

CHAPTER 4

MARIE: An Introduction to a Simple Computer

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4.1 Introduction 195

- In this chapter, we first look at a very simple computer called MARIE: A **M**achine **A**rchitecture that is **R**eally **I**ntuitive and **E**asy.
- We then provide brief overviews of **Intel** and **MIPS** machines, two popular architectures reflecting the **CISC** (Complex Instruction Set Computer) and **RISC** (Reduced Instruction Set Computer) design philosophies.
- The objective of this chapter is to give you an understanding of how a computer functions.

4.2 CPU Basics and Organization 195

- The Central processing unit (CPU) is responsible for **fetching** program instructions, **decoding** each instruction that is fetched, and **executing** the indicated sequence of operations on the correct data.
- All computers have a CPU that can be divide into two pieces: **datapath** and the **control unit**.
- The datapath consists of an arithmetic-logic unit (**ALU**) and storage units (**registers**) that are interconnected by a data bus that is also connected to main memory. Check page 29 **Figure 1.4**.
- Various CPU components perform sequenced operations according to **signals** provided by its control unit.

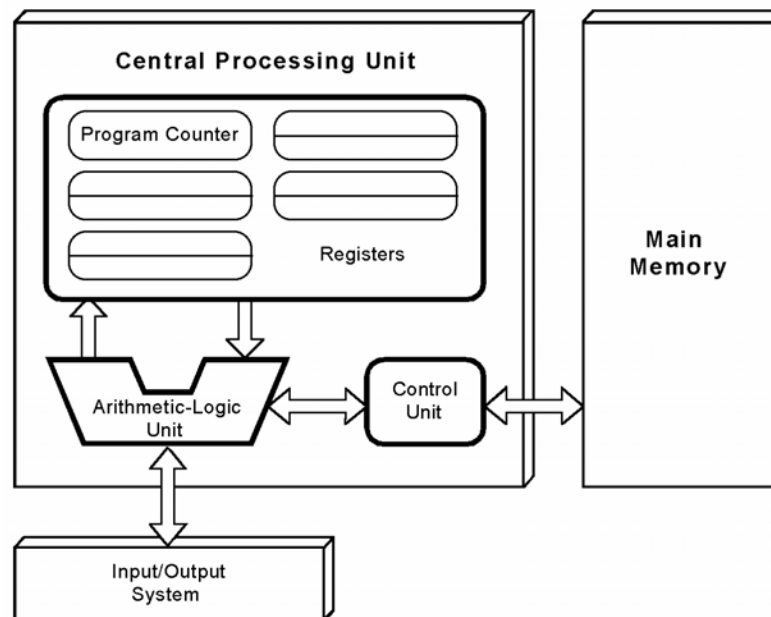


FIGURE 1.4 The von Neumann Architecture

4.2.1 The Registers 196

- Registers hold data that can be readily accessed by the CPU.
- They can be implemented using **D** flip-flops. A 32-bit register requires 32 D flip-flops.

4.2.2 The ALU 197

- The arithmetic-logic unit (ALU) carries out logical operations (such as comparisons) and arithmetic operations (such as add or multiply) directed by the control unit.

4.2.3 The Control Unit 197

- The control unit determines which actions to carry out according to the values in a program counter register and a status register.

4.3 The Bus 197

- The CPU **shares** data with other system components by way of a data bus.
- A bus is **a set of** wires that simultaneously convey a single bit along each line.
- Two types of buses are commonly found in computer systems: **point-to-point**, and **multipoint buses**.

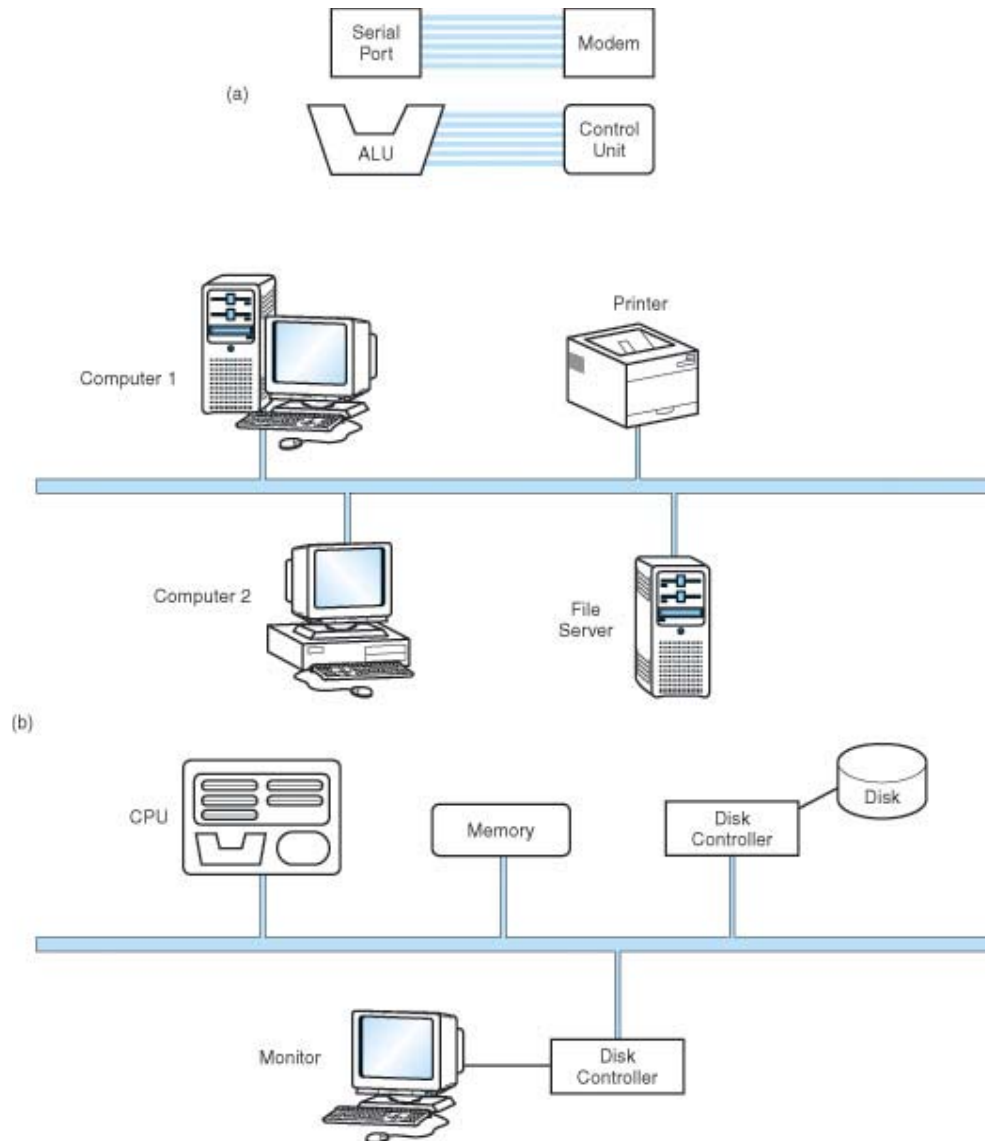


FIGURE 4.1 (a) Point-to-Point Buses; (b) Multipoint Buses

- At any one time, **only one** device (be it a register, the ALU, memory, or some other component) may use the bus.
- However, the sharing often results in a communications bottleneck.
- Master device is one that **initiates** actions and a slave **responds** to requests by a master.

- Buses consist of **data** lines, **control** lines, and **address** lines.
- While the data lines convey bits from one device to another, **control lines** determine the **direction** of data flow, and **when** each device can access the bus.
- Address lines determine the location of the source or destination of the data.

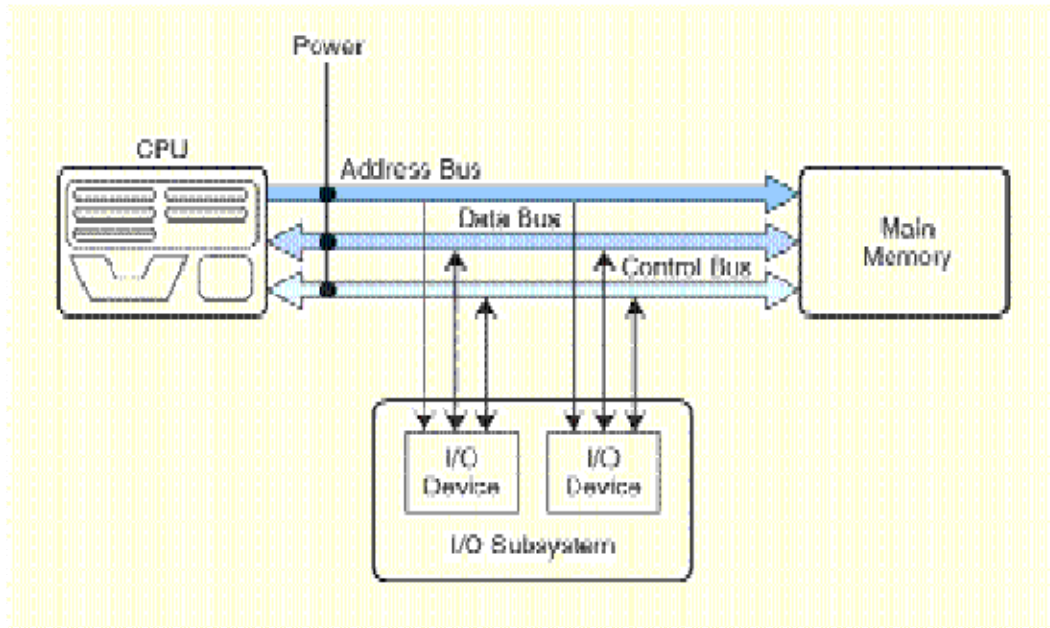


FIGURE 4.2 The Components of a Typical Bus

- In a master-slave configuration, where more than one device can be the bus master, concurrent bus master requests must be arbitrated.
- Four categories of bus arbitration are:
 - Daisy chain arbitration: Permissions are passed from the highest **priority** device to the lowest.
 - Centralized parallel arbitration: Each device is directly connected to an arbitration circuit, and a **centralized arbiter** selects who gets the bus.
 - Distributed arbitration using self-detection: Devices decide which gets the bus among **themselves**.
 - Distributed arbitration using collision-detection: Any device can try to use the bus. If its data **collides** with the data of another device, the device tries again (**Ethernet** uses this type arbitration).

4.4 Clocks 201

- Every computer contains at least one clock that synchronizes the activities of its components.
- A fixed number of clock cycles are required to carry out each data movement or computational operation.
- The clock frequency, measured in megahertz or gigahertz, determines the speed with which all operations are carried out.
- Clock cycle time is the reciprocal of clock frequency.
 - An 800 MHz clock has a cycle time of 1.25 ns.
- The **minimum** clock cycle time must be at least as great as the **maximum** propagation delay of the circuit.
- The CPU time required to run a program is given by the general performance equation:

$$\text{CPU Time} = \frac{\text{seconds}}{\text{program}} = \frac{\text{instructions}}{\text{program}} \times \frac{\text{avg. cycles}}{\text{instruction}} \times \frac{\text{seconds}}{\text{cycle}}$$

- We see that we can improve CPU throughput when we reduce the number of instructions in a program, reduce the number of cycles per instruction, or reduce the number of nanoseconds per clock cycle.
- In general, multiplication requires more time than addition, floating point operations require more cycles than integer ones, and accessing memory takes longer than accessing registers.
- Bus clocks are usually slower than CPU clocks, causing bottleneck problems.

4.5 The Input/Output Subsystem 203

- I/O devices allow us to communicate with the computer system. A computer communicates with the outside world through its input/output (I/O) subsystem.
- I/O is the transfer of data between **primary memory** and various I/O peripherals.
- I/O devices are **not** connected directly to the CPU. I/O devices connect to the CPU through various **interfaces**.
- The CPU communicates to these external devices via **input/output registers**.
- This exchange of data is performed in two ways:
 - In **memory-mapped I/O**, the registers in the interface appear in the computer's **memory** and there is no real difference accessing memory and accessing an I/O device. It **uses up** memory space in the system.
 - With **instruction-based I/O**, the CPU has specialized instructions that input and output. Although this does **not use** memory space, it requires specific I/O instructions.
- **Interrupts** play a very important part in I/O, because they are an efficient way to notify CPU that input or output is available for use.

4.6 Memory Organization and Addressing 204

- You can envision memory as a matrix of **bits**.
- Each row, implemented by a register, has a length typically equivalent to the word size of machine.
- Each register (more commonly referred to as a memory location) has a **unique** address; memory addresses usually start at zero and progress upward.

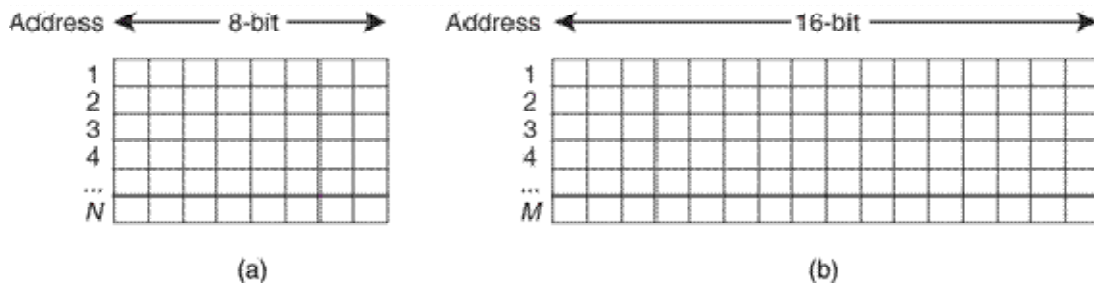


FIGURE 4.4 (a) N 8-Bit Memory Locations; (b) M 16-Bit Memory Locations

- Normally, memory is **byte-addressable**, which means that each individual byte has a **unique** address.
- For example, a computer might handle 32-bit word, but still employ a byte-addressable architecture. In this situation, when a word uses multiple bytes, the byte with the **lowest** address determines the address of the entire word.
- It is also possible that a computer might be **word-addressable**, which means each word has its own address, but most current machines are byte-addressable.
- If architecture is byte-addressable, and the instruction set architecture word is larger than 1 byte, the issue of **alignment** must be addressed.
- Memory is built from random access memory (RAM) chips. Memory is often referred to using the notation L X W (length X Length). For example,
 - 4M X 16 means the memory is 4M long ($4M = 2^2 \times 2^{20} = 2^{22}$ words) and it is 16 bits wide (each word is 16 bits).
 - To address this memory (assuming word addressing), we need to be able to uniquely identify 2^{22} different items.
 - The memory locations for this memory are numbered 0 through $2^{22} - 1$.
 - The memory bus of this system requires at least 22 address lines.
- In general, if a computer 2^n addressable units of memory, it will require N bits to uniquely address each byte.

- Physical memory usually consists of more than one RAM chip.

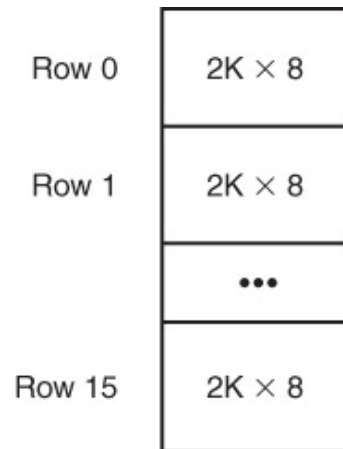


FIGURE 4.5 Memory as a Collection of RAM Chips (32K X 8)

- Access is more efficient when memory is organized into banks of chips with the addresses interleaved across the chips:
 - Accordingly, in **high-order** interleaving, the **high** order address bits specify the memory bank.

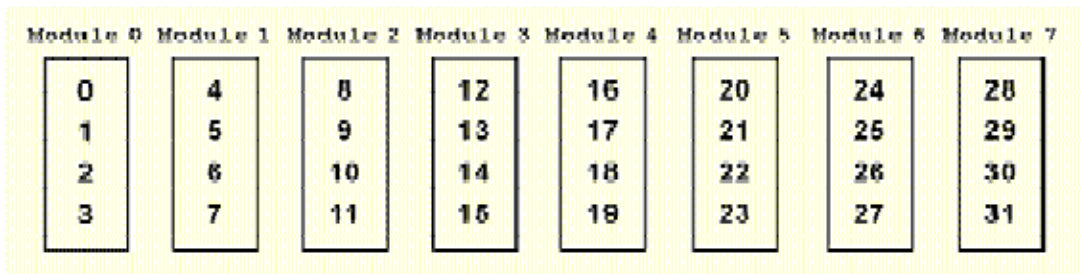


FIGURE 4.6 High-Order Memory Interleaving (4bytes X 8chips)

- With **low-order** interleaving, the **low** order bits of the address specify which memory bank contains the address of interest.

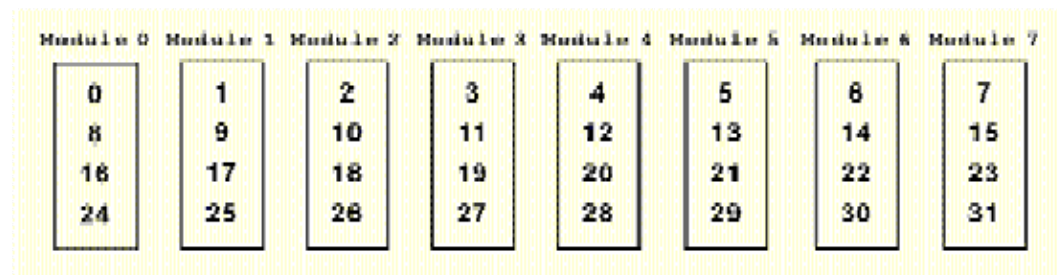


FIGURE 4.7 Low-Order Memory Interleaving (4bytes X 8chips)

4.7 Interrupts 208

- Interrupts are events that alter (or interrupt) the normal flow of execution in the system. An interrupt can be triggered for a variety of reasons, including:
 - I/O requests
 - Arithmetic errors (e.g., division by zero)
 - Arithmetic underflow or overflow
 - Hardware malfunction (e.g., memory parity error)
 - User-defined break points (such as when debugging a program)
 - Page faults (this is covered in detail in Chapter 6)
 - Invalid instructions (usually resulting from pointer issues)
 - Miscellaneous
 - Each interrupt is associated with a **procedure** that directs the actions of the CPU when an interrupt occurs.

4.8 MARIE 209

- MARIE: a Machine Architecture that is Really Intuitive and Easy, is a simple architecture consisting of memory (to store program and data) and a CPU (consisting of an ALU and several registers).
- It has all the functional components necessary to be a real working computer.

4.8.1 The Architecture 209

- MARIE has the following characteristics:
 - Binary, two's complement data representation.
 - Stored program, fixed word length data and instructions.
 - **Word (but not byte) addressable**
 - **4K** words of main memory (this implies **12** bits per address).
 - **16-bit** data (words have 16 bits).
 - **16-bit** instructions, **4** for the opcode and **12** for the address.
 - A **16-bit** accumulator (AC)
 - A **16-bit** instruction register (IR)
 - A **16-bit** memory buffer register (MBR)
 - A **12-bit** program counter (PC)
 - A **12-bit** memory address register (MAR)
 - A **8-bit** input register
 - A **8-bit** output register

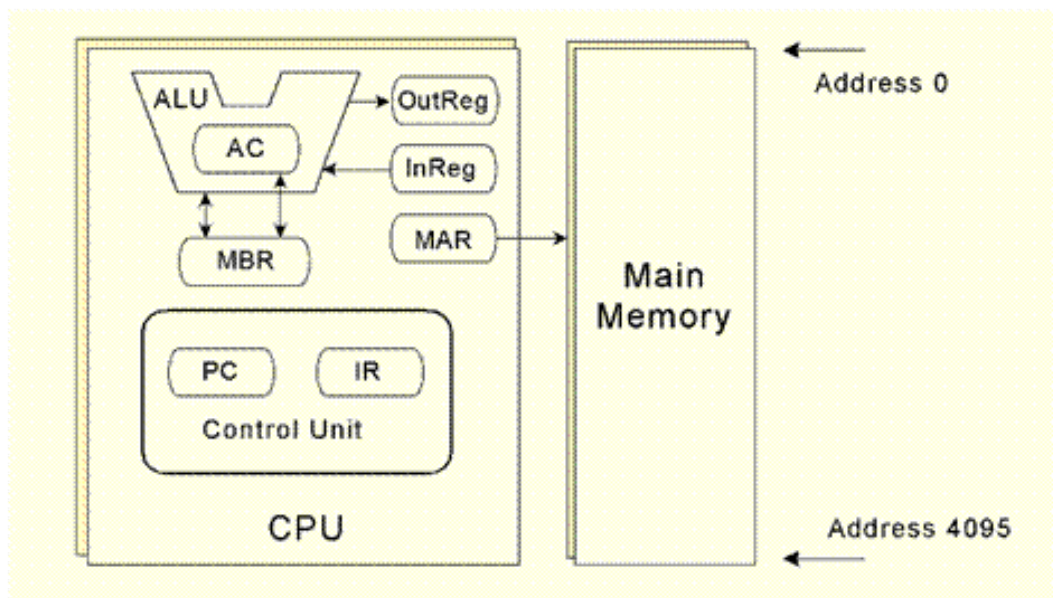


FIGURE 4.8 MARIE's Architecture

4.8.2 Registers and Buses 211

- In MARIE, there are seven register, as follows:
 - AC: The accumulator, which holds **data** values. This is a general purpose register and holds data that the CPU needs to process.
 - MAR: The memory address register, which holds the memory **address** of the data being refereed.
 - MBR: The memory buffer register, which holds either the **data** just read from memory or the data ready to be written to memory.
 - PC: The program counter, which hold the **address** of the **next** instruction to be executed in the program.
 - IR: The instruction register, which hold the **next** instruction to be executed.
 - InREG: The input register, which holds data from the input device.
 - OutREG: The output register, which holds data from the output device.
- In MARIE, we assume a common bus scheme.

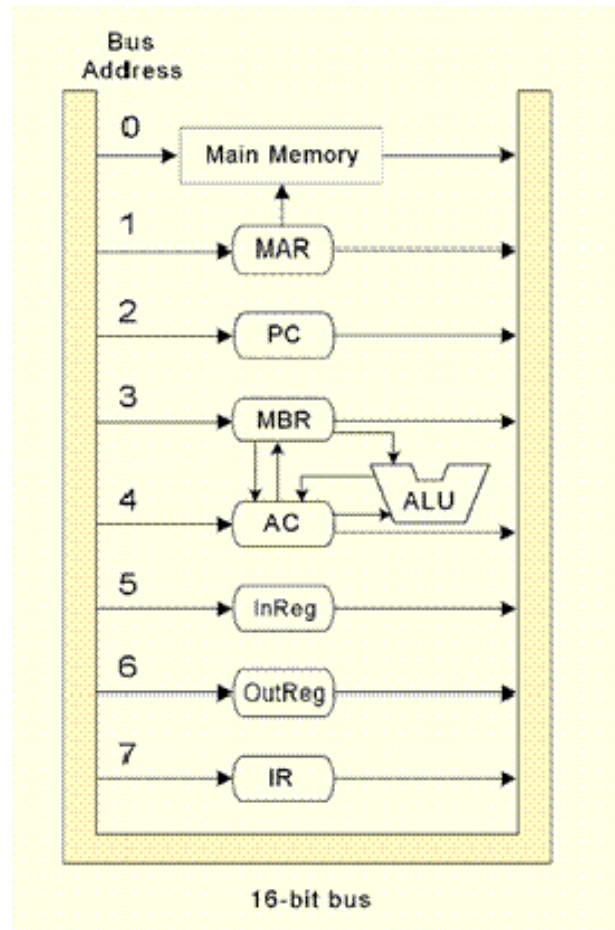


FIGURE 4.9 The Data Path in MARIE

4.8.3 The Instruction Set Architecture 212

- A computer's instruction set architecture (ISA) specifies the format of its instructions and the primitive operations that the machine can perform.
- The ISA is an interface between a computer's hardware and its software.
- Some ISAs include hundreds of different instructions for processing data and controlling program execution.
- The MARIE ISA consists of only thirteen instructions.

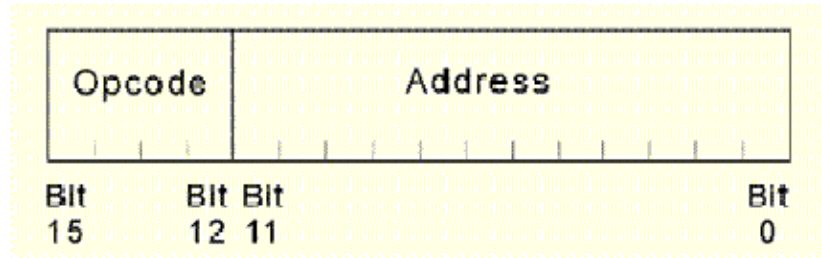


FIGURE 4.10 MARIE's Instruction Format

Instruction Number		Instruction	Meaning
Binary	Hex		
0001	1	Load X	Load contents of address X into AC.
0010	2	Store X	Store the contents of AC at address X.
0011	3	Add X	Add the contents of address X to AC.
0100	4	Subt X	Subtract the contents of address X from AC.
0101	5	Input	Input a value from the keyboard into AC.
0110	6	Output	Output the value in AC to the display.
0111	7	Halt	Terminate program.
1000	8	Skipcond	Skip next instruction on condition.
1001	9	Jump X	Load the value of X into PC.

TABLE 4.2 MARIE's Instruction Set

4.8.4 Register Transfer Notation 215

- Each of our instructions actually consists of a sequence of smaller instructions called **microoperations**.
- The symbolic notation used to describe the behavior of microoperations is called register transfer notation (RTN) or register transfer language (RTL).
- In the MARIE RTL, we use the notation $M[X]$ to indicate the actual data value stored in memory location X , and \leftarrow to indicate the transfer of bytes to a register or memory location.
- For example:
 - **Load X** The RTL for the LOAD instruction is:

$MAR \leftarrow X$
 $MBR \leftarrow M[MAR]$
 $AC \leftarrow MBR$

- **Add X** The RTL for the ADD instruction is:

$MAR \leftarrow X$
 $MBR \leftarrow M[MAR]$
 $AC \leftarrow AC + MBR$

- **SKIPCOND** skips the next instruction according to the value of the AC.

If **IR[11 - 10] = 00 then** (if bits 11 and 10 in the IR are both 0)
 If AC < 0 then PC ← PC + 1

else If **IR[11 - 10] = 01 then** (if bit 11 = 0 and bit 10 = 1)
 If AC = 0 then PC ← PC + 1

else If **IR[11 - 10] = 10 then** (if bit 11 = 1 and bit 10 = 0)
 If AC > 0 then PC ← PC + 1

4.9 Instruction Processing 218

- All computers follow a basic machine cycle: the fetch, decode, and execute cycle.

4.9.1 The Fetch-Decode-Execute Cycle 218

- The fetch-decode-execute cycle represents the steps that a computer follows to run a program.

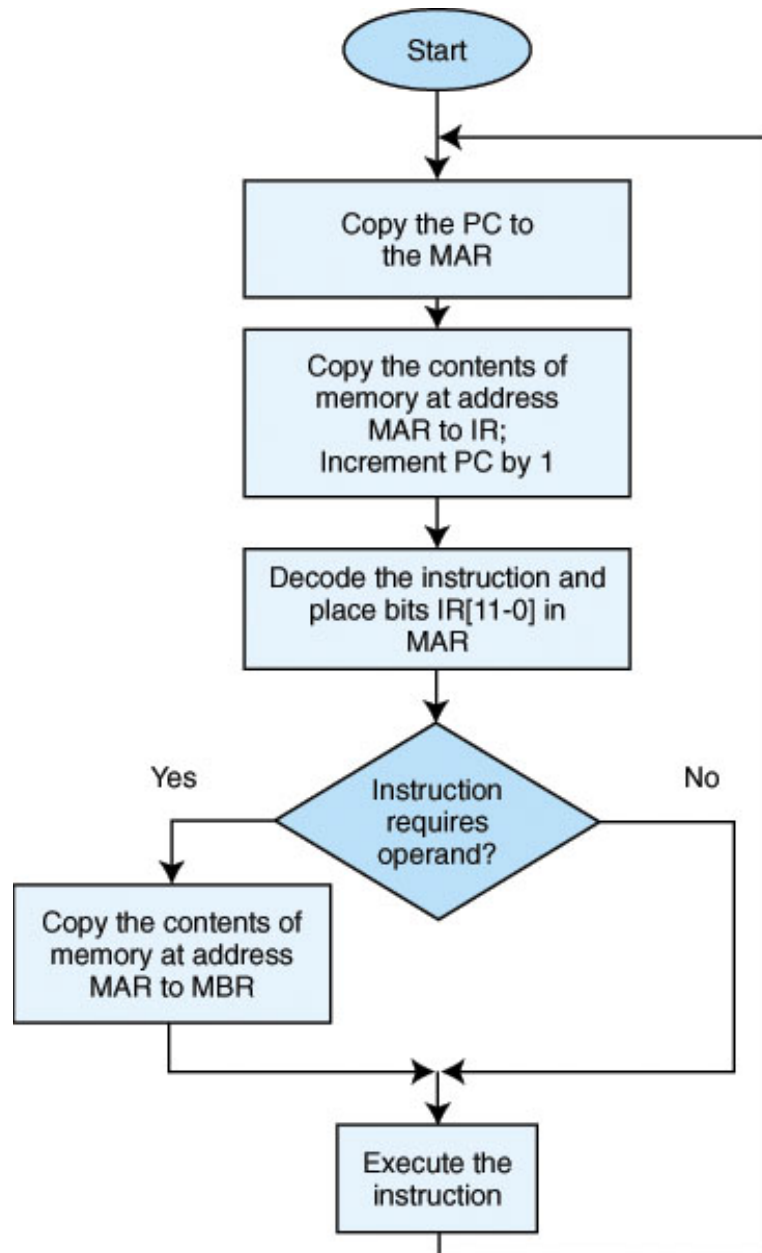


FIGURE 4.11 The Fetch-Decode-Execute Cycle

4.9.2 Interrupts and the Instruction Cycle 219

- All computers provide a means for the normal fetch-decode-execute cycle to be interrupted.
- These interruptions may be necessary for many reasons, including:
 - A program error (such as division by 0, arithmetic overflow, stack overflow, or attempting to access a protected area of memory)
 - A hardware error (such as a memory parity error or power failure)
 - An I/O completion (which happens when a disk read is requested and the data transfer is complete)
 - A user interrupt (such as hitting Ctrl-C or Ctrl-Break to stop a program)
 - An interrupt from a timer set by the operating system (such as is necessary when allocating virtual memory or performing certain bookkeeping functions)
- When the CPU executes an input or output instruction, the appropriate I/O device is notified.
- The CPU then continues with other useful work until the device is ready.
- At that time, the device sends an interrupt signal to the CPU.
- The CPU then processes the interrupt, after which it continues with normal fetch-decode-execute cycle.

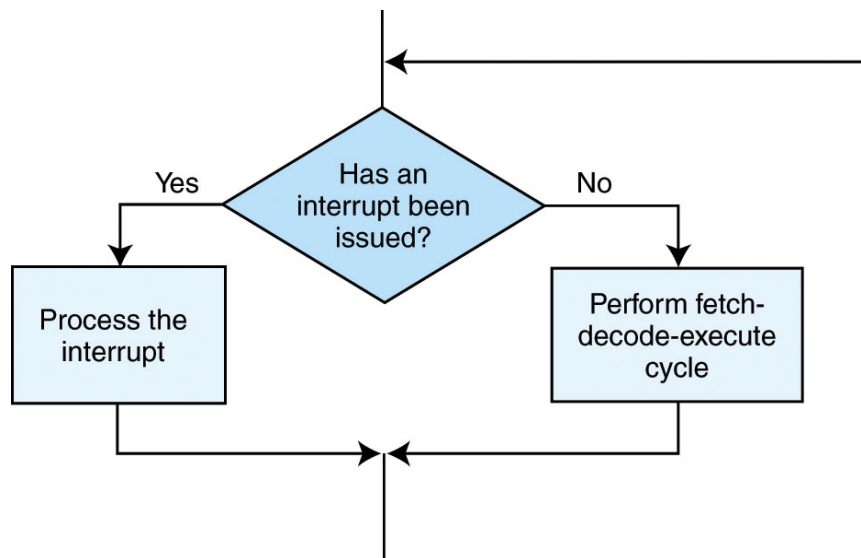


FIGURE 4.12 Modified Instruction Cycle to Check for Interrupt

4.9.3 MARIE's I/O 223

- MARIE has two registers to handle input and output. All output is placed in an output register, **OutREG**, and the CPU polls the input register, **InREG**, until input is sensed, at which time the value is copied into the accumulator.

4.10 A Simple Program 223

- Consider the simple MARIE program given in TABLE 4.3. We show a set of mnemonic instructions stored at addresses 100 - 106 (hex):

Address	Instruction	Binary Contents of Memory Address	Hex Contents of Memory
100	Load 104	0001000100000100	1104
101	Add 105	0011000100000101	3105
102	Store 106	0100000100000110	4106
103	Halt	0111000000000000	7000
104	0023	0000000000100011	0023
105	FFE9	1111111111101001	FFE9
106	0000	0000000000000000	0000

TABLE 4.3 A Program to Add Two Numbers

a) Load 104

Step	RTN	PC	IR	MAR	MBR	AC
(initial values)		100	-----	-----	-----	-----
Fetch	MAR ← PC	100	-----	100	-----	-----
	IR ← M[MAR]	100	1104	100	-----	-----
	PC ← PC + 1	101	1104	100	-----	-----
Decode	MAR ← IR[11-0]	101	1104	104	-----	-----
	(Decode IR[15-12])	101	1104	104	-----	-----
Get operand	MBR ← M[MAR]	101	1104	104	0023	-----
Execute	AC ← MBR	101	1104	104	0023	0023

b) Add 105

Step	RTN	PC	IR	MAR	MBR	AC
(initial values)		101	1104	104	0023	0023
Fetch	MAR ← PC	101	1104	101	0023	0023
	IR ← M[MAR]	101	3105	101	0023	0023
	PC ← PC + 1	102	3105	101	0023	0023
Decode	MAR ← IR[11-0]	102	3105	105	0023	0023
	(Decode IR[15-12])	102	3105	105	0023	0023
Get operand	MBR ← M[MAR]	102	3105	105	FFE9	0023
Execute	AC ← AC + MBR	102	3105	105	FFE9	000C

c) Store 106

Step	RTN	PC	IR	MAR	MBR	AC
(initial values)		102	3105	105	FFE9	000C
Fetch	MAR ← PC	102	3105	102	FFE9	000C
	IR ← M[MAR]	102	2106	102	FFE9	000C
	PC ← PC + 1	103	2106	102	FFE9	000C
Decode	MAR ← IR[11-0]	103	2106	106	FFE9	000C
	(Decode IR[15-12])	103	2106	106	FFE9	000C
Get operand	(not necessary)	103	2106	106	FFE9	000C
Execute	MBR ← AC	103	2106	106	000C	000C
	M[MAR] ← MBR	103	2106	106	000C	000C

FIGURE 4.14 A Trace of the Program to Add Two Numbers

4.11 A Discussion on Assemblers 226

- Mnemonic instructions, such as LOAD 104, are easy for humans to write and understand.

4.11.1 What Do Assemblers Do? 226

- An assembler's job is to convert assembly language (using mnemonics) into machine language (which consists entirely of binary values, or string of zeros and ones).
- In assembly language, there is a one-to-one correspondence between a mnemonic instruction and its machine code.
- The assembler reads a source file (assembly program) and produces an object file (the machine code).
- Assemblers create an object program file from mnemonic source code in two passes.
 - During the first pass, the assembler assembles as much of the program as it can, while it builds a symbol table that contains memory references for all symbols in the program.

Address	Instruction
100	Load X
101	Add Y
102	Store Z
103	Halt
X, 104	DEC 35
Y, 105	DEC -23
Z, 106	HEX 0000

TABLE 4.5 An Example Using Directives for Constants

X	104
Y	105
Z	106

1	X
3	Y
2	Z
7	0000

During the first pass, we have a symbol table and the partial instructions

- During the second pass, the instructions are completed using the values from the symbol table.

1 1 0 4
3 1 0 5
2 1 0 6
7 0 0 0
0 0 2 3
F F E 9
0 0 0 0

4.11.2 Why Use Assembly Language? 228

- Most programmers agree that **10%** of the code in a program uses approximately 90% of the CPU time.
- In time-critical applications, we often need to optimize this 10% of code. Programmers can make the program more efficient in terms of time (and space).
- If the overall size of the program or response time is critical, assembly language often becomes the language of choice.
- **Embedded Systems** must be reactive and often are found in time-constrained environments. These systems are designed to perform either a single instruction or a **very specific set of instructions**.
- Chance are you use some type of embedded system every day:
 - Consumer electronics (such as cameras, camcorders, cellular phones, PDAs, and interactive games)
 - Consumer products (such as washers, microwave ovens, and washing machines)
 - Automobiles (particularly engine control and antilock brakes)
 - Medical instruments (such as CAT scanners and heart monitors)
 - Industry (for process controllers and avionics)

4.12 Extending Our Instruction Set 229

Opcode	Instruction	RTN
0000	JnS X	$MBR \leftarrow PC$ $MAR \leftarrow X$ $M[MAR] \leftarrow MBR$ $MBR \leftarrow X$ $AC \leftarrow 1$ $AC \leftarrow AC + MBR$ $PC \leftarrow AC$
0001	Load X	$MAR \leftarrow X$ $MBR \leftarrow M[MAR], AC \leftarrow MBR$
0010	Store X	$MAR \leftarrow X, MBR \leftarrow AC$ $M[MAR] \leftarrow MBR$
0011	Add X	$MAR \leftarrow X$ $MBR \leftarrow M[MAR]$ $AC \leftarrow AC + MBR$
0100	Subt X	$MAR \leftarrow X$ $MBR \leftarrow M[MAR]$ $AC \leftarrow AC - MBR$
0101	Input	$AC \leftarrow InREG$
0110	Output	$OutREG \leftarrow AC$
0111	Halt	
1000	Skipcond	If $IR[11-10] = 00$ then If $AC < 0$ then $PC \leftarrow PC + 1$ Else If $IR[11-10] = 01$ then If $AC = 0$ then $PC \leftarrow PC + 1$ Else If $IR[11-10] = 10$ then If $AC > 0$ then $PC \leftarrow PC + 1$
1001	Jump X	$PC \leftarrow IR[11-0]$
1010	Clear	$AC \leftarrow 0$
1011	AddI X	$MAR \leftarrow X$ $MBR \leftarrow M[MAR]$ $MAR \leftarrow MBR$ $MBR \leftarrow M[MAR]$ $AC \leftarrow AC + MBR$
1100	JumpI X	$MAR \leftarrow X$ $MBR \leftarrow M[MAR]$ $PC \leftarrow MBR$

TABLE 4.7 MARIE's Full Instruction Set

- **EXAMPE 4.1** Here is an example using a loop to add five numbers
- **EXAMPE 4.2** This example illustrates the use of an if/else construct to allow for selection. In particular, it implements the following:
 if $X = Y$ then
 $X := X * 2$
 else
 $Y := Y - X;$
- **EXAMPE 4.3** This example illustrates the use of a simple subroutine to double any number and can be coded. (Note: the line numbers are given for information only.)

4.13 A Discussion on Decoding: Hardwired vs. Microprogrammed Control 235

- A computer's control unit keeps things synchronized, making sure that bits flow to the correct components as the components are needed.
- There are two general ways in which a control unit can be implemented: hardwired control and microprogrammed control.
 - With microprogrammed control, a small program is placed into read-only memory in the microcontroller.
 - Hardwired controllers implement this program using digital logic components.

4.13.1 Machine Control 235

- P0, P1, P2, controls reading from memory or a register, and the other set consisting of P3, P4, P5, controls writing to memory or a register.
- This register (MBR) is enabled for reading when P0 and P1 are high, and it is enabled for writing when P3 and P4 are high

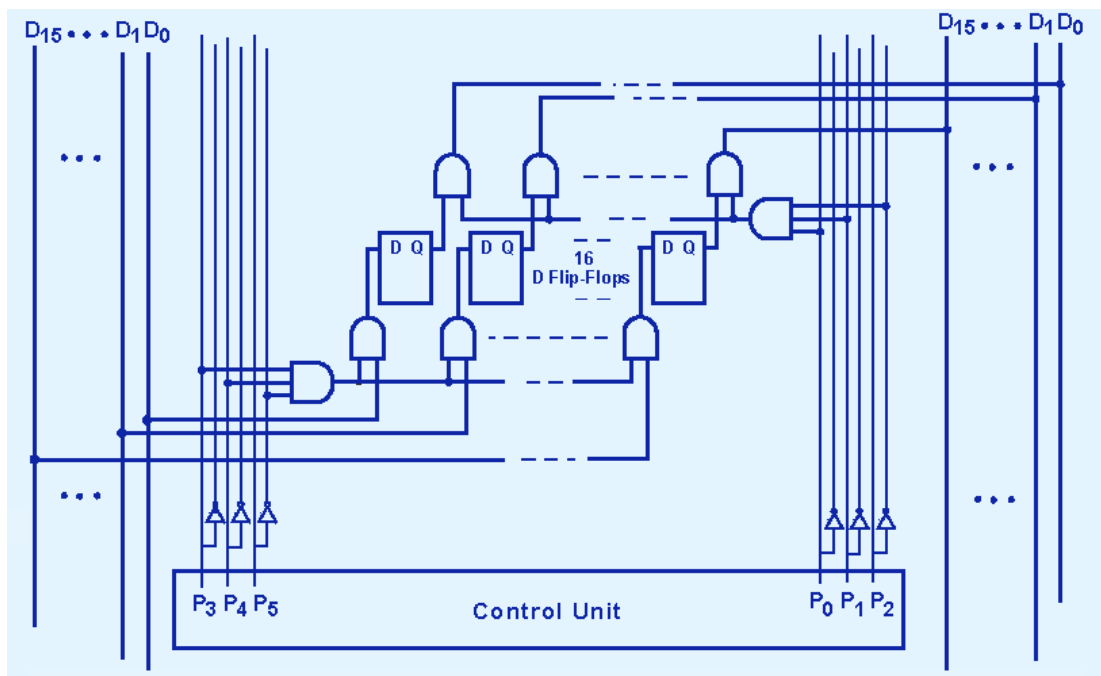


FIGURE 4.15 Connection of MARIE's MBR to the Datapath

4.13.2 Hardwired Control 238

- The advantage of hardwired control is that it is very **fast**.
- The disadvantage is that the instruction set and the control logic are directly tied together by special circuits that are complex and difficult to design or **modify**.
- For example, a 4-to-16 decoder could be used to decode the opcode. By using the contents of the IR register and the status of the ALU, this controls the registers, the ALU operations, all shifters, and bus access.

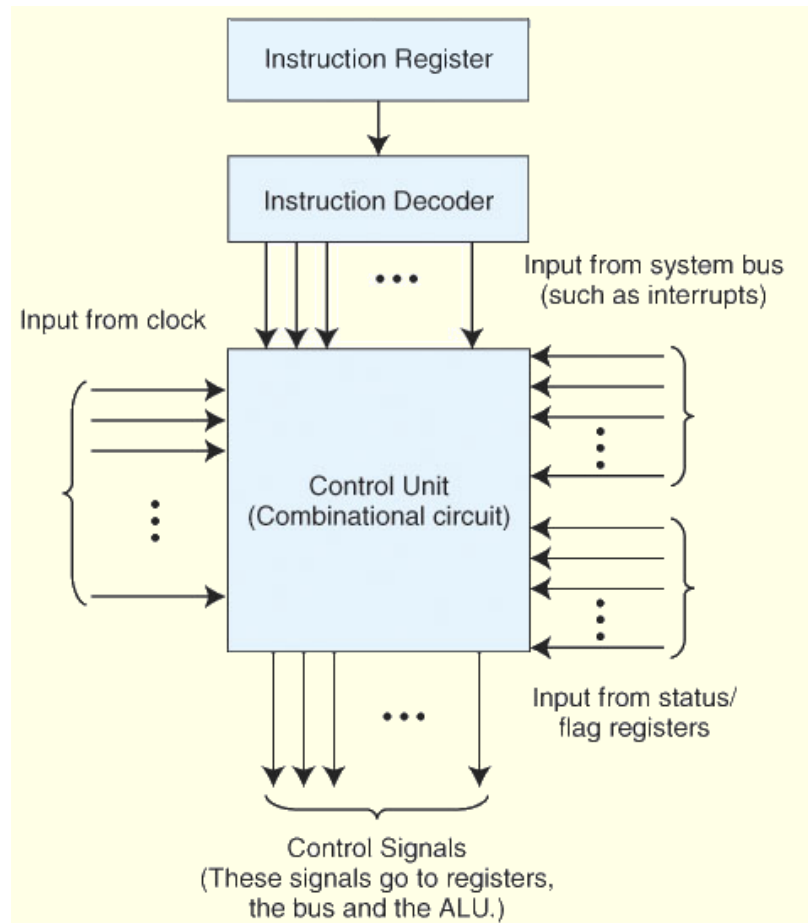


FIGURE 4.17 Hardwired Control Unit

- Careful inspection of MARIE’s RTL reveals that the ALU has only three operations: add, subtract, and clear.
 - We will also define a fourth “do nothing” state.
- The entire set of MARIE’s control signals consists of:
 - Register controls: P_0 through P_5 ($P_0P_1P_2$ for read and $P_3P_4P_5$ for write)
 - ALU controls: A_0 through A_1 (do nothing, add, subtract, and clear)
 - Timing: T_0 through T_7 and counter reset C_r
- In FIGURE 4.9, Main Memory (address 0 or 111), MAR (address 1 or 001), PC (address 2 or 010), MBR (address 3 or 011), AC (address 4 or 100), InREG (address 5 or 101), OutREG (address or 110), and IR (address 7 or 111).
- Here is the complete signal sequence for MARIE’s Add instruction:

```

P0P1P2P3T0: MAR ← X           // X is in the rightmost 12 bits of the IR; OpCode 0011 (Add)
                                   // T0
                                   // P0P1P2: Read from IR (address 7 or 111)
                                   // P3: Write to MAR (address 1 or 001)

P3P4T1:      MBR ← M[MAR]       // T1
                                   // Read from Mem (address 0 or 000)
                                   // P3P4: Write to MBR (address 3 or 011)

A0P0P1P5T2: AC ← AC + MBR     // T2
                                   // P0P1: Read from MBR (address 3 or 011)
                                   // P5: Write to AC (address 4 or 100)
                                   // A0: ALU Add (address 1 or 01)

CrT3:      [Reset counter]

```

- These signals are ANDed with combinational logic to bring about the desired machine behavior.

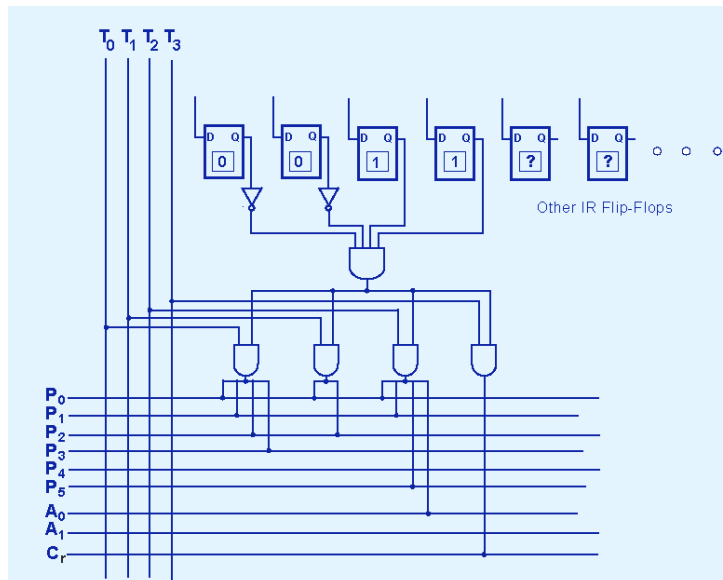


FIGURE 4.20 Combinational Logic for Signal Controls of MARIE’s Add Instruction

4.13.3 Microprogrammed Control 242

- The other approach called microprogramming, uses software for control illustrated in Figure 4.19.
- All machine instructions are input into a **special program**, the **microprogram**, to **convert** the instruction into the appropriate controls signals.
- The microprogram is essentially an interpreter, written in **microcode**, that is stored in **firmware** (ROM, PROM, EPROM), which is often referred to as the control store.
- Essentially there is **one subroutine** in this program for **each machine instruction**.
- The advantage of this approach is that if the instruction set requires modification the microprogram is simply updated to match – **no change** is required in the actual hardware.
- The disadvantage to this approach is that all instructions must go through an additional level of **interpretation**, **slowing down** the program execution.

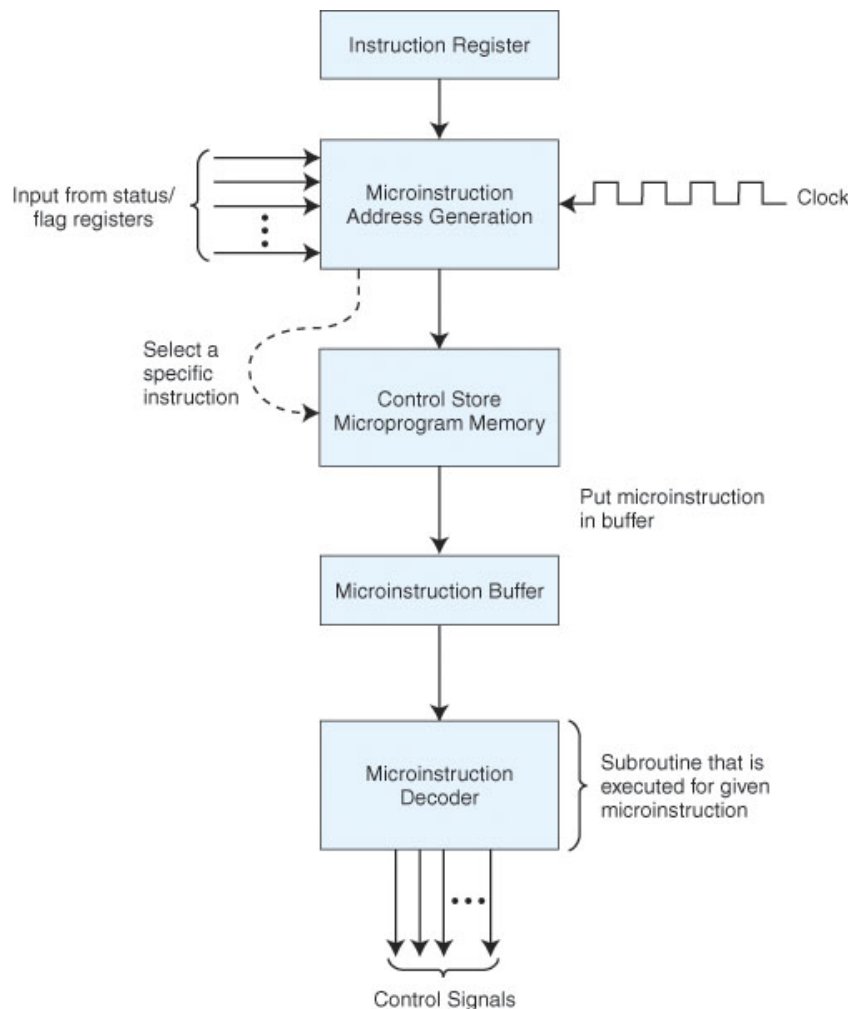


FIGURE 4.21 Microprogrammed Control Unit

4.14 Real-World Examples of Computer Architectures 246

- Each member of the x86 family of Intel architectures is known as a **CISC** (Complex Instruction Set Computer) machine, whereas the Pentium family and the MIPS architectures are examples of **RISC** (Reduced Instruction Set Computer) machines.
- The main objective of RISC machines is to simplify instructions so they can execute more quickly. Each instruction performs only one operation; they are all **the same size**.

4.14.1 Intel Architectures 247

- The classic Intel architecture, the 8086, was born in 1979. It is a CISC architecture.
- It was adopted by IBM for its famed PC, which was released in 1981.
- The 8086 operated on **16-bit** data words and supported **20-bit** memory addresses.
- Later, to lower costs, the 8-bit 8088 was introduced. Like the 8086, it used 20-bit memory addresses.
- In 1985, Intel introduced the **32-bit 80386**.
- It also had no built-in floating-point unit.
- The 80486, introduced in 1989, was an 80386 that had built-in floating-point processing and cache memory.
- The 80386 and 80486 offered downward compatibility with the 8086 and 8088.
- Software written for the smaller word systems was directed to use the lower 16 bits of the 32-bit registers.
- Intel's most advanced **32-bit** microprocessor is the **Pentium 4**.
- It can run as fast as 3.06 GHz. This clock rate is over 350 times faster than that of the 8086.
- The introduction of the **Itanium** processor in 2001 marked Intel's first 64-bit chip (**IA-64**). This processor has four integer units, two floating-point units, a significant amount of cache memory at four different levels, 128 floating-point registers, 128 integer registers, and multiple miscellaneous registers.
- Speed enhancing features include multilevel cache and instruction pipelining.
- Intel, along with many others, is marrying **many of the ideas of RISC architectures** with microprocessors that are largely CISC.

4.14.2 MIPS Architectures 253

- The MIPS family of CPUs has been one of the most successful in its class.
- In 1986 the first MIPS CPU was announced.
- It had a **32-bit** word size and could address 4GB of memory.
- Over the years, MIPS processors have been used in general purpose computers as well as in games.
- The MIPS architecture now offers 32- and **64-bit** versions.
- MIPS was one of the first **RISC** microprocessors.

- The original MIPS architecture had **only 55** different instructions, as compared with the 8086 which had over 100.
- **SPIM** is a popular simulator widely used by students and professional.
- MIPS was designed with performance in mind: It is a load/store architecture, meaning that only the load and store instructions can access memory.
- The large number of registers in the MIPS architecture keeps bus traffic to a minimum.

Chapter Summary 255

- The major components of a computer system are its control unit, registers, memory, ALU, and data path.
- MARIE has 4K **16-bit** words of main memory, uses 16-bit instructions, and has seven registers.
- There is only one general purpose register, the AC.
- Instructions for MARIE use **4** bits for the opcode and **12** bits for an address.
- A built-in clock keeps everything synchronized.
- Computers run programs through iterative **fetch-decode-execute cycles**.
- Computers can run programs that are in machine language.
- An assembler converts mnemonic code to machine language.
- Control units can be microprogrammed or hardwired.
- Hardwired control units give better performance, while microprogrammed units are more adaptable to changes.
- The Intel architecture is an example of a **CISC** architecture; MIPS is an example of a **RISC** architecture.