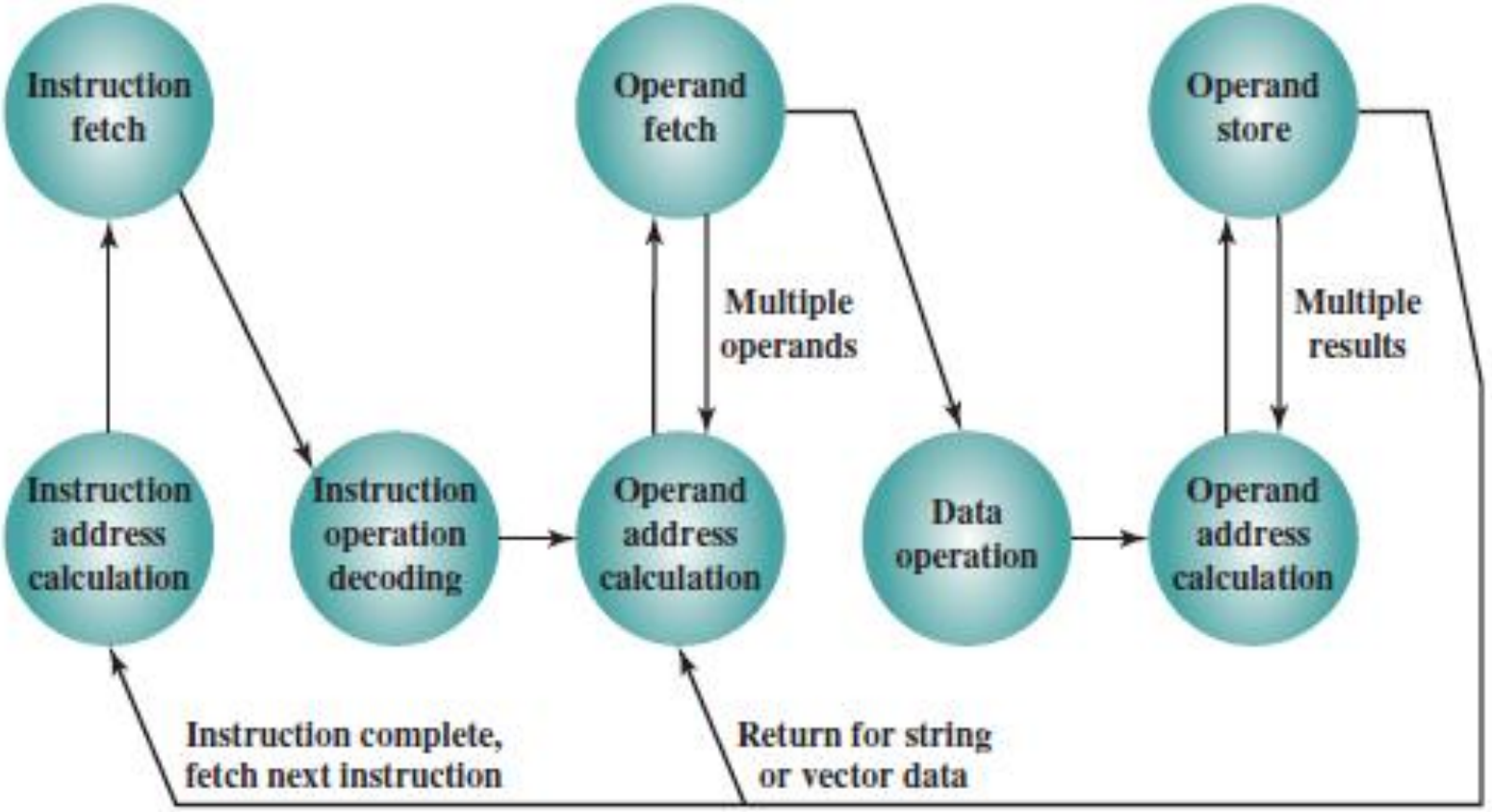
0001 = Load AC from memory
0010 = Store AC to memory
0101 = Add to AC from memory

(d) Partial list of opcodes

Example of Program Execution



Instruction Cycle State Diagram



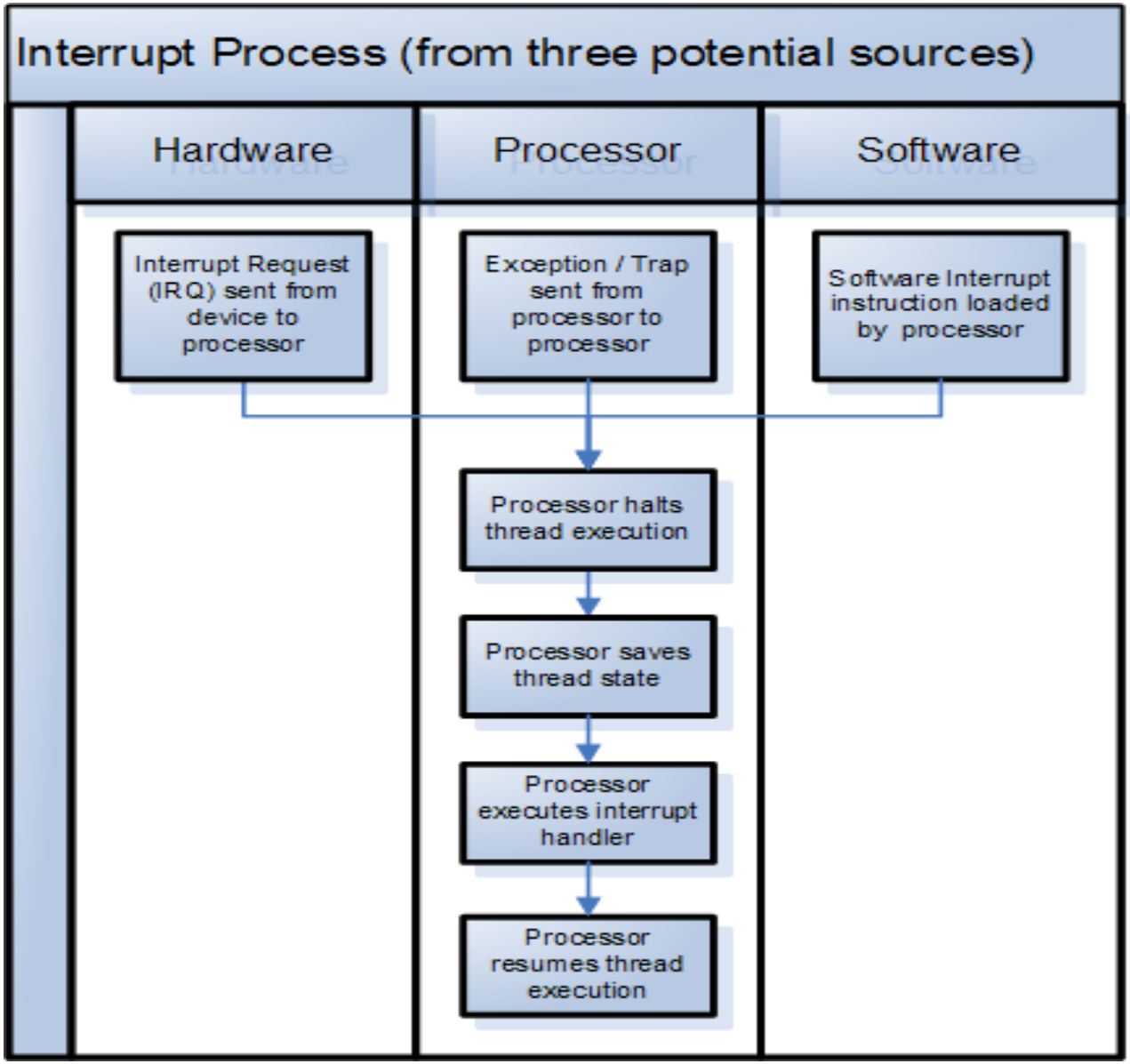
Interrupt

- In system programming, an **Interrupt** is a signal to the processor emitted by hardware or software indicating an **event that needs immediate attention.**

- Interrupt causes transfer of control to an **Interrupt service routine (ISR).** ISR is also called a **Handler**.

- When the ISR is completed, the original program resumes execution.

- Interrupts provide an efficient way to handle unanticipated events.


Interrupt Process (from three potential sources)
Hardware
Processor
Software
Interrupt Request (IRQ) sent from device to processor
Exception / Trap sent from processor to processor
Software Interrupt instruction loaded by processor
Processor halts thread execution
Processor saves thread state
Processor executes interrupt handler
Processor resumes thread execution

Interrupts Vs. Procedures

Interrupts

- Initiated by both *software* and *hardware.*
- Can handle *anticipated* and *unanticipated* internal as well as external events.
- ISRs or interrupt handlers are memory resident.
- Use numbers to identify an interrupt service.
- (E)FLAGS register is saved automatically.

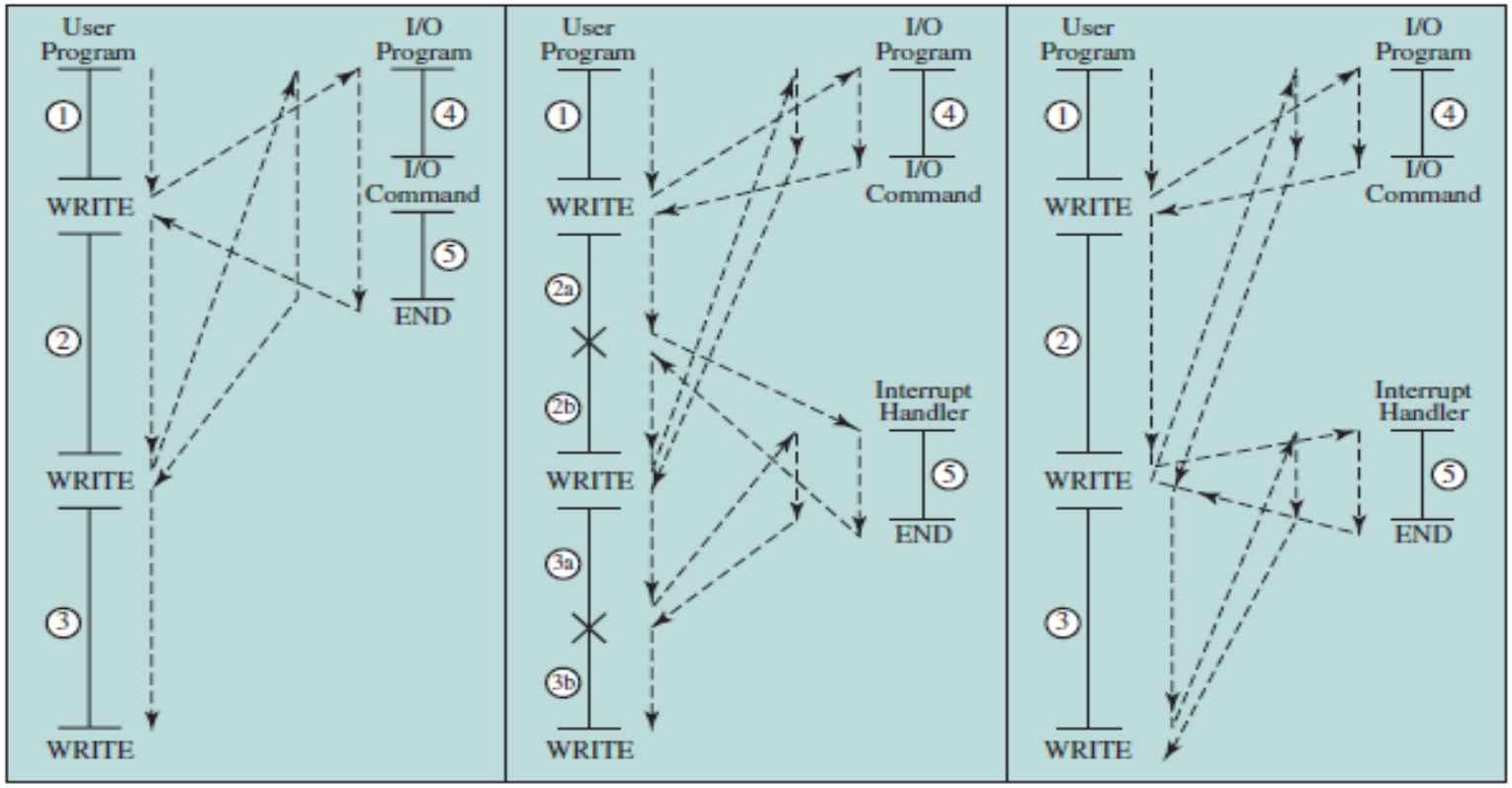
Procedures

- Can only be initiated by *software.*
- Can handle *anticipated* events that are coded into the program.
- Typically loaded along with the program.
- Use meaningful names to indicate their function.
- Do not save the (E)FLAGS register.

Classes of Interrupt

Program	Generated by some condition that occurs as a result of an instruction execution, such as arithmetic overflow, division by zero, attempt to execute an illegal machine instruction, or reference outside a user's allowed memory space.
Timer	Generated by a timer within the processor. This allows the operating system to perform certain functions on a regular basis.
I/O	Generated by an I/O controller, to signal normal completion of an operation, request service from the processor, or to signal a variety of error conditions.
Hardware failure	Generated by a failure such as power failure or memory parity error.

Program Flow of Control without and with Interrupts

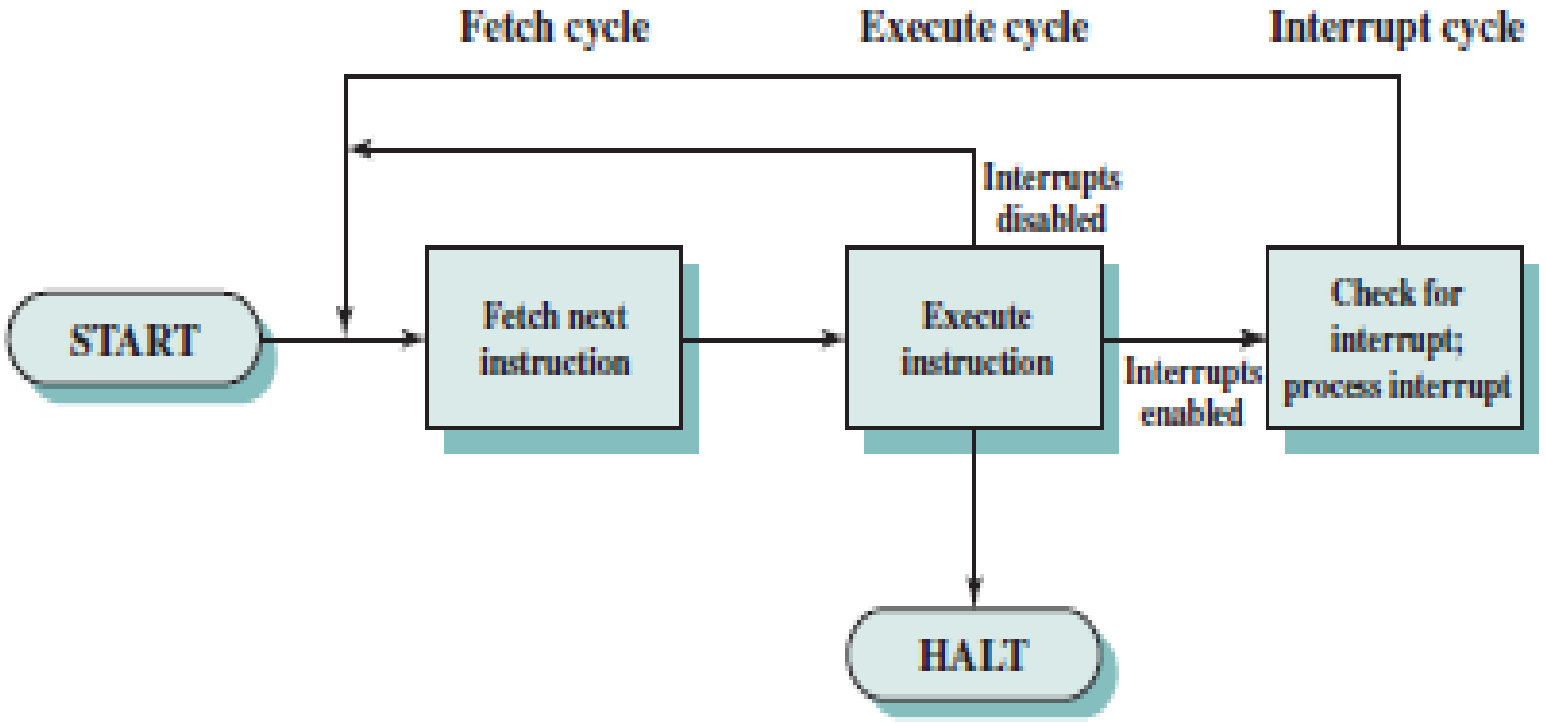


(a) No interrupts (b) Interrupts; short I/O wait (c) Interrupts; long I/O wait

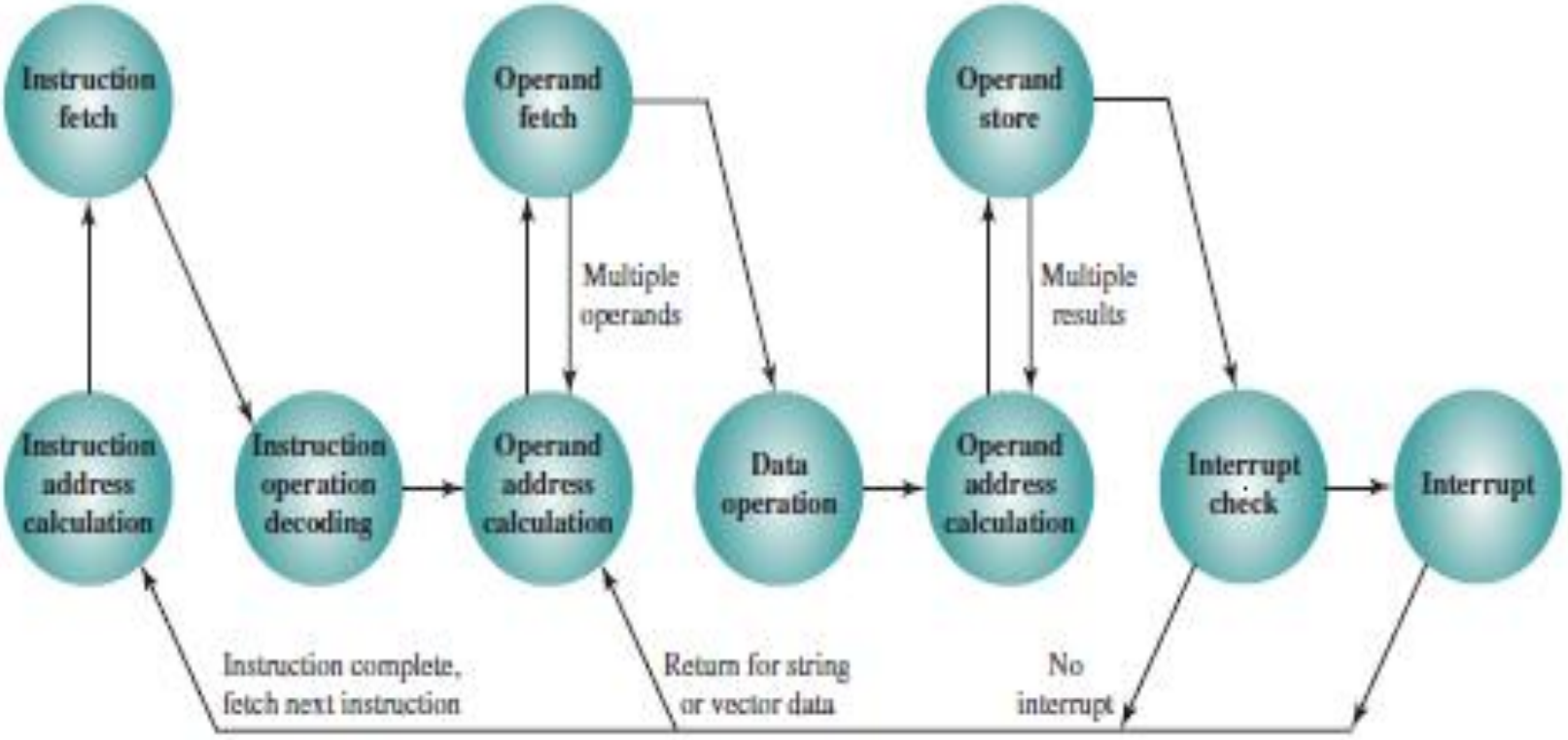
× = interrupt occurs during course of execution of user program

Figure 3.7 Program Flow of Control without and with Interrupts

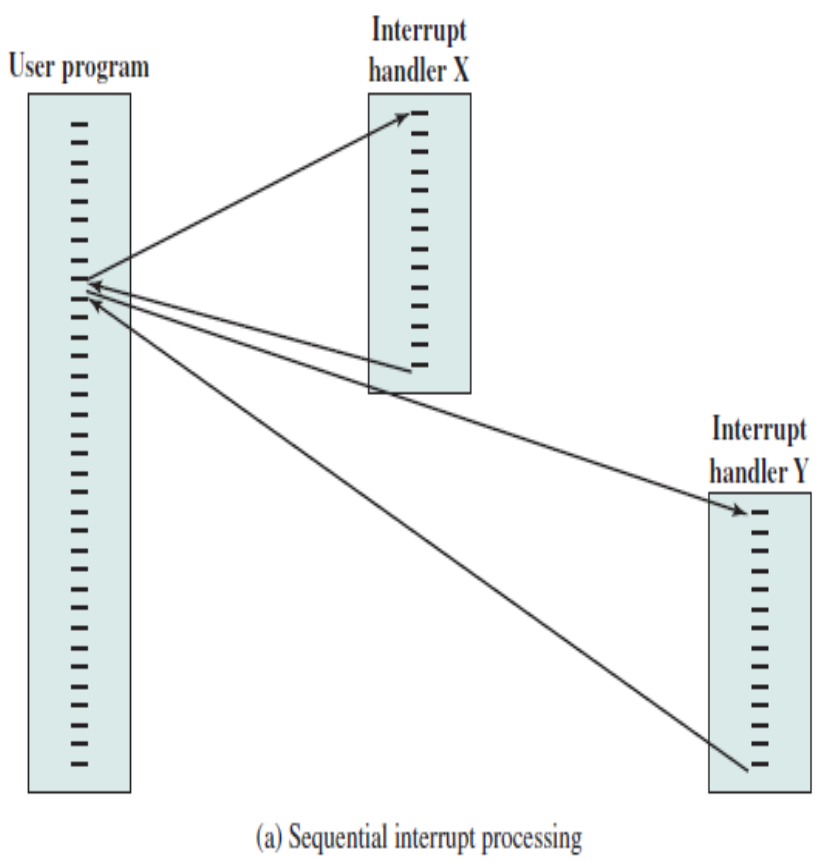
Instruction Cycle With Interrupts



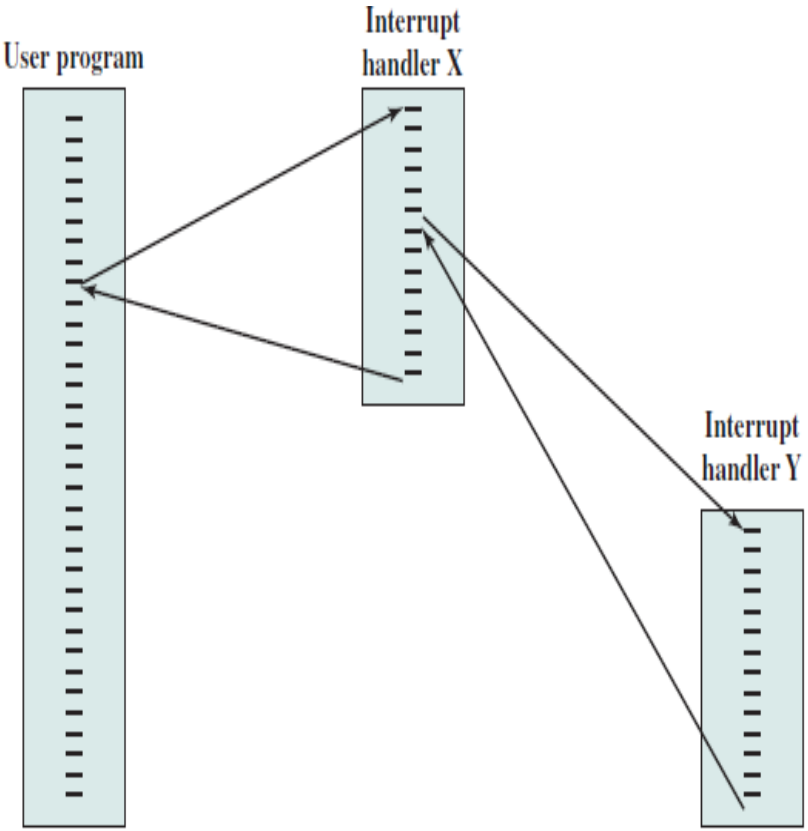
Instruction Cycle State Diagram, with Interrupts



Transfer of Control with Multiple Interrupts



(a) Sequential interrupt processing



(b) Nested interrupt processing

I/O Function

- I/O module can exchange data directly with the processor.

- Processor can read data from or write data to an I/O module.

  - Processor **identifies a specific device that is controlled by a particular I/O module.**
  - **Uses I/O instructions** rather than memory referencing instructions.

- In some cases **it is desirable to allow I/O exchanges to occur directly with memory.**
  - **The processor grants to an I/O module the authority to read from or write to memory** so that the I/O memory transfer can occur without tying up the processor.
  - **The I/O module issues read or write commands** to memory relieving the processor of responsibility for the exchange.
  - This operation is known as **Direct Memory Access (DMA).**

Interconnection Structures

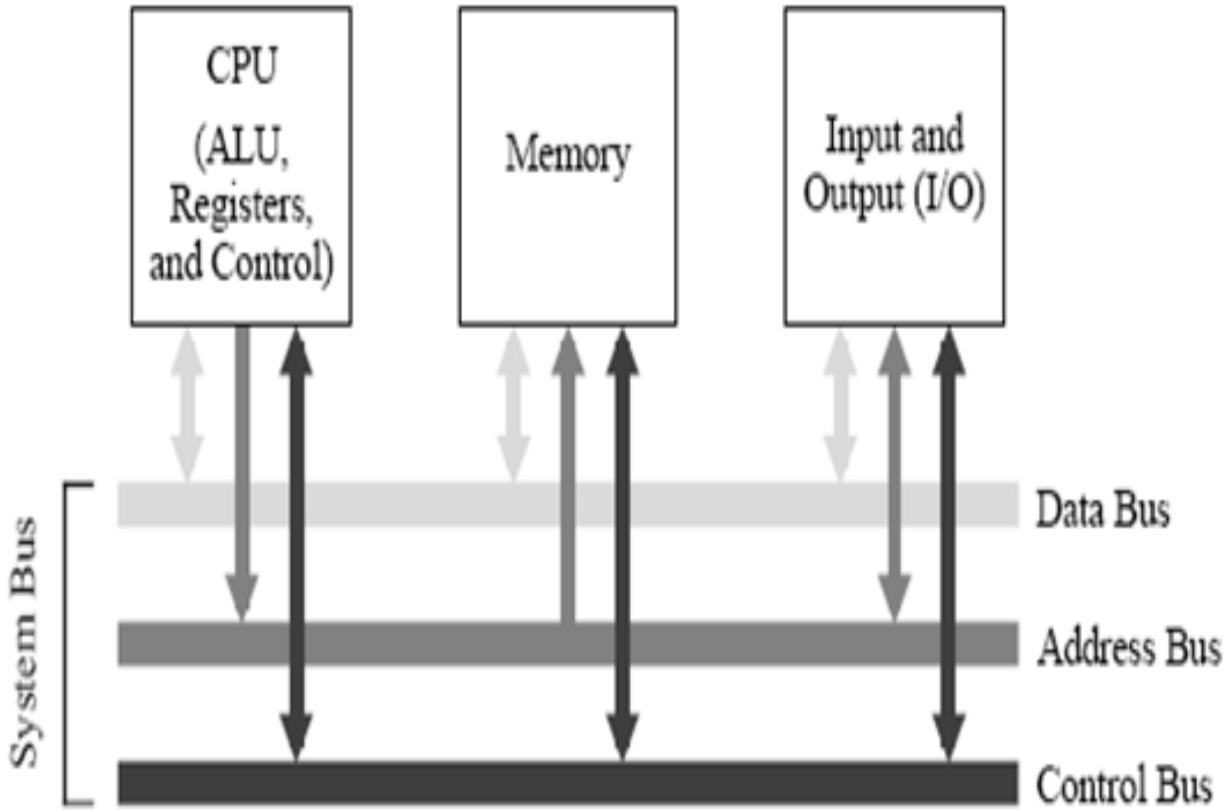
- **A computer consists of a set of components or modules** of three basic types (**CPU, Memory, I/O**) that communicate with each other.

- In effect, a computer is a network of basic modules. **Thus, there must be paths for connecting the modules**.

- The collection of paths connecting the various modules is called the **Interconnection Structure**.

- The design of this structure will depend on the exchanges that must be made among modules.

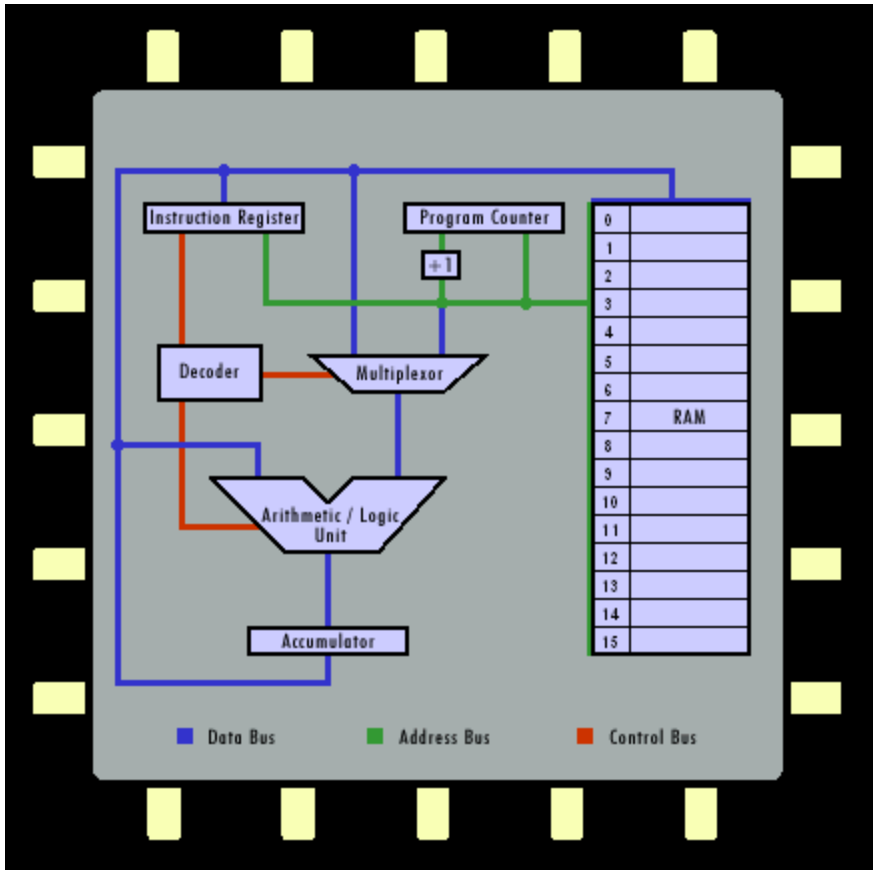
Review: Bus Concept



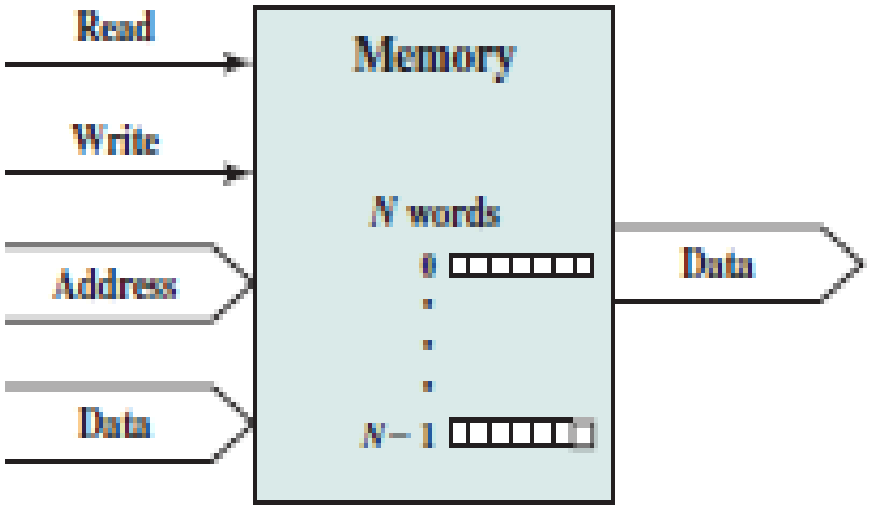
- There are normally three types of bus in any processor system:
  - **Address Bus**: this determines the location in memory that the processor will read data from or write data to.
  - **Data Bus**: this contains the contents that have been read from the memory location or are to be written into the memory location.
  - **Control Bus**: this manages the information flow between components indicating whether the operation is a read or a write and ensuring that the operation happens at the right time.

Review: CPU Building Blocks

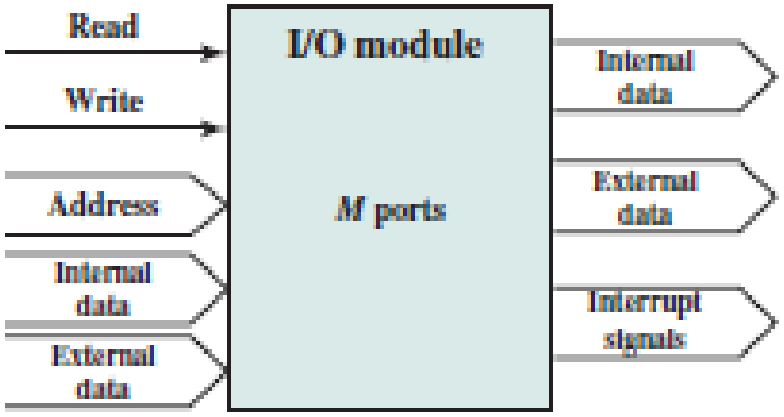
- Registers
- Control Unit (CU)
- Arithmetic Logic Unit (ALU)



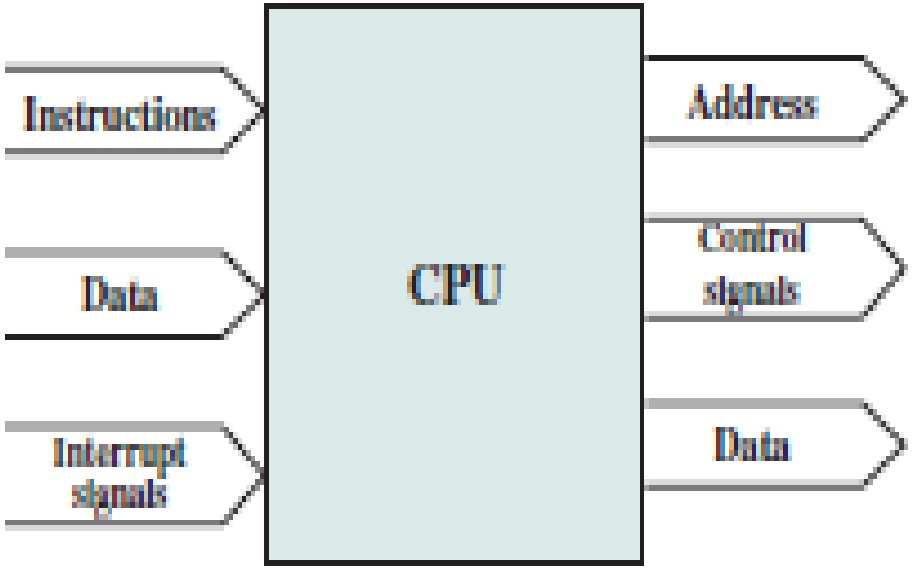
- **Memory:** Typically, a memory module will consist of *N words of equal length.* Each word is assigned a unique numerical address (0, 1, …, *N - 1). A word of* data can be read from or written into the memory. The nature of the operation.



- **I/O Modules:** From an internal (to the computer system) point of view, I/O is functionally similar to memory. There are two operations, read and write. Further, an I/O module may control more than one external device. We can refer to each of the interfaces to an external device as a *port and give each* a unique address (e.g., 0, 1, …, *M - 1). In addition, there are external data* paths for the input and output of data with an external device. Finally, an I/O module may be able to send interrupt signals to the processor.



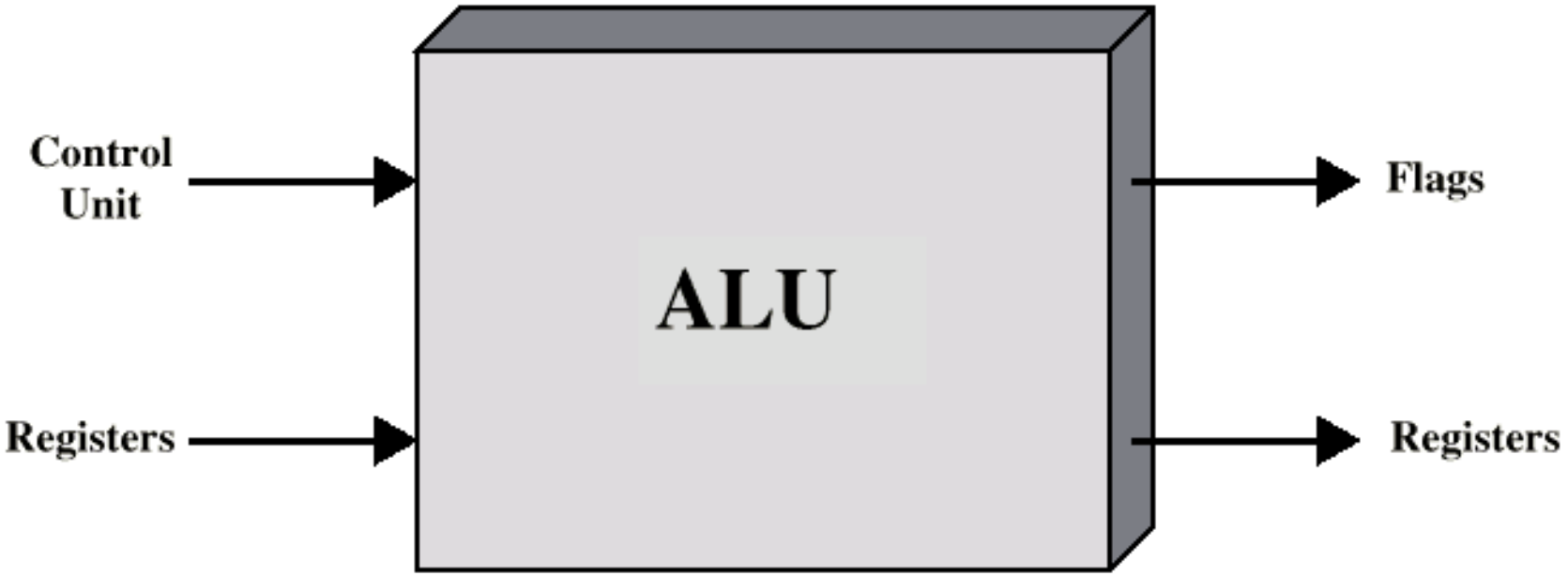
- **Processor:** The processor reads in instructions and data, writes out data after processing, and uses control signals to control the overall operation of the system. It also receives interrupt signals.



Arithmetic & Logic Unit

- Does the calculations.
- Everything else in the computer is there to service this unit.
- Handles integers.
- May handle floating point (real) numbers.
- May be separate **FPU** (math co-processor).
- May be **on chip separate FPU** (486DX +).

ALU Inputs and Outputs



Integer Representation

- Only have 0 & 1 to represent everything.
- Positive numbers stored in binary.
  - e.g. 41=00101001
- No minus sign.
- Two ways to represent negative numbers:
  - Sign Magnitude
  - Two's Complement

Sign-Magnitude

- Left most bit is sign bit.
- 0 means Positive.
- 1 means Negative.
- +18 = 00010010
- -18 = 10010010
- Problems
  - Need to consider both sign and magnitude in arithmetic.
  - Two representations of zero (+0 and -0).

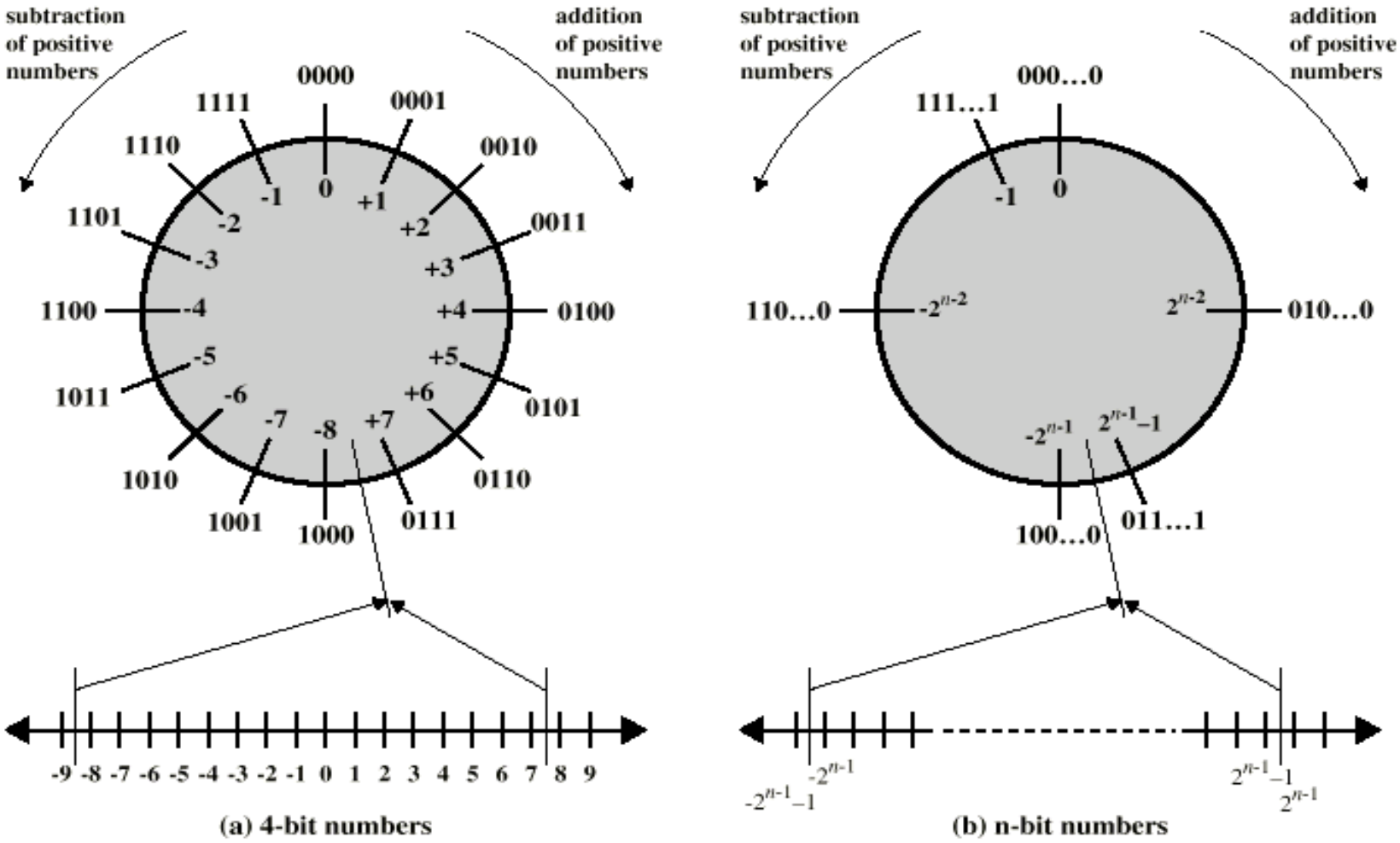
Two's Compliment

- +3 = 00000011
- +2 = 00000010
- +1 = 00000001
- +0 = 00000000
- -1 = 11111111
- -2 = 11111110
- -3 = 11111101

Benefits of 2's Complement

- One representation of zero.
- Arithmetic works easily.
- Negating is fairly easy
  - 3 = 00000011
  - Boolean complement gives 11111100
  - Add 1 to LSB 11111101

Geometric Depiction of Twos Complement Integers



Range of Numbers

- 8 bit 2s compliment
  - **+127 = 01111111 = 2^7 -1**
  - **-128 = 10000000 = -2^7**

- 16 bit 2s compliment
  - **+32767 = 011111111 11111111 = 2^{15} - 1**
  - **-32768 = 100000000 00000000 = -2^{15}**

General concept: Addition

- Decimal addition

```
(carry)  1_
          19
        + 7
        ---
          26
```

- Binary addition

```
( carry)  111_
          10011
        + 111
        -----
          11010
```

- 16+8+2 = 26

Signed and unsigned additions

- Unsigned addition in 4-bit arithmetic

```
( carry)   11_
            1011
          + 0011
          ------
            1110
```

- 11 + 3 = 14 (8 + 4 + 2)

- Signed addition in 4-bit arithmetic

```
( carry)   11_
            1011
          + 0011
          ------
            1110
```

- -8 + 6 = -2

Subtraction

```
        0010 =  2
       +1001 = −7
        1011 = −5

(a) M = 2 = 0010
    S = 7 = 0111
   −S =     1001
```

```
        0101 =  5
       +1110 = −2
       10011 =  3

(b) M = 5 = 0101
    S = 2 = 0010
   −S =     1110
```

```
        1011 = −5
       +1110 = −2
       11001 = −7

(c) M = −5 = 1011
    S =  2 = 0010
   −S =     1110
```

```
        0101 = 5
       +0010 = 2
        0111 = 7

(d) M =  5 = 0101
    S = −2 = 1110
   −S =     0010
```

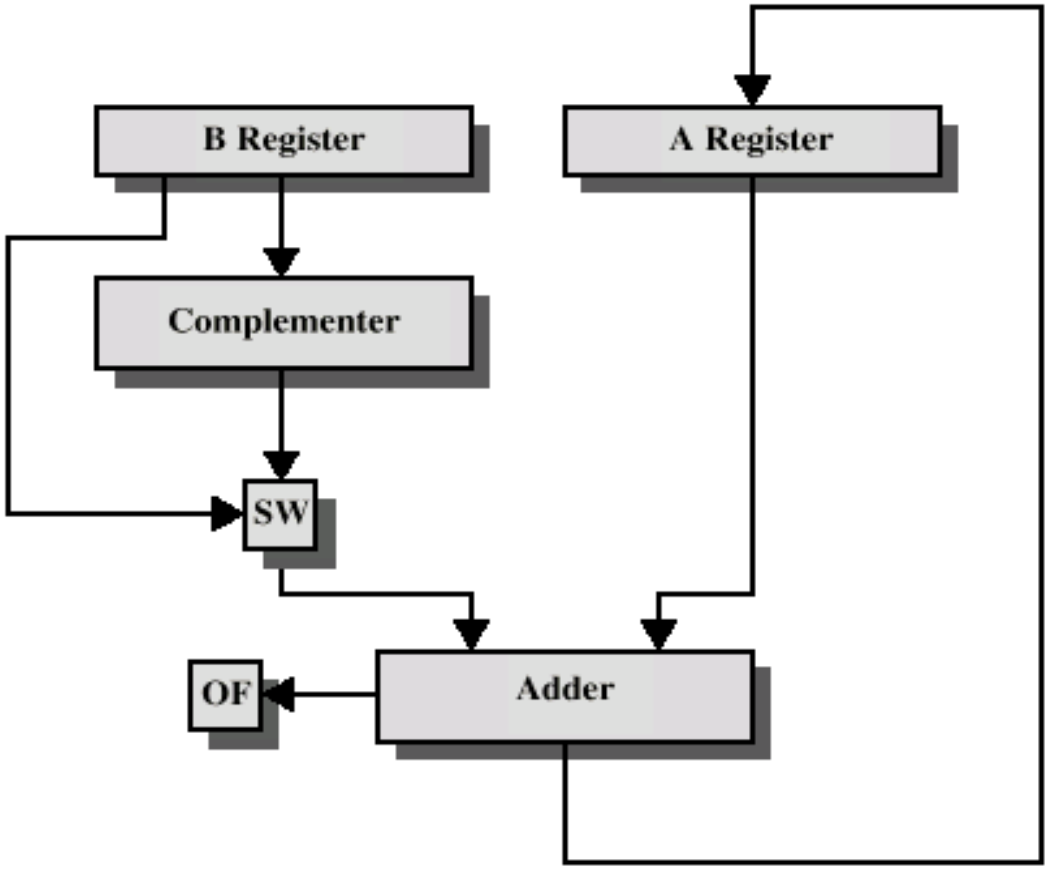
```
        0111 = 7
       +0111 = 7
        1110 = Overflow

(e) M =  7 = 0111
    S = −7 = 1001
   −S =     0111
```

```
        1010 = −6
       +1100 = −4
       10110 = Overflow

(f) M = −6 = 1010
    S =  4 = 0100
   −S =     1100
```

Hardware for Addition and Subtraction

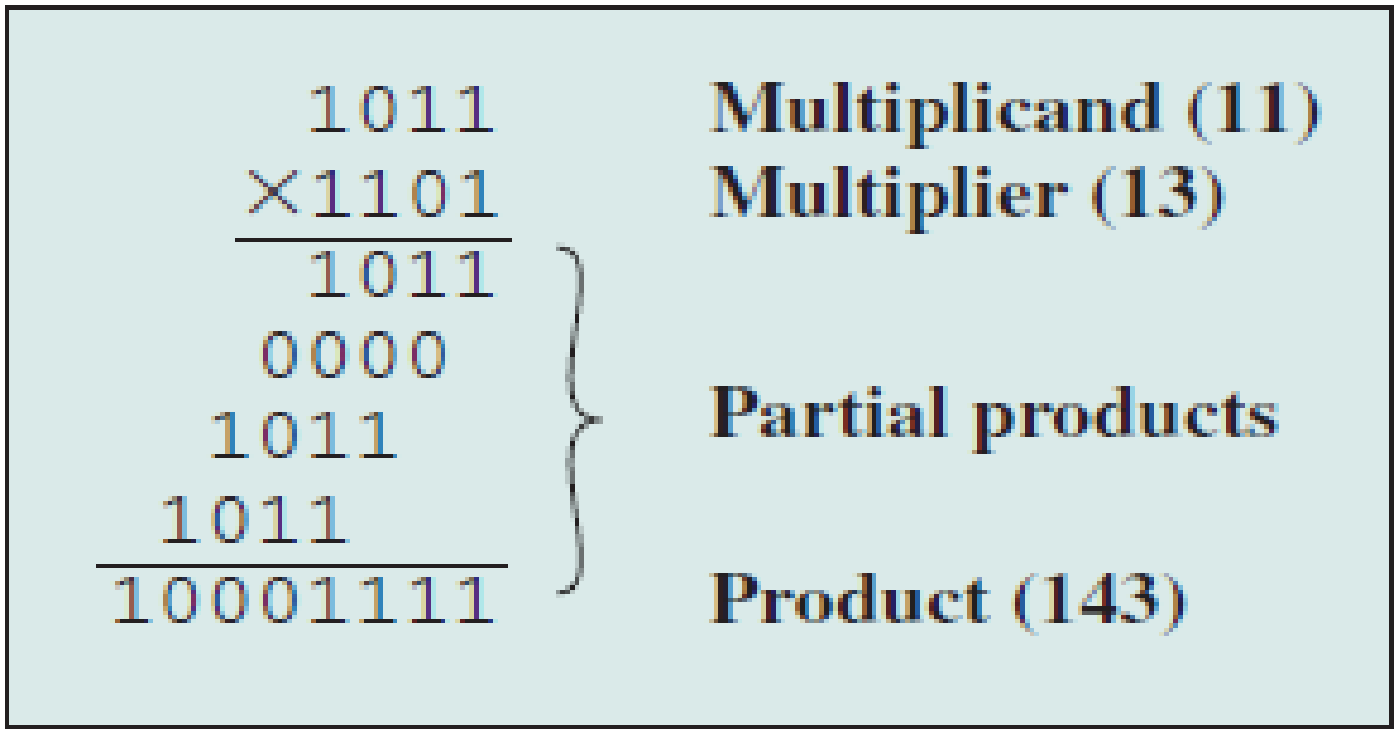


OF = overflow bit
SW = Switch (select addition or subtraction)

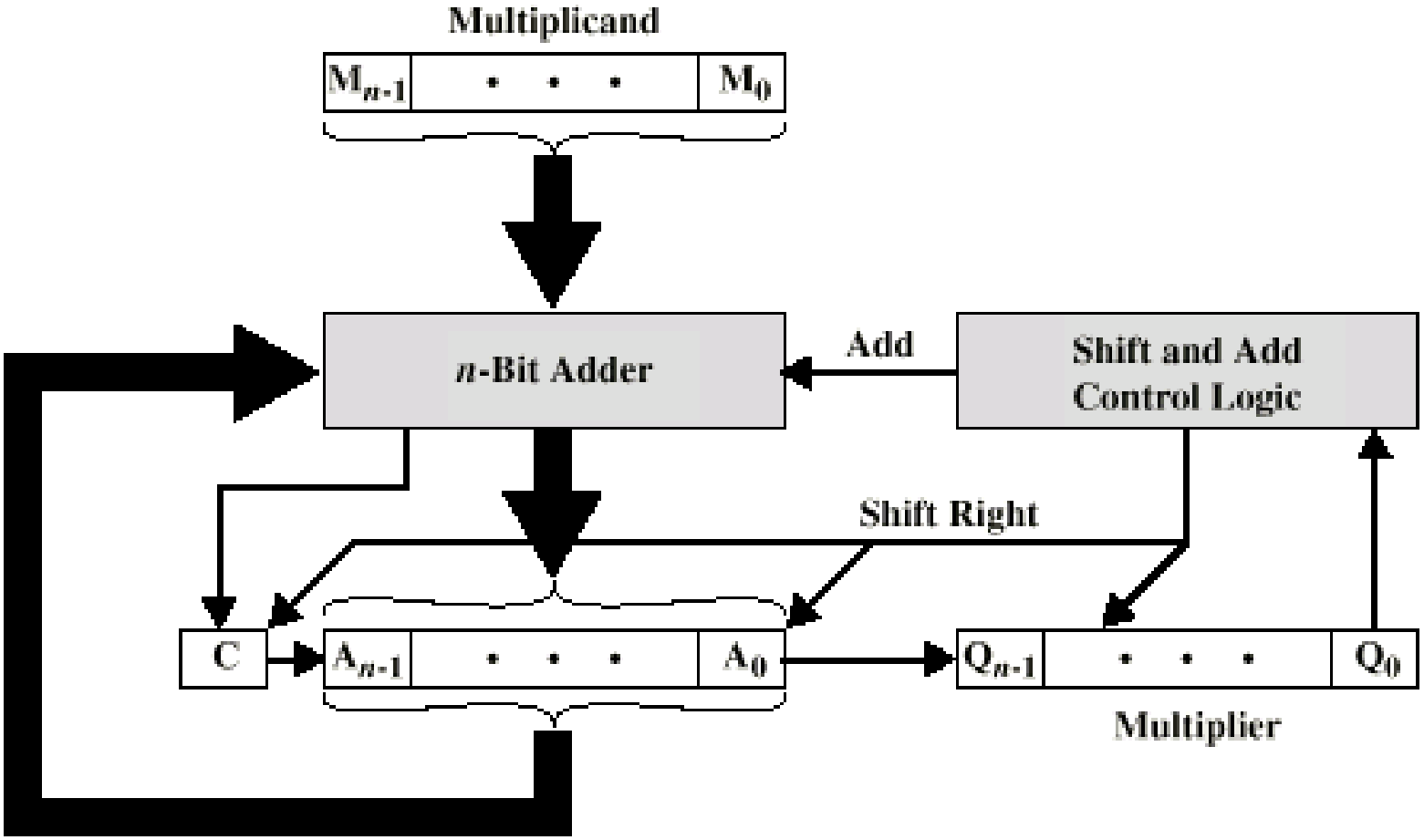
Multiplication

- Complex.
- Work out partial product for each digit.
- Take care with place value (column).
- Add partial products.

Multiplication Example

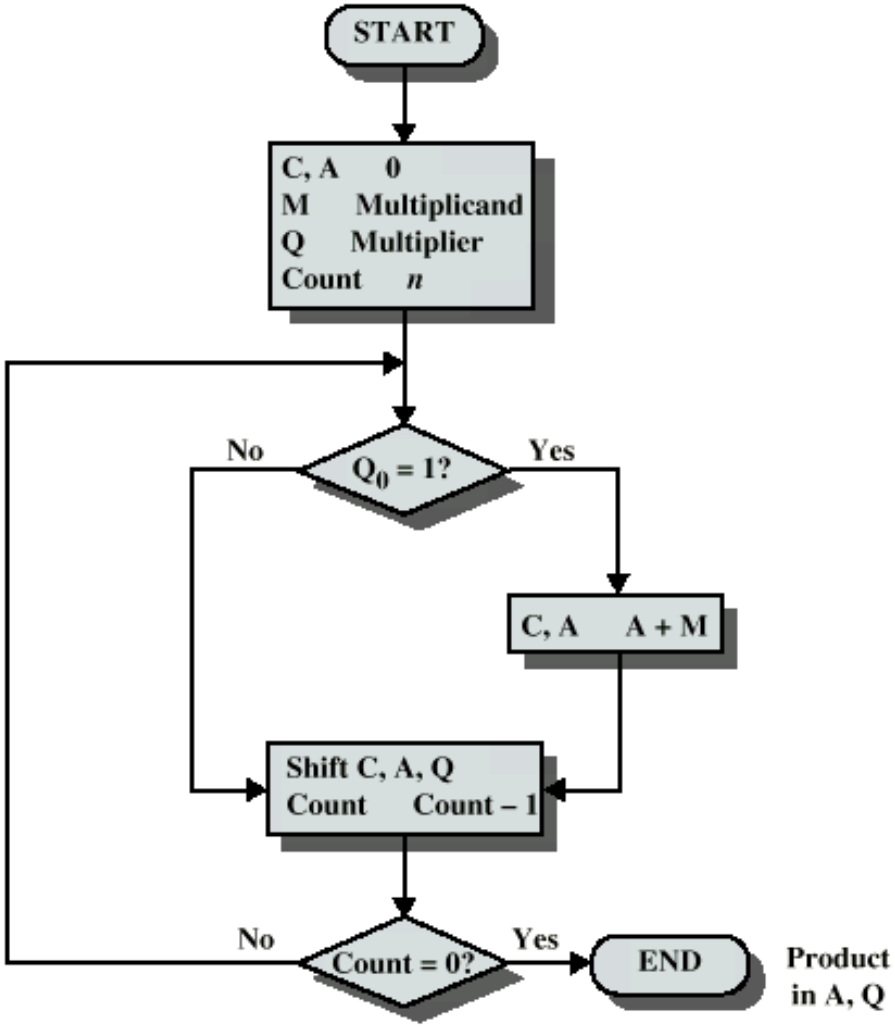


Unsigned Binary Multiplication



(a) Block Diagram

Flowchart for Unsigned Binary Multiplication



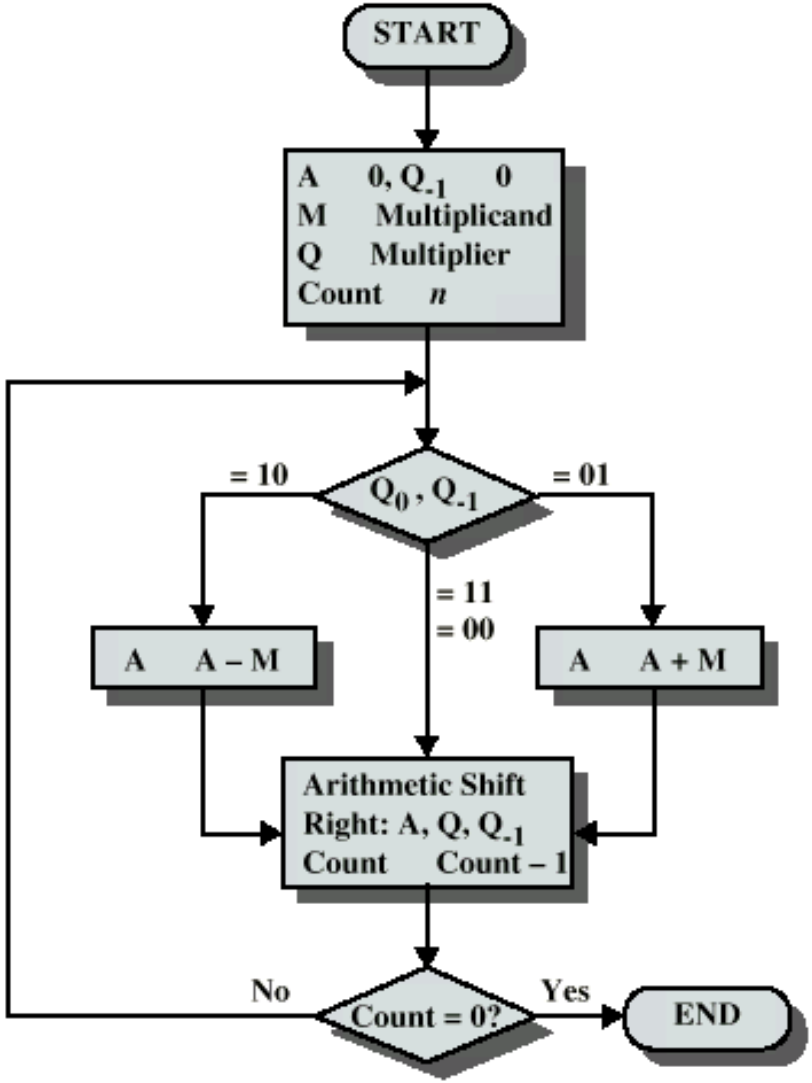
Multiplying Negative Numbers

- This does not work!

- Solution 1
  - Convert to positive if required.
  - Multiply as above.
  - If signs were different, negate answer.

- Solution 2
  - Booth's algorithm.

Booth's Algorithm



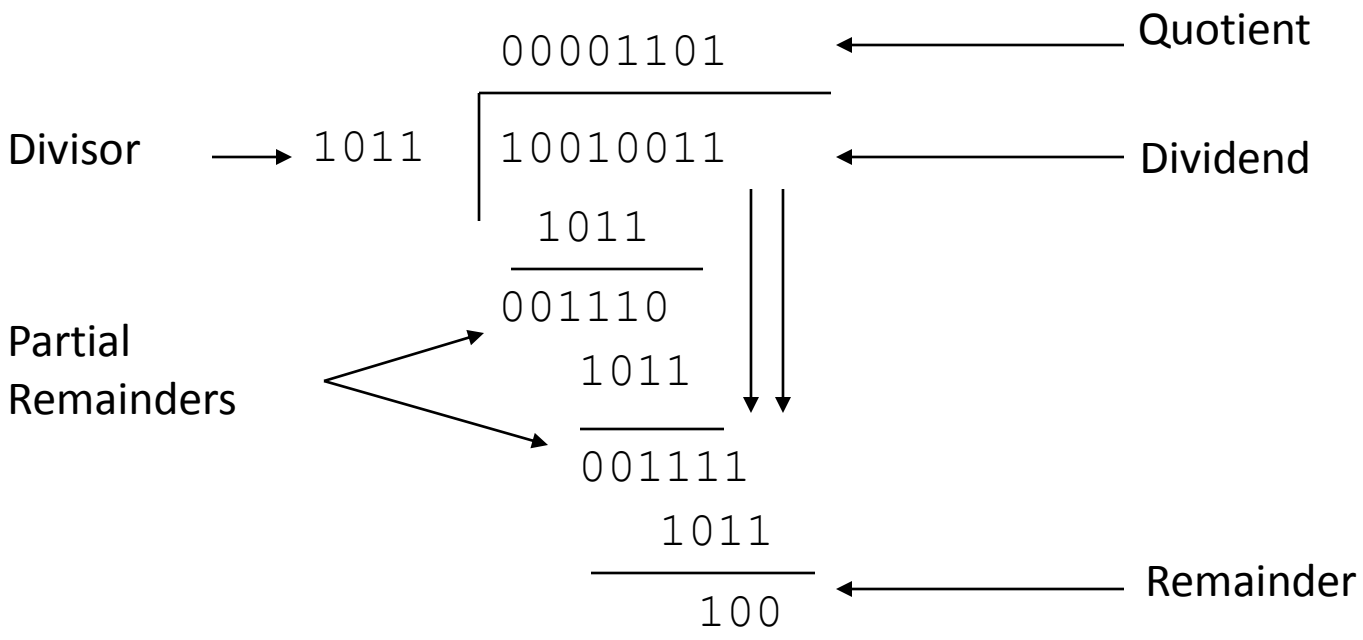
Example of Booth's Algorithm

A	Q	Q_{-1}	M		
0000	0011	0	0111	Initial Values	
1001	0011	0	0111	A A - M	First Cycle
1100	1001	1	0111	Shift	
1110	0100	1	0111	Shift	Second Cycle
0101	0100	1	0111	A A + M	Third Cycle
0010	1010	0	0111	Shift	
0001	0101	0	0111	Shift	Fourth Cycle

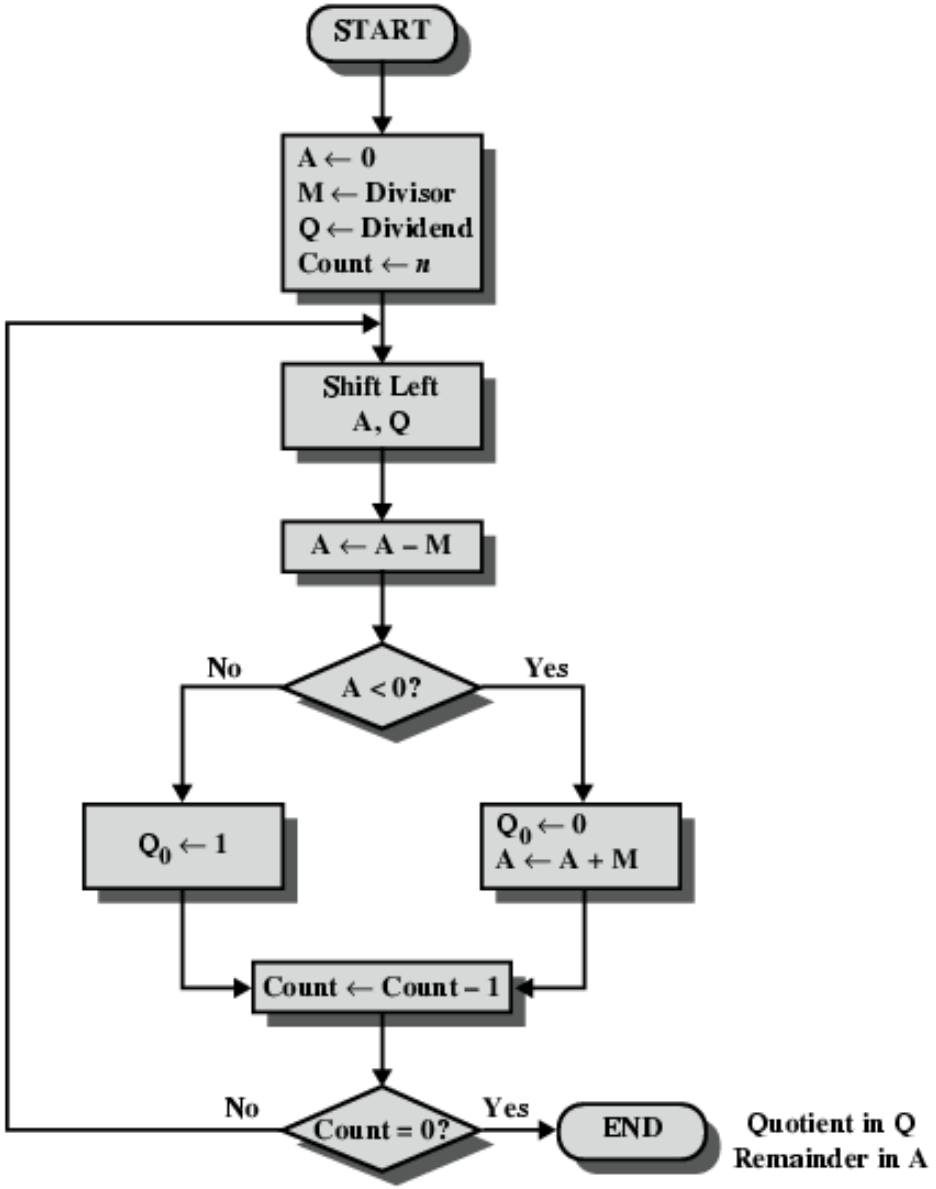
Division

- More complex than multiplication.
- Based on long division.

Division of Unsigned Binary Integers



Flowchart for Unsigned Binary Division



IEEE Standards

Two Types

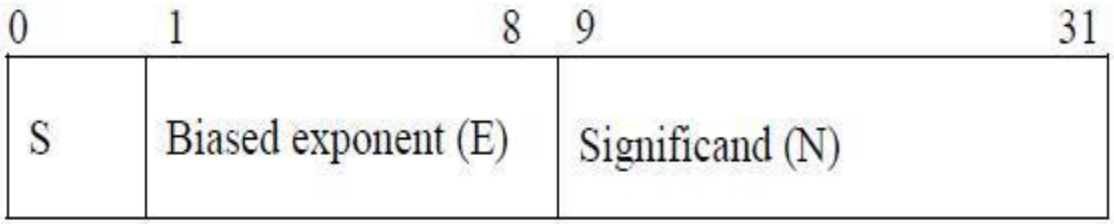
1. Single Precision (bias of 127)

2. Double Precision (bias of 1023)

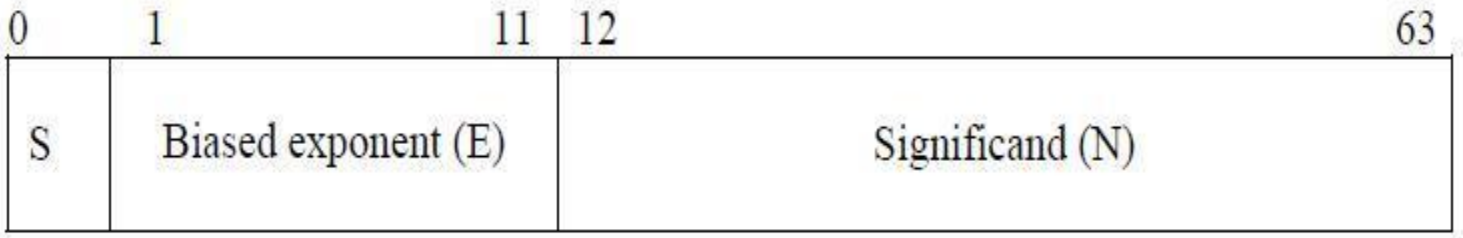
IEEE 754 Standard

- Most common standard for representing floating point numbers
- Single precision: 32 bits, consisting of...
  - Sign bit (1 bit)
  - Exponent (8 bits)
  - Mantissa (23 bits)
- Double precision: 64 bits, consisting of…
  - Sign bit (1 bit)
  - Exponent (11 bits)
  - Mantissa (52 bits)

Single Precision & Double Precision



Single Precision = 32 bits



Double Precision = 64 bits

IEEE Standard 754 format

Guard Bits

- We mentioned that, prior to a floating-point operation, the **exponent and significand of each operand are loaded into ALU registers.**

- **In the case of the significand, the length of the register is almost always greater** than the length of the significand plus an implied bit.

- **The register contains additional bits, called guard bits,** which are used to pad out the right end of the significand with 0s.

Rounding

- The result of any operation on the significands is generally stored in a longer register.

- When the result is put back into the floating-point format, the extra bits must be eliminated in such a way as to produce a result that is close to the exact result. This process is called **rounding.**

- **Round to nearest:** The result is rounded to the nearest representable number.
- **Round toward + Infinity:** The result is rounded up toward plus infinity.
- **Round toward - Infinity:** The result is rounded down toward negative infinity.
- **Round toward 0:** The result is rounded toward zero.