

Ata Elahi

Computer Systems

Digital Design, Fundamentals of
Computer Architecture and Assembly
Language



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Springer

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ISBN 978-3-319-66774-4 ISBN 978-3-319-66775-1 (eBook)
<https://doi.org/10.1007/978-3-319-66775-1>

Library of Congress Control Number: 2017952347

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*This book is dedicated to
Sara, Shabnam and Aria*

Preface

This textbook is the result of my experiences teaching computer systems at the Computer Science Department at Southern Connecticut State University since 1986. The book is divided into three sections: Digital Design, Introduction to Computer Architecture and Memory, and ARM Architecture and Assembly Language. The Digital Design section includes a laboratory manual with 12 experiments using Logisim software to enforce important concepts. The ARM Architecture and Assembly Language section includes several examples of assembly language programs using Keil µVision 5 development tools.

Intended Audience

This book is written primarily for a one semester course as an introduction to computer hardware and assembly language for students majoring in Computer Science, Information Systems and Engineering Technology.

Organization

The material of this book is presented in such a way that no special background is required to understand the topics.

Chapter 1 – Signals and Number Systems: Analog Signal, Digital Signal, Binary Numbers, Addition and Subtraction of binary numbers, IEEE 754 Floating Point representations, ASCII, Unicode, Serial Transmission, and Parallel Transmission.

Chapter 2 – Boolean Logics and Logic Gates: Boolean Logics, Boolean Algebra Theorems, Logic Gates, Integrate Circuit (IC), Boolean Function, Truth Table of a function and using Boolean Theorems to simplify Boolean Functions.

Chapter 3 – Minterms, Maxterms, Karnaugh Map (K-Map) and Universal Gates: Minterms, Maxterms, Karnaugh Map (K-Map) to simplify Boolean Functions, Don't Care Conditions and Universal Gates.

Chapter 4 – Combinational Logic: Analysis of Combination Logic, Design of Combinational Logic, Decoder, Encoder, Multiplexer, Half Adder, Full Adder, Binary Adder, Binary Subtractor, Designing Arithmetic Logic Unit (ALU) and BCD to Seven Segment Decoder.

Chapter 5 – Synchronous Sequential Logic: Sequential Logic such as S-R Latch, D-Flip Flop, J-K Flip Flop, T-Flip Flop, Register, Shift Register, Analysis of Sequential Logic, State Diagram, State Table, Flip Flop Excitation Table and Designing Counter.

Chapter 6 – Introduction to Computer Architecture: Components of a Microcomputer, CPU Technology, CPU Architecture, Instruction Execution, Pipelining, PCI, PCI Express, USB, and HDMI.

Chapter 7 – Memory: Memory including RAM, SRAM, DISK, SSD, Memory Hierarchy, Cache Memory, Cache Memory Mapping Methods, Virtual Memory, Page Table and the memory organization of a computer.

Chapter 8 – ARM Architecture and Instructions Part I: ARM Processor Architecture, and ARM Instruction Set such as Data Processing, Shift, Rotate, Unconditional Instructions and Conditional Instructions, Stack Operation, Branch, Multiply Instructions and several examples of converting HLL to Assembly language.

Chapter 9 – ARM Instructions Part II: This chapter is the continuation of Chapter 8 which covers Load and Store Instructions, Pseudo Instructions, ARM Addressing Mode and data representation in memory.

Chapter 10 – ARM Assembly Language Programming Using Keil Development Tools: Covers how to use Keil development software for writing assembly language using ARM Instructions, Compiling Assembly Language and Debugging.

Instruction Resources: The instruction resources contains

- Laboratory experiments using Logisim.
- Solutions to the problems of each chapter.

Acknowledgments

I would like to express my special thanks to Professor Lancor Chairman of Computer Science Department at Southern Connecticut State University for her support as well as Professor Herv Podnar for his guidance.

I wish to acknowledge and thank Ms. Mary E. James, Senior Editor in Applied Sciences and her assistant, Ms. Zoe Kennedy, for their support.

My special thanks to Marc Gajdosik, Nickolas Santini, Nicholas Bittar, Eric Basini, Omar Abid and Alireza Ghods for their help in developing the manuscript. Finally, I would like to thank the students of CSC 207 Computer Systems of Spring 2017.

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Chapter 1

Signals and Number Systems

Objectives: After completing this chapter, you should be able to:

- Explain the basic components of a computer.
- Distinguish between analog and digital signal.
- Learn the characteristics of signal.
- Convert decimal numbers to binary and vice versa.
- Learn addition and subtraction of binary numbers.
- Represent floating numbers in binary.
- Convert from binary to hexadecimal and vice versa.
- Distinguish between serial and parallel transmission.

1.1 Introduction

Numerical values have become an integral part of our daily lives. Numerical values can be represented by analog or digital; examples include an analog watch, digital watch, or thermometer. The following are advantages of digital representation of numerical values compared to analog representation:

1. Digital representation is more accurate.
2. Digital information are easier to store
3. Digital systems are easier to design.
4. Noise has less effect.
5. Digital systems can easily be fabricated in an integrated circuit.

A digital signal is a discrete signal (step by step), and an analog signal is a continuous signal. Digital systems are widely used and its applications can be seen in computers, calculators, and cell phones. In a digital system, information is transferred between components of the digital system in the form of digital signals.

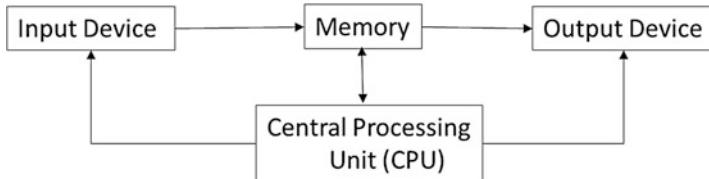


Fig. 1.1 Basic components of a computer

A computer consists of two components: hardware and software. Hardware refers to the physical components of a computer such as the keyboard, CPU, and memory. Software refers to programs run by CPU including operating systems and application programs. Computers can come in several different forms such as a desktop, laptop, tablet, server, and iPhone. Regardless of the form, all computers consist of the same basic structures. Figure 1.1 shows the basic components of a computer.

Input Device The input device is used for entering information into memory. Examples of input devices include the keyboard, mouse, touch pad screen, light pen, barcode reader, and scanner. The input device converts information into bits, and the bits are stored in memory.

Output Device A computer's memory transfers information to the *output device* in the form of bits. The output device converts bits to characters, images, and voices which can be interpreted by humans.

Memory Memory is used to store information and programs. Memory comes in the form of solid-state electronics such as RAM, ROM, flash drive, or hard disk.

The Central Processing Unit (CPU) The CPU is used to perform computations on information.

1.2 Analog Signals

An analog signal is a signal whose amplitude is a function of time and changes gradually as time changes. Analog signals can be classified as nonperiodic and periodic signals.

Nonperiodic Signal In a nonperiodic signal, there is no repeated pattern in the signal as shown in Fig. 1.2.

Periodic Signal A signal that repeats a pattern within a measurable time period is called a periodic signal, and completion of a full pattern is called a *cycle*. The simplest periodic signal is a sine wave, which is shown in Fig. 1.3. In the time domain, the sine wave amplitude $a(t)$ can be represented mathematically as $a(t) = A \sin(\omega t + \theta)$ where A is the maximum amplitude, ω is the angular frequency, and θ is the phase angle.

Fig. 1.2 Representation of a nonperiodic analog signal

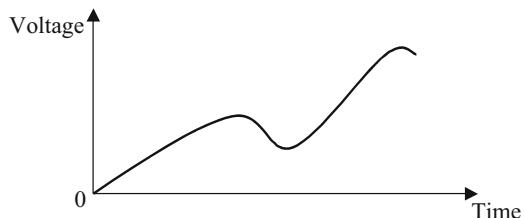


Fig. 1.3 Time domain representation of a sine wave

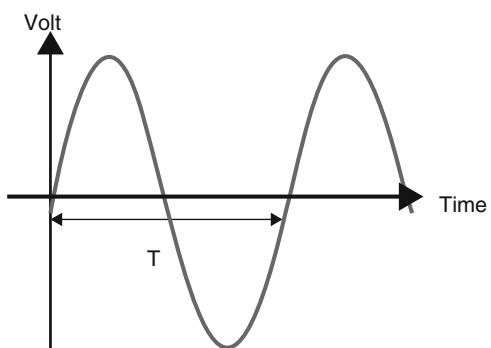
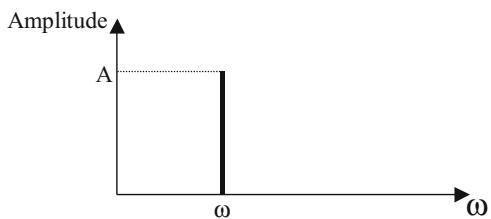


Fig. 1.4 Frequency representation of a sine wave



A periodic signal can also be represented in the frequency domain where the horizontal axis is the frequency and the vertical axis is the amplitude of the signal. Figure 1.4 shows the frequency domain representation of a sine wave signal.

An electrical signal, usually representing voice, temperature, or a musical sound, is made of multiple wave forms. These signals have one fundamental frequency and multiple frequencies that are called harmonics.

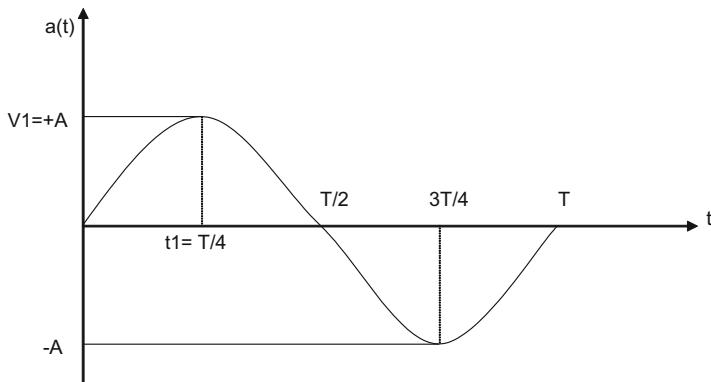
1.2.1 Characteristics of an Analog Signal

The characteristics of a periodic analog signal are frequency, amplitude, and phase.

Frequency Frequency (F) is the number of cycles in 1 s, $F = \frac{1}{T}$, represented in Hz (Hertz). If each cycle of an analog signal is repeated every 1 s, the frequency of the signal is 1 Hz. If each cycle of an analog signal is repeated 1000 times every second (once every millisecond), the frequency is

Table 1.1 Typical units of frequency and period

Units of frequency	Numerical value	Units of period	Numerical value
Hertz (Hz)	1 Hz	Second (s)	1 s
Kilohertz (kHz)	10^3 Hz	Millisecond (ms)	10^{-3} s
Megahertz (MHz)	10^6 Hz	Microsecond (μ s)	10^{-6} s
Gigahertz (GHz)	10^9 Hz	Nanosecond (ns)	10^{-9} s
Terahertz (THz)	10^{12} Hz	Picosecond (ps)	10^{-12} s

**Fig. 1.5** A sine wave signal over one cycle

$$f = \frac{1}{T} = \frac{1}{10^{-3}} = 1000 \text{ Hz} = 1 \text{ kHz}$$

Table 1.1 shows different values for frequency and their corresponding periods.

Amplitude The amplitude of an analog signal is a function of time as shown in Fig. 1.5 and may be represented in volts (unit of voltage). In other words, the amplitude is its voltage value at any given time. At the time t_1 , the amplitude of the signal is V_1 .

Phase Two signals with the same frequency can differ in phase. This means that one of the signals starts at a different time from the other one. This difference can be represented in degrees (0° to 360°) or by radians. A phase angle of 0° indicates that the sine wave starts at time 0, and a phase angle of 90° indicates that the signal starts at 90° as shown in Fig. 1.6.

Example 1.1 Find the equation for a sine wave signal with a frequency of 10 Hz, maximum amplitude of 20 volts, and phase angle of 0° :

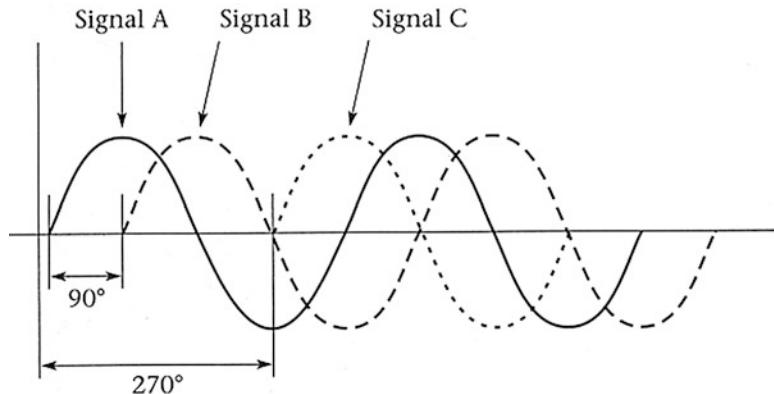


Fig. 1.6 Three sine waves with different phases

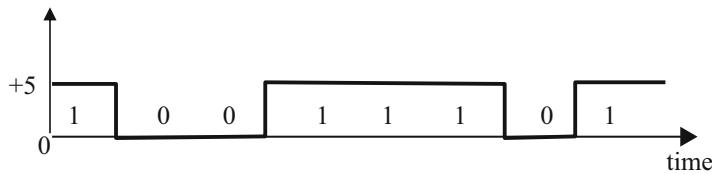


Fig. 1.7 Digital signal

$$\omega = 2\pi f = 2 \times 3.1416 \times 10 = 62.83 \frac{\text{rad}}{\text{sec}}$$

$$a(t) = 20 \sin(62.83t)$$

1.3 Digital Signals

Modern computers communicate by using digital signals. *Digital signals* are represented by two voltages: one voltage represents the number 0 in binary, and the other voltage represents the number 1 in binary. An example of a digital signal is shown in Fig. 1.7, where 0 volts represents 0 in binary and +5 volts represents 1. 0 or 1 is called a bit and 8 bits is called a byte.

1.4 Number System

Numbers can be represented in different bases. A base of ten is called a decimal. In the example, below consider 356 in decimal:

$$356 = 6 + 50 + 300 = 6*10^0 + 5*10^1 + 3*10^2$$

In general, a number can be represented in the form:

$$(a_5a_4a_3a_2a_1a_0.a_{-1}a_{-2}a_{-3})_r,$$

where r is the base of the number and a_i must be less than r .

$(10011)_2$ is a valid number but $(211.01)_2$ is not.

Equation 1.1 can be used to convert a number in a given base to decimal:

$$\begin{aligned} \underbrace{(a_5a_4a_3a_2a_1a_0)}_{\text{Integer}} \cdot \underbrace{a_{-1}a_{-2}a_{-3}}_{\text{Fraction}})_r &= a_0 \times r^0 + a_1 \times r^1 + a_2 \times r^2 + a_3 \times r^3 + \dots \\ &\quad + a_{-1} \times r^{-1} + a_{-2} \times r^{-2} + a_{-3} \times r^{-3} \dots \end{aligned} \quad (1.1)$$

Example 1.2 Convert $(27.35)_8$ to the base of 10.

$$\begin{aligned} (27.35)_8 &= 7*8^0 + 2*8^1 + 3*8^{-1} + 5*8^{-2} = 7 + 16 + .375 + .078125 \\ &= (23.45)_{10} \end{aligned}$$

Example 1.3 Convert 1101111 to decimal.

$$\begin{aligned} (1101111)_2 &= 1*2^0 + 1*2^1 + 1*2^2 + 1*2^3 + 0*2^4 + 1*2^5 + 1*2^6 \\ &= 1 + 2 + 4 + 8 + 32 + 64 = (111)_{10} \end{aligned}$$

1.4.1 Converting from Binary to Decimal

Equation 1.2 represents the general form of a binary number:

$$(a_5a_4a_3a_2a_1a_0.a_{-1}a_{-2}a_{-3})_2 \quad (1.2)$$

where a_i is a binary digit or bit (either 0 or 1).

Equation 1.2 can be converted to decimal number by using Eq. 1.1:

$$\begin{aligned} \underbrace{(a_5a_4a_3a_2a_1a_0)}_{\text{Integer}} \cdot \underbrace{a_{-1}a_{-2}a_{-3}}_{\text{Fraction}})_2 &= a_0 \times 2^0 + a_1 \times 2^1 + a_2 \times 2^2 + a_3 \times 2^3 + \dots \\ &\quad + a_{-1} \times 2^{-1} + a_{-2} \times 2^{-2} + \dots \end{aligned} \quad (1.3)$$

$$(a_5 a_4 a_3 a_2 a_1 a_0 \cdot a_{-1} a_{-2} a_{-3})_2 = a_0 + 2 a_1 + 4 a_2 + 8 a_3 + 16 a_4 + 32 a_5 + 64 a_6 \\ + \frac{1}{2} * a_{-1} + \frac{1}{4} * a_{-2} + \frac{1}{8} * a_{-3}$$

Example 1.4 Convert $(110111.101)_2$ to decimal.

$$(110111.101)_2 = 1 * 2^0 + 1 * 2^1 + 1 * 2^2 + 0 * 2^3 + 1 * 2^4 + 1 * 2^5 + 1 * 2^{-1} \\ + 0 * 2^{-2} + 1 * 2^{-3} \\ = 55.625$$

Or

2^5	2^4	2^3	2^2	2^1	2^0	.	2^{-1}	2^{-2}	2^{-3}
1	1	0	1	1	1	.	1	0	1

$$32 + 16 + 0 + 4 + 2 + 1 + 1/2 + 0 + 1/8$$

If a binary value is made of n bits of ones, then its decimal value is $2^n - 1$.

Example 1.5

$$11 = 2^2 - 1 = 3$$

$$111 = 2^3 - 1 = 7$$

$$1111 = 2^4 - 1 = 15$$

$$11111 = 2^5 - 1 = 31$$

$$111111 = 2^6 - 1 = 63$$

Binary, or base of 2 numbers, is represented by 0s and 1s. A binary digit, 0 or 1, is called a bit, 8 bits is called a byte, 16 bits is called a half word, and 4 bytes is called a word.

1.4.2 Converting from Decimal Integer to Binary

To convert an integer number from decimal to binary, divide the decimal number by the new base (2 for binary), which will result in a quotient and a remainder (either 0 or 1). The first remainder will be the least significant bit of the binary number. Continually divide the quotient by the new base, while taking the remainders as each subsequent bit in the binary number, until the quotient becomes 0.

Example 1.6 Convert 34 in decimal to binary.

	Quotient	Remainder
34/2 =	17	0 = a_0
17/2 =	8	1 = a_1
8/2	4	0 = a_2
4/2	2	0 = a_3
2/2	1	0 = a_4
1/2	0	1 = a_5
Therefore $34 = (100010)_2$		

If a binary number is made of all ones, then by using the equation $2^n - 1$, it can be converted to decimal.

Examples

Binary number	$2^n - 1$	Decimal number
11	$2^2 - 1$	3
111	$2^3 - 1$	7
1111	$2^4 - 1$	15
11111	$2^5 - 1$	32

A binary number is represented by $a_5\ a_4\ a_3\ a_2\ a_1\ a_0$ where a_0 is 2^0 , a_1 is 2^1 , and a_5 is 2^5 . Table 1.2 shows 2^n .

1.4.3 Converting Decimal Fraction to Binary

A decimal number representation of $(0.XY)_10$ can be converted into base of 2 and represented by $(0.a_{-1}, a_{-2}, a_{-3}, \text{etc.})_2$.

The fraction number is multiplied by 2, the result of integer part is a_{-1} and fraction part multiply by 2, and then separate integer part from fraction, the integer part represents a_{-2} ; this process continues until the fraction becomes 0.

$$(0.35)_{10} = (\quad)_2$$

0.35*2	=	0.7	=	0	+	0.7	$a_{-1} = 0$
0.7*2	=	1.4	=	1	+	0.4	$a_{-2} = 1$
0.4*2	=	0.8	=	0	+	0.8	$a_{-3} = 0$
0.8*2	=	1.6	=	1	+	0.6	$a_{-4} = 1$
0.6*2	=	1.2	=	1	+	0.2	$a_{-5} = 1$

Sometimes, the fraction does not reach 0 and the number of bits use for the fraction depends on the accuracy that the user defines, therefore the $0.35 = 0.010011$ in binary

Table 1.2 2^n with different values of n

2^n	Decimal value	2^n	Decimal value	2^n	Decimal value
2^0	1	2^8	256	2^{16}	$65,536 = 64 \text{ K}$
2^1	2	2^9	512	2^{17}	$131,072 = 128 \text{ K}$
2^2	4	2^{10}	$1024 = 1 \text{ M}$	2^{18}	$262,144 = 256 \text{ K}$
2^3	8	2^{11}	$2048 = 2 \text{ M}$	2^{19}	$524,288 = 512 \text{ K}$
2^4	16	2^{12}	$4096 = 4 \text{ M}$	2^{20}	$1,048,576 = 1 \text{ G}$
2^5	32	2^{13}	$8192 = 8 \text{ M}$	2^{21}	2 G
2^6	64	2^{14}	$16,384 = 16 \text{ M}$	2^{22}	4 G
2^7	128	2^{15}	$32,768 = 32 \text{ M}$	2^{23}	8 G

Table 1.3 Decimal numbers with binary and hexadecimal equivalents

Decimal	Binary (base of 2)	Hexadecimal (base of 16) or HEX
0	0000	0
1	0001	1
2	0010	2
3	0011	3
4	0100	4
5	0101	5
6	0110	6
7	0111	7
8	1000	8
9	1001	9
10	1010	A
11	1011	B
12	1100	C
13	1101	D
14	1110	E
15	1111	F

The hexadecimal number system has a base of 16 and therefore has 16 symbols (0 through 9, and A through F). Table 1.3 shows the decimal numbers, their binary values from 0 to 15, and their hexadecimal equivalents.

1.4.4 Converting from Hex to Binary

Table 1.3 can also be used to convert a number from hexadecimal to binary and from binary to hexadecimal.

Example 1.7 Convert the binary number 001010011010 to hexadecimal. Each 4 bits are grouped from right to left. By using Table 2.2, each 4-bit group can be converted to its hexadecimal equivalent.

0010	1001	1010
2	9	A

Example 1.8 Convert $(3D5)_{16}$ to binary. By using Table 2.2, the result in binary is:

3	D	5
0011	1101	0101

The resulting binary number is 001111010101.

Example 1.9 Convert 6DB from hexadecimal to binary. By using Table 1.3, the result in binary is:

6	D	B
0110	1101	1011

The resulting binary number is 011011011011.

Example 1.10 Convert $(110111.101)_2$ to decimal.

$$\begin{aligned}(110111.101)_2 &= 1*2^0 + 1*2^1 + 1*2^2 + 0*2^3 + 1*2^4 + 1*2^5 + 1*2^{-1} \\ &\quad + 0*2^{-2} + 1*2^{-3} \\ &= 55.625\end{aligned}$$

1.4.5 Binary Addition

$$1 + 0 = 1, 1 + 1 = 10,$$

Carry bits	11 1
	10101
+	01101
	<hr/>
	100010

In a binary number, the first bit from the left of number is called the *most significant bit (MSb)*, and the first bit from the right of number is called *least significant bit (LSb)*.

$$\underline{\text{MSb}} \rightarrow 1 0 0 1 0 \leftarrow \underline{\text{LSb}}$$

1.5 Complement and Two's Complement

The complement of 1 is 0 and the complement of 0 is 1.

The complement of a binary number is calculated by complementing each bit of the number.

Example 1.11 The complement of 101101 is 010010.

$$\text{Two's Complement of a number} = \text{Complement of a number} + 1$$

Example 1.12 The two's complement of 101011 is

$$010100(\text{complement}) + 1 = 010101$$

Example 1.13 Find the two's complement of 10000:

$$01111(\text{complement}) + 1 = 10000$$

1.5.1 Subtraction of Unsigned Number Using Two's Complement

The following procedure is used to subtract $B = b_5 b_4 b_3 b_2 b_1 b_0$ from $A = a_5 a_4 a_3 a_2 a_1 a_0$:

1. Add two's complement of B to the A.
2. Check to see if the result produces a carry:
 - (a) If the result produces a carry, discard the carry and the result is positive.
 - (b) If the result does not produce a carry, take two's complement of the result, and the result is negative.

Example 1.14 Subtract $B = 101010$ from $A = 110101$.

$$010101 = \text{Complement of } B$$

$$\text{Two's complement of } B = 010101 + 1 = 010110$$

Add two's complement of B to A.

$$\begin{array}{r}
 110101 \\
 + 010110 \\
 \hline
 10\ 01011
 \end{array}$$

Carry, discard the carry and the result is +001011.

Example 1.15 Subtract B = 110101 from A = 101010.

Two's complement of B is 001010 + 1 = 001011.

Add two's complement of B to A.

$$\begin{array}{r}
 001011 \\
 + 101010 \\
 \hline
 110101
 \end{array}$$

As we can see, adding two 6-bit number results in a 6-bit answer. There is no carry; we just take the two's complement of the result.

$$\text{Two's Complement of } 110101 = 001010 + 1 = -001011$$

1.6 Unsigned, Signed Magnitude, and Signed Two's Complement Binary Number

A binary number can be represented in form unsigned number or signed number or signed two's complement, + sign represented by 0 and – sign represented by 1.

Unsigned Number In an unsigned number, all bits of a number are used to represent the number, but in a signed number, the most significant bit of the number represents the sign. A 1 in the most significant position of number represents a negative sign, and 0 in the most significant position of number represents a positive sign.

The 1101 unsigned value is 13.

Signed Magnitude Number In a signed number, the most significant bit represents the sign, where 1101 = -5 or 0101 = +5

In unsigned number, 1101 = 13.

Signed Two's Complement A signed two's complement applies to a negative number. If the sign of the number is one, then the number is represented by signed two's complement.

Example 1.16 Representing $(-5)_{10}$ with 4 bits in signed two's complement.

$(-5)_{10}$ in signed number is 1101, then the two's complement of 101 is 011, and by adding sign bit results in 1011 which represents -5 in signed two's complement.

Example 1.17 Represent $(-23)_{10}$ with an 8-bit signed two's complement.

$(23)_{10} = (1\ 0\ 1\ 1\ 1)_2$ in unsigned base-2

$(1\ 0\ 0\ 10111)_2$ – Extended to signed 8 bits (notice the MSb is **1**)

the two's complement of $(0010111)_2$ is $(1101001)_2$

$(11101001)_2$ is $(-23)_{10}$ in **signed two's complement**.

1.7 Binary Addition Using Signed Two's Complement

The following examples show the results of the addition of two signed numbers:

$$(a) (+3) + (+4)$$

Represent both numbers in binary, and the most significant bit represents the sign, and the result is positive.

$$0011 + 0100 = 0111 = +7$$

$$(b) (+3)_{10} + (-4)_{10}$$

$(-4)_{10}$ in signed two's complement is 1100, then

$0011 + 1100 = 1111$; result does not generate carry of then take two's complement of result which is -1

$$(-3) + (+5) = 1101 + 0101 = 1\ 0010 \text{ (discard carry and result is } +2\text{)}$$

$$(c) (-7)_{10} + (-5)_{10}$$

By representing both numbers in 4-bit signed two's complement,

$$\begin{aligned} (-7)_{10} &= 1001 \\ (-5)_{10} &= 1011 \end{aligned}$$

$$\begin{array}{r} 1001 + 1011 = 10100 \\ \quad \quad \quad \uparrow \\ \quad \quad \quad \text{Sign bit} \end{array}$$

The addition of two negative numbers results positive, and it is called overflow:

$$(+7) + (+6) = (0111) + (0110) = 1101$$

The addition of two positive numbers results negative, and it is called overflow:

Example 1.18 A. Following addition using 8-bit signed two's complement

$$(-38)_{10} + (44)_{10}$$

$$\begin{array}{r} (-38)_{10} \text{ in signed two's complement} = 11011010 \\ (+44)_{10} \qquad \qquad \qquad + 00101100 \\ \hline 100000110 \end{array} \text{ discard the carry and result is } 00000110 = 6$$

B. Add -38 to -44 using 8 bit signed two's complement

$$\begin{array}{r} -38 = 11011010 \\ -44 = 11010100 \\ \hline 10101110 = -82 \end{array}$$

C. Add $+100$ to $+44$

$$\begin{array}{r} 100 = 01100100 \\ 44 = 00101100 \\ \hline 10010000 \end{array}$$

the sign of result is negative then results produce overflow

Addition Overflow The following cases result overflow for adding two signed numbers if:

(a) Both numbers are negative, and results of addition become positive:

$$(-A) + (-B) = +C$$

(b) Both numbers are positive, and results of addition become negative:

$$(+A) + (+B) = -C$$

1.8 Floating Point Representation

The central processing unit (CPU) typically consists of an arithmetic logic unit (ALU), floating point unit (FLU/FPU), registers, control unit, and the cache memory.

The *arithmetic logic unit* performs integer arithmetic operations such as addition, subtraction, and logic operations such as AND, OR, XOR, etc. *Integers* are whole numbers without fractional components. 1, 2, and 3 are integers, while 0.1, 2.2, and 3.0001 all have fractional components are called floating point numbers.

The *floating point unit* performs floating point operations. Floating point numbers have a sign, a mantissa, and an exponent. The Institute of Electrical and Electronics Engineers (IEEE) developed a standard to represent floating point numbers, referred to as IEEE 754. This standard defines a format for both single (32-bit) and double (64-bit) precision floating point numbers. Decimal floating points are represented by $M \times 10^E$, where M is the signed mantissa and E is the exponent.

1.8.1 Single Precision Representation

Floating point numbers in single precision represented by 32 bits as shown in Fig. 1.8

Biased Exponent The biased exponent is the exponent + 127 (01111111_2); therefore, the exponent is represented by a positive number.

Normalized Mantissa The mantissa is represented by 1. M, where M is called normalized mantissa; if M = 00101, then mantissa is 1.00101.

Example 1.19 Find normalized mantissa and biased exponent of $(111.0000111)_2$.
 111.0000111 can be written in the form of $1.110000111 \times 2^{10}$

Where

$$M = 110000111$$

$$\text{Biased exponent} = 10 + 0111111 = 10000001$$

The representation of 111.0000111 in single precision is

1bit	8 bits	23 bits
0	10000001	1100001110000000000000000

Example 1.20 Convert the following single precision floating point to decimal number.

$$101111101\ 1100100000000000000000000$$

S = 1 means mantissa is negative.

$$\text{Biased exponent} = 01111101.$$

$$\text{Exponent} = 01111101 - 01111111 = -00000010.$$

$$\text{Normalized mantissa} = 1100100000000000000000000.$$

$$\text{Mantissa} = -1.1100100000000000000000000.$$

$$\text{Decimal number} = 1.1100100000000000000000000 * 2^{-10} = 0.01110011.$$

Double Precision. In order to increase the accuracy of a floating point number, IEEE 754 offers double precision represented by 64 bits as shown in Fig. 1.9.

$$\text{Biased exponent} = \text{exponent} + 1023$$

1bit		8 bits	23 bits
S	Biased Exponent	Normalized Mantissa	

Fig. 1.8 IEEE 745 floating point single precision (S = represent sign of mantissa. S = 0 means mantissa is positive, and S = 1 means mantissa is negative)

1bit		11 bits	52 bits
S	Biased Exponent	Normalized Mantissa	

Fig. 1.9 IEEE 745 double precision floating point format

Table 1.4 Binary-coded decimal (BCD)

Decimal	BCD
0	0000
1	0001
2	0010
3	0011
4	0100
5	0101
6	0110
7	0111
8	1000
9	1001

Example 1.21 Represent 5.75 in IEEE 745 single precision.

$$\begin{aligned} -15.625 &= (1111.101)_2 \\ -1111.101 &= -1.11101101 * 2^{11} \end{aligned}$$

$$S = 1$$

$$\text{Normalized mantissa} = 0.11101101.$$

$$\text{Biased exponent} = 11 + 01111111 = 10000010.$$

IEEE745 single precision is

$$1\ 10000010\ 111011010000000000000000.$$

1.9 Binary-Coded Decimal (BCD)

In daily life, we use decimal numbers where the largest digit is 9, which is represented by 1001 in binary. Table 1.4 shows decimal numbers and their corresponding BCD code.

Example 1.21 Converting 345 to BCD

Using the table: 0011 0100 0101

Example 1.22 Convert $(10100010010)_{BCD}$ to decimal, separate each 4 bits from right to left, and substitute the corresponding decimal number with BCD the results in 512.

1.10 Coding Schemes

1.10.1 ASCII Code

Each character in ASCII code has a representation using 8 bits, where the most significant bit is used for a parity bit. Table 1.5 shows the *ASCII code* and its hexadecimal equivalent.

Characters from hexadecimal 00 to 1F and 7F are control characters which are nonprintable characters, such as NUL, SOH, STX, ETX, ESC, and DLE (data link escape).

Example 1.23 Convert the word “network” to binary and show the result in hexadecimal. By using Table 1.4, each character is represented by 7 bits and results in:

1001110	1100101	1110100	1110111	1101111	1110010	1101011
N	e	t	w	o	r	k
Or in hexadecimal						
4E	65	74	77	6F	72	6B

1.10.2 Universal Code or Unicode

Unicode is a new 16-bit character-encoding standard for representing characters and numbers in most languages such as Greek, Arabic, Chinese, and Japanese. The ASCII code uses 8 bits to represent each character in Latin, and it can represent 256 characters. The ASCII code does not support mathematical symbols and scientific symbols. Since *Unicode* uses 16 bits, it can represent 65,536 characters or symbols. A character in Unicode is represented by 16-bit binary, equivalent to 4 digits in hexadecimal. For example, the character B in Unicode is U0042H (U represents Unicode). The ASCII code is represented between $(00)_{16}$ and $(FF)_{16}$. For converting ASCII code to Unicode, two zeros are added to the left side of ASCII code; therefore, the Unicode to represent ASCII characters is

Table 1.5 American Standard Code for Information Interchange (ASCII)

Binary	Hex	Char	Binary	Hex	Char	Binary	Hex	Char	Binary	Hex	Char
00000000	00	<i>NUL</i>	01000000	20	SP	10000000	40	@	11000000	60	,
00000001	01	<i>SOH</i>	01000001	21	!	10000001	41	A	11000001	61	a
00000010	02	<i>STX</i>	01000010	22	"	10000010	42	B	11000010	62	b
00000011	03	<i>ETX</i>	01000011	23	#	10000011	43	C	11000011	63	c
00000100	04	<i>EOT</i>	01000100	24	\$	10001000	44	D	11001000	64	d
00000101	05	<i>ENQ</i>	01000101	25	%	10001001	45	E	11001001	65	e
00000110	06	<i>ACK</i>	01000110	26	&	10001100	46	F	11001100	66	f
00000111	07	<i>BEL</i>	01001111	27	,	10001111	47	G	11001111	67	g
00001000	08	<i>BS</i>	01010000	28	(10010000	8	H	11010000	68	h
00001001	09	<i>HT</i>	01010001	29)	10010001	49	I	11010001	69	i
00001010	0A	<i>LF</i>	01010100	2A	*	10010100	4A	J	11010100	6A	j
00001011	0B	<i>VT</i>	01010111	2B	+	10010111	4B	K	11010111	6B	k
00001100	0C	<i>FF</i>	01011000	2C	,	10011000	4C	L	11011000	6C	l
00001101	0D	CR	01011001	2D	-	10011001	4D	M	11011001	6D	m
00001110	0E	<i>SO</i>	01011100	2E	.	10011100	4E	N	11011100	6E	n
00001111	0F	SI	01011111	2F	/	10011111	4F	O	11011111	6F	o
00010000	10	DLE	01100000	30	0	10100000	50	P	11100000	70	p
00010001	11	DC1	01100001	31	1	10100001	51	Q	11100001	71	q
00010010	12	DC2	01100010	32	2	10100010	52	R	11100010	72	r
00010011	13	DC3	01100011	33	3	10100011	53	S	11100011	73	s
00010100	14	DC4	01101000	34	4	10101000	54	T	11101000	74	t
00010101	15	NACK	01101001	35	5	10101001	55	U	11101001	75	u
00010110	16	SYN	01101010	36	6	10101010	56	V	11101010	76	v
00010111	17	ETB	01101011	37	7	10101011	57	W	11101011	77	w
00110000	18	CAN	01110000	38	8	10110000	58	X	11110000	78	x
00110001	19	EM	01110001	39	9	10110001	59	Y	11110001	79	y

0011010	1A	SUB	0111010	3A	:	1011010	5A	Z	1111010	7A	z
0011011	1B	ESC	0111011	3B	;	1011011	5B	I	1111011	7B	i
0011100	1C	FS	0111100	3C	<	1011100	5C	\	1111100	7C	\
0011101	1D	GS	0111101	3D	=	1011101	5D	J	1111101	7D	j
0011110	1E	RS	0111110	3E	<	1011110	5E	^	1111110	7E	~
0011111	1F	US	0111111	3F	?	1011111	5F	-	1111111	7F	DEL

Table 1.6 Unicode values for some Latin and Greek characters

Latin		Greek	
Character	Code (hex)	Character	Code (hex)
A	U0041	φ	U03C6
B	U0042	α	U03B1
C	U0043	γ	U03B3
0	U0030	μ	U03 BC
8	U0038	β	U03B2

Table 1.7 Unicode block allocations

Start code (hex)	End code (hex)	Block name
U0000	U007F	Basic Latin
U0080	U00FF	Latin supplement
U0370	U03FF	Greek
U0530	U058F	Armenian
U0590	U05FF	Hebrew
U0600	U06FF	Arabic
U01A0	U10FF	Georgian

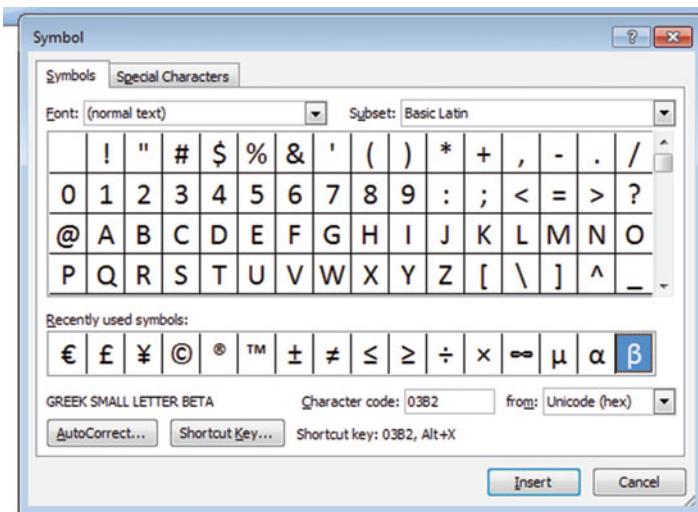


Fig. 1.10 Example of Unicode

between $(0000)_{16}$ and $(00FF)_{16}$. Table 1.6 shows some of the Unicode for Latin and Greek characters. Unicode is divided into blocks of code, with each block assigned to a specific language. Table 1.7 shows each block of Unicode for some different languages (Fig. 1.10).

Example of Unicode: open Microsoft Word and click on insert then symbol will result Fig. 1.10. Click on any character to display the Unicode value of the character, for example, Unicode for β is 03B2 in hex

1.11 Parity Bit

A parity bit is used for error detection of information, since a bit or bits may be changed during the transmission of information from source to destination, a parity bit is an extra bit appended to the information. It represents whether the number of ones or zeroes is either even or odd in the original transmission and can alert the destination to a loss of information.

Even Parity. The extra bit (0 or 1) is chosen such that the number of ones becomes even.

Example 1.24 Our message is $(00111)_2$. By appending a one to the left side of the message, we create $(100111)_2$. Our *even* parity bit has made the total number of ones even (from 3 to 4 ones).

Our message is $(10111)_2$. By appending a zero to the left side of the message, we create $(010111)_2$. Our *even* parity bit has left the total number of ones even (4 ones).

Odd Parity. The extra bit (0 or 1) is chosen such that the number of ones becomes odd.

Our message is $(10111)_2$. By appending a one to the left side of the message, we create $(110111)_2$. Our *odd* parity bit has made the total number of ones even (from 4 to 5 ones).

1.12 Clock

0 and 1 continuously repeated is called clock as shown in Fig. 1.11, when clock change from 0 to 1 is called rising edge of clock and when clock change from 1 to 0 is called falling edge of clock.

Each cycle of the clock consists of 1 and 0 or 0 and 1; it is measured by time (second). If one cycle represented by T and the unit of T is seconds, then

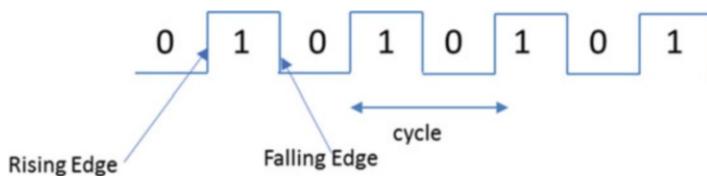


Fig. 1.11 Clock signals

F (frequency) = $1/T$ where the unit of frequency is hertz (Hz) and the unit of T is seconds.

Example 1.25 What is the frequency of a clock if one cycle of the clock is equal to 0.5 ms?

$$F = 1/T = 1/0.5 \times 10^{-3} = 2000 \text{ Hz}$$

1000 Hz	Kilohertz (KHz)
10^6 Hz	Megahertz (MHz)
10^9 Hz	Gigahertz (GHz)

1.13 Transmission Modes

When data is transferred from one computer to another by digital signals, the receiving computer has to distinguish the size of each signal to determine when a signal ends and when the next one begins. For example, when a computer sends a signal as shown in Fig. 1.12, the receiving computer has to recognize how many ones and zeros are in the signal. Synchronization methods between source and destination devices are generally grouped into two categories: asynchronous and synchronous.

1.13.1 Asynchronous Transmission

Asynchronous transmission occurs character by character and is used for serial communication, such as by a modem or serial printer. In asynchronous transmission, each data character has a start bit which identifies the start of the character and 1 or 2 bits which identifies the end of the character, as shown in Fig. 1.13. The data character is 7 bits. Following the data bits may be a parity bit, which is used by the

Fig. 1.12 Digital signals

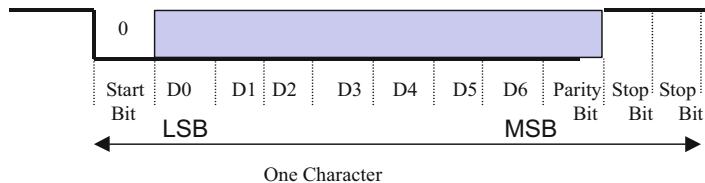
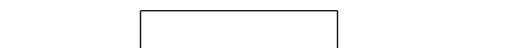


Fig. 1.13 Asynchronous transmission

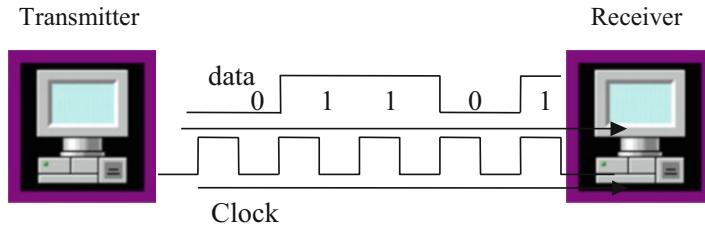


Fig. 1.14 Synchronous transmission

receiver for error detection. After the parity bit is sent, the signal must return to high for at least 1 bit time to identify the end of the character. The new start bit serves as an indicator to the receiving device that a data character is coming and allows the receiving side to synchronize its clock. Since the receiver and transmitter clock are not synchronized continuously, the transmitter uses the start bit to reset the receiver clock so that it matches the transmitter clock. Also, the receiver is already programmed for the number of bits in each character sent by the transmitter.

1.13.2 Synchronous Transmission

Some applications require transferring large blocks of data, such as a file from disk or transferring information from a computer to a printer. *Synchronous transmission* is an efficient method of transferring large blocks of data by using time intervals for synchronization.

One method of synchronizing transmitter and receiver is through the use of an external connection that carries a clock pulse. The clock pulse represents the data rate of the signal, as shown in Fig. 1.14, and is used to determine the speed of data transmission. The receiver of Fig. 1.14 reads the data as 01101, each bit width represented by one clock.

Figure 1.14 shows an extra connection is required to carry the clock pulse for synchronous transmission. In networking, one medium is used for transmission of both information and the clock pulse. The two signals are encoded in a way that the synchronization signal is embedded into the data. This can be done with Manchester encoding or Differential Manchester encoding.

1.14 Transmission Methods

There are two types of transmission methods used for sending digital signals from one station to another across a communication channel: serial transmission and parallel transmission.

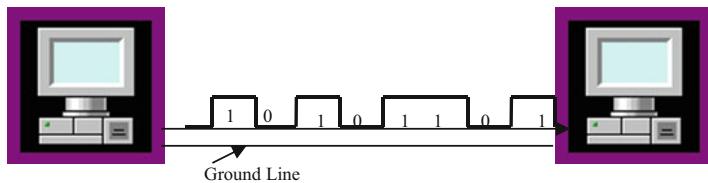


Fig. 1.15 Serial transmission

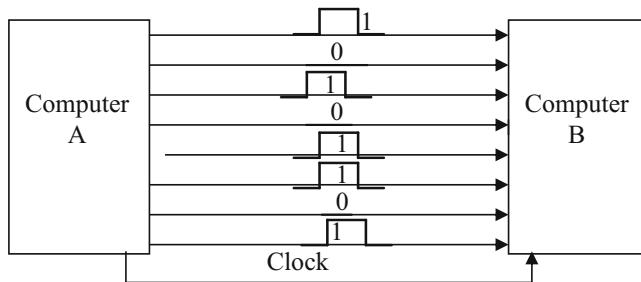


Fig. 1.16 Parallel transmission

1.14.1 Serial Transmission

In *serial transmission*, information is transmitted 1 bit at a time over one wire as shown in Fig. 1.15.

1.14.2 Parallel Transmission

In *parallel transmission*, multiple bits are sent simultaneously, 1 byte or more at a time, instead of bit by bit as in serial transmission. Figure 1.16 shows how computer A sends 8 bits of information to computer B at the same time by using eight different wires. Parallel transmission is faster than serial transmission, at the same clock speed.

1.15 Summary

Information exchanges between two electrical systems are in the form of digital or analog signals.

Modern computers work with digital signals:

- A digital signal is represented by two voltages.

- Binary is the representation of a number in base of 2.
- The frequency of a signal is the inverse of its cycle time.
- One digit in binary is called a bit, 8 bits is called 1 byte, and 4 bytes is called one word.
- Information is represented inside the computer by binary or base of 2.
- Negative numbers inside the computer is represented by the two's complement.
- The most significant bit in signed numbers is represented by the sign of the number.
- Positive is represented by zero and negative is represented by one.
- One's complement of a binary number is the complement of each bit of the number.
- Two's complement of a binary number is the complement of the number plus one.
- Binary-coded decimal (BCD) is used for representing decimal numbers from 0 to 9.
- The hexadecimal number system is used in digital systems and computers as an efficient way of representing binary quantities.
- Parity bit is used for error detection of one bit error.
- IEEE 757 standard is used to represent floating point number.
- Information is represented by ASCII code inside the computer; ASCII code is made of 7 bits.
- Information between components of a computer can be transmitted in serial or parallel form.
- In serial transmission, information is transmitted 1 bit at a time
- In parallel transmission, information is transmitted in multiple bits at a time.
- The next chapter will cover Boolean logic, Boolean algebra theorems, and logic gates. Logic gate is the basic component of an integrated circuit (IC)

Problems and Questions

1. List three computer input devices.
2. List three computer output devices.
3. Show an analog signal.
4. Show a digital signal.
5. How many bits is:
 - (a) Byte
 - (b) Half word
 - (c) Word
6. Convert the following decimal numbers to binary:
 - (a) 35
 - (b) 85
 - (c) 23.25
7. Convert the following binary numbers to decimal:

- (a) 1111101
 (b) 1010111.1011
 (c) 11111111
 (d) 10000000
8. Convert the following binary numbers to hexadecimal:
- (a) 1110011010
 (b) 1000100111
 (c) 101111.101
9. Find the frequency of digital signal with the following clock cycles:
- (a) 1 s
 (b) 0.1 s
 (c) 0.02 s
 (d) 0.02 ms
10. The following frequencies of a digital signal are given, find the clock cycle of digital signal:
- (a) 10 Hz
 (b) 200 Hz
 (c) 10,000 Hz
 (d) 4 MHz
11. Convert each of the following numbers to base of 10:
- (a) $(34A)_{16}$
 (b) $(FAC)_{16}$
12. Convert the following decimal numbers to base of 16:
- (a) $(234)_{10}$
 (b) $(75)_{10}$
13. Convert the following numbers to binary:
- (a) $(3FDA)_{16}$
 (b) $(FDA.5F)_{16}$
14. Perform the following additions:
- $$\begin{array}{r}
 1101010 \quad 1100101 \\
 1011011 \quad +1010111 \\
 \hline
 \end{array}$$
15. Find two's complements of the following numbers:
- (a) 11111111
 (b) 10110000
 (c) 10000000

- (d) 00000000
16. The word “LOGIC” is given.
- Represent in ASCII.
 - Add even parity bit to each character and represent each character in hex.
17. Represent $(465)_{10}$ in BCD.
18. Represent $(100101100111)_{BCD}$ in decimal.
19. Represent $(110010000100)_{BCD}$ in decimal.
20. Convert the following two's complement numbers to decimal:
- 1011
 - 11111001
 - 10011111
21. Subtract the following unsigned numbers using two's complement:
- $11110011 - 11000011$
 - $10001101 - 11111000$
22. Perform addition of the following signed numbers; assume each number is represented by 6 bits and state if the result of each addition produces overflow:
- $(+12) + (+7)$
 - $(+25) + (+30)$
 - $(-5) + (+9)$
 - $(-6) + (-7)$
 - $(-36) + (-12)$
23. What is the largest 16-bit binary value that can be represented by:
- Unsigned number
 - Signed magnitude
 - Signed two's complement
24. Represent the following decimal numbers in IEEE 745 single precision:
- 34.375
 - 0.045
25. Convert the following IEEE 745 single precision to decimal number:
- $1\ 10000100\ 01110000000000000000000000000000$
 - $0\ 01111100\ 11100000000000000000000000000000$
26. List the types of transmission modes.
27. Convert each of the following signed magnitude numbers to decimal:
- 11000011
 - 10001111
28. Represent each of the following numbers in 8-bit signed two's complement:

- (a) -15
- (b) -24
- (c) -8

29. Perform the following addition:

$$\begin{array}{r} \text{0F4A} \\ +\text{420B} \\ \hline \end{array}$$

Chapter 2

Boolean Logics and Logic Gates

Objectives: After completing this chapter, you should be able to:

- Understand the basic operation of Boolean theorems.
- Explain the operation of different logic gates such as AND, OR, NOT, XOR, and NAND gates.
- Show the truth table of different logic gates.
- Distinguish between the different types of integrated circuits (ICs).
- Apply Boolean theorems to simplify Boolean function.
- Draw logic circuit for Boolean function.
- Show the truth table of Boolean function.
- Find the output function of a digital logic circuit.
- Distinguish between the SSI, MSI, LSI, and VLSI.

2.1 Introduction

Logic gates are made of transistors, and they are the basic components of integrated circuit (IC). Logic gates are used for designing digital system; there are three basic logic operations and they are called AND, OR, and NOT. The characteristic of a digital system can be represented by a function or truth table. Boolean theorems are used to simplify Boolean function in order to use fewer logic gates. Integrated circuits are classified based on the number of gates that they contain, and they are called SSI, MSI, LSI, and VLSI.

2.2 Boolean Logics and Logic Gates

AND Logic The AND logic is denoted by a period “.”, but most of the time, the period is left out. $X.Y$ or XY is pronounced as X AND Y .

$$X \text{ AND } Y = Z, \quad Z = 1 \text{ if and only if } X = 1 \text{ and } Y = 1 \text{ otherwise } Z = 0.$$

The AND logic operation can be represented by the electrical circuit of Fig. 2.1.

Assume X and Y are switches and Z is the light; $X = 0$, $Y = 0$ means the switches are open and the light being off means zero and the light on means one. Then we can make a table; Table 2.1 shows the operation of Fig. 2.1.

Figure 2.2 shows a 2-input AND gate and Table 2.2 shows the truth table for the AND gate. The output of the AND gate is one when both inputs are one.

OR Logic. The OR operation is represented by a plus sign, “+” or a V, where “+” is the most popular symbol used. $X + Y$ is pronounced X OR Y .

$$X + Y = Z, \quad Z = 1 \text{ if } X = 1 \text{ OR } Y = 1 \text{ or both } X = 1 \text{ and } Y = 1.$$

The OR operation can be represented by the electrical circuit in Fig. 2.3. In Fig. 2.3, the light is off when both switches are off, and the light is on when at least one switch is closed. Figure 2.4 shows a 2-input OR gate and Table 2.3 shows truth table for the 2-input OR gate.

Fig. 2.1 Representation of the AND operation

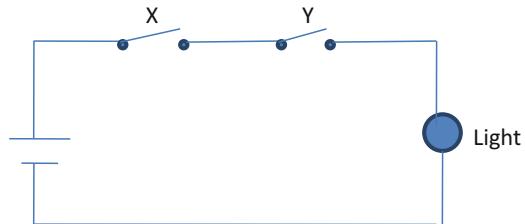


Table 2.1 Operation of Fig. 2.1

X	Y	Light
Off	Off	Off
Off	On	Off
On	Off	Off
On	On	On

Fig. 2.2 2-input AND gate



Table 2.2 AND gate truth table

X	Y	Z
0	0	0
0	1	0
1	0	0
1	1	1

Fig. 2.3 Electrical circuit representation of the OR operation

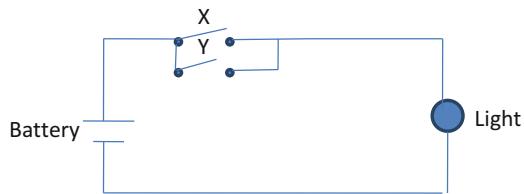


Fig. 2.4 2-input OR gate

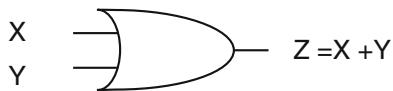


Table 2.3 Truth table of the 2-input OR gate

X	Y	Z
0	0	0
0	1	1
1	0	1
1	1	1

Fig. 2.5 NOT gate

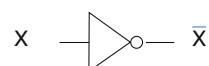


Table 2.4 Truth table for the NOT gate

X	X'
0	1
1	0

NOT Logic The NOT logic performs a complement, meaning it converts a 1 to 0 and 0 to 1. Also called an inverter, the NOT X is represented by X' or \bar{X} . Figure 2.5 shows the NOT gate and Table 2.4 shows truth table for the NOT gate (inverter).

NAND Gate. Figure 2.6 shows 2-input NAND gate. The NAND gate can be made from an AND gate and a NOT gate as shown in Fig. 2.7. Table 2.5 shows the truth table of the 2-input NAND gate.

NOR Gate. Figure 2.8 shows a NOR logic gate. NOR gates are made of OR and NOT gates. Table 2.6 shows the truth table of the 2-input NOR gate.

Fig. 2.6 2-input NAND gate



Fig. 2.7 AND-NOT gates used together to act as NAND

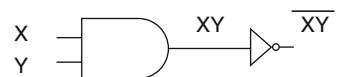


Table 2.5 Truth table of the 2-input NAND

X	Y	\overline{XY}
0	0	1
0	1	1
1	0	1
1	1	0

Fig. 2.8 NOR gate

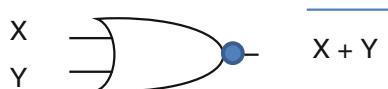


Table 2.6 Truth table for the 2-input NOR gate

X	Y	$X + Y$
0	0	1
0	1	0
1	0	0
1	1	0

Fig. 2.9 2-input XOR

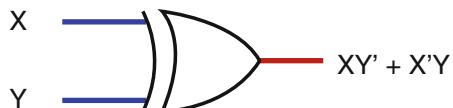


Table 2.7 Truth table for XOR gate

X	Y	$X \oplus Y$
0	0	0
0	1	1
1	0	1
1	1	0

Exclusive OR Gate Figure 2.9 shows an exclusive OR gate. Exclusive OR is represented by \oplus and is labeled XOR. Table 2.7 shows the truth table for the XOR gate.

$$X \oplus Y = X'Y + XY'$$

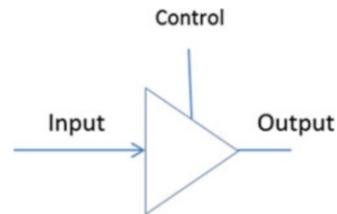
Fig. 2.10 Exclusive NOR gate



Table 2.8 Truth table for exclusive NOR gate

X	Y	X ⊕ Y
0	0	1
0	1	0
1	0	0
1	1	1

Fig. 2.11 Tri-state device



Exclusive NOR Gate Figure 2.10 shows an exclusive NOR gate. Exclusive NOR is represented by \oplus and labeled XNOR. Table 2.8 shows the truth table for the exclusive NOR gate.

Tri-State Device

Figure 2.11 shows the diagram of a tri-state device; the control line controls the operation of tri-state devices.

In Fig. 2.11, if the control line is set to zero, then there is no connection between input and output (the output is high impedance). If the control line is set to one, then output value is equal to the input value.

Multiple Inputs Logic Gates

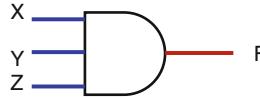
Figure 2.12 shows 3-input AND gate with its truth table, Fig. 2.13 shows 3-input OR gate with its truth table, Fig. 2.14 shows 3-input NOR gates with its truth table, and Fig. 2.15 shows 3-input NAD gate with its corresponding table.

2.3 Integrated Circuit (IC) Classifications

A transistor is a basic component of integrated circuits (IC). Figure 2.16 shows a transistor with an IC. Transistors act like a switch in integrated circuits. An integrated circuit is made from a hundred to millions of transistors.

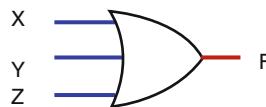
Integrated circuits are classified based on the number of the gates inside the IC such as SSI, MSI, LSI, and VLSI.

Fig. 2.12 3-input AND gate and its truth table



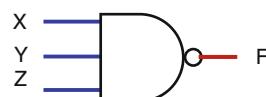
X	Y	Z	F
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	0
1	0	0	0
1	0	1	0
1	1	0	0
1	1	1	1

Fig. 2.13 3-input OR gate and its truth table



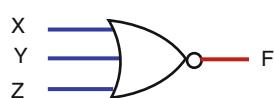
X	Y	Z	F
0	0	0	0
0	0	1	1
0	1	0	1
0	1	1	1
1	0	0	1
1	0	1	1
1	1	0	1
1	1	1	1

Fig. 2.14 3-input NAND gate and its truth table



X	Y	Z	F
0	0	0	1
0	0	1	1
0	1	0	1
0	1	1	1
1	0	0	1
1	0	1	1
1	1	0	1
1	1	1	0

Fig. 2.15 3-input NOR gate and its truth table



X	Y	Z	F
0	0	0	1
0	0	1	0
0	1	0	0
0	1	1	0
1	0	0	0
1	0	1	0
1	1	0	0
1	1	1	0

Small-Scale Integration (SSI) SSI refers to an IC that has less than 10 gates. Figure 2.17 shows the inside of a 74HC08 (7408) IC, and Fig. 2.18 shows an image of a 74HC08 IC.

Fig. 2.16 Transistor (left),
IC (right)

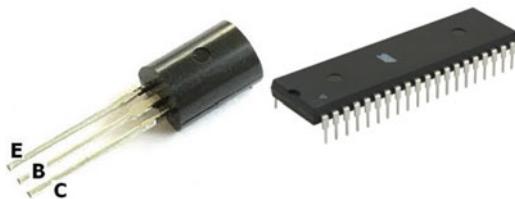


Fig. 2.17 TTL 7408
2 input AND gate

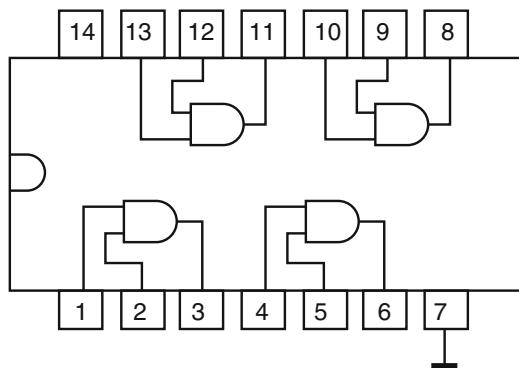
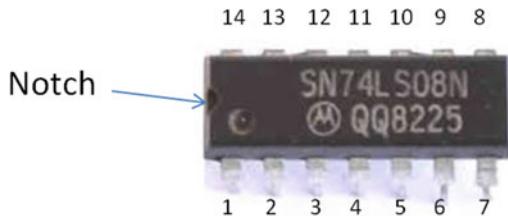


Fig. 2.18 74LS08 pins



Integrated Circuit Pins Numbering Figure 2.18 shows a TTL 7408 IC; an IC chip should be read with the notch on the left hand side. The labeling convention starts with the left bottom pin under the notch and goes in a counterclockwise direction.

The left bottom pin is pin #1.

The right bottom pin is pin #7.

The right upper pin is pin #8.

The left upper pin is pin #14.

As shown in Fig. 2.18, the IC number is 74LS08 where LS represents the material IC was made with. Also on the IC, there is the letter M representing Motorola which is the manufacturer of the IC, Intel uses the character “i,” and Texas Instruments uses a map of Texas.

Medium-Scale Integration (MSI). Refers to an IC that contains between 10 and 100 gates such as decoders and multiplexers.

Large-Scale Integration (LSI). Refers to an IC that contains between 100 and 1000 gates.

Very-Large-Scale Integration (VLSI). Refers to an IC that contains more than 1000 gates.

2.4 Boolean Algebra Theorems

Boolean theorems are used to simplify Boolean functions in order to use fewer gates. Any variable such as X in binary can have a value of one or zero.

Theorem #1

$$\mathbf{X} + \mathbf{X} = \mathbf{X}$$

Proof: Select X as 0 then $0 + 0 = 0$; select X = 1 then $1 + 1 = 1$ results: $\mathbf{X} + \mathbf{X} = \mathbf{X}$.

Theorem #2

$$\mathbf{X} + \mathbf{1} = \mathbf{1}$$

Proof: Select X = 0 then $0 + 1 = 1$; select X = 1 then $1 + 1 = 1$; both cases result in 1 then $\mathbf{X} + \mathbf{1} = \mathbf{1}$.

Theorem #3

$$\mathbf{X} + \mathbf{0} = \mathbf{X}$$

Proof: Select x = 0 then $0 + 0 = 0$; select X = 1 then $1 + 0 = 1$; the result is whatever value X is.

Theorem #4

$$\mathbf{X} + \mathbf{X}' = \mathbf{1}$$

Proof: Select X = 0 then $0 + 1 = 1$; select X = 1 then $1 + 0 = 1$; in both cases the result is 1.

Theorem #5

$$\mathbf{X}\mathbf{X} = \mathbf{X}$$

Proof: Select X = 1 then $1 \cdot 1 = 1$; select X = 0 then $0 \cdot 0 = 0$; therefore $\mathbf{X}\mathbf{X} = \mathbf{X}$.

Table 2.9 The truth table for $X(Y + Z) = XY + XZ$

X	Y	Z	$Y+Z$	$X(Y+Z)$	XY	XZ	$XY + XZ$
0	0	0	0	0	0	0	0
0	0	1	1	0	0	0	0
0	1	0	1	0	0	0	0
0	1	1	1	0	0	0	0
1	0	0	0	0	0	0	0
1	0	1	1	1	0	1	1
1	1	0	1	1	1	0	1
1	1	1	1	1	1	1	1

Theorem #6

$$X \cdot 1 = X$$

Proof: Select $X = 1$ then $1 \cdot 1 = 1$; select $X = 0$ then $0 \cdot 1 = 0$; therefore $X \cdot 1 = X$.

Theorem #7

$$X \cdot X' = 0$$

Proof: Select $X = 0$ then $0 \cdot 1 = 0$; select $X = 1$ then $1 \cdot 0 = 0$; both values of X result in 0.

Theorem #8

$$(X')' = X$$

$(0')' = (1)' = 0$, $(1')' = (0)' = 1$ Whatever the value X has.

Distributive Theorem

$$X(Y + Z) = XY + XZ$$

In order to prove the above theorem, the truth table of both sides of the theorem is generated as shown in Table 2.9 and shows both sides generate the same truth table.

Table 2.10 The truth table showing De Morgan's Law

X	Y	$X+Y$	$(X+Y)'$	X'	Y'	$X'Y'$
0	0	0	1	1	1	1
0	1	1	0	1	0	0
1	0	1	0	0	1	0
1	1	1	0	0	0	0

De Morgan's Theorem I

$$(X + Y)' = X' Y'$$

In this theorem the OR between X and Y is negated and changes the OR operation to the AND operation.

Proof: By making a truth table for both sides of the theorem, it shows that both sides of the theorem generate the same truth table (Table 2.10).

De Morgan's Theorem II

$$(XY)' = X' + Y'$$

In this theorem the XY is complemented and changes it from an AND operation to an OR operation with each component complemented.

$$\text{Example: } (WXYZ)' = W' + X' + Y' + Z'$$

If the truth table of both sides were generated, then it would show that both sides have the same truth table result.

Commutative Law

$$\begin{aligned} X + Y &= Y + X \\ XY &= YX \end{aligned}$$

Associative Law

$$\begin{aligned} X(YZ) &= (XY)Z \\ X + (Y + Z) &= (X + Y) + Z \end{aligned}$$

More Theorems

The following are useful theorems:

- (a) $X + X'Y = X + Y$
- (b) $X' + XY = X' + Y$
- (c) $X + X'Y' = X + Y'$
- (d) $X' + XY' = X' + Y'$

Example: Simplify the Following Functions

- (a) $F(X, Y, Z) = XY'Z + XY'Z' + XY$
 $F(X, Y, Z) = XY'(Z + Z') + YZ$ where $Z + Z' = 1$ then
 $F(X, Y, Z) = XY' + XY = X(Y + Y') = X$
- (b) $F(X, Y, Z) = (X' + Y)(X + Y') = X'X + X'Y' + XY + YY'$ where $X'X$ and YY' are zero then $F(X, Y, Z) = X'Y' + XY$

2.5 Boolean Function

Boolean function is represented by algebraic expression which is made of binary variables such as X, Y, and Z and logic operations between variables such as AND, OR, and NOT.

$F(X, Y, Z) = X + YZ$ is a Boolean function.

Figure 2.19 shows the logic circuit for function F where X, Y, and Z are the inputs and F is the output; Table 2.11 shows the truth table of the function F.

The truth table shows the characteristics of function F; the function F = 1 when the inputs to the circuit are 100 or 101 or 110 or 111.

Fig. 2.19 Logic circuit for a function $F(X, Y, Z) = X + YZ$

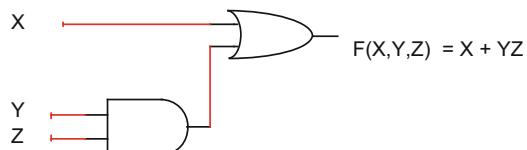


Table 2.11 The truth table for function $F(X, Y, Z) = X + YZ$

X	Y	Z	YZ	$X + YZ$
0	0	0	0	0
0	0	1	0	0
0	1	0	0	0
0	1	1	1	1
1	0	0	0	1
1	0	1	0	1
1	1	0	0	1
1	1	1	1	1

Complement of a Function

In order to complement a function, both sides of the function must be complemented.

Example: Complement the following function:

$$F(X, Y, Z) = XY + Y'Z$$

Complementing both sides of the function $F(X, Y, Z)$ results in the following:

$$F'(X, Y, Z) = (XY + Y'Z)' \text{ using De Morgan's theorem.}$$

$$F'(X, Y, Z) = (XY)'(Y'Z)'$$

$$F'(X, Y, Z) = (X' + Y')(Y + Z')$$

Example: Find the complement of the following function:

$$F(X, Y, Z) = (X' + Y')(Y + Z')$$

Complement both sides of the function:

$$F'(X, Y, Z) = [(X' + Y')(Y + Z')]'$$

Applying De Morgan's theorem results

$$F'(X, Y, Z) = [(X' + Y')]' + [(Y + Z')]'$$

$$F'(X, Y, Z) = [(XY)] + [(Y'Z)]$$

$$F'(X, Y, Z) = (XY) + (Y'Z)$$

2.6 Summary

- Boolean logic consists of the AND, OR, and NOT logics.
- The output of the 2-input AND gate is one when both inputs are one; otherwise the output is zero.
- The output of the 2-input OR gate is one when at least one of the inputs is one; otherwise the output is zero.
- NOT gate performs one's complement.
- The integrated circuits (IC) are classified by SSI (small-scale integration), MSI (medium-scale integration), LSI (large-scale integration), and very-large-scale integration.
- A NAND gate is equivalent of the AND-NOT.
- A NOR gate is equivalent of the NOR-NOT.
- The 2-input XOR has output one when the inputs are not equal; otherwise the output is zero.

- The 2-input exclusive NOR (XNOR) is equivalent of the XOR-NOT.
- Chapter 3 will cover minterms and maxterms, apply K-map to simplify a function, and use universal gates to draw logic circuit.

Problems

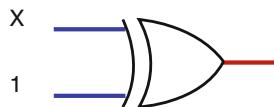
1. Show truth table for 4-input AND, OR, NOR, and NAD gates.
2. If $A = 11001011$ and $B = 10101110$, then what is the value of the following operations:
 - (a) A AND B
 - (b) A OR B
3. If $A = 11001011$ and $B = 10101110$, what is the value of the following operations (F in hex = 1111):
 - (a) A NOT
 - (b) A XOR B
 - (c) A AND 0F
 - (d) A AND F0
4. Draw a logic circuit for the following functions:
 - (a) $F(X, Y, Z) = XY' + XZ' + YZ$
 - (b) $F(X, Y, Z) = (X + Y')(X' + Z')(Y + Z)$
5. Use Boolean theorems to simplify the following expressions:
 - (a) $X + X + X$
 - (b) $XY + XY$
 - (c) YYY
 - (d) $X + XY$
 - (e) $XY' + Y'$
 - (f) $(X + Y)Y'$
 - (g) $(XY) + (XY)'$
 - (h) $X'Y' + XY$
6. Simplify the following functions:
 - (a) $F(X, Y, Z) = XY + X'Y + XZ$
 - (b) $F(X, Y, Z) = (X + Y)(X' + Y + Z)$
 - (c) $F(X, Y, Z) = XY'Z + XYZ + Y'Z$
 - (d) $F(X, Y, Z) = XY + X'YZ$
 - (e) $F(X, Y, Z) = X'Y + XYZ'$
 - (f) $F(X, Y, Z) = (XY) + (X + Y + Z)'X + YZ$
 - (g) $F(X, Y, Z) = (XY)' + (X + Y + Z)'$
7. Find the truth table for the following functions:
 - (a) $F(X, Y, Z) = XY' + YZ + XZ'$
 - (b) $F(X, Y, Z) = (X + Y')(Y + Z)(X' + Z')$

8. If $A = 10110110$ and $B = 10110011$, then find

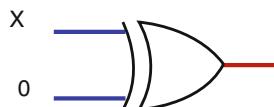
- (a) A NAND B
- (b) A NOR B
- (c) A XOR B

9. Find the output of the following gates:

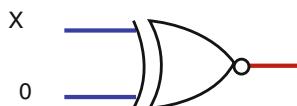
(a)



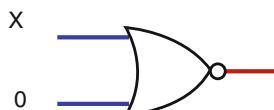
(b)



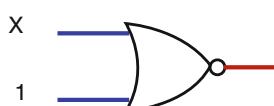
(c)



(d)

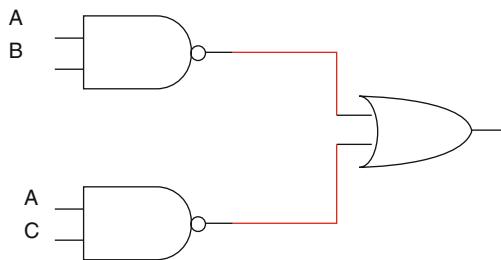


(e)

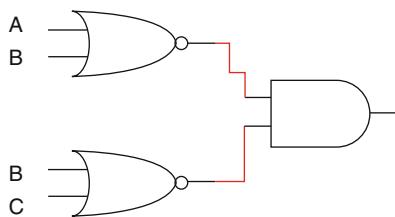


10. Show the output of the following logic circuits:

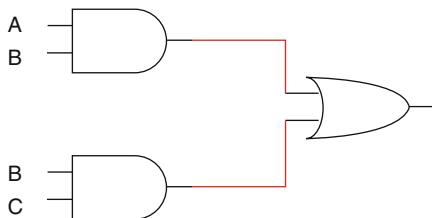
(a)



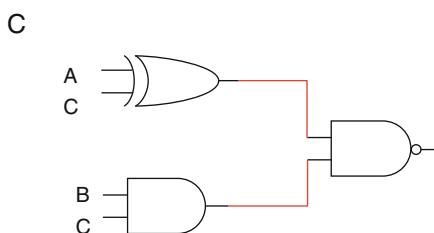
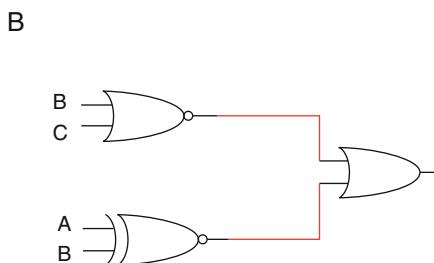
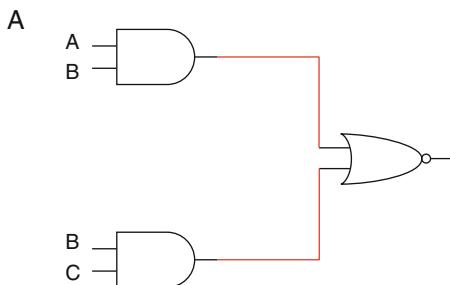
(b)



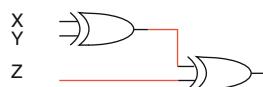
(c)



11. Find the output function of the following logic circuits:



12. Find the output function of the following logic circuit:



13. Draw a logic circuit and show the truth table for the following functions:

- $F(X, Y) = (XY)' + X(X + Y')$
- $F(X, Y, Z) = (X + Y + Z')' (X' + Y')$
- $F(X, Y, Z) = (X \text{ XOR } Y) (X \text{ NOR } Y')$
- $F(X, Y, Z) = (X' + Y' + Z) (X + Y)$

14. Show truth table for each of the following functions:

- (a) $F(X, Y, Z) = XY' + XZ' + YZ$
- (b) $F(X, Y, Z) = (X + Y)(X + Z')$
- (c) $F(X, Y, Z) = XY(Y + Z')$

15. Simplify the following functions:

- (a) $F(X, Y, Z) = YZ + (X + Y)' + (XYZ)'$
- (b) $F(X, Y, Z) = (X + Y + Z)'(X + Y)$

16. Draw Logic circuits for the following functions

- (a) $F(X, Y, Z) = (X + Y)' + YZ$
- (b) $F(X, Y, Z) = (XYZ)' + XZ + YZ$

Chapter 3

Minterms, Maxterms, Karnaugh Map (K-Map), and Universal Gates

Objectives: After completing this chapter, you should be able to:

- Represent a Boolean function in the form of sum of minterms and product of maxterm.
- Generate a truth table from a function that is represented by the sum of minterms.
- Generate a truth table from a function that is represented by the product of minterms.
- Develop a function from the truth table.
- Use K-map to simplify a function.
- Apply don't care condition in a K-map.
- Draw logic circuit using only NAND or NOR gates.

3.1 Introduction

Digital circuit can be represented by a truth table or Boolean function. In a digital circuit with multiple digital inputs and multiple digital outputs, the outputs depend on the current value of inputs. A Boolean function can be represented in the form of *sum of minterms* or the *product of maxterms*, which enable the designer to make a truth table more easily. Also, Boolean functions can be simplified using Karnaugh map (**K-map**) without using Boolean theorems, by transferring a function to K-map and reading simplified function from K-map. Most digital systems are designed by using universal gates (NAND or NOR).

3.2 Minterms

A *minterm* is associated with each combination of variables in a function. If a function has n variables, then it has 2^n minterms. Consider two Boolean variables, X and Y. There are four different possible combinations that can be generated from X AND Y, and they are $\bar{X}\bar{Y}$, $\bar{X}Y$, $X\bar{Y}$, and XY . These four combinations are called the *minterms* for X AND Y. Table 3.1 shows the minterms and their designations for $F(X,Y) = (X \text{ AND } Y)$.

In Table 3.1, $\bar{X}\bar{Y} = 1$, if $X = 0$ and $Y = 0$ then $\bar{X}\bar{Y}$ is represented by m_0 (decimal number of 00); $\bar{X}Y = 1$ if $X = 0$ and $Y = 1$ then $\bar{X}Y$ is represented by m_1 ; $X\bar{Y} = 1$ if $X = 1$ and $Y = 0$ and $X\bar{Y}$ is represented by m_2 ; $XY = 1$ if $X = 1$ and $Y = 1$ then XY is represented by m_3 .

Application of Minterms. It is simple to generate a truth table from minterms and vice versa. Consider the function $F(X,Y) = X\bar{Y} + \bar{X}Y$ and its truth table (Table 3.2); this function can be represented as $F(X,Y) = m_1 + m_2$ or each minterm that represents a *one* in the truth table. This may also be rewritten as $F(X,Y) = \sum(1,2)$.

Three-Variable Minterms The three variables X, Y, and Z generate eight minterms as shown in Table 3.3.

Example 3.1 Find the truth table for the following function:

$$F(X,Y,Z) = X'Y'Z + X'YZ + XYZ$$

The function F can be represented by a *sum of the minterms* (or where $F = 1$):

$$F(X,Y,Z) = m_1 + m_3 + m_7$$

or

$$F(X,Y,Z) = \sum(1,3,7)$$

Table 3.1 Minterms of $F(X,Y)$

X Y	Minterm	Designation
0 0	$\bar{X}\bar{Y}$	m_0
0 1	$\bar{X}Y$	m_1
1 0	$X\bar{Y}$	m_2
1 1	XY	m_3

Table 3.2 Truth table for function $F(X,Y) = X\bar{Y} + \bar{X}Y$ with minterms

X	Y	F	
0	0	0	m_0
0	1	1	m_1
1	0	1	m_2
1	1	0	m_3

Table 3.3 Three-variable minterms

X Y Z	Minterms	Designation
0 0 0	$X'Y'Z'$	m_0
0 0 1	$X'Y'Z$	m_1
0 1 0	$X'YZ'$	m_2
0 1 1	$X'YZ$	m_3
1 0 0	$XY'Z'$	m_4
1 0 1	$XY'Z$	m_5
1 1 0	XYZ'	m_6
1 1 1	XYZ	m_7

Table 3.4 Truth table for function $F(X, Y, Z) = X'Y'Z + X'YZ + XYZ$

X Y Z	F
0 0 0	0
0 0 1	1
0 1 0	0
0 1 1	1
1 0 0	0
1 0 1	0
1 1 0	0
1 1 1	1

The truth table for this function contains a *one* in row 1, row 3, and row 7. The rest of the rows are *zeros* as shown in Table 3.4. The function for a truth table can also be determined from the sum of the minterms.

Example 3.2 The following truth table is given; find the function F.

In the following table, the output of function F is one when the input is $001 = m_1$, $011 = m_3$, $101 = m_5$, and $111 = m_7$; therefore $F(X, Y, Z) = m_1 + m_3 + m_5 + m_7$ or

$$F(X, Y, Z) = \sum (1, 3, 5, 7)$$

X Y Z	F
0 0 0	0
0 0 1	1
0 1 0	0
0 1 1	1
1 0 0	0
1 0 1	1
1 1 0	0
1 1 1	1

Substituting each designation of a minterm with its actual product term (e.g., $m_0 = X'Y'Z'$) results in the following function:

$$F(X, Y, Z) = X'Y'Z + X'YZ + XY'Z + XYZ$$

Example 3.3 For the following truth table:

- (a) Find the function F.
- (b) Simplify the function.
- (c) Draw the logic circuit for the simplified function.

X Y Z	F
0 0 0	1
0 0 1	0
0 1 0	1
0 1 1	1
1 0 0	0
1 0 1	0
1 1 0	0
1 1 1	1

From the truth table, where $F = 1$, we select the minterms m_0 , m_2 , m_3 , and m_7 :

$$F(X, Y, Z) = m_0 + m_2 + m_3 + m_7$$

Or

$$F(X, Y, Z) = \bar{X}\bar{Y}\bar{Z} + \bar{X}Y\bar{Z} + \bar{X}YZ + XYZ$$

$$F(X, Y, Z) = \bar{X}\bar{Z}(\bar{Y} + Y) + YZ(\bar{X} + X)$$

$$F(X, Y, Z) = \bar{X}\bar{Z} + YZ$$

The logic circuit for the simplified function F is given in Fig. 3.1.

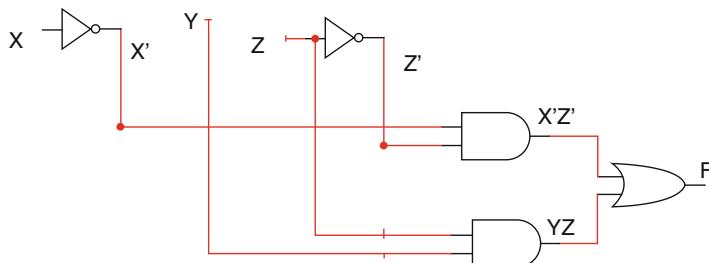


Fig. 3.1 Logic circuit for $F(X, Y, Z) = \bar{X}\bar{Z} + YZ$

3.3 Maxterms

Maxterm is complement of a minterm. If the *minterm* \mathbf{m}_0 is $(\bar{X}\bar{Y}\bar{Z})$, then the *maxterm* \mathbf{M}_0 is

$$(\overline{\bar{X}\bar{Y}\bar{Z}}) = X + Y + Z$$

Table 3.5 shows the maxterms for three variables.

In a truth table, an output of *one* represents *minterms*, and an output of *zero* represent *maxterms*. Consider the truth Table 3.6, where the function F can be expressed as the *product of maxterms*. (Please note: the *product* of maxterms, as opposed to the *sum* of minterms.)

$F(X, Y, Z) = M_0 M_2 M_4 M_5 M_6$, or it can be represented by

$$F(X, Y, Z) = \pi(0, 2, 4, 5, 6)$$

Substituting each designated maxterm with the corresponding maxterm results in:

$$F(X, Y, Z) = (X + Y + Z)(X + Y' + Z)(X' + Y + Z)(X' + Y + Z')$$

Table 3.5 Maxterms of function $F(X, Y, Z)$

X Y Z	Maxterm	Designation
0 0 0	$X + Y + Z$	M_0
0 0 1	$X + Y + Z'$	M_1
0 1 0	$X + Y' + Z$	M_2
0 1 1	$X + Y' + Z'$	M_3
1 0 0	$X' + Y + Z$	M_4
1 0 1	$X' + Y + Z'$	M_5
1 1 0	$X' + Y' + Z$	M_6
1 1 1	$X' + Y' + Z'$	M_7

Table 3.6 Truth Table for $F(X, Y, Z) = M_0 M_2 M_4 M_5 M_6$

X Y Z	F
0 0 0	0
0 0 1	1
0 1 0	0
0 1 1	1
1 0 0	0
1 0 1	0
1 1 0	0
1 1 1	1

3.4 Karnaugh Map (K-Map)

Karnaugh maps are used to simplify a Boolean function without using Boolean algebra theorems. A K-map is also another way to represent the truth table of a function. K-maps are made of cells where each cell represents a minterm. Cells marked with a *one* will be the minterms used for the *sum of the minterms* representation of a function. Conversely, cells marked with a *zero* will be used for the *product of the maxterms* representation.

Two variables X and Y can have four minterms as shown in Table 3.7. Each minterm is represented by a cell in the K-map, so a two-variable K-map contains four cells as shown in Fig. 3.2.

In Fig. 3.2 each cell represents a minterm. The cell located at row 0 and column 0 represents m_0 (minterm zero) or $X'Y'$. The cell located at row 1 and column 1 is represented by m_3 or XY . As shown in Fig. 3.2, both cells in row zero contain X' , so this row is labeled the X' row. Both cells in row 1 contain X so that row is labeled as the X row.

A K-map of a function is another way to represent the truth table of the function, as seen in Fig. 3.3.

Consider the function $F(X, Y) = XY' + X'Y' = m_2 + m_0$. The truth table for the function is given in Table 3.8, and the function is also mapped to a K-map as shown in Fig. 3.3.

Adjacent Cell Two cells are adjacent if they differ on only one variable. The cells $X'Y'$ and $X'Y$ are adjacent because their only difference is Y' and Y. Adjacent cells can be combined in order to simplify a K-map's function.

Table 3.7 Minterms for two variables

X Y	Minterms	Designation
0 0	$X'Y'$	m_0
0 1	$X'Y$	m_1
1 0	XY'	m_2
1 1	XY	m_3

Fig. 3.2 Two-variable K-map

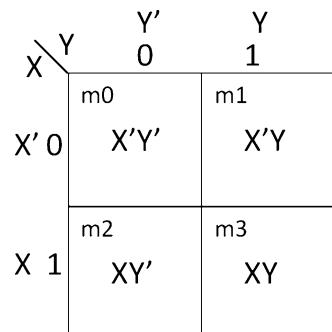


Fig. 3.3 The function in a K-map

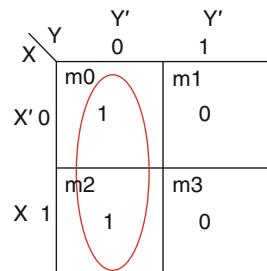


Table 3.8 The truth table for the function $F(X, Y) = XY' + X'Y'$

X	Y	F
0	0	1
0	1	0
1	0	1
1	1	0

As shown in the K-map, the cells m_0 and m_2 contain ones and the other cells contain zeros. The cells m_0 and m_2 are adjacent to each other. Note that the adjacent cells take up the entire column of Y' , and all other cells are *zero*. Our simplified function is therefore $F(X, Y) = Y'$.

Example 3.4 Simplify the following function:

$$F(X, Y) = X'Y + XY' + XY$$

or

$$F(X, Y) = m_1 + m_2 + m_3$$

Transferring minterms into a K-map results in Fig. 3.4.

As shown in Fig. 3.4, the cells m_2 and m_3 are adjacent, so they can be combined. Likewise, the cells m_1 and m_3 can be combined. By reading the map, you will have the simplified function.

Cells m_2 and m_3 are the entire row X , and cells m_1 and m_3 are the entire column Y , with the other cell being *zero*. Therefore,

$$F(X, Y) = X + Y$$

3.4.1 Three-Variable Map

A three-variable K-map contains eight cells, and each cell represents a minterm as shown in Fig. 3.5.

Fig. 3.4 K-map for $F(X, Y) = X'Y + XY' + XY$

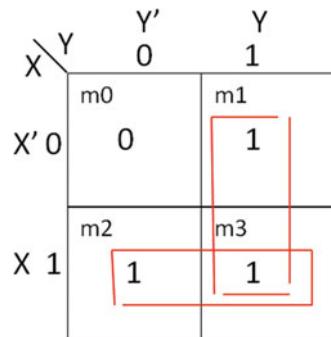
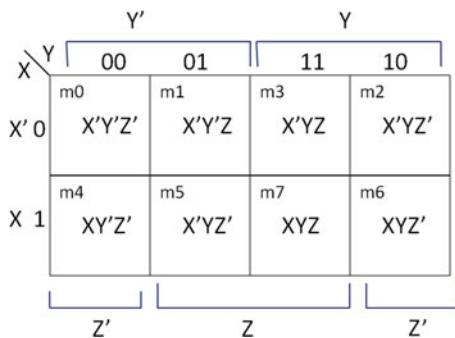


Fig. 3.5 Three-variable Map



Observe the following about the K-map in Fig. 3.5:

- At row 0, all four cells contain X' ; therefore this row is labeled X' .
- At row 1, all four cells contain X ; therefore this row is labeled X .
- At the columns 11 and 10, all four cells contain Y ; therefore these columns are labeled Y .
- At the columns 00 and 01, all four cells contain Y' ; therefore these columns are labeled Y' .
- At the columns 01 and 11, all four cells contain Z ; therefore these columns are labeled Z .
- At the columns 00 and 10, all four cells contain Z' ; therefore these columns are labeled Z' .

Adjacent cells can be grouped together in a K-map; in a K-map it can combine 2 cells, 4 cells, 8 cells, and 16 cells. Figure 3.6 shows how the *ones* could be grouped in a K-map.

In Fig. 3.6, all four cells can be combined. Folding the K-map horizontally twice will result in all of the *ones* overlapping, and row X' covers all four *ones*.

For Fig. 3.7, consider folding a K-map once more. The four *ones* will overlap if the map is folded once horizontally, then vertically. Also note that Z' covers all four *ones*.

Fig. 3.6 The grouping of four cells in a K-map where the simplified $F(X,Y,Z) = X'$

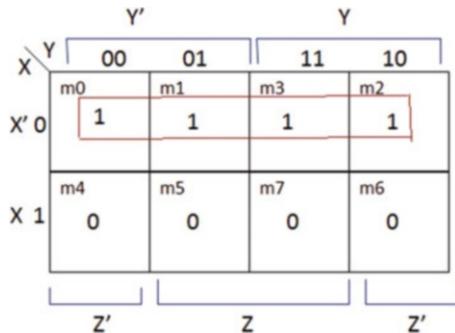


Fig. 3.7 Combing the four Z' cells together in the K-map

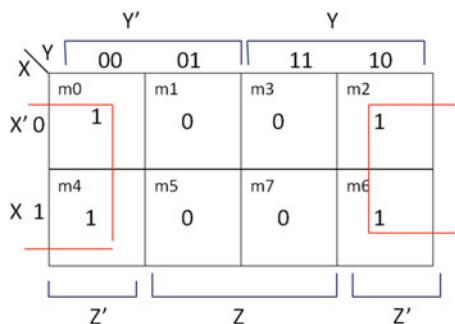
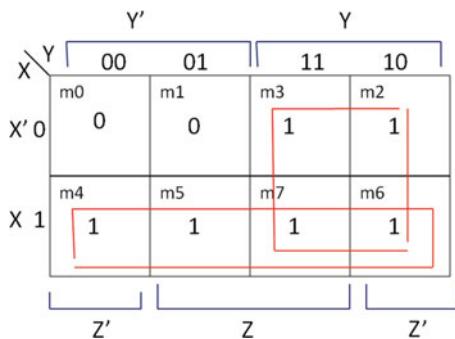


Fig. 3.8 The combination of the cells of the example function in a K-map



Example 3.5 Simplify the following function:

$$F(X, Y, Z) = X'Y + XZ + XZ'$$

First, each term of the function must be transferred to the K-map.

- (a) The first term being $X'Y$, place a *one* on each cell located at the intersection of the X' row and the Y column as shown in Fig. 3.8. (m_3 and m_2)

- (b) The second term is XZ , so place a *one* on each cell located at the intersection of the Y' column and the X row. (m_5 and m_7)
- (c) The third term being XZ' , place a *one* on each cell in the intersection of the X row and the Z column. (m_4 and m_6)

Since our adjacent cells include the entire row X and every cell in the columns Y , a simplified form of this function would be $F(X,Y,Z) = X + Y$.

Example 3.6 Read the K-maps of Fig. 3.9a–d to determine the simplified function.

- (a) All adjacent cells in columns Z' and columns Y are *one*.

$$F(X, Y, Z) = Z' + Y$$

- (b) The cells in row X' , columns Y' are adjacent, as are the cells in row X , columns Y .

$$F(X, Y, Z) = X'Y' + XY$$

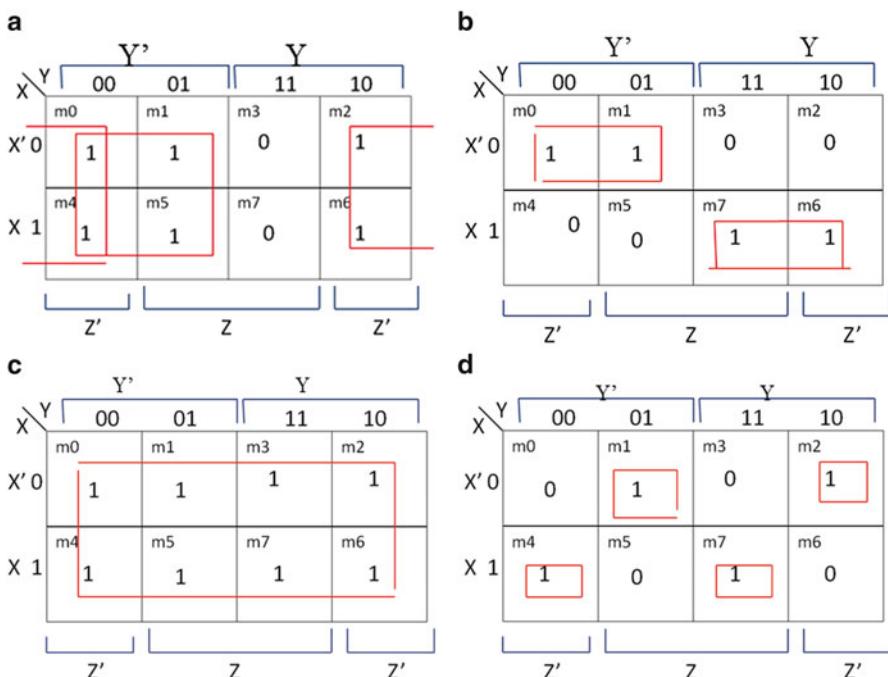


Fig. 3.9 K-Maps for Example 3.6

(c) All cells are *one*, so the function is always equal to *one*.

$$F(X, Y, Z) = 1$$

(d) Without adjacent cells to simplify the terms, the function equals the *ones*:

$$F(X, Y, Z) = X'Y'Z + X'YZ' + XY'Z' + XYZ$$

3.4.2 Four-Variable K-Map

Four-variable K-maps contain 16 cells as shown in Fig. 3.10. Please note the specific layout of the map.

The following describes the coverage of each variable by K-map:

- W covers rows 11 and 10.
- W' covers rows 00 and 01.
- X covers rows 01 and 11.
- X' covers rows 00 and 10.
- Y covers columns 11 and 10.
- Y' covers columns 00 and 01.
- Z covers columns 01 and 11.
- Z' covers columns 00 and 10.

Example 3.7 Simplify the following function:

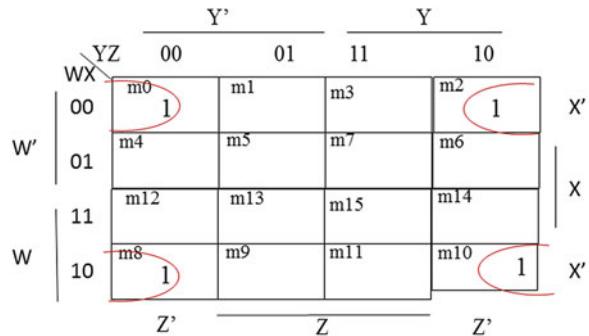
$$F(W, X, Y, Z) = m_0 + m_2 + m_8 + m_{10}.$$

The function is transferred to the K-map as shown in Fig. 3.11. If the K-map is folded once vertically and horizontally from the middle, then all four cells

Fig. 3.10 Four-variable K-map

		Y'		Y		
		00	01	11	10	
		WZ	WX	WY	WY'	
W'	00	m ₀		m ₃	m ₂	
	01	m ₄		m ₇	m ₆	
	11		m ₁₃	m ₁₅	m ₁₄	
	10	m ₈	m ₉	m ₁₁	m ₁₀	
		Z'	Z		Z'	
		X'	X		X'	

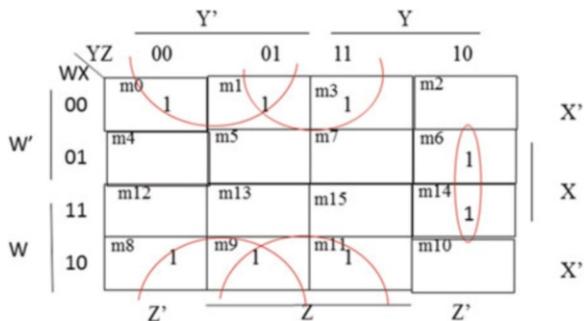
Fig. 3.11 K-map for $F(W, X, Y, Z) = m_0 + m_2 + m_8 + m_{10}$



containing *one* overlap each other. Note that each of these cells make up all intersections of X' and Z' .

The simplified function is $F(W, X, Y, Z) = X'Z'$.

Example 3.8 Read the following K-map:



$$F(W, X, Y, Z) = X'Y' + X'Z + XYZ'$$

3.5 Sum of Products (SOP) and Product of Sums (POS)

The *sum of products* of a function is its simplified *sum of minterms*.

Observe the function $F(X, Y) = XY' + XY$ is in the form of SOP where the addition sign is used for OR logic, and XY is called product. Consider function $F_1(X, Y, Z) = XY' + YZ' + XZ$, and Fig. 3.12 shows logic circuit for function F_1 which is made of AND-OR.

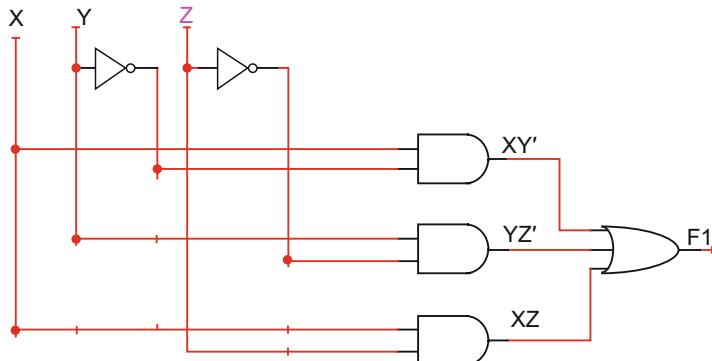


Fig. 3.12 Logic circuit for $F_1(X,Y,Z) = XY' + YZ' + XZ$ made of AND-OR gates

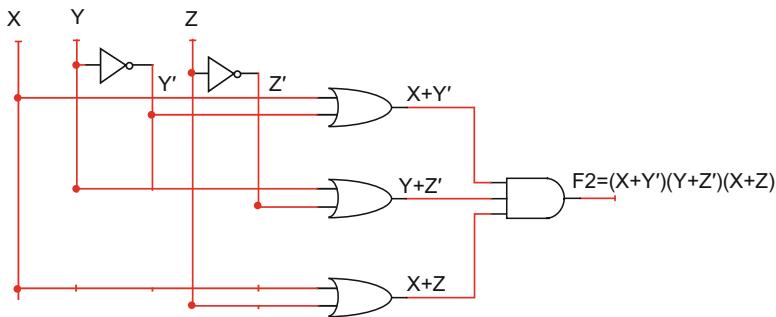


Fig. 3.13 Logic circuit for $F_2(X,Y,Z) = (X + Y')(Y + Z')(X + Z)$

Consider function $F_2(X,Y,Z) = (X + Y')(Y + Z')(X + Z)$ which is represented by the product of sums, and Fig. 3.13 shows logic circuit for function F_2 which is in the form OR-AND.

Example 3.9 Simplify the following function in the form of SOP and POS.

- $F(X,Y,Z) = \sum(0,1,6,7)$

Combining the *ones* (the minterms m_0 , m_1 , m_6 , and m_7) in a K-map results in Fig. 3.14.

The *sum of products* is therefore: $F(X,Y,Z) = X'Y' + XY$.

Combining the *zeros* in a K-map returns the significant *maxterms* as in Fig. 3.15. If F equals $\sum(0,1,6,7)$, then F' equals $\pi(M_2M_3M_4M_5)$.

Since the *product of maxterms* is equal to the *complement* of F , in order to find F , both sides of the function will be complemented:

$$F(X, Y, Z) = (XY' + X'Y')'$$

Fig. 3.14 K-map for $F(X, Y, Z) = \sum(0, 1, 6, 7)$

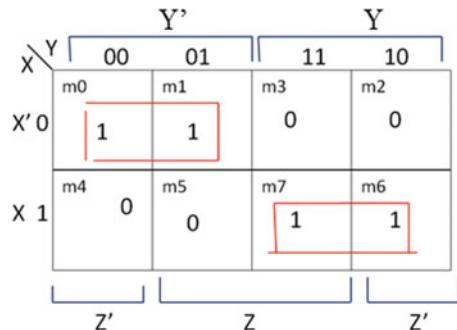
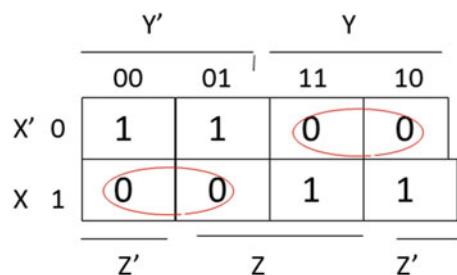


Fig. 3.15 K-map for $F'(X, Y, Z) = \pi(M_2 M_3 M_4 M_5)$



Using DeMorgan's theorem

$$F(X, Y, Z) = (XY')'(X'Y)'$$

or

$F(X, Y, Z) = (X' + Y)(X + Y')$ in the final, *product of sums* form.

3.6 Don't Care Conditions

In a truth table, if certain combinations of the input variables are impossible, they are considered *don't care* conditions. These conditions are where the output of the function does not matter. For example, binary-coded decimal (BCD) is 4 bits and only 0000 to 1001 are used, so from 1010 to 1111 are not BCD; the truth table or K-map values are *don't cares*. A truth table or K-map cell marked with a "X" or "d" is a *don't care* term, and output will not be affected whether it is a *one* or *zero*. The *don't care* can be used to expand the adjacency of cells in a K-map to further simplify a function, since their output does not matter.

Example 3.10 Figure 3.16 shows a K-map with *don't care* minterms at m_1, m_{10} , and m_{13} . Since a *don't care* can output either a *zero* or *one*, we can assume it is a *one* in order to expand a grouping of adjacent cells.

Fig. 3.16 K-map with *don't care* minterms

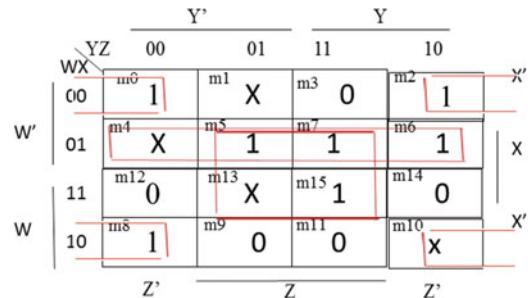
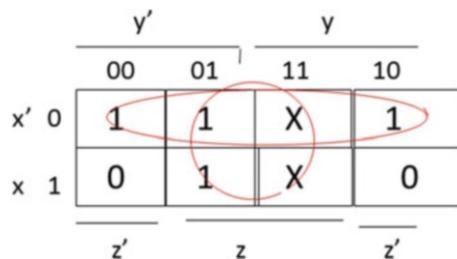


Fig. 3.17 K-map for $F(X, Y, Z) = m_0 + m_1 + m_2 + m_5$ and $D(X, Y, Z) = m_3 + m_7$



From Fig. 3.16, the function would be $F(W, X, Y, Z) = XZ + X'Z' + XW'$.

When minterms for function F are *don't care* terms, the *don't care function* D is equal to the sum of the *don't care* minterm(s). If m_7 is the only *don't care*, then *don't care* function is represented by $D(X, Y, Z) = m_7$.

Example 3.11 Simplify the following function where D is a *don't care* function:

$$\begin{aligned} F(X, Y, Z) &= m_0 + m_1 + m_2 + m_5 \\ D(X, Y, Z) &= m_3 + m_7 \end{aligned}$$

Using these values results in the K-map in Fig. 3.17. By grouping adjacent cells and using the *don't care* terms, $F(X, Y, Z) = X' + Z$.

3.7 Universal Gates

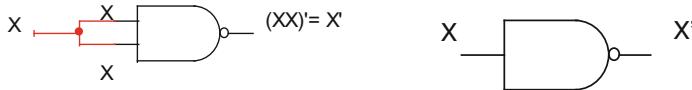
The NAND and NOR gates are called universal gates. With NANDs or NORs, designers are able to construct other logic gates such as OR, AND, and NOT gates.

3.7.1 Using NAND Gates

(a) NOT from NAND

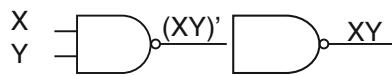
A NOT gate is generated by connecting the inputs of a NAND gate together as shown in the following figure.

Or, it can be represented by:



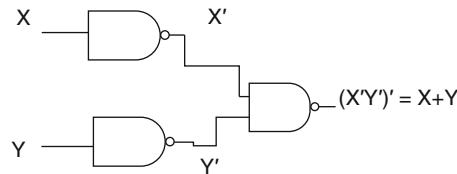
(b) AND from NAND

An AND gate is constructed by connecting the inputs to a NAND gate and putting another NAND on the output (to act as a NOT gate).



(c) OR from NAND

An OR gate is constructed by connecting each input to an individual NAND gate and putting every output into a single NAND which acts as a NOT gate.

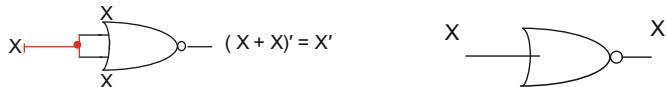


3.7.2 Using NOR Gates

(a) NOT from NOR

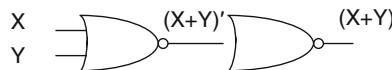
A NOT gate is generated by connecting the inputs of a NOR gate together as shown in the following figure.

Or, it can be represented by:



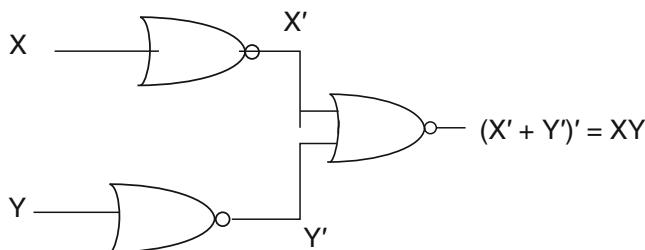
(b) OR from NOR

An OR gate is constructed by connecting the inputs to a NOR gate and putting another NOR on the output (to act as a NOT gate).



(c) AND from NOR

An AND gate is constructed by connecting each input to an individual NOR gate and putting every output into a single NOR which acts as a NOT gate.



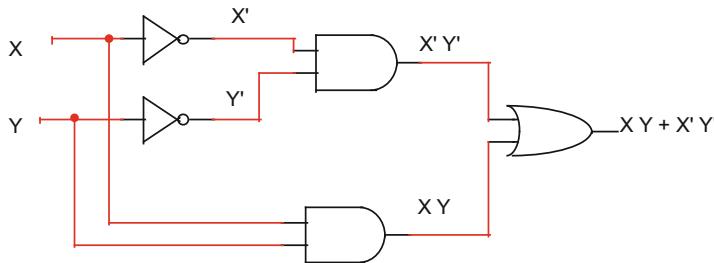


Fig. 3.18 Logic circuit for $F(X,Y) = XY + X'Y'$

3.7.3 Implementation of Logic Functions Using NAND Gates or NOR Gates Only

Many logic functions are implemented using only NAND or NOR gates, rather than a combination of various gates. Most logic gate ICs contain multiple gates of a single type, such as an IC containing eight AND gates. Using a single type of gate can reduce the number of ICs needed.

Consider the function $F(X,Y) = X'Y' + XY$ and its logic circuit diagram in Fig. 3.18.

This diagram would require one IC for AND gates, another for NOT gates, and one OR gate, or a total of three separate ICs.

By complementing the function twice, the right side of the equation may be easier to use with NAND and NOR gates.

Example 3.12 Create a logic circuit using only NAND and only NOR for the function $F(X,Y) = X'Y' + XY$.

3.7.4 Using NAND Gates

- Complement the right side of the equation twice.
- $F(X,Y) = X'Y' + XY \rightarrow F(X, Y) = [(X'Y' + XY)']'$.
- Use Boolean theorems to make it NAND friendly:

$$- F(X,Y) = [(X'Y')'(XY)']'$$

Consider the final function once more: $F(X, Y) = [(X'Y')'(XY)']'$, and substitute placeholders for the inner terms (Fig. 3.19).

- $F = [(X'Y')'(XY)']' = [AB]'$ (A NAND B)
 - A = $(X'Y')' = X' \text{ NAND } Y'$
 - B = $(XY)' = X \text{ NAND } Y$
 - $X' = X \text{ NAND } X$
 - $Y' = Y \text{ NAND } Y$

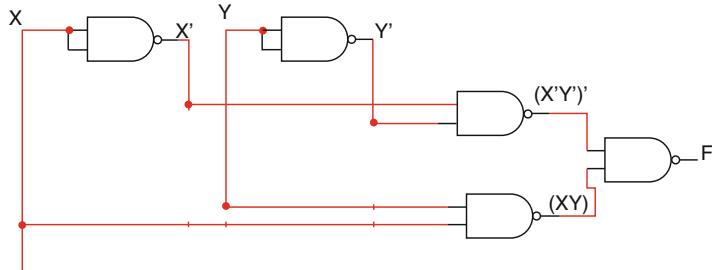


Fig. 3.19 Logic circuit of $F(X,Y) = X'Y' + XY$ using only NAND gates

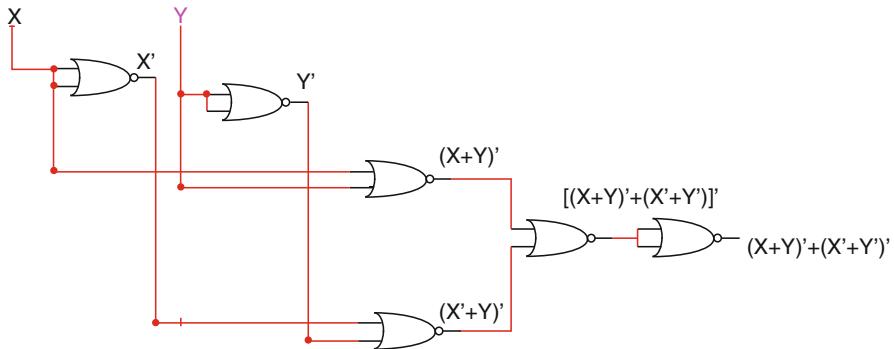


Fig. 3.20 Logic circuit of $F(X,Y) = X'Y' + XY$ using only NOR gates

3.7.5 Using NOR Gates

- Complement the right side of the equation twice:
 - $F(X,Y) = X'Y' + XY \rightarrow F(X, Y) = [(X'Y' + XY)']'$
- Use Boolean theorems to make it NOR friendly:
 - $F(X,Y) = [(X'Y')'(XY)']'$
 - $F(X,Y) = [(X+Y)(X'+Y')]'$
 - $F(X,Y) = [(X+Y)' + (X'+Y')']'$

Consider the final function once more: $F(X, Y) = [(X+Y)' + (X'+Y')']'$, and substitute placeholders for the inner terms (Fig. 3.20).

- $F = [(X'Y')'(XY)']' = [A+B]'$ (A NOR B)
 - $A = (X+Y)' = X$ NOR Y
 - $B = (X'+Y')' = X'$ NOR Y'
 - $X' = X$ NOR X
 - $Y' = Y$ NOR Y

3.8 Summary

- A digital circuit is made of the combination of the different gates with the multiple digital inputs and the multiple digital outputs; the outputs depend only to the current values of the inputs.
- A combinational logic circuit can be represented by a Boolean function or truth table.
- Boolean theorems or K-map can be used to simplify a Boolean function.
- Boolean function can be represented by the sum of the products (SOP) or the product of sums (POS).
- The NAND and NOR gates are called universal gates. It can generate other gates by using NAND or NOR gates.
- Don't care condition is the input value that never applied to a combinational circuit which results output with don't care condition (0 or 1).
- Chapters 1, 2, and 3 cover basic topics in order to be able to design digital system; Chap. 4 presents how to design a digital system and covers digital components that are used for designing digital system such as decoder, multiplexer, binary adder, binary subtractor, and arithmetic logic unit (ALU).

Problems

1. Find the output function of each truth table:

- (a) As the sum of minterms
- (b) As the product of maxterms

X Y Z	F
0 0 0	1
0 0 1	0
0 1 0	0
0 1 1	1
1 0 0	0
1 0 1	1
1 1 0	0
1 1 1	1

A B C D	F
0 0 0 0	1
0 0 0 1	0
0 0 1 0	1
0 0 1 1	1
0 1 0 0	0
0 1 0 1	1
0 1 1 0	1
0 1 1 1	1
1 0 0 0	1

(continued)

1 0 0 1	1
1 0 1 0	0
1 0 1 1	0
1 1 0 0	0
1 1 0 1	1
1 1 1 0	1
1 1 1 1	1

2. Generate truth table for the following functions:

- (a) $F(X,Y,Z) = \sum(1,3,6,7)$
- (b) $F(X,Y,Z) = \pi(1,3,4)$
- (c) $F(W,X,Y,Z) = \sum(1,4,7,10,12,15)$
- (d) $F(W,X,Y,Z) = \pi(2,3,4,7,10,11,12,13)$

3. Generate the function F for the following K-maps:

(a)

		Y'		Y	
		00	01	11	10
		m0	m1	m3	m2
X' 0	0	1	0	1	1
	1	1	1	0	1
		Z'	Z	Z	Z'

(b)

		Y'		Y	
		00	01	11	10
		m0	m1	m3	m2
X' 0	0	0	0	1	1
	1	1	1	1	1
		Z'	Z	Z	Z'

(c)

		Y'		Y	
		00	01	11	10
		m0	m1	m3	m2
X' 0	0	0	1	1	1
	1	0	1	1	1
		m4	m5	m7	m6
		0	1	1	1
		Z'	Z	Z'	

(d)

		Y'		Y			
		00	01	11	10	X'	
		m0	m1	m3	m2	1	
W' 00	WX	1					
	01		m5		m6	1	X
W' 01	W			m7			
	11	m12	m13	m15	m14	1	X'
W' 11	W						
	10	m8	m9	m11	m10	1	X'
		Z'	Z	Z'			

(e)

		Y'		Y			
		00	01	11	10	X'	
		m0	m1	m3	m2		
W' 00	WX	1					
	01		m5		m6		X
W' 01	W			m7	1		
	11	m12	m13	m15	m14		
W' 11	W						
	10	m8	m9	m11	m10		X'
		Z'	Z	Z'			

(f)

		Y'		Y		
		00	01	11	10	
		W' YZ	WX	X' X	X' X	
W	00	m ₀ 1	m ₁	m ₃	m ₂ 1	
	01	m ₄	m ₅ 1	m ₇ 1	m ₆ 1	
	11	m ₁₂	m ₁₃ 1	m ₁₅ 1	m ₁₄	
	10	m ₈ 1	m ₉	m ₁₁	m ₁₀	
		Z'	Z		Z'	

4. Find the simplified output function for the following truth table using a K-map:

(a)

X	Y	F
0	0	1
0	1	1
1	0	1
1	1	0

(b)

X	Y	Z	F
0	0	0	1
0	0	1	1
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	0

(c)

A B C D	F
0 0 0 0	1
0 0 0 1	0
0 0 1 0	1
0 0 1 1	1
0 1 0 0	0
0 1 0 1	1

(continued)

A B C D	F
0 1 1 0	1
0 1 1 1	1
1 0 0 0	1
1 0 0 1	1
1 0 1 0	0
1 0 1 1	0
1 1 0 0	0
1 1 0 1	1
1 1 1 0	1
1 1 1 1	1

5. Simplify the following functions using a K-map:

- (a) $F(X, Y) = m_2 + m_3$
- (b) $F(X, Y) = X + X'Y$
- (c) $F(X, Y) = X' + XY'$
- (d) $F(X, Y, Z) = m_0 + m_2 + m_5 + m_7$
- (e) $F(X, Y, Z) = X'Y'Z' + X'YZ + XY'Z + XYZ$
- (f) $F(X, Y, Z) = \pi(0, 2, 5, 7)$
- (g) $F(X, Y, Z) = XY'Z + X' + Z + Y'Z'$
- (h) $F(W, X, Y, Z) = X'Y'Z' + XYZ' + WXY + W'X'Y' + WZ$
- (i) $F(W, X, Y, Z) = X' + XZ' + WX'Y + W'Y' + WZ$

6. Simplify the following functions where D is a *don't care* function:

- (a) $F(X, Y, Z) = \sum(0, 3, 4)$
 $D(X, Y, Z) = \sum(2, 6)$
- (b) $F(W, X, Y, Z) = \sum(0, 1, 3, 5, 9, 11)$
 $D(W, X, Y, Z) = \sum(2, 4, 8, 10)$

7. Simplify the following functions in the form of SOP and POS, and draw a logic circuit:

- (a) $F(X, Y, Z) = \sum(0, 2, 5, 7)$
- (b) $F(W, X, Y, Z) = \sum(0, 1, 4, 6, 9, 11, 13, 15)$

8. Draw logic circuits for the simplified functions from Problem 6:

- (a) Using NAND gates
- (b) Using NOR gates

9. Simplify the following function and draw a logic circuit using:

- (a) NAND gates
- (b) NOR gates

$$F(W, X, Y, Z) = W'X'Z' + XY'Z' + WX + WY + WX''Y'Z'$$

Chapter 4

Combinational Logic

Objectives: After completing this chapter, you should able to:

- Find output function of a given digital circuit.
- Design a combinational logic circuit using problem description.
- Learn the operation of decoder and its application.
- Learn application of encoder.
- Design and learn the function of a multiplexer.
- Develop half adder, full adder from logic gates.
- Use full adder to design binary adder and subtractor.
- Learn how to design ALU (arithmetic logic unit).
- Use BCD to seven-segment decoder to display a number in decimal.

4.1 Introduction

Digital circuit is classified as combinational or sequential logic. Combinational logic is a digital circuit with digital input or inputs and digital output or outputs, this digital circuit performs a specific function, the output of combinational logic depends on current value of inputs, and it is a memoryless circuit, but sequential logic contains memory element. Figure 4.1 shows the block diagram of a combinational logic with inputs and outputs; in combinational logic, the outputs are a function of the inputs.

Consider $F(X,Y) = XY' + X'Y$ which is given by Fig. 4.2; the logic circuit is made of NOT, AND, and OR gates; the output of combinational logic will change by changing the inputs. Table 4.1 shows truth table of Fig. 4.2.

Fig. 4.1 Block diagram of a combinational logic

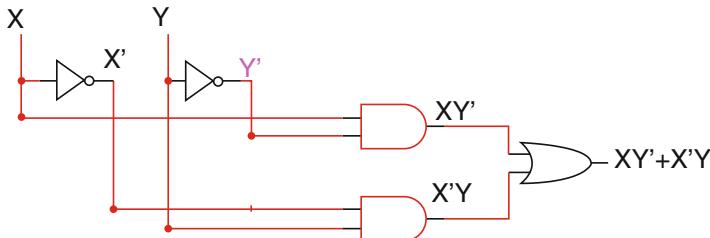
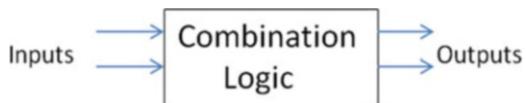


Fig. 4.2 Combinational logic circuit

Table 4.1 Truth table of Fig. 4.2

X	Y	XY'	X'Y	F
0	0	0	0	0
0	1	0	1	1
1	0	1	0	1
1	1	0	0	0

4.2 Analysis of Combinational Logic

The objective of the analysis of combinational logic is to find the output function and truth table of a combinational logic circuit, Fig. 4.3 shows a combinational logic, the output of the combinational logic is given by function F, and Table 4.2 shows the truth table of function F.

$$\begin{aligned} T1 &= [(X+Z)' + XY]' = (XY)'(X+Z)(XY)' = (X+Z)(X'+Y') \\ &= XY' + X'Z + Y'Z \end{aligned}$$

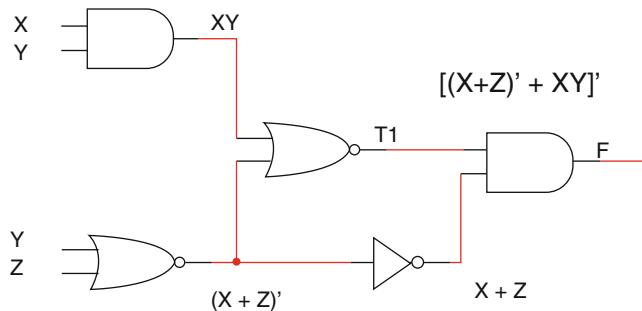
$$\begin{aligned} F(X, Y, Z) &= (X+Z)T1 = (X+Z)(XY' + X'Z + Y'Z) \\ &= XY' + XY'Z + XY'Z + X'Z + Y'Z \end{aligned}$$

$$\begin{aligned} F(X, Y, Z) &= XY' + XY'Z + X'Z + Y'Z = XY' + Y'Z(X+1) + X'Z \\ &= XY' + Y'Z + X'Z \end{aligned}$$

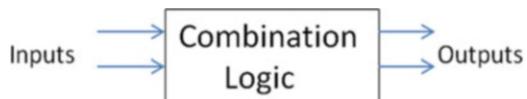
4.3 Design of Combinational Logic

Figure 4.4 shows a block diagram of combinational logic; The following steps show how to design a combinational logic:

1. Statement of the problem which describes the function of the combinational logic.

**Fig. 4.3** Combinational logic**Table 4.2** Truth table of Fig. 4.3

X Y Z	XY'	Y'Z	XZ'	F
0 0 0	0	0	0	0
0 0 1	0	1	0	1
0 1 0	0	0	0	0
0 1 1	0	0	0	0
1 0 0	1	0	1	1
1 0 1	1	1	0	1
1 1 0	0	0	1	1
1 1 1	0	0	0	0

Fig. 4.4 Block diagram of a combinational logic

2. Define the number of inputs and outputs or maybe they are given by the statement of the problem.
3. Assign variables to the inputs and outputs.
4. Develop a truth table by writing all combinations for inputs. The outputs will be determined by the statement of the problem.
5. Write the output functions using K-map.
6. Draw a logic circuit.

Example 4.1 Design a combinational logic circuit with three inputs and one output; the output is one when the binary value of the inputs is greater than or equal to three; otherwise the output will be zero.

Solution Figure 4.4 shows the block diagram of combinational logic with three inputs and one output: the variables X, Y, and Z are assigned to the inputs, and variable F is assigned to the output. Table 4.3 shows truth table for the problem (Fig. 4.5).

In Table 4.3, all input combinations for X, Y, and Z are listed; then according to the statement of the problem, the output F is one when the input is three or more;

Table 4.3 The truth table for example 1

X	Y	Z	F
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	1
1	0	1	1
1	1	0	1
1	1	1	1

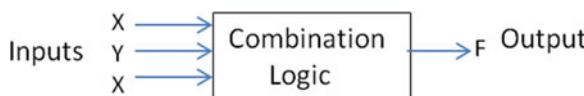


Fig. 4.5 Block diagram of combinational logic of example 4

Fig. 4.6 The K-map for example 4

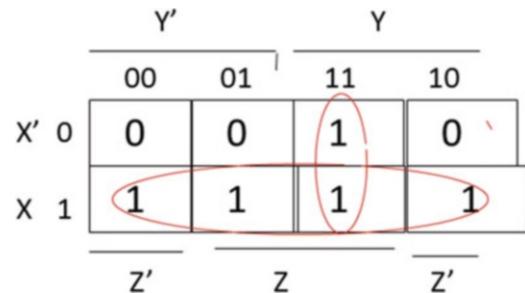
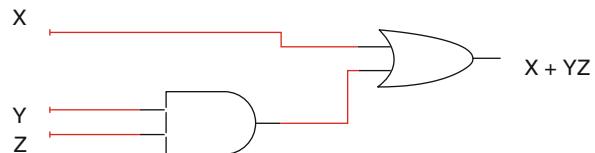


Fig. 4.7 The circuit diagram for example 4



otherwise the output is zero. The output function F can be represented by the sum of minterms:

$$F(X, Y, Z) = m_3 + m_4 + m_5 + m_6 + m_7 \quad (\text{sum of minterms})$$

By transferring the minterms of $F(X, Y, Z)$ into the K-map as shown in Fig. 4.6 and reading the simplified function from the K-map results $F(X, Y, Z) = X + YZ$. Figure 4.7 shows the logic circuit for function F (Fig. 4.7).

Fig. 4.8 The block diagram of a 2*4 decoder

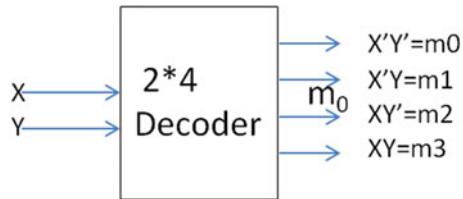
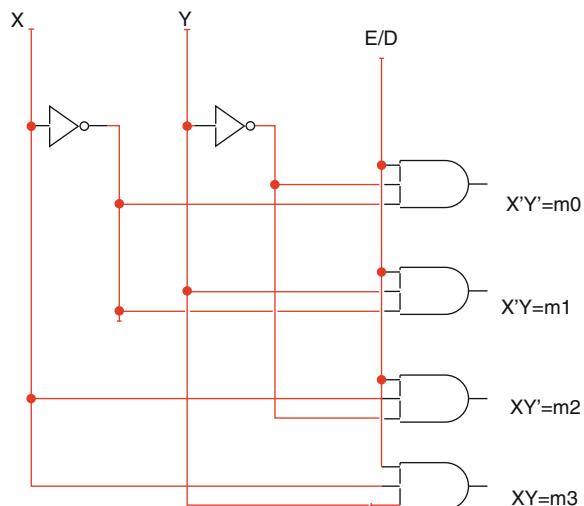


Table 4.4 The truth table for a 2*4 decoder

X Y	m ₀	m ₁	m ₂	m ₃
0 0	1	0	0	0
0 1	0	1	0	0
1 0	0	0	1	0
1 1	0	0	0	1

Fig. 4.9 Logic circuit of a 2*4 decoder with E/D



4.4 Decoder

A decoder is an MSI logic which generates the minterms of a set of inputs; the two variables X and Y generate four minterms, and they are $X'Y' = m_0$, $X'Y = m_1$, $XY' = m_2$, and $XY = m_3$. Figure 4.8 shows the block diagram of a 2*4 decoder (2 inputs and 4 outputs), and Table 4.4 shows the truth table for a 2*4 decoder.

From the truth table of the decoder, the following functions are the outputs of a decoder:

$$m_0 = X'Y', m_1 = X'Y, m_2 = XY', \text{ and } m_3 = XY$$

Figure 4.9 shows logic circuit of 2*4 decoder. Most MSI ICs have an extra input called enable/disable (E/D); the function of the E/D input is to enable or disable an

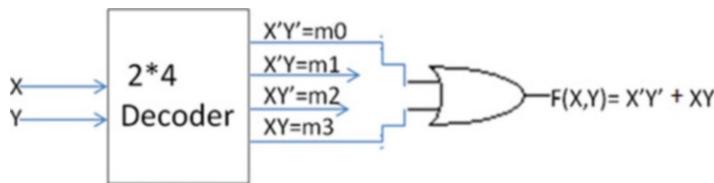
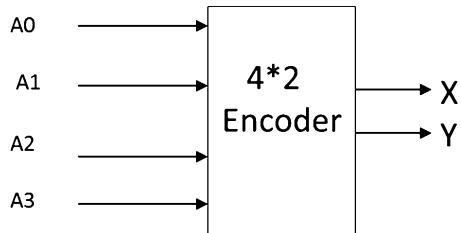


Fig. 4.10 Implementing a function using decoder

Fig. 4.11 The block diagram of a 4*2 encoder



IC as shown in Fig. 4.9. When E/D = 0, all outputs of the decoder will be zeros (meaning the decoder is disabled); the decoder only generates minterms when E/D is set to one.

4.4.1 Implementing a Function Using a Decoder

Decoders can be used to design combinational circuits. Consider $F(X, Y) = XY + X'Y'$ which can be implemented using a decoder. The function can be represented by $F(X, Y) = m_3 + m_0$. The function contains two variables which are the inputs to the decoder; therefore, a 2*4 decoder is needed, and the output F is the sum of minterms m_3 and m_0 which is shown in Fig. 4.10.

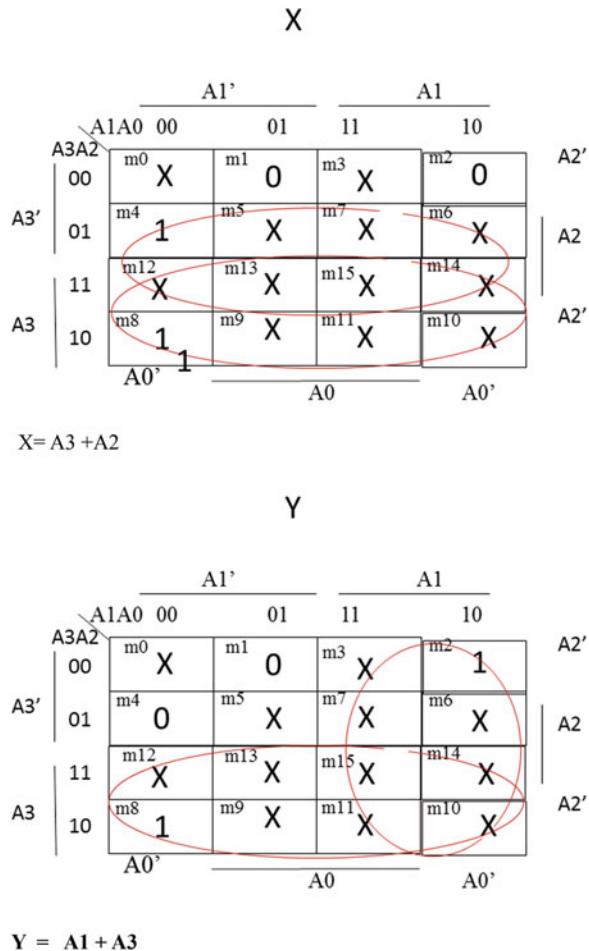
4.5 Encoder

An encoder is the opposite of a decoder; it has 2^n inputs and n output, for $n = 2$ means encoder has $2^2 = 4$ inputs and 2 outputs; the output is binary value of selected input. Figure 4.11 shows block diagram of 4*2 encoder, and Table 4.5 shows the truth table for a 4*2 encoder. In Table 4.5, if $A_3 = 1$, then the output $XY = 11$, or if $A_2 = 1$, then the output $XY = 10$.

Figure 4.12 shows the K-map for functions X and Y; the input combinations that are not listed in the truth table of the 2*4 decoder are *don't care*, designated by "X," in both K-maps. Figure 4.13 shows the logic circuit diagram of the 2*4 decoder.

Table 4.5 The truth table for a 4*2 encoder

A3	A2	A1	A0	X	Y
0	0	0	1	0	0
0	0	1	0	0	1
0	1	0	0	1	0
1	0	0	0	1	1

Fig. 4.12 The K-maps for functions X and Y

4.6 Multiplexer (MUX)

A MUX is a combinational logic circuit with N inputs and one output; the function of the MUX is to select one of the inputs from many and direct the input to the output. Figure 4.14 shows the basic architecture of a multiplexer. A multiplexer that has N inputs and one output is called an N-to-1 multiplexer. The internal switch

Fig. 4.13 The logic circuit diagram of the 4×2 encoder

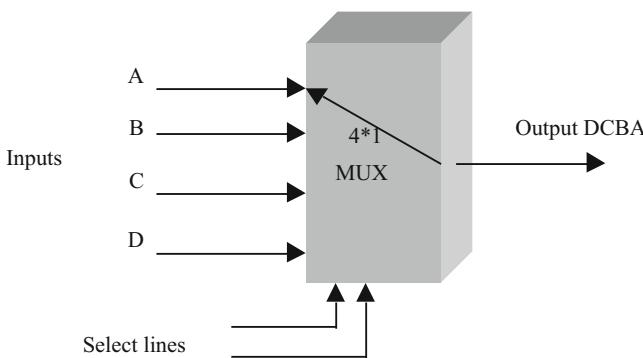
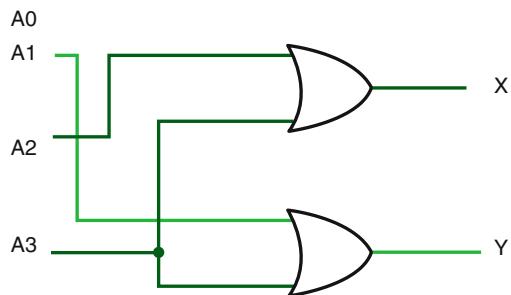


Fig. 4.14 A 4-to-1 multiplexer

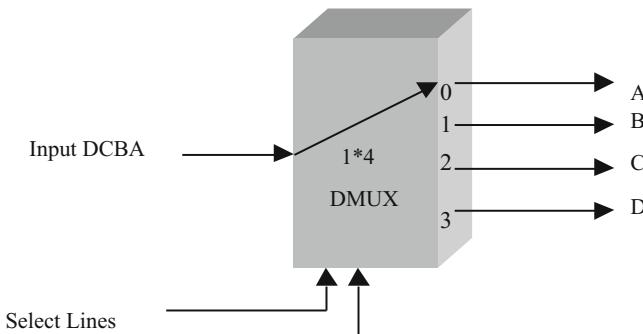


Fig. 4.15 A 1-to-4 demultiplexer (DMUX)

selects one input line at a time and transfers that input to the output. When the switch is in position A, it transfers input A to the output; when the switch moves to position B, it transfers input B to the output. This method continues until the switch moves to position D and transfers input D to the output.

The opposite of a multiplexer is a **demultiplexer** (DMUX), shown in Fig. 4.15. The switch moves to send each input to the appropriate output. A DMUX has one

Fig. 4.16 Block diagram of 2*1 MX

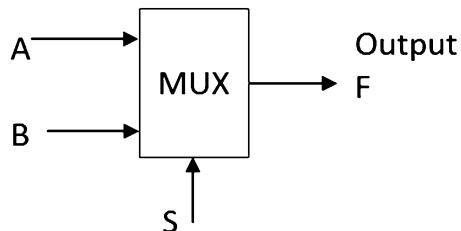


Table 4.6 Truth table 2*1 MUX

S	A	B	F
0	0	0	0
0	0	1	0
0	1	0	1
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	0
1	1	1	1

input and N outputs – this is called a 1-to-N demultiplexer. When the switch is in position 0, it transfers A to output port 0 and then moves to output port 1 and transfers B to this port. This process continues until the switch moves to output port 3 and transfers D to port 3.

Figure 4.16 shows a 2*1 MUX where A and B are inputs and S is select line; when S = 0, the output of multiplexer is the value of A; when S = 1, the output of MUX is value of B.

Table 4.6 shows truth table of MUX for Fig. 4.16.

$$F(S, A, B) = m_3 + m_5 + m_7$$

		A'		A			
		00	01	11	10		
S' 0		0	0	1	1		
S 1		0	1	1	0		
		B'	B	B	B'		

Fig. 4.17 Logic circuit for 2*1 MUX

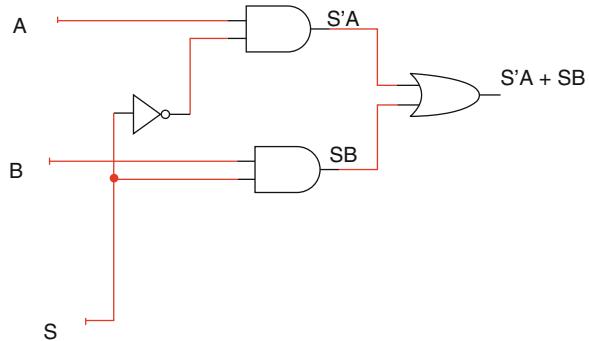


Fig. 4.18 The block diagram of 4*1 MUX

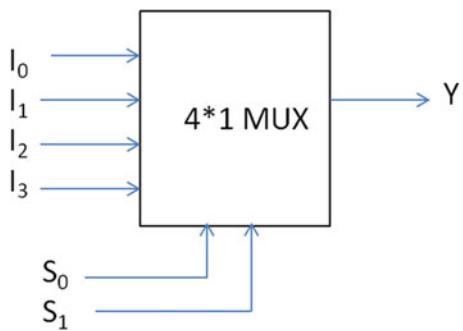


Table 4.7 The MUX operation

S ₀	S ₁	Y
0	0	I ₀
0	1	I ₁
1	0	I ₂
1	1	I ₃

Reading K-map results $F(S,A,B) = S'A + SB$.

Figure 4.17 shows logic circuit for 2*1 MUX.

Figure 4.18 shows a 4*1 MUX where I_0, I_1, I_2 , and I_3 are the inputs, Y is the output, and S_0 and S_1 are select lines. Table 4.11 shows the operation of the MUX.

The function Y can be generated from Table 4.7; when the inputs $S_0S_1 = 00$, then $Y = I_0$; when $S_0S_1 = 01$, then $Y = I_1$; when $S_0S_1 = 10$, then $Y = I_2$; when $S_0S_1 = 11$, then $Y = I_3$; therefore, the Y output is

$$Y = S_0' S_1' I_0 + S_0' S_1 I_1 + S_0 S_1' I_2 + S_0 S_1 I_3$$

Figure 4.19 shows the block diagram for a 4*1 MUX with E/D. Figure 4.20 shows logic circuit of 4*1 MUX; as shown in this figure, the E/D input is added to the logic diagram of MUX; when $E/D = 0$, the output $Y = 0$, and the MUX is disabled.

Fig. 4.19 Shows block diagram of 4*1 MUX with E/D

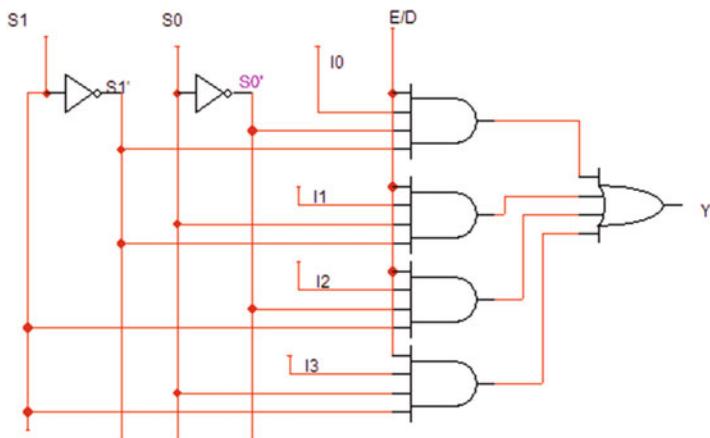
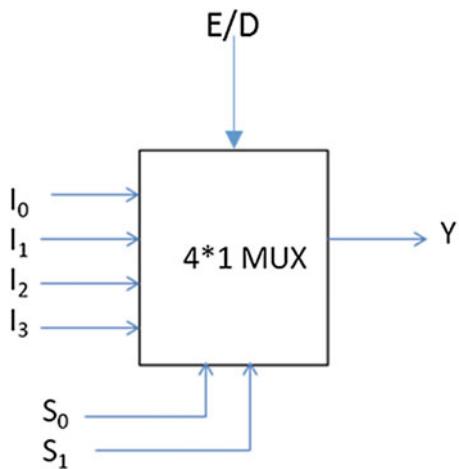


Fig. 4.20 The circuit logic diagram for a 4*1 MUX

4.6.1 Designing Large Multiplexer Using Smaller Multiplexers

By combining small MUXes, then it is able to generate a bigger MUX; an 8*1 MUX can be constructed by two 4*1 multiplexers and one OR gate as shown in Fig. 4.21. In this figure, A, B, and C are select lines. When $A = 0$, the top MUX is enabled, and when $A = 1$, the lower MUX is enabled. Also, the 8*1 MUX can be implemented using two 4*1 and one 2*1 MUX as shown in Fig. 4.22. In Fig. 4.22, when $A = 0$, the output $F = Y_0$, and when $A = 1$, the output $F = Y_1$.

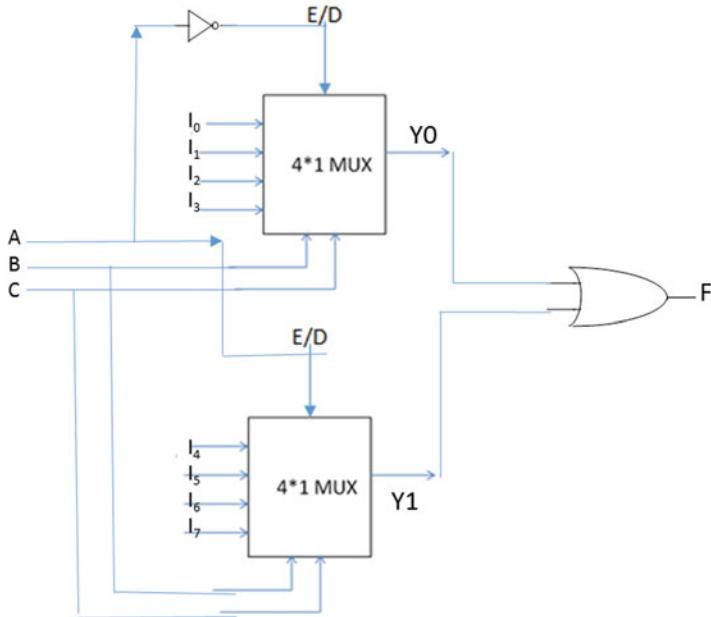


Fig. 4.21 8*1 MUX using 4*1 MUX and OR gate

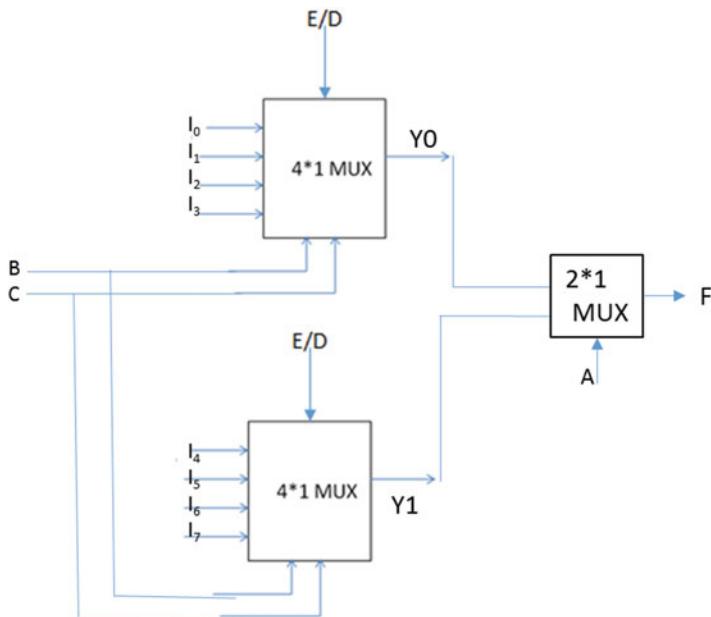


Fig. 4.22 8*1 MUX constructed with two 4*1 MUX and 2*1 MUX

4.6.2 Implementing Functions Using Multiplexer

(a) Implementing a three-variable truth table using a 8*1 MUX

MUX can be used to implement a digital function; consider truth Table 4.8; the truth table is made of three variables, and it can use an 8*1 MUX to implant the truth table (Table 4.8).

The truth table is made of three variables; therefore, an 8*1 MUX is needed; the A, B, and C variables are connected to the select lines of MUX, and the inputs of the MUX correspond to the output of truth table (Fig. 4.23).

(b) Implementing Table 4.8 using a 4*1 MUX

Number of variables – 1 = number of select lines.

Three variables – 1 = 2 number of select lines for MUX

If A and B are connected to select lines, when AB = 00, there are two rows in Table 4.9 with AB = 00, then the output F depends on the value of C; in this case C = 0. Consider rows with AB = 01, F = 0 for C = 0, and F = 1 for C = 1; therefore, F = C. Figure 4.24 shows implementation of Table 4.9 using 4*1 MUX.

Table 4.8 The truth table for a MUX with three variables

A	B	C	F
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	1
1	0	1	0
1	1	0	1
1	1	1	1

Fig. 4.23 The block diagram of an 8*1 MUX

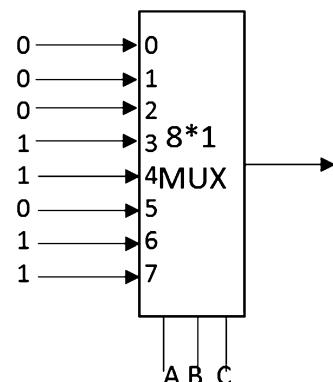
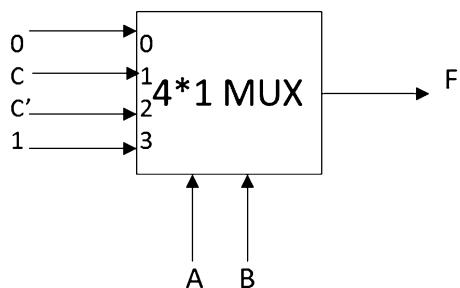


Table 4.9 Truth table for Fig 4.24

A	B	C	F	
0	0	0	0	0
0	0	1	0	
0	1	0	0	C
0	1	1	1	
1	0	0	1	C'
1	0	1	0	
1	1	0	1	1
1	1	1	1	

Fig. 4.24 Multiplexer for Table 4.9



4.7 Half Adder, Full Adder, Binary Adder, and Subtractor

Half adder (HA) is a logic circuit that adds the bits X and Y; Fig. 4.25 shows block diagram of a HA; the inputs to the HA are X and Y; the outputs of the HA are S (sum) and C (carry). Table 4.10 shows the truth table for a HA. In this truth table, when X = Y = 1, then X plus Y = 10 results S = 0 and C = 1.

The functions S and C are

$$S = m_1 + m_2 = X'Y + XY' = X \text{ XOR } Y$$

$$C = XY = X \text{ AND } Y$$

Figure 4.26 shows logic circuit of half adder (HA).

Full Adder (FA) Figure 4.27 shows the block diagram of a full adder (FA). The FA will add X + Y + Cin (each is only 1 bit), the outputs of the FA are called S and Cout, and Table 4.11 shows the truth table of a FA; in this table, X, Y, and Cin are added, and the results generate the sum (S) and carry (Cout).

The function of S can be represented by the sum of minterms as shown in Eq. 4.1:

$$S(X, Y, Cin) = X'Y'Cin + X'Y'Cin' + X'Y'Cin + XY'Cin' + XYCin \quad (4.1)$$

OR

Fig. 4.25 The block diagram of a half adder

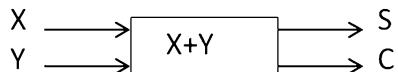


Table 4.10 The truth table for a half adder

X Y	C	S
0 0	0	0
0 1	0	1
1 0	0	1
1 1	1	0

Fig. 4.26 Logic circuit for HA

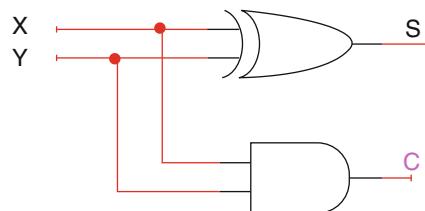


Fig. 4.27 The block diagram of a half adder



Table 4.11 The truth table for a half adder

X Y Cin	Cout	s
0 0 0	0	0
0 0 1	0	1
0 1 0	0	1
0 1 1	1	0
1 0 0	0	1
1 0 1	1	0
1 1 0	1	0
1 1 1	1	1

$$S(X, Y, Cin) = Cin(X'Y' + XY) + Cin'(X'Y + X'Y') \quad (4.2)$$

$$X'Y + X'Y' = X \text{ XOR } Y = A$$

$$X'Y' + XY = (X'Y + X'Y')' = A'$$

Therefore, Eq. 4.2 can be written in the form of Eq. 4.3:

$$S(X, Y, Cin) = CinA' + Cin'A = Cin \text{ XOR } A \quad (4.3)$$

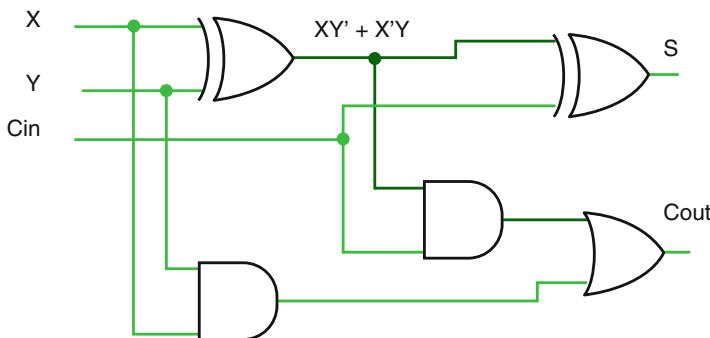
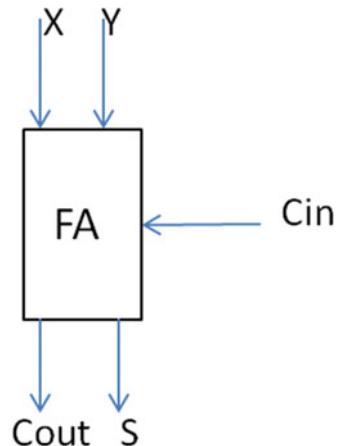


Fig. 4.28 Full adder logic circuit

Fig. 4.29 Block diagram of FA



Cout can be written in the form of the sum of minterms:

$$\text{Cout} (X, Y, \text{Cin}) = X'Y\text{Cin}, + XY'\text{Cin} + XY\text{Cin}' + XY\text{Cin}$$

OR

$$\text{Cout} (X, Y, \text{Cin}) = \text{Cin} (X'Y, +XY') + XY (\text{Cin}' + \text{Cin})$$

OR

$$\text{Cout} (X, Y, \text{Cin}) = \text{Cin} (X'Y, +XY') + XY$$

Figure 4.28 shows the logic circuit for a full adder.

Figure 4.29 shows block diagram of a full adder (FA), where X, Y, and Cin are the inputs and S and Cout are the outputs.

4.7.1 4-Bit Binary Adder

The function of a 4-bit binary adder is to add two 4-bit numbers such as:

$$X_3 X_2 X_1 X_0 + Y_3 Y_2 Y_1 Y_0$$

When adding X_0 by Y_0 , it results in a sum (S_0) and a carry (C_0); the C_0 is then added to X_1 and Y_1 which results in a S_1 and a C_1 . Figure 4.30 shows 4-bit binary adder; the Cin is connected to ground to represent zero.

The manufacturer diagram of the 4-bit binary adder is shown in Fig. 4.31 as one IC, and the IC number is 7483.

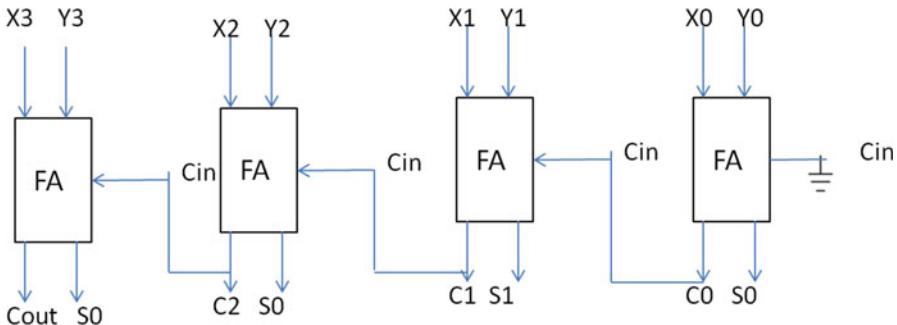
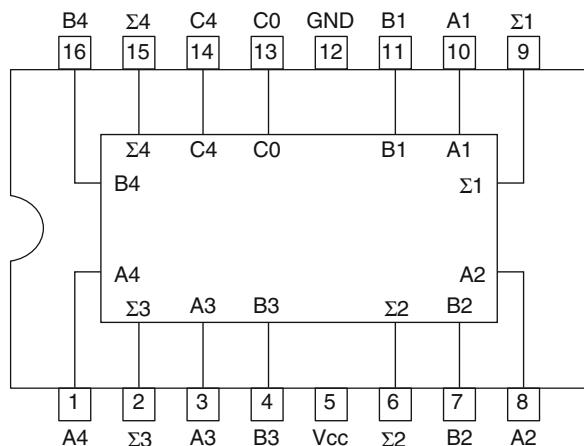


Fig. 4.30 4-bit binary adder

Fig. 4.31 7483 4-bit binary adder



4.7.2 Subtractor

A subtractor performs the subtraction of $A - B$ or $A + B' + 1$. Figure 4.32 shows a diagram of a subtractor using a 4-bit binary adder. The CI is set to one, and inputs B0, B1, B2, and B3 are complemented.

Figure 4.33 is a modification of Fig. 4.32 which can perform both addition and subtraction. CI is the carry in and CO is the carry out of the 4-bit binary adder. By setting the Add/Sub switch to zero, it performs addition, and by setting Add/Sub switch to one, it performs subtraction.

4.8 ALU (Arithmetic Logic Unit)

The function of the **arithmetic logic unit (ALU)** is to perform arithmetic operations such as addition and subtraction and bit-wise logic operations such as AND, OR, and NOT. Figure 4.34 shows the block diagram of an ALU.

In Fig. 4.34, A and B buses are the inputs, and the C bus is the output of the ALU; S1 and S0 are select lines that select the function of the ALU; Table 4.12 shows the function of an ALU; assume A and B are 4 bits and represented by A3, A2, A1, and A0 and B3, B2, B1, and B0.

The select lines of ALU defines the size of the multiplexer, since there are 2 select lines; therefore, the size of the MUX is 4×1 (4 inputs and 1 output); the number of bits define the number of multiplexer. A and B are 4 bits; therefore, four 4×1 multiplexers are needed. Figure 4.35 shows a diagram of an ALU.

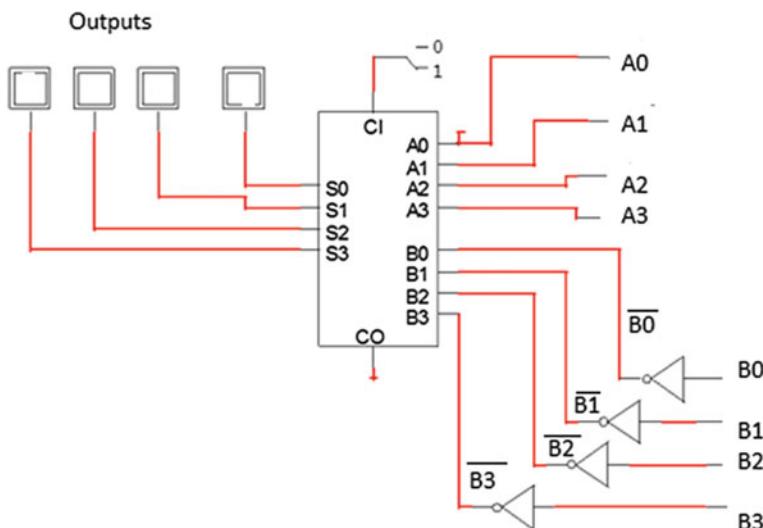


Fig. 4.32 4 bit subtractor

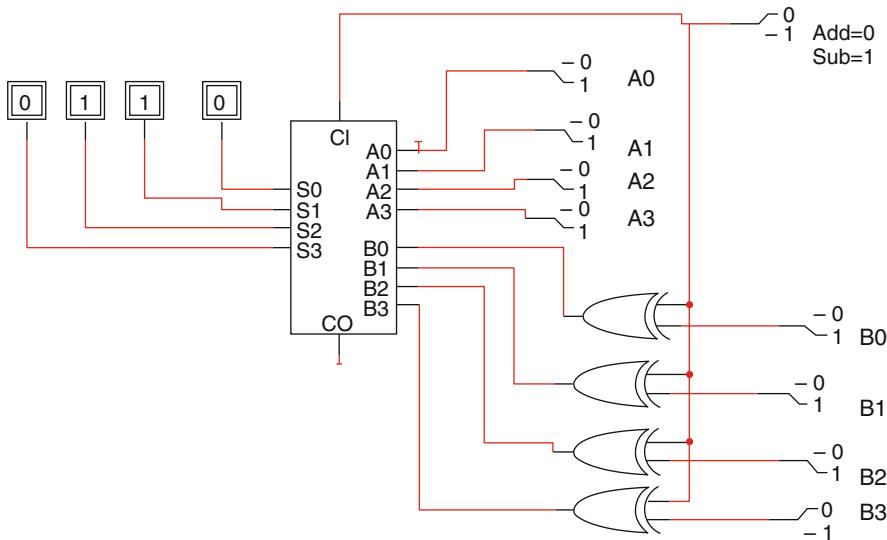
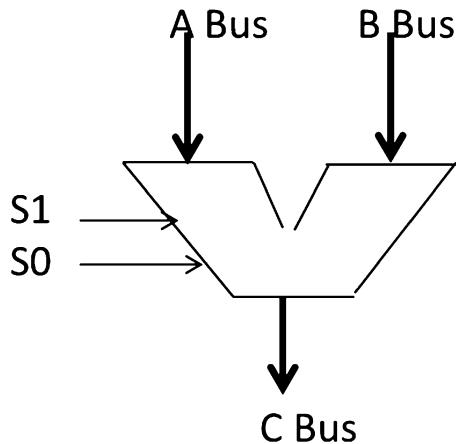


Fig. 4.33 Logic circuit for 4-bit adder and subtractor

Fig. 4.34 Block diagram of an ALU



4.9 Seven-Segment Display

A seven-segment display is made of seven LEDs (light-emitting diode) as shown in Fig. 4.36; a seven-segment display can display any one digit from zero to nine; Fig. 4.37 shows the segments that should be on in order to display the digits from 0 through 9.

For displaying 0, all segments should be on except for g; for displaying 8, all segments should be on. It requires a special decoder called a BCD to seven-segment decoder to convert binary-coded decimal (BCD) to seven-segment display.

Table 4.12 The functions of an ALU

S1	S0	ALU
0	0	A OR B
0	1	A + B
1	0	A AND B
1	1	A'

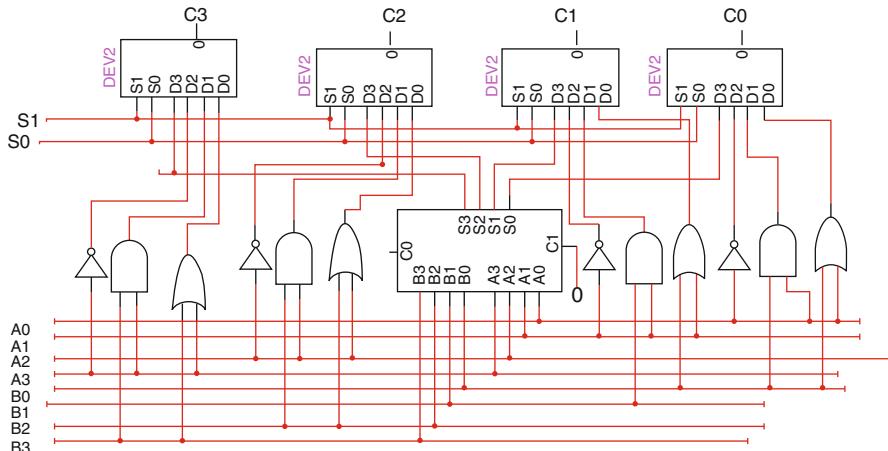


Fig. 4.35 A logic circuit diagram of an ALU

Fig. 4.36 Seven-segment display

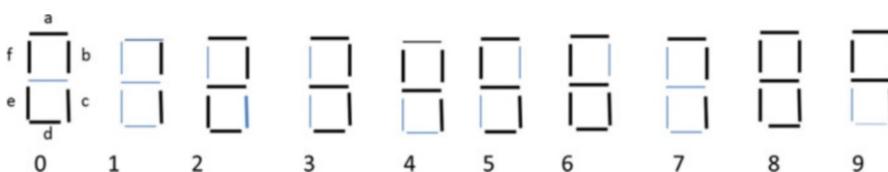
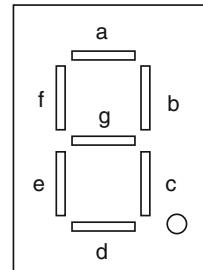


Fig. 4.37 Seven-segment display from 0 to 9

Fig. 4.38 A block diagram of a BCD to seven-segment decoder

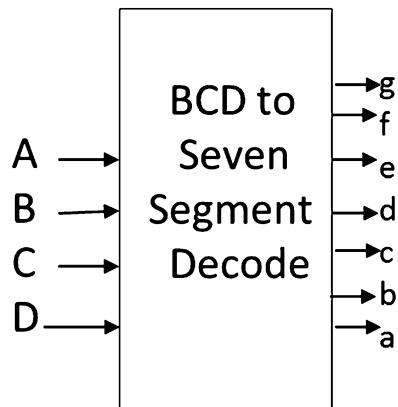


Table 4.13 The truth table for a BCD to seven-segment decoder

A	B	C	D	a	b	c	d	e	f	g
0	0	0	0	1	1	1	1	1	1	0
0	0	0	1	0	1	1	0	1	0	0
0	0	1	0	1	1	0	1	1	0	1
0	0	1	1	1	1	1	1	0	0	1
0	1	0	0	0	1	1	0	0	1	1
0	1	0	1	1	0	1	1	0	1	1
0	1	1	0	1	0	1	1	1	1	1
0	1	1	1	1	1	1	0	0	0	0
1	0	0	0	1	1	1	1	1	1	1
1	0	0	1	1	1	1	0	0	1	1
1	0	1	0	d	d	d	d	d	d	d
1	0	1	1	d	d	d	d	d	d	d
1	1	0	0	d	d	d	d	d	d	d
1	1	0	1	d	d	d	d	d	d	d
1	1	1	0	d	d	d	d	d	d	d
1	1	1	1	d	d	d	d	d	d	d

Figure 4.38 shows a block diagram of the BCD to seven-segment decoder, and Table 4.13 shows the truth table of the BCD to seven-segment decoder. The decoder has 4 inputs and 7 outputs; the input to the decoder is BCD (binary-coded decimal which is from 0000 through 1001), as shown in Table 4.13; if the input value is greater than 1001, then the output is *don't care*.

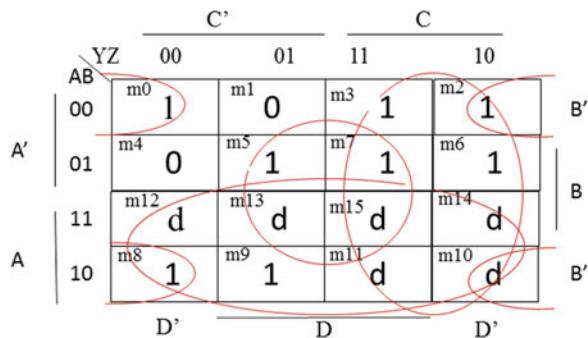
There are seven outputs, and each output requires a K-map in order to find the output functions. Figure 4.39 shows the K-map for output a.

By reading the K-map of Fig. 4.39, the result is function a:

$$a = B'D' + A + C + BD$$

Using the above procedure, one can find other output functions.

Fig. 4.39 The K-map for output a



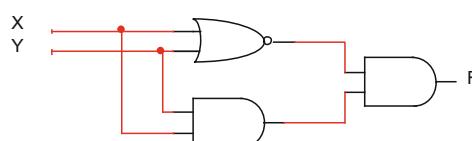
4.10 Summary

- Combinational circuit is a digital circuit with one or more digital inputs and digital outputs.
- The outputs of combinational circuit depend on current values of inputs.
- A combinational logic circuit can be represented by a function or a truth table.
- Decoder is a combinational logic with n inputs and 2^n outputs; if $n = 2$ then decoder is 2×4 .
- Decoder generates minterms of inputs; a decoder with two inputs generates four minterms.
- Multiplexer is a combinational circuit with 2^n inputs and one output, where n is number of select lines. If $n = 2$, then multiplexer will be 4×1 .
- The function of half adder (HA) is to add 2 bits and generate sum and carry.
- The function of full adder (FA) is to add 3 bits.
- The function of a 4-bit binary adder is to add two 4-bit numbers.
- Arithmetic logic unit (ALU) is a combinational logic that performs arithmetic operations and logic operations.
- Seven-segment displays are used for displaying one digit of decimal number.
- BCD to seven-segment decoder converts 4-bit BCD to 7 bits for interfacing to 7-segment displays.
- Chapter 5 covers sequential logic circuit, and the topics presented in this chapter are D, J-K, and T flip-flops, register, shift register, state diagram, state table, and designing counter.

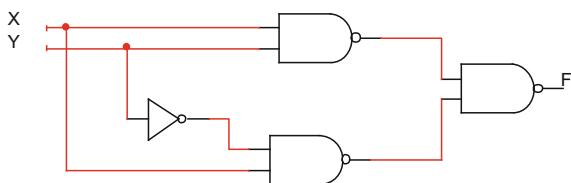
Problems

1. The following combinational circuit logic diagrams are given; find the output function and truth table for each function.

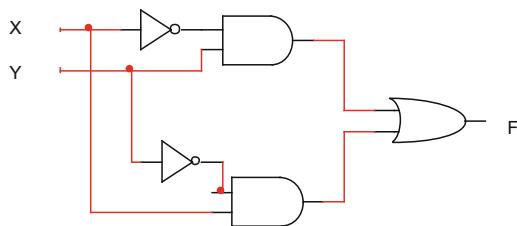
(a)



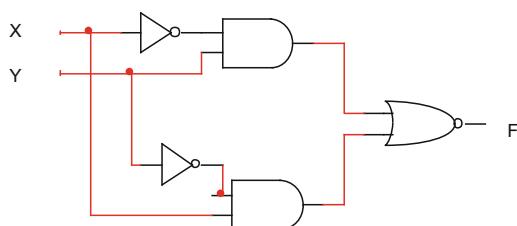
(b)



(c)



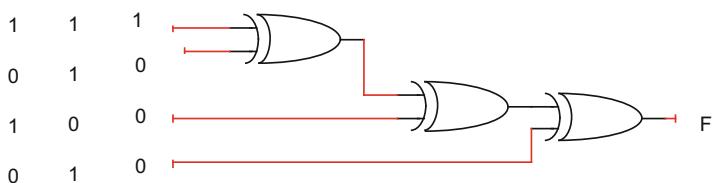
(d)



2. Find the output of following gates.



3. Find the output F for each set of inputs.



4. Design a logic circuit with three inputs and one output; the output generates even parity bit of the inputs.

- (a) Show the truth table.
- (b) Find output function.
- (c) Draw logic circuit.

5. Implement function $F(X,Y,Z) = XY' + XZ'$ using:

- (a) Decoder
- (b) Multiplexer

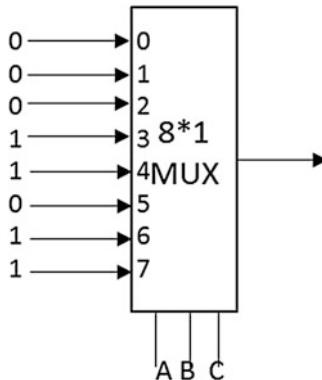
6. Implement the following functions using only one decoder and external gates:

$$F1(X,Y,Z) = \sum(0,3,4)$$

$$F2(X,Y,Z) = \sum(2,3,5)$$

7. Implement a full adder using decoder.

8. The following multiplexer is given; complete its table.



A	B	C	F
0	0	0	
0	1	1	
0	1	0	
1	1	1	
1	0	0	
1	0	1	
1	1	0	
0	0	1	

9. Implement function $F(W,X,Y,Z) = \sum(0,1,3,4,7,8,9,11,12,15)$ using MUX.
 10. Design an 8-bit binary adder using 4-bit binary adders.

11. Design a 16-bit binary adder using 4-bit binary adders.
12. Design a combinational logic with three inputs and three outputs; if input 0, 1, 2, or 3 then output 3 more than input, if input 4, 5, 6, or 7 then output 3 less than the input.
13. A train with 7 wagons carry passenger and numbered from 1 to 7; each wagon contains a binary switch for emergency, and when any of the switches become on, then display wagon number in conductor cabin in decimal. Verify your design using Logisim.
14. Design a combinational circuit with four inputs and one output; the input to the combinational circuit is BCD, and output generates even parity for the input.
15. Design a 16*1 MUX using 4 *1 MUXs.
16. Design a 4-bit ALU to perform the following functions:

$A + B$, $A - B$, $A + 1$, A' , B' , $A \text{ OR } B$, $A \text{ XOR } B$, $A \text{ AND } B$

17. Design a combinational logic that compares X and Y, where $X = X_1X_0$ and $Y = Y_1Y_0$; the output of combinational logic is 1, when $X < Y$; otherwise the output is 0.
 - (a) Show truth table.
 - (b) Find output function using K-map.

Chapter 5

Synchronous Sequential Logic

Objectives: After completing this chapter, you should be able to:

- Analyze the sequential logic.
- Learn operation of the S-R latch.
- Design D flip-flop from S-R latch.
- Learn the application of the D flip-flop.
- Learn operation of the J-K and T flip-flops.
- Design register and shift register using the D flip-flops.
- Develop state table for a sequential circuit.
- Develop state diagram from the state table.
- Develop excitation table for each types of flip-flop.
- Design digital counter.

5.1 Introduction

Sequential logic circuit contains memory elements, and the output depends on the current value of input and prior input-level conditions. Figure 5.1 shows block diagram of sequential logic as shown in this figure; the outputs depend on the inputs and current state of memory elements; in this figure, the outputs of combinational logic are the inputs to memory elements, and the outputs of memory elements are the inputs to combinational logic; the basic elements of memory elements are flip-flops that can hold binary values as long as the device is powered. The output of a synchronous sequential logic depends on the outputs of memory elements and inputs. The applications of synchronous sequential logic are designing register, counter, and memory. Synchronous sequential logic operates with the clock pulse.

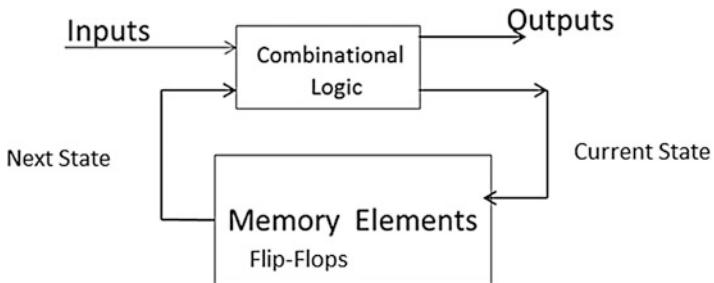


Fig. 5.1 Block diagram of synchronous sequential logic

Fig. 5.2 Block diagram of S-R latch

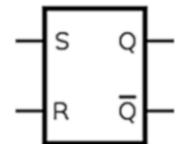


Fig. 5.3 Logic circuit of S-R latch using NOR gates

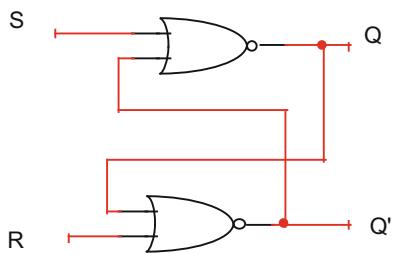
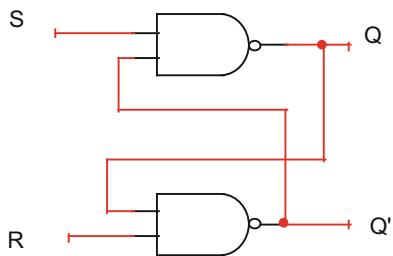


Fig. 5.4 Logic circuit of S-R latch using NAND gates



5.2 S-R Latch

S-R latch is a type of memory with two inputs S (set) and R (reset), two outputs Q, and \bar{Q} , and the outputs are the complement of each other. Figure 5.2 shows block diagram of a S-R latch.

A S-R latch can be constructed with NOR or NAND gates: Fig. 5.3 shows S-R latch using NOR gates and Fig. 5.4 shows S-R latch using NAND gates.

Table 5.1 Characteristic table of S-R latch

S	R	Q	Q'
0	0	1	1
0	1	1	0
1	1	1	0
1	0	0	1
1	1	0	1

Forbidden
No change

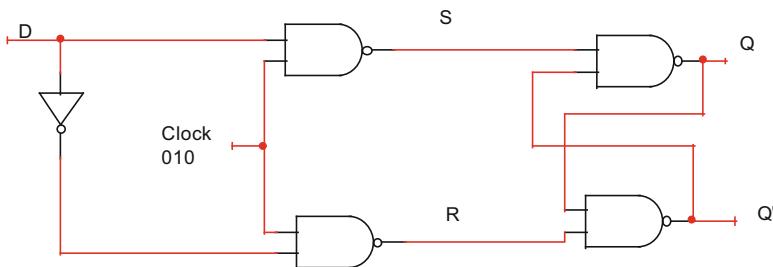


Fig. 5.5 Logic circuit of D flip-flop

S-R Latch Operation Consider S-R latch of Fig. 5.4 which is constructed with NAND gates; the following steps describe the operation of S-R latch, and Table 5.1 shows its characteristic table:

1. By setting $S = 0$ and $R = 0$, results outputs $Q = Q' = 1$ which are not permitted because Q and Q' must be a complement of each other; therefore, $S = R = 0$ is prohibited.
2. By setting $S = 0$ and $R = 1$, results $Q = 1$ and $Q' = 0$ as shown in Table 5.1, if S changes from 0 to 1 then Q does not change.
3. By setting $S = 1$ and $R = 0$, results $Q = 0$ and $Q' = 1$, if R changes from 0 to 1 then the Q does not change. It can conclude when $S = R = 1$ the output of Q does not change (if $Q = 0$ stays 0 or $Q = 1$ stays 1). The S-R latch is a basic logic circuit for D, J-K, and T flip-flops.

5.3 D Flip-Flop

D flip-flop is a 1-bit memory, and it is used for designing SRAM (Static RAM) and register; Fig. 5.5 shows the logic diagram of D flip-flop. The inputs to flip-flop are D and clock. When the clock is 0, then $S = R = 1$, and according to Table 5.2 the output of flip-flop doesn't change, by setting D to 0, and changing clock from 0 to 1 results $S = 0$ and $R = 1$ then $Q = 0$ and $Q' = 1$; this means when input D = 0 and applying clock, the output Q changes to 0. Setting D to 1 and changing clock from 0 to 1 results $S = 0$ and $R = 1$, and then according to Table 5.2, the Q sets to one; this means when input D = 1 and applying clock, the output Q changes to 1. Figure 5.6 shows block diagram of D flip-flop, and rising edge of the clock is represented by “ ” and Table 5.2 shows a characteristic table of D flip-flop.

Table 5.2 Characteristic table of D flip-flop

Clock	D	Q
↑	0	0
↑	1	1

Fig. 5.6 Block diagram of D flip-flop

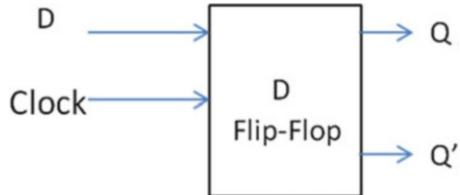


Fig. 5.7 J-K flip-flop

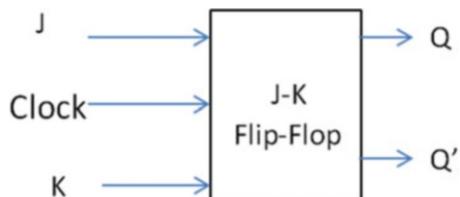


Table 5.3 Characteristic table of J-K flip-flop

Clock	J	K	Q
↑	0	0	No change
↑	0	1	0
↑	1	0	1
↑	1	1	Complement

5.4 J-K Flip-Flop

Figure 5.7 shows block diagram of a J-K flip-flop where J, K, and clock are the inputs to the J-K flip-flop. The application of J-K flip-flop is counter and frequency divider. Table 5.3 shows characteristic table of J-K flip-flop, and the following steps describe J-K flip-flop operations:

- By setting $J = K = 0$ and applying clock pulse to the flip-flop, the output Q does not change, if $Q = 0$ then stays 0, or if $Q = 1$ then stays 1.
- By setting $J = 0, K = 1$ and applying clock pulse to the flip-flop, then output Q changes to 0.
- By setting $J = 1, K = 0$ and applying clock to the flip-flop, the output Q changes to 1.
- By setting $J = K = 1$ and applying a clock pulse, the output of the flip-flop is the complement of present output; this means if $Q = 0$ and applying clock, then output changes to 1 and if $Q = 1$ and applying clock pulse then the output will change to 0.

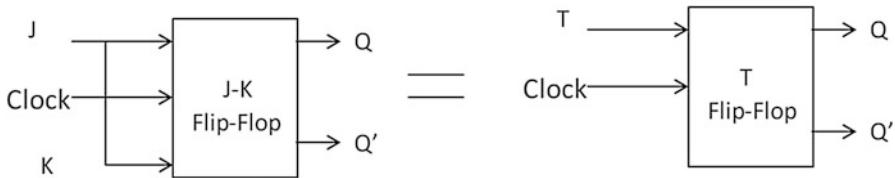


Fig. 5.8 Block diagram of T flip-flop

Table 5.4 Characteristic table of T flip-flop

Clock	T	Q
↑	0	No change
↑	1	Complement

5.5 T Flip-Flop

T flip-flop is a special case of J-K flip-flop, and by connecting J and K inputs of J-K flip-flop together results in a T flip-flop; Fig. 5.8 shows a block diagram of T flip-flop, and Table 5.4 shows the characteristic table of T flip-flop; as shown in Table 5.4 if T = 0 and applying clock pulse, then the output of T flip-flop does not change, and if T = 1 and applying clock, then output of flip-flop becomes the complement of the present output.

5.6 Register

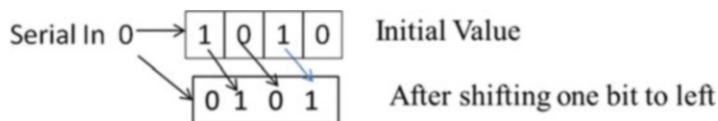
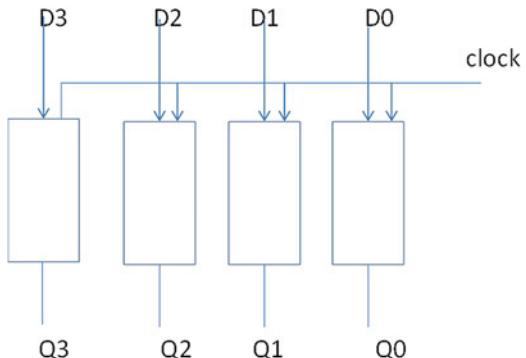
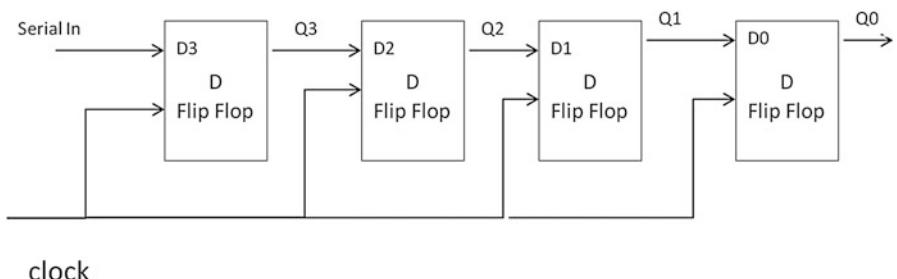
D flip-flop is 1-bit memory or 1-bit register. If a group of D flip-flops share a common clock, it is called register; the N-bit register is constructed with N D flip-flops, and if 32 D flip-flops use a common clock, then it is called a 32-bit register. Figure 5.9 shows a 4-bit register, and in this figure by placing 1101 at the inputs and applying clock pulse, then the output will be 1101.

Shift Register

A shift register has one serial input, and one bit is loaded from serial input into the register by every clock pulse, and then each bit of register is shifted to the next bit position. Figure 5.10 shows 4-bit shift right register operation, and after shifting one bit to the right, the contents of the register will be 0101. Figure 5.11 shows 4-bit serial shift right register.

Example Figure 5.12 shows 4-bit shift right register; show the contents of register after applying four clock pulses, and assume initial output of each D flip-flop is zero.

Figure 5.13 shows shift left register with serial input of 1110100, and Table 5.5 shows contents of register after applying five clock pulses; assume the initial output of each flip-flop is 0.

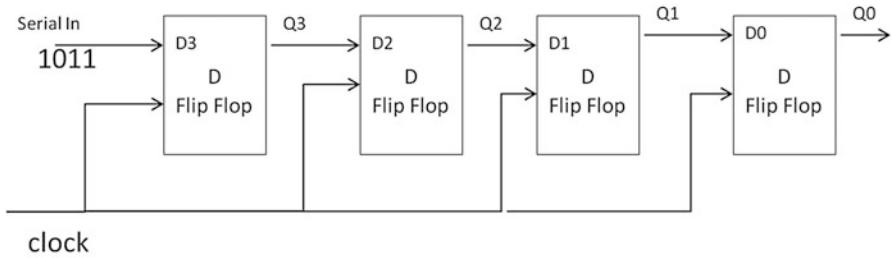
Fig. 5.9 4-bit register**Fig. 5.10** 4-bit shift right register operation**Fig. 5.11** 4-bit serial shift right register

Barrel Shifter

Barrel shifter is used for shifting data left and right; barrel shifter uses combinational logic rather than shift register; combinational logic does not require a clock and it is the fastest shifter; Fig. 5.14 shows a 4-bit barrel shifter and Table 5.5 shows operation table for barrel shifter.

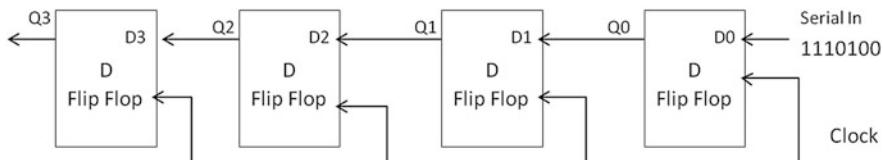
5.7 Frequency Divider Using J-K Flip-Flop

Figure 5.15 shows a J-K flip-flop as frequency divider; the inputs J and K are set to 1 and assume the initial value of Q = 0; as shown in this figure, for every two clock pulses applied to the flip-flop, then Q generates one clock pulse as shown in Fig. 5.15; this means the circuit divides the frequency by 2.



Clock#	Q3	Q2	Q1	Q0	
	0	0	0	0	Initial values
1	1	0	0	0	
2	1	1	0	0	
3	0	1	1	0	
4	1	0	1	1	

Fig. 5.12 4-bit shift right register



Q3	Q2	Q1	Q0	Clock #	
0	0	0	0	0	initial values
0	0	0	1	1	
0	0	1	1	2	
0	1	1	1	3	
1	1	1	0	4	
1	1	0	1	5	

Fig. 5.13 4-bit shift left register

Table 5.5 Barrel shifter operation

S1	S0	D3	D2	D1	D0
0	X	A3	A2	A1	A0
1	0	0	A3	A2	A1
1	1	A2	A1	A0	0

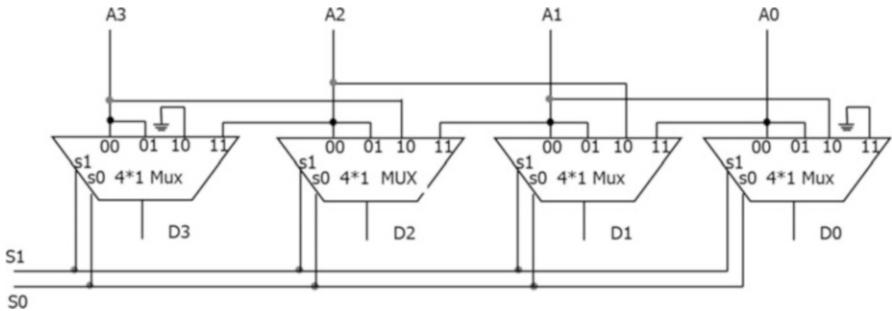


Fig. 5.14 4-bit barrel shifter

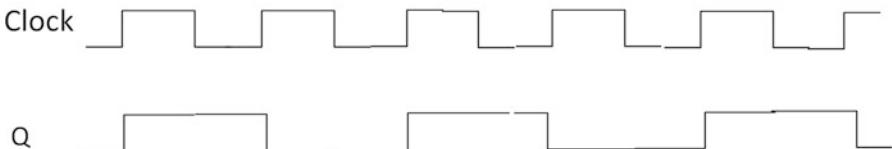
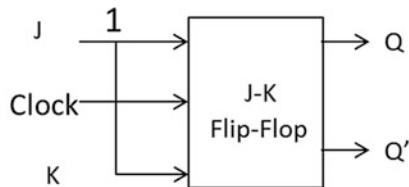
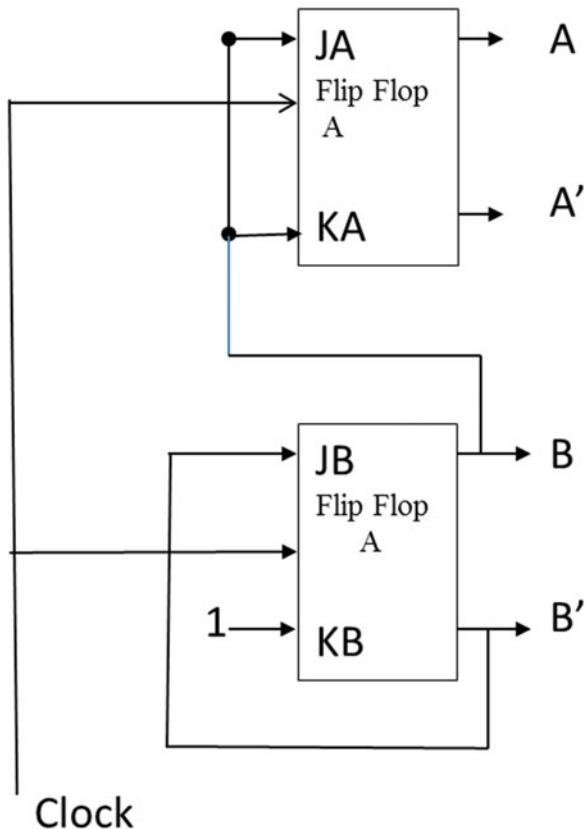


Fig. 5.15 Frequency divider using J-K flip-flop

5.8 Analysis of Sequential Logic

In a combinational logic, the truth table represents the characteristic of a function, but characteristic of sequential logic is represented by state table. State table is represented by present state, next state, and output. The present state is the current state of the flip-flop (current output), and the next state is the output of flip-flop after applying clock to the sequential logic. Figure 5.16 shows a sequential circuit with two J-K flip-flops with two states A and B; the state table consists of two columns present state and next state; present state represents current outputs of the flip-flops with all possible values for A and B (00, 01, 10, and 11) as shown in Table 5.6.

Consider the first row; the present state is 00 (means A = 0 and B = 0); it is interested to find the outputs of flip-flops (next state) by applying clock pulse. If

Fig. 5.16 Sequential logic**Table 5.6** State table for Fig. 5.16

Present state		Next state	
A	B	A	B
0	0	0	1
0	1	1	0
1	0	1	1
1	1	0	0

$A = 0$ and $B = 0$ result in $JA = KA = 0$, $JB = KB = 1$, then applying clock pulse to flip-flops results $A = 0$ and $B = 1$ ($AB = 01$ next state).

Consider the second row, for present state $A = 0$ and $B = 1$; therefore, $JA = KA = 1$, $JB = 0$, and $KB = 1$; applying a clock pulse to the flip-flops results to next state with $A = 1$ and $B = 0$; the same procedure is used for row 10 and 11 to find the next states. Table 5.6 shows state table for sequential logic of Fig. 5.16.

Fig. 5.17 Sequential circuit

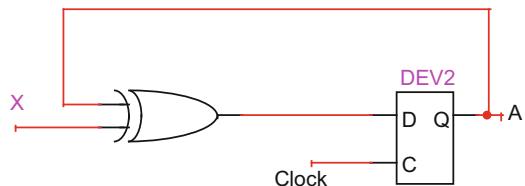


Table 5.7 State table for Fig. 5.17

Present state	Next state for $X = 0$	Next state for $X = 1$
A	A	A
0	0	1
1	1	0

Fig. 5.18 State diagram

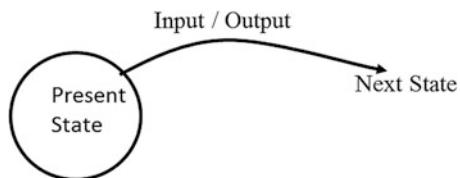
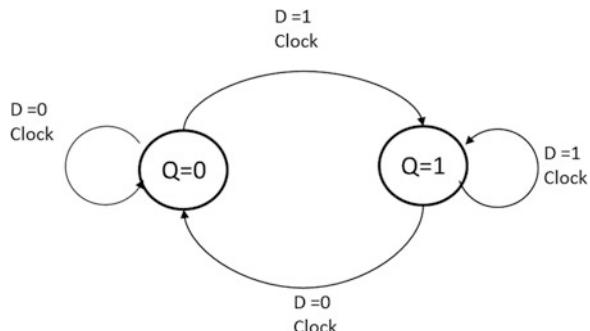


Fig. 5.19 State diagram for D flip-flop



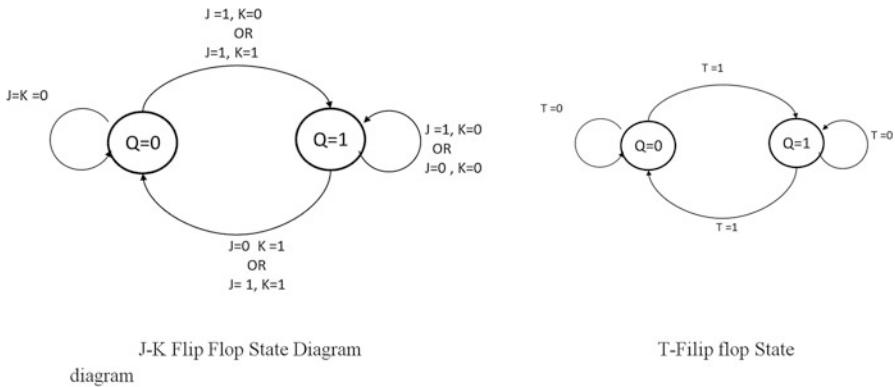
Example 5.1 Find the state table of Fig. 5.17.

Figure 5.17 contains external input X, and Table 5.7 shows stable with two columns for next state: one for $X = 0$ and another one for $X = 1$.

5.9 State Diagram

Another way to represent the characteristic of sequential logic is by state diagram, as shown in Fig. 5.18. The present state is the current value of flip-flop, and applying clock the present state changes to next state.

D Flip-Flop State Diagram Figure 5.19 shows state diagram of D flip-flop, and the following steps describe state diagram:

**Fig. 5.20** J-K and T flip-flops state diagrams**Table 5.8** Excitation table
for D flip-flop

$Q(t)$	$Q(t + 1)$	D
0	0	0
0	1	1
1	0	0
1	1	1

1. If $Q = 0$ (present state), by setting $D = 1$ and applying clock, then Q changes from 0 to 1 (next state).
2. If $Q = 1$, by setting $D = 1$ and applying clock, then output stays 1.
3. If $Q = 1$, by setting $D = 0$ and applying clock, then output changes to 0.
4. If $Q = 0$, by setting $D = 0$ and applying clock, then output stays 0.

Figure 5.20 shows state diagram of J-K and T flip-flops.

5.10 Flip-Flop Excitation Table

The application of excitation table is to determine input or inputs of a flip-flop in order to get predefined output.

D Flip-Flop Excitation Table

Table 5.8 shows excitation table for D flip-flop: $Q(t)$ is present output (present state) and $Q(t + 1)$ is the next state.

Excitation Table Operation Consider the first row of Table 5.8, if $Q(t) = 0$ (present state) and it is desired after applying a clock pulse, the output $Q(t + 1)$ stays 0 and then D must be set to 0.

Consider the second row, the current output of D flip-flop (present state) is 0, and it is desired to change the output $Q(t + 1)$ to one; therefore, the input D must set to 1.

Table 5.9 J-K flip-flop excitation table

$Q(t)$	$Q(t + 1)$	J	K
0	0	0	d
0	1	1	d
1	0	d	1
1	1	d	0

Table 5.10 T flip-flop excitation table

$Q(t)$	$Q(t + 1)$	T
0	0	0
0	1	1
1	0	1
1	1	0

Consider the third row, the present output is 1, and it is desired to change the output (next state) to 0; therefore the input D must be set to 0.

Consider the fourth row, the present state is 1, and it is desired to stay 1; therefore, D must set to one.

J-K Flip-Flop Excitation Table

Table 5.9 shows J-K flip-flop excitation table, and the following steps describe how this table was generated:

1. Consider the first row of excitation table, the present state of the flip-flop is zero, and it desired to stay 0 by applying clock pulse; therefore, J must set to zero and K is don't care (0 or 1).
2. Consider the second row, the present state of the flip-flop is 0, and it is desired to change the output to 1 by applying clock pulse; therefore, J must set to 1 and K can don't care.
3. Consider the third row, the present state $Q(t)$ is 1, and it is desired to change it to 0; therefore, the J can don't care and k = 1.
4. Consider the fourth row, the present state is 1, and it is desired to stay 1; therefore, J can don't care and K = 0.

T Flip-Flop Excitation Table. Table 5.10 shows excitation table of T flip-flop.

5.11 Counter

A counter is a sequential logic which is used to count the number of pulses applied to it or divide a clock frequency if a system has a clock of 16 Hz, and it is possible to use a counter to change 16 Hz clock to 4 Hz. The following steps describe how to design a counter:

Table 5.11 State table of counter

Present state		Next state	
A	B	A	B
0	0	0	1
0	1	1	0
1	0	1	1
1	1	0	0

Table 5.12 Excitation table for counter

Present state		Next state					
A	B	A	B	JA	KA	JB	KB
0	0	0	1	0	d	1	d
0	1	1	0	1	d	d	1
1	0	1	1	d	0	1	d
1	1	0	0	d	1	d	1

- (a) Define count sequence which is a sequence that the counter will count.
- (b) Use count sequence to determine the number of flip-flops.
- (c) Select the types of flip-flop.
- (d) Use count sequence to develop state table.
- (e) Use state table and flip-flop excitation table to develop excitation table for counter.
- (f) Use K-map to find the input functions or function to each flip-flop.
- (g) Draw the sequential logic for the counter.

Example: Design a counter to count 0—1—2—3 and repeat using J-K flip-flops.

The biggest number in count sequence is 3 which is represented in binary by 11; therefore, two flip-flops are needed and it is called A and B as shown in Fig. 5.22, and Table 5.11 shows state table for the counter.

The present state defines the current output of flip-flops, and the next state is the output of flip-flops after applying a clock pulse.

Table 5.12 shows excitation table for the counter which was developed by using excitation table of JK flip-flop.

Consider the first row, the present output of J-K flip-flops is 00 ($A = 0, B = 0$), and it is desired the outputs change to 01 ($A = 0$ and $B = 1$); therefore, it must set $JA = 0, KA = d$ (don't care) in order for the A to stay 0 and set $JB = 1, KB = d$ in order for B to change from 0 to 1.

Consider the second row, the present state is 01 ($A = 0$ and $B = 1$), and it is desired the output changes to 10 ($A = 1$ and $B = 0$); therefore, it must set $JA = 1, KA = d$, and $JB = 0, KB = d$.

It is desired to find the input functions to the flip-flops, the present state are the inputs, and JA, KA, JB , and KB are the outputs of the Table 5.12, by transferring the outputs to the K-maps, and reading the K-maps results the input functions to the flip-flops; Fig. 5.21 shows K-maps for JA, KA, JB , and KB .

The input functions to the flip-flops are $JA = JB = B, JB = B'$ and $KB = 1$, and Fig. 5.22 shows the circuit of 2-bit counter.

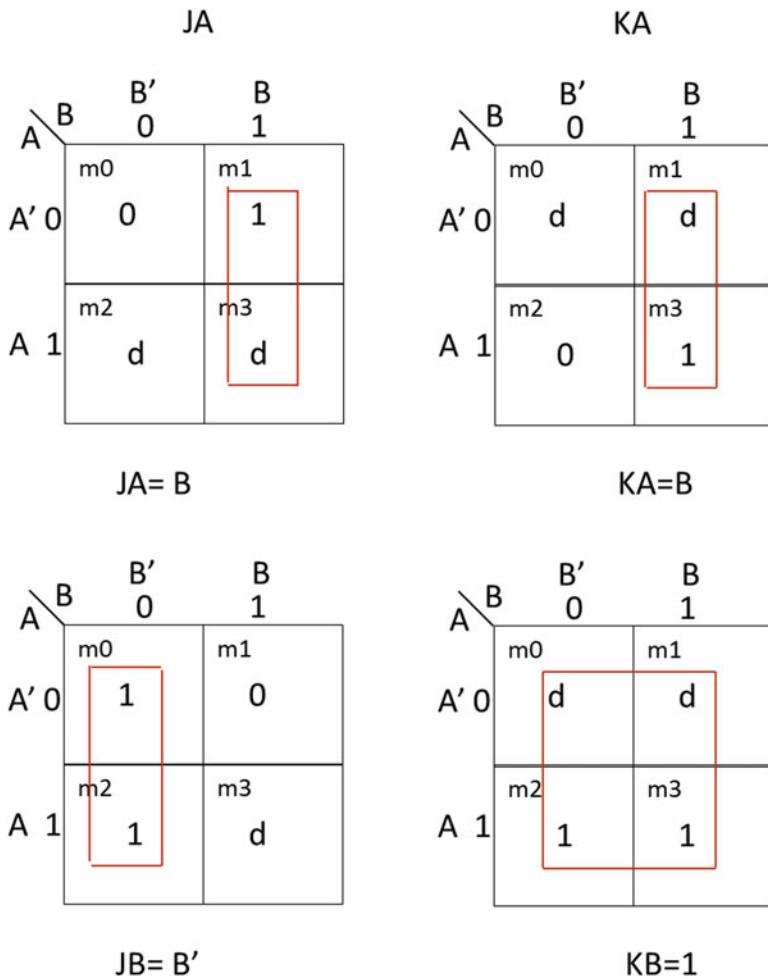
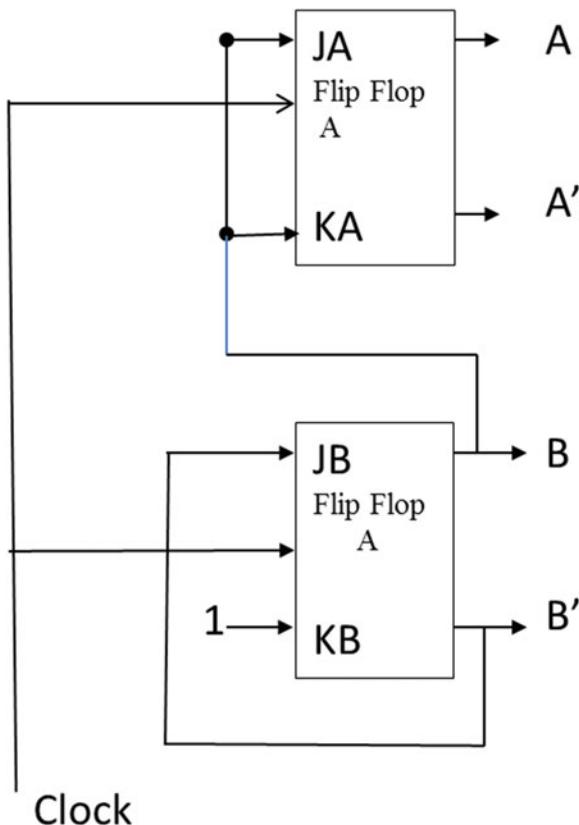


Fig. 5.21 K-maps for 2-bit counter

5.12 Summary

- Sequential logic circuit requires clock to operate.
- A S-R latch is the basic component for flip-flop.
- S-R latch can be constructed by the NAND or NOR gates.
- The basic element of sequential logic is flip-flop.
- Flip-flop is a memory element with the two outputs Q and Q'.
- By applying clock to the D flip-flop, the value of the D input copies at the Q output.
- D flip-flop use for designing register.

Fig. 5.22 Sequential logic of 2-bit counter



- Register is a group of the D flip-flop sharing the same clock.
- J-K flip-flop is used for the designing counter.
- Connecting inputs of a J-K flip-flop together results a T flip-flop.
- State table and state diagram show operation of a sequential circuit.
- Chapter 6 is an introduction to computer architecture which covers basic components of a microcomputer as well as CPU technologies, CPU architectures, multicore processor, instruction execution steps, pipelining, and microcomputer buses.

Problems 1. Complete the following table for D flip-flop.

D	Q(t) present output	Q($t + 1$) next output
0	0	
0	1	
1	0	
1	1	

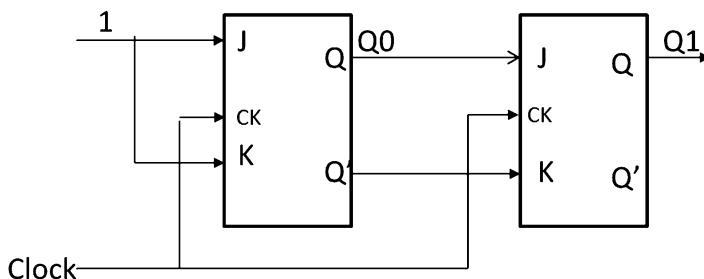
2. Complete the following table for J-K flip-flop.

J	K	$Q(t)$ present output	$Q(t + 1)$ next output
0	0	0	
0	0	1	
0	1	0	
0	1	1	
1	0	0	
1	0	1	
1	1	0	
1	1	1	

3. Complete the following table for T flip-flop.

T	$Q(t)$ present output	$Q(t + 1)$ next output
0	0	
0	1	
1	0	
1	1	

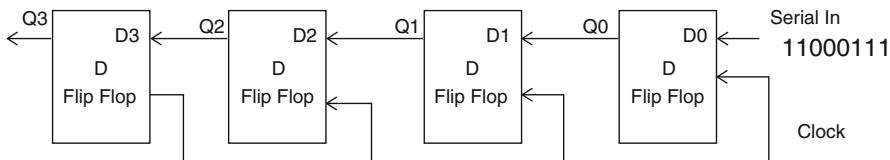
4. The following figure shows a sequential logic; complete the following table assuming initial value of $Q_1 = 0$ and $Q_2 = 0$. Use logisim to verify your answer.



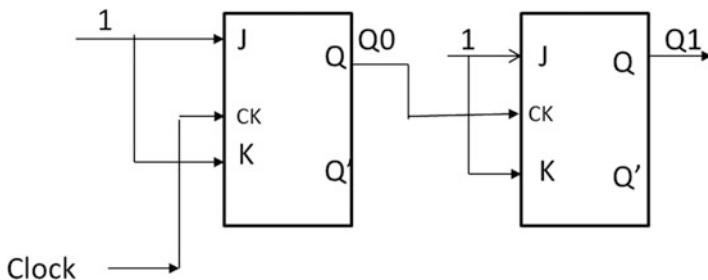
Clock	Q_0	Q_1
Initial value	0	0
Clock #1		
Clock #2		
Clock #3		

5. Show an 8-bit register using D flip-flops.

6. The following shift register given, find the output after five clock pulses.



7. With the following sequential logic given, assume initial value for $Q_0 = 0$ and $Q_1 = 0$, and flip-flop changes state in rising edge of clock pulse; complete the following table and then use logisim to verify your result.



Clock	Q_0	Q_1
Initial value	0	0
Clock #1		
Clock #2		
Clock #4		
Clock #4		

8. Complete the following excitation table for J-K flip-flop.

$Q(t)$	$Q(t + 1)$	J	K
0	0		
0	1		
1	0		
1	1		

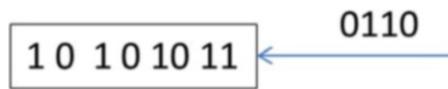
9. Design a counter to count 0—1—2—3—4—5—6—7 and repeat.

- (a) Use J-K flip-flops.
- (b) Use T flip-flops.
- (c) Verify your design using logisim.

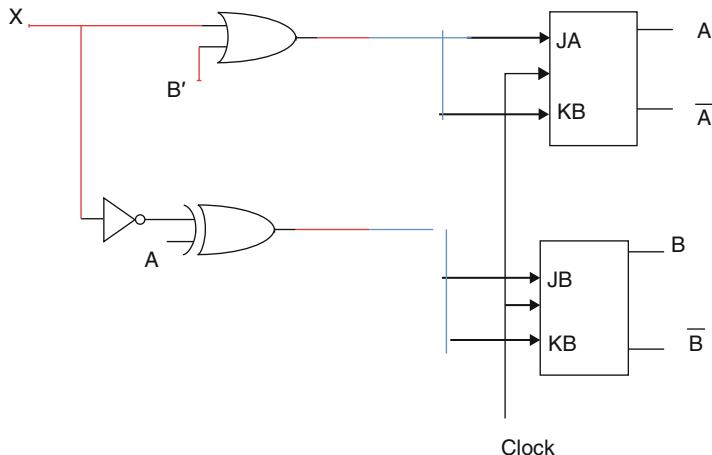
10. Find the state diagram for the following state table.

	AB X = 0	AB X = 1
AB	X = 0	X = 1
00	01	10
01	10	00
10	11	01
11	00	10

11. What is the content of the following register after shifting five times to the left?



12. Show state table and state diagram for following circuit.



Chapter 6

Introduction to Computer Architecture

Objectives: After completing this chapter, you should be able to:

- List the components of a microcomputer.
- List the components of CPU.
- Distinguish CPU technologies.
- Learn architecture of multicore processor.
- Compare the RISC processor with the CISC processor.
- Explain the difference between the von Neumann and the Harvard architecture.
- Distinguish between the 32-bit processor and the 64-bit processor.
- Explain the instruction execution steps.
- Show advantage of the instruction pipelining.
- Distinguish different types of the microcomputer buses.
- Explain operation of the USB bus.

6.1 Introduction

Just as the architecture of a building defines its overall design and functions, so computer architecture defines the design and functionality of a computer system. The components of a microcomputer are designed to interact with one another, and this interaction plays an important role in the overall system operation.

6.2 Components of a Microcomputer

A standard microcomputer consists of a microprocessor (CPU), buses, memory, parallel input/output, serial input/output, programmable I/O interrupt, and direct memory access DMA. Figure 6.1 shows components of microcomputer.

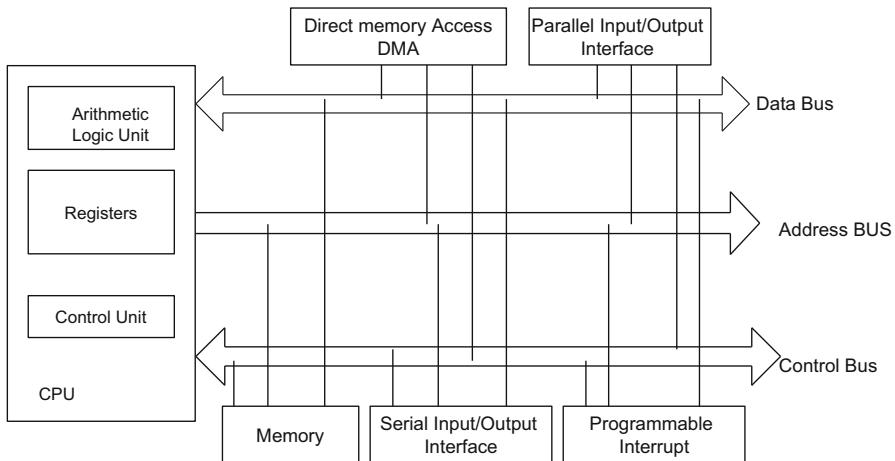


Fig. 6.1 Components of a microcomputer

6.2.1 Central Processing Unit (CPU)

The *central processing unit (CPU)* is the “brain” of the computer and is responsible for accepting data from input devices, processing the data into information, and transferring the information to memory and output devices. The CPU is organized into the following three major sections:

1. Arithmetic logic unit (ALU)
2. Control unit
3. Registers

The function of the *arithmetic logic unit (ALU)* is to perform arithmetic operations such as addition, subtraction, division, and multiplication and logic operations such as AND, OR, and NOT.

The function of the *control unit* is to control input/output devices, generate control signals to the other components of the computer such as read and write signals, and perform instruction execution. Information is moved from memory to the registers; the registers then pass the information to the ALU for logic and arithmetic operations.

Register Register is the fastest memory in a computer which holds information.

6.2.2 CPU Buses

When more than one wire carries the same type of information, it is called a bus. The most common buses inside a microcomputer are the address bus, the data bus, and the control bus.

Fig. 6.2 A memory with three address lines and four data lines

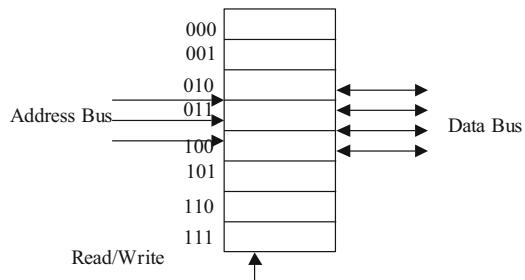
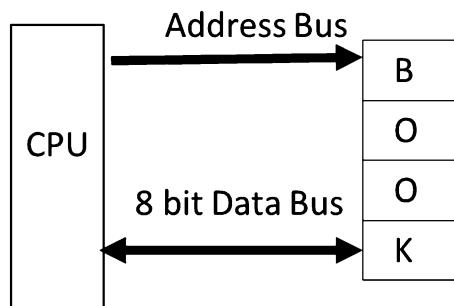


Fig. 6.3 CPU with 8 bit Data Bus



Address Bus The address bus defines the number of addressable locations in a memory IC by using the 2^n formula, where n represents the number of address lines. If the address bus is made up of three lines, then there are $2^3 = 8$ addressable memory locations, as shown in Fig. 6.2. The size of the address bus directly determines the maximum numbers of memory locations that can be accessed by the CPU. For example, a CPU with 32 address bus can have 2^{32} addressable memory locations.

Data Bus The data bus is used to carry data to and from the memory. In Fig. 6.2, each location can hold only four bits. The size of a memory IC is represented by $2^n \times m$ where n is the number of address lines and m is the size of each location. In Fig. 6.2, where n = 3 and m = 4, the size of the memory is

$$2^3 * 4 = 32 \text{ bits.}$$

The size of data bus plays important factor on CPU performance, current CPU's data bus is 32 bits or 64 bits, and a CPU with 32-bit data bus means it can read or write 32 bits of data in and from memory.

Early generation of CPU contains 8-bit data bus, and each memory location holds one byte, for reading word “book” as shown in Fig. 6.3. The CPU requires to access memory four times.

By increasing data bus from 8 bits to 32 bits, then CPU can access memory and read entire word “book.” Most CPUs offer instruction to read 1 byte, 2 bytes, or 4 bytes from memory.

Control Bus The control bus carries control signals from the control unit to the computer components in order to control the operation of each component. In addition, the control unit receives control signals from computer components. Some of the control signals are as follows:

- Read signal:* The read line is set to high to read from memory location or input/output (I/O) devices.
- Write signal:* The write line is used to write data into the memory.
- Interrupt:* Indicates an interrupt request.
- Bus request:* The device is requesting to use the computer bus.
- Bus Grant:* Gives permission to the requesting device to use the computer bus.
- I/O Read and Write:* I/O read and write are used to read from or write to I/O devices.

6.2.3 32-Bit Versus 64-Bit CPU

The size of register plays an important role in the performance of CPU. A 32-bit processor means it can perform operations on 32-bit data; therefore, the size of registers is 32 bits and ALU also performs 32-bit operations. A 64-bit CPU performs operation in 64-bit data; therefore, it contains 64-bit register and 64-bit ALU.

Most desktop and server computers are using AMD and Intel processors; they might use 32 bits or 64 bits. Intel and AMD processor use the same architecture; this means a program in computer with Intel processor can run on a computer with AMD processor.

6.3 CPU Technology

There are two types of technology used for designing CPU and they are called CISC and RIS.

CISC (Complex Instruction Set Computer) In 1978, Intel developed the 8086 microprocessor chip. The 8086 was designed to process a 16-bit data word; it had no instruction for floating point operations. At the present time, the Pentium processes 32-bit and 64-bit words, and it can process floating point instructions.

Intel designed the Pentium processor in such a way that it can execute programs written for earlier 80×86 processors.

The characteristics of 80×86 are called complex instruction set computers (CISC), which include instructions for earlier Intel processors. Another CISC processor is VAX 11/780, which can execute programs for the PDP-11 computer. The CISC processor contains many instructions with different addressing modes, for example, the VAX 11/780 has more than 300 instructions with 16 different address modes.

The major characteristics of CISC processor are as follows:

1. A large number of instructions.
2. Many addressing modes.
3. Variable length of instructions.
4. Most instruction can manipulate operands in the memory.
5. Control unit is microprogrammed.

RISC Until the mid-1990s, computer manufacturers were designing complex CPUs with large sets of instructions. At that time, a number of computer manufacturers decided to design CPUs capable of executing only a very limited set of instructions.

One advantage of reduced-instruction set computer is that they can execute their instructions very fast because the instructions are simple. In addition, the RISC chip requires fewer transistors than the CISC chip. Some of the RISC processors are the PowerPC, MIPS processor, IBM RISC System/6000, ARM, and SPARC.

The major characteristics of RISC processors are as follows:

1. Require few instructions.
2. All instructions are the same length (they can be easily decoded).
3. Most instructions are executed in one machine clock cycle.
4. Control unit is hardwired.
5. Few address modes.
6. A large number of registers.

RISC processor uses hardware and CISC processor microprogram for control unit, and the control unit with hardware uses less space in a CPU; therefore, the designer of CPU can add more registers to RISC processor compared with CISC.

The advantage of CISC processor is that designer can add new instruction without changing the architecture of the processor. Table 6.1 shows the comparison of CISC and RISC.

Table 6.1 Comparison of RISC and CISC processor

CISC	RISC
Variable instruction length	Fixed instruction length
Variable opcode length	Fixed opcode length
Memory operands	Load/store instructions
Example: Pentium	ARM, MIPS

Fig. 6.4 Von Neumann architecture

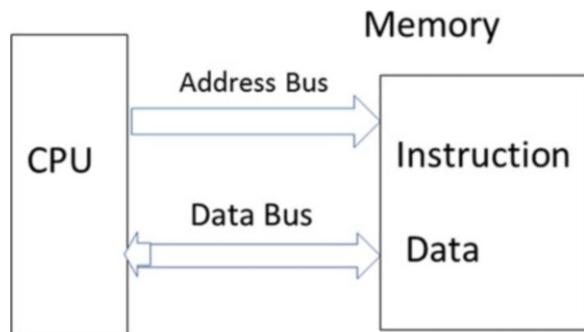
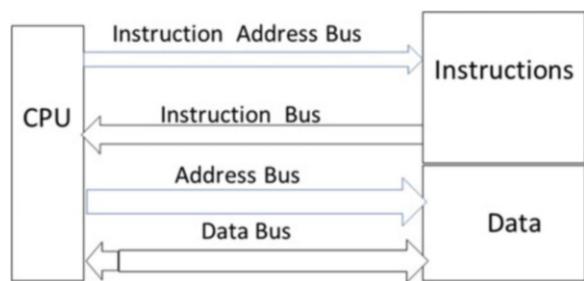


Fig. 6.5 Harvard architecture



6.4 CPU Architecture

There are two types of CPU architecture and they are *von Neumann* and *Harvard architecture*.

Von Neumann Architecture It is a program consists of code (instructions) and data. Figure 6.4 shows a block diagram of the von Neumann architecture. Von Neumann uses the data bus to transfer data and instructions from the memory to the CPU.

Harvard Architecture Harvard architecture uses separate buses for instructions and data as shown in Fig. 6.5. The instruction address bus and instruction bus are used for reading instructions from memory. The address bus and data bus are used for writing and reading data to and from memory.

6.5 Intel Microprocessor Family

Intel designs and manufactures microprocessors for microcomputers. Each processor has a number or name, which is used by the computer designer to access the information provided by the manufacturer of the processor.

Intel microprocessor IC numbers and names are 8088, 80,286, 80,386, 80,486, Pentium, Pentium II, Pentium III, and Pentium IV which they called IA-86 (Intel architecture-86). Recently Intel and HP developed a new processor called Itanium which is a 64-bit processor, which is described later in this chapter. The following is a list of the characteristics of a microprocessor:

1. *Register size*: Registers are used to store information inside the processor. Register sizes can vary from 8- to 16- to 32- to 64-bit.
2. *Number of registers*: A processor with several registers can store more information in the CPU for processing.
3. *Data bus size*: The size of the data bus determines how many bits of data can be transferred in parallel to or from memory or input/output ports.
4. *Address bus size*: The typical address sizes are 16, 32, and 64 bits. The size of the address bus determines the number of memory locations that may be accessed by the microprocessor.
5. *Clock speed*: The speed of the clock determines the speed at which the processor executes instructions.
6. *Math coprocessor*: The math coprocessor is a special processor that performs complex mathematical operations.
7. *Real mode*: Real mode allows for software compatibility with older software. It enables the processor to emulate the lowest Intel 8088 processor and use only the first 1 MB of memory.
8. *Protected mode*: Protected mode is a type of memory usage that is available on 80,286 and later model microprocessors. In protected mode, each program can be allocated a certain section of memory and other programs cannot use this memory. Protected mode also enables a single program to access more than 1 MB of memory.
9. *Cache size*: Cache memory is a small amount of high-speed memory used for temporary data storage based between the processor and main memory. The size of cache can help to speed up the execution time of a program.
10. *MMX technology*: Intel's MMX technology is designed to speed up multimedia and communication applications, such as video, animation, and 3D graphics. The technology includes single instruction multiple data (SIMD) technique (meaning that with one instruction, the computer can perform multiple operations), 57 new instructions, eight 64-bit MMX register, and four new data types.

Table 6.2 Provide a quick reference to the preceding list of characteristics

Most workstations or laptops use CPU which is manufactured by Intel and AMD Corporations. Intel processor is classified by the IA-16 (Intel architecture 16-bit processor), IA-32, and IA-64.

Upward Compatibility Intel architecture is upward compatible meaning a program written for IA-16 processor can run on IA-32.

Figure 6.6 shows general register IA-16, where AH, AL, BH, BL, CH, CL, DH, and DL are 8-bit registers and AX, BX, CX, and DX are 16-bit register. The AX, BX, CX, and DX are combinations of two registers.

Table 6.2 Characteristics of Intel microprocessor

	80486dx	Pentium	Pentium Pro	Pentium Pro II	Pentium II
Register size	32 bits	32 bits	32 bits	32/64 bits	32/64 bits
Data bus size	32 bits	64 bits	64 bits	64 bits	64 bits
Address size	32 bits	32 bits	32 bits	32 bits	32 bits
Max memory	4 GB	4 GB	4 GB	4 GB	4 GB
Clock speed	25, 33 MHz	60, 166 MHz	150, 200 MHz	233, 340, 400 MHz	450, 500 MHz
Math processor	Built-in	Built-in	Built-in	Built-in	Built-in
L1 cache	8 KB, 16 KB	8 KB instruction 8 KB data	8 KB instruc- tion 8 KB data	16 KB instruc- tion 16 KB data	16 KB instruction 16 KB data
L2 cache	No	No	256 KB or 512 KB	512 KB	512 KB
MMX technology	No	No	Yes	Yes	Yes

L1 cache is the cache memory built inside the microprocessor

L2 cache is not part of microprocessor; it is in a separate IC

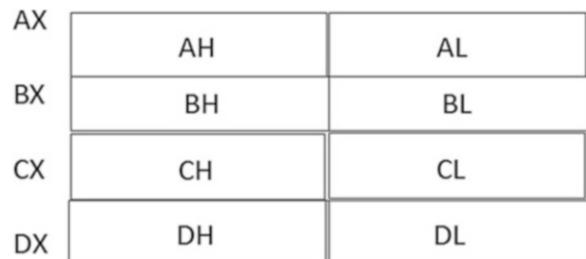
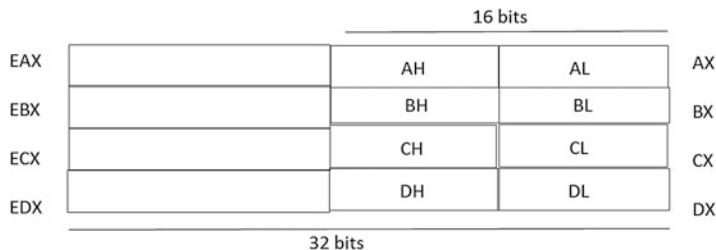
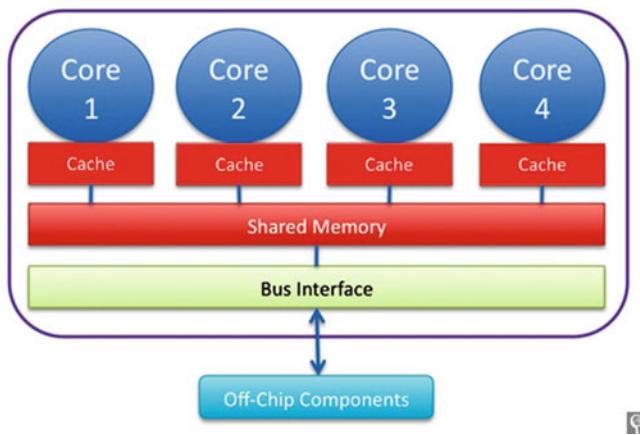
Fig. 6.6 IA-16 registers

Figure 6.7 shows IA-32 general registers where EAX, EBX, ECX, and EDX are 3-bit general registers, and also Figure 6.6 also contains IA-16-bit registers; therefore, a program was written for IA-16 can be executed by IA-32.

6.6 Multicore Processors

A *multicore processor* is an integrated circuit (IC) with two or more independent CPU which is called core, and they are executing multiple instructions simultaneously in order to increase performance. A quad-core [processor](#) is a [chip](#) with four independent units called cores that read and execute instructions such as add, move data, and branch. Figure 6.8 shows a block diagram of quad-core processors which are all sharing a memory. The following are some of the multicore processors:

Two cores (dual-core CPUs) such as AMD Phenom II X2 and Intel Core Duo

**Fig. 6.7** Intel IA-32-bit registers**Fig. 6.8** Multicore processor architecture

Three cores (tri-core CPUs) such as AMD Phenom II X3

Four cores (quad-core CPUs) such as AMD Phenom II X4, Intel's i5 and i7 processors

Six cores (hexa-core CPUs) such as AMD Phenom II X6 and Intel Core i7 Extreme Edition 980X

Eight cores (octa-core CPUs) such as Intel Core i7 5960X Extreme Edition and AMD FX-8350

Ten cores (deca-core CPUs) such as Intel Xeon E7-2850

6.7 CPU Instruction Execution

In general, CPU performs the following steps to execute one instruction:

1. Fetch instruction (F): Moving Instruction from memory to CPU.
2. Decode instruction (D): Determine types of instruction such as ADD, AND, OR, and Store operands into registers if needed.

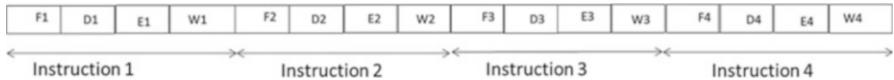


Fig. 6.9 Execution of instruction without pipeline



Fig. 6.10 Execution of instruction using pipeline

3. Execute instruction (E): Execute the instruction such as addition.
4. Write results (R): Store the result of execution into register or memory.

Pipelining. Pipelining will increase the performance of CPU meaning executing more instructions in less time.

Figure 6.9 shows execution of four instructions without pipelining; in this figure, CPU executes one instruction at a time, and each stage takes T second; then total execution time is 16 T.

Figure 6.10 shows execution of four instructions using pipeline; CPU fetches I1 instruction and moves it to decode unit; CPU while decoding I1 will fetch I2 instruction and this process will continue.

As shown in Fig. 6.10, it takes 7 T to complete the execution of four instructions. Figure 5.11 shows that at time T4 CPU writes the results of execution I1 into memory and at the same time fetches instruction I4 from memory, but it is impossible to read and write at the same time into or from memory; therefore, having two separate caches (instruction cache and data cache) will overcome this conflict, and this type of architecture is called Harvard architecture.

Direct memory access: Direct memory access (DMA) allows for the transfer of blocks of data from memory to an I/O device or vice versa. Without DMA, the CPU reads data from memory and writes it to an I/O device. Transferring blocks of data from memory to an I/O device requires the CPU to do one read and one write for each operation. This method of data transfer takes a lot of time. The function of DMA is to transfer data from memory to an I/O device directly, without using the CPU, so that the CPU is free to perform other functions.

The DMA performs the following functions in order to use of the computer bus:

- The DMA sends a request signal to the CPU.
- The CPU responds to the DMA with a grant request, permitting the DMA to use the bus.

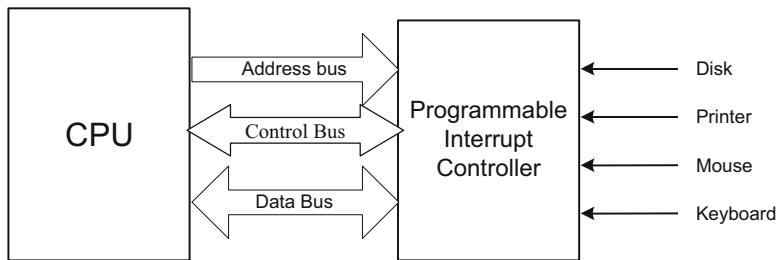


Fig. 6.11 Programmable interrupt controller

- The DMA controls the bus and the I/O device is able to read or write directly to or from memory.
- The DMA is able to load a file off an external disk into main memory when large blocks of data need to be transferred to a sequential range of memory. DMA is much faster and more efficient than a CPU.

Programmable I/O Interrupt When multiple I/O devices such as external drives, hard disks, printers, monitors, and modems are connected to a computer as shown in Fig. 6.11; a mechanism is necessary to synchronize all device requests. The function of a programmable interrupt is to check the status of each device and inform the CPU of the status of each; for example, the printer is not ready, a disk is write protected, this is an unformatted disk, and there is a missing connection to a modem. Each device sends a signal to the programmable I/O interrupt controller in order to update its status. Figure 6.11 shows the programmable I/O interrupt controller.

6.8 Disk Controller

The disk controller moves the disk drive head, reads, and/or writes data. Today, there are two types of disk controllers: IDE (integrated disk electronics) and SCSI (small computer systems interface).

Integrated Disk Electronics (IDE). An IDE disk drive is connected to the ISA bus with a flat ribbon cable. The IDE disk controller supports two hard disks, each with a 528-megabyte capacity. In 1994, hard disk drive vendors introduced EIDE (extended IDE) which supports four devices, such as hard disks, tape drives, CD-ROM devices, and larger hard disk drives. The EIDE has two connectors. Each cable is connected to the EIDE controller and can support two hard disk drives with a capacity of up to 250 GB. EIDE is used in IBM-compatible computers.

Small Computer System Interface (SCSI) The small computer system interface (SCSI) standard is defined by the American National Standards Institute (ANSI) for

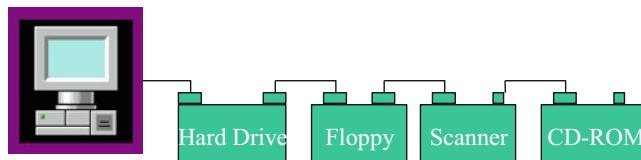


Fig. 6.12 SCSI bus

Table 6.3 Characteristics of several types of SCSI controllers

	Bandwidth	Data rate MB/s
SCSI-1	8 bits	5
SCSI-2	16 bits	10–20
Ultra SCSI	8 bits	20
SCSI-3	16 bits	40

MB/s millions bytes per second



Fig. 6.13 SCSI-1, SCSI-2, and SCSI-3 connectors

connecting daisy chaining multiple I/O devices, such as scanners, hard disks, and CD-ROMs, to the microcomputer, as shown in Fig. 6.12.

SCSI is a standard interface for all types of microcomputers. It is used in Macintosh, RISC workstations, and minicomputers, as well as in higher-end IBM-compatible computers. The SCSI bus comes with different types of controllers. Table 6.3 shows the characteristics of several types of SCSI controllers, and Fig. 6.13 shows SCSI-1, SCSI-2, and SCSI-3 connectors.

SATA (Serial Advanced Technology Attachment) SATA is a serial bus for connecting mass storage such as hard disk, optical drive, and solid-state drive to computer.

6.9 Microcomputer Bus

There are currently a number of different computer buses on the market that are designed for microcomputers. Some of the computer BUS are ISA, MCA, EISA, VESA PCI, FireWire, USB, and PCI Express. Universal serial bus (USB) and PC Express are covered in more detail because they are more advanced than other buses.

6.9.1 ISA Bus

The *industry standard architecture (ISA) bus* was introduced by IBM for the IBM PC using an 8088 microprocessor. The ISA bus has an 8-bit data bus and 20 address lines at a clock speed of 8 MHz. The PC AT type uses the 80,286 processor which has a 16-bit data bus and 24-bit address lines and is compatible with the PC.

6.9.2 Microchannel Architecture Bus

The *microchannel architecture (MCA) bus* was introduced by IBM in 1987 for its PS/2 microcomputer. The MCA bus is a 32-bit bus that can transfer four bytes of data at a time and runs at a 10 MHz clock speed. It also supports 16-bit data transfer and has 32-bit address lines. Microchannel architecture was so expensive the non-IBM vendors developed a comparable but less expensive solution called the EISA bus.

6.9.3 EISA Bus

The *extended ISA (EISA) bus* is a 32-bit bus that also supports 8- and 16-bit data transfer bus architectures. EISA runs at 8-MHz clock speeds and has 32-bit address lines.

6.9.4 VESA Bus

The *video electronics standard association (VESA) bus*, which is also called a video local bus (VL-BUS), is a standard interface between the computer and its expansion. As applications became more graphically intensive, the VESA bus was introduced to maximize throughput of video graphics memory. The VESA bus provides fast data flow between stations and can transfer up to 132 Mbps.

6.9.5 PCI Bus

The *peripheral component interconnect (PCI) bus* was developed by Intel Corporation. PCI bus technology includes a 32-/64-bit bus that runs at a 33/66 MHz clock speed. PCI offers many advantages for connections to hubs, routers, and network

Table 6.4 Characteristics of various buses

Bus type	ISA	EISA	MCA	VESA	PCI	PCI-64
Speed (MHz)	8	8.3	10	33	33	64
Data bus bandwidth (bits)	16	32	32	32	32	66
Max. data rate (MB/s) ^a	8	32	40	132	132	508
Plug and play capable	No	No	Yes	Yes	Yes	Yes

^aMB/s megabytes/second

Fig. 6.14 PCI card

interface cards (NIC). In particular, PCI provides more bandwidth: up to 1 gigabit per second as needed by these hardware components.

The PCI bus was designed to improve the bandwidth and decrease latency in computer systems. Current versions of the PCI bus support data rates of 1056 Mbps and can be upgraded to 4224 Mbps. The PCI bus can support up to 16 slots or devices in the motherboard. Most suppliers of ATM (asynchronous transfer mode) and 100BaseT NICs offer a PCI interface for their products. The PCI bus can be expanded to support a 64-bit data bus. Table 6.4 compares different bus architectures showing characteristics of ISA, EISA, MCA, VESA, and PCI buses. Figure 6.14 shows the PCI bus.

6.9.6 Universal Serial BUS (USB)

The *universal serial bus (USB)* is a computer serial bus which enables users to connect peripherals such as the mouse, keyboard, modem, CD-ROM, scanner, and printer, to the outside of a computer without any configuration. Personal computers equipped with USB will allow the user to connect peripherals to the computer, and the computer will automatically be configured as the devices are attached to it. This means that a USB has the capability to detect when a device has been added or removed from a PC. USB is a true plug-and-play bus. Up to 127 peripherals can be connected to a PC with a USB. USB version 1.1 was released in 1998 which supports data rate of 12 Mbps (full speed) and 1.5 Mbps (low speed); the low

speed is used for devices such mouse, keyboards, and joysticks. The USB version 2 is a high speed (480 Mbps) that is compatible with USB 1.1. The USB 2.0 specification was developed by seven leading computer manufacturers and it was announced in 1999. The maximum cable length for USB is 5 meters.

6.9.7 USB Architecture

Figure 6.15 shows the USB architecture; the USB system is logically a tree topology but physical is a star topology because each USB device communicates directly with the Root Hub. There is only one host Controller in any USB system.

A USB system consists of USB host controller, USB root hub, USB hub, USB cable, USB device, client software, and host controller software.

Host Controller The host controller initiates all data transfer, and root hub provides a connection between devices and host controller. The root hub receives transaction generated by host controller and transmits to the USB devices. The host controller uses polling to detect a new device and is connected to the bus or disconnected from. Also, USB host controller performs the following functions:

- Host controller sets up the device for operation (device configuration).
- Packet generation.
- Serializer/deserializer.
- Process request from device and host.
- Manage USB protocol.

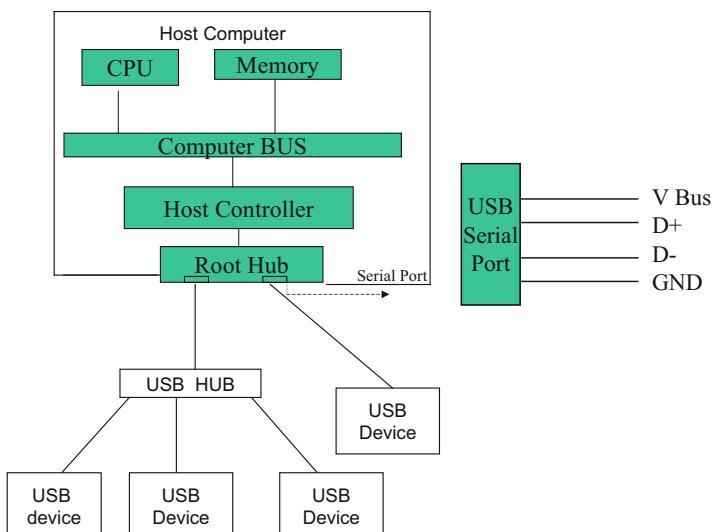


Fig. 6.15 Architecture of USB

Fig. 6.16 Architecture of hub

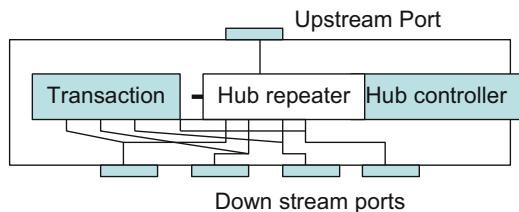


Table 6.5 USB version and its data rate

USB version	Release date	Data rate	Data rate designation
USB 1.0	1996	1.5 Mbps	Low speed
USB 1.1	1998	12 Mbps	Full speed
USB 2.0	2000	480 Mbps	High speed
USB 3.0	2008	5 Gbps	Super speed
USB 3.1	2013	10 Gbps	Super speed +

- (f) Managing flow between host and USB devices.
- (g) Assign address to the devices.
- (h) Execute client software.
- (i) Collecting status bit from USB ports.

Root Hub The root hub performs power distribution to the devices, enables and disables the ports, and reports status of each port to the host controller. The root hub provides the connection between the host controller and USB ports.

Hub Hubs are used to expand the number of devices connected to the USB system. Hubs are able to detect when a device is attached or removed from port. Figure 6.16 shows the architecture of hub. The upstream port is connected to the host, and USB devices are connected to downstream port.

In downstream transmission, all devices that are connected to the hub will receive the packet, but only the device accepts the packet that the device address matches with address in the token. In upstream transmission, the device sends the packet to the hub, and hub transmits the packet to its upstream port only. USB improves its speed and every few years a new version was developed. Table 6.5 shows different versions of USB.

USB Cable. Figure 6.15 shows USB port with four pins, which consists of four wires, with the V bus used to power the devices. D+ and D– are used for signal transmission.

USB Device USB device is divided into the classes such as hub, printer, or mass storage. The USB device has information about its configuration such as class, type, manufacture ID, and data rate. Host controller uses this information to load device software from the hard disk. USB device might have multiple functions such as a volume in a speaker. Each function in a USB device is specified by the endpoint address.

6.9.8 PCI Express Bus

PCI express was introduced in mid-1990 with 33 MHz frequency, and during the time the speed of BUS was increased to 66 MHz. Due to new development in networking technology such as Gigabit Ethernet and I/O devices that demand more bandwidth, there is a need for a new bus technology with higher bandwidth. The PCI express was approved by Special Interest Group in 2002, and chipset starts shipping in 2004. The PCI express has the following features:

- PCI express is point-to-point connection between devices.
- PCI express is a serial bus.
- PCI express uses pocket and layer architecture.
- Compatible with PCI bus through software.
- End-to-end link data integrity (error detection).
- Isochronous data transfer.
- Selectable bandwidth.

6.9.9 PCI Express Architecture

Figure 6.17 shows PCI express architecture, and the function of host bridge is to interface CPU bus with memory and PCI express switch. The switch is used to increase the number of PCI's express ports.

Fig. 6.17 PCI express architecture

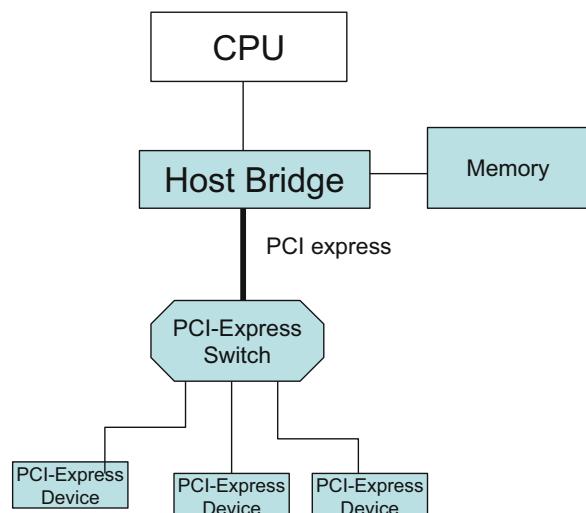


Fig. 6.18 PCI express protocol architecture

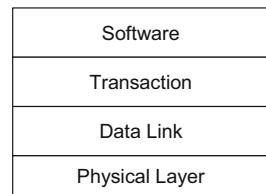
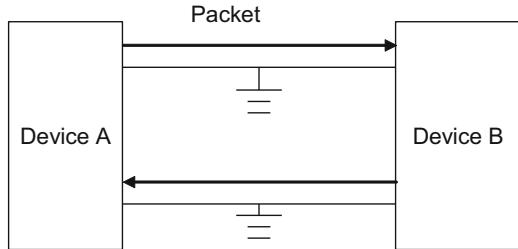


Fig. 6.19 PCI express connections



6.9.10 PCI Express Protocol Architecture

Figure 6.18 shows PCI express protocol architecture. The protocol consists of PCI software, transaction, data link, and physical layer.

Software Layer The software layer is used for compatibility with PCI, initialization, and enumeration of the devices connected to the PCI express.

PCI Express Physical Layer Figure 6.19 shows two devices are connected through PCI express link (lane); each lane is made of four wires, and each PCI express lane consists of two simplex connections, one for transmitting the packet and another one for receiving the packet. The PCI express lane supports 2.5 giga transfer/second each direction.

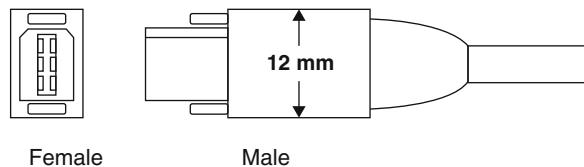
PCI express link may configure X1, X2, X4, X8, X16, and X32 lane, where X1 means 1 lane with 4 wires and X4 means 4 lanes with 16 wires and finally X32 means 32 lanes with 128 wires. PCI-32 means PCI express with 32 lanes. The clock for PCI express serial link is embedded into the data by using 8B/10B encoding.

6.10 FireWire

FireWire or IEEE 1394 is a high-speed serial bus used for connecting digital devices such as a digital video or camcorder. The bus is able to transfer data at the rate of 100, 200, or 400 Mpbs. The IEEE 1394 cable consists of six copper wires; two of the wires carry power and four of the wires carry signal as illustrated in Table 6.6. Some FireWire connectors come with four pins, without having power pins. Figure 6.20 shows FireWire male and female connectors.

Table 6.6 IEEE 1394 pins

Pin	Signal name	Description
1	Power	Unregulated DC; 17–24 V no load
2	Ground	Ground return for power and inner cable shield
3	TPB–	Twisted-pair B, differential signals
4	TPB+	Twisted-pair B, differential signals
5	TPA–	Twisted-pair A, differential signals
6	TPA+	Twisted-pair A, differential signals

Fig. 6.20 FireWire male and female connectors

6.10.1 HDMI (High-Definition Multimedia Interface)

HDMI is an interface between two devices for transferring uncompressed video data and compressed or uncompressed digital audio data. Some of the applications of HDMI are computer monitor, digital TV, and video projector. Figure 6.21 shows different types of HDMI connectors.

Motherboard The motherboard is a printed circuit board (PCB) that contains most components of a computer such as CPU, RAM, ROM, expansion slots, and USB. Figure 6.22 shows an image of motherboard.

6.11 Summary

- The components of a microcomputer are the CPU, memory, parallel I/O, serial I/O, programmable interrupt, and DMA.
- The function of the CPU is executing instruction.
- The components of the CPU are the arithmetic logic unit (ALU), control unit, and registers.
- Most computers use three types of memory: cache memory (SRAM), main memory (DRAM or SDRAM), and secondary memory (hard disk, tape drive, and floppy disk).
- Semiconductor memory types are DRAM, SDRAM, EDORAM, DDR, SDRAM, RDRAM, ROM, and EPROM.
- SRAM is used in the cache memory; DRAM and SDRAM are used in the main memory.
- SATA, SCSI-1, SCSI-2, and SCSI-3 are the computer peripheral controllers.



Fig. 6.21 HDMI connectors

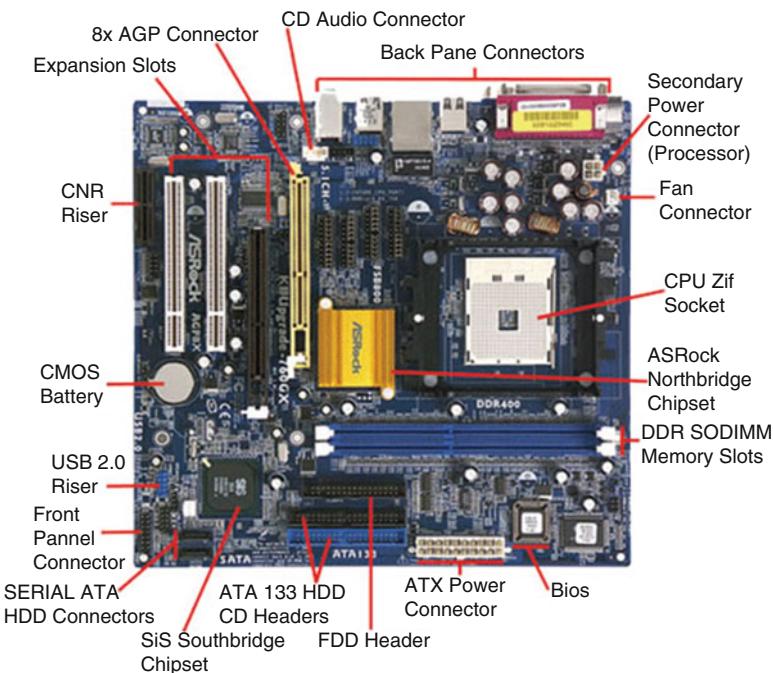


Fig. 6.22 Image of motherboard

- ISA bus, EISA, MCA, and PCI are the microcomputer buses, and FireWire is a high-speed serial bus with a data rate up to 400 Mbps.
- USB is a serial bus.
- PCI express is a serial bus.
- Chapter 7 covers semiconductor memory, hard disk, solid-state drive, cache memory mapping methods, and virtual memory.

Review Questions

- *Multiple choice questions*

1. The function of the _____ is to perform arithmetic operations.
 - (a) Bus
 - (b) Serial port
 - (c) ALU
 - (d) Control unit
2. When you compare the functions of a CPU and a microprocessor, _____.
 - (a) They are the same
 - (b) They are not the same
 - (c) The CPU is faster than microprocessor
 - (d) The microprocessor is faster than CPU
3. RISC processors use _____.
 - (a) Complex instruction sets
 - (b) Reduced instruction sets
 - (c) a and b
 - (d) None of the above
4. The CISC processor control unit is _____.
 - (a) Hardware
 - (b) Microcode
 - (c) a and b
 - (d) None of the above
5. Direct memory access allows for the transfer of blocks of data from memory to an I/O device (or vice versa) without using the _____.
 - (a) CPU
 - (b) Data bus
 - (c) Control bus
 - (d) DMA controller
6. Which of the following buses are 32-bit?
 - (a) ISA
 - (b) PCI and EISA
 - (c) EISA and ISA
 - (d) MCA and ISA
7. Which of the following operating systems support plug and play?
 - (a) Window NT and Window 95
 - (b) Window 98 and Window NT
 - (c) Window XP and Window 2000
 - (d) DOS and Windows NT

1. List the components of a microcomputer.
2. Explain the functions of a CPU.
3. List the functions of an ALU.
4. What is the function of a control unit?
5. List components of a CPU?
6. How many bits a half word?
7. How many bits is a word?
8. Distinguish between a CPU and a microprocessor.
9. Explain the function of an address bus and a data bus.
10. Explain the function of DMA.
11. What is the application of a parallel port?
12. What is the application of a serial port?
13. What is an interrupt?
14. What is maximum memory for a CPU with 16 address lines and 8 data lines?
15. List characteristics of CISC processor.
16. List characteristics of RISC processor.
17. Distinguish between von Neumann architecture and Harvard architecture.
18. What is the advantage of multicore processor versus single core?
19. List CPU instruction execution steps.
20. Explain fetch instruction
21. How long does it take for a CPU to execute five instructions using pipelining if each stage of pipeline takes 20 min.
22. Calculate execution time for problem 21 using non-pipeline processor.
23. What are characteristics of 64-bit processor?
24. List types of disk controller.
25. List computer buses.
26. List two serial buses.
27. What is maximum number USB ports a computer can have?
28. Show pin connection of USB port.
29. Show diagram of PCIe lane.
30. What is the application of FireWire?
31. What is application of HDMI?

Chapter 7

Memory

Objectives: After completing this chapter, you should be able to:

- Distinguish different types of semiconductor memory.
- Explain sector, track on hard disk.
- To calculate disk capacity.
- Learn memory hierarchy.
- Explain cache miss, cache hit, and cache hit ratio.
- Describe types of memory use in a computer.
- Explain different mapping methods use in cache memory.
- Translate virtual address to physical address.
- Explain function of page table.
- Generate physical address from virtual address.

7.1 Introduction

In a computer, memory holds instructions (code) and data, memory plays an important part of a computer performance, and register is a type of memory with small capacity. There are two types of memory used in a computer, and they are classified as semiconductor memory and hard disk. Semiconductor memory can be volatile or nonvolatile memory. Volatile memory loses its contents when power is removed from it, while nonvolatile memory will keep its contents without power.

7.2 Semiconductor Memory

There are two types of *semiconductor memory*: random-access memory (RAM) and read-only memory (ROM).

RAM Data can be read from or written into *random-access memory (RAM)*. The RAM can hold the data as long as power is supplied to it and it is called *volatile memory*. Figure 7.1 shows a general block diagram of RAM consisting of a data bus, address bus, and read/write signals. The data bus carries data out from or into the RAM. The address bus is used to select a memory location. The read signal becomes active when reading data from RAM, and the write line becomes active when writing to the RAM. Remember, RAM can only hold information when it has power. Figure 7.2 shows a 16 * 8 bit RAM or $2^4 * 8$ bit or 16 B RAM.

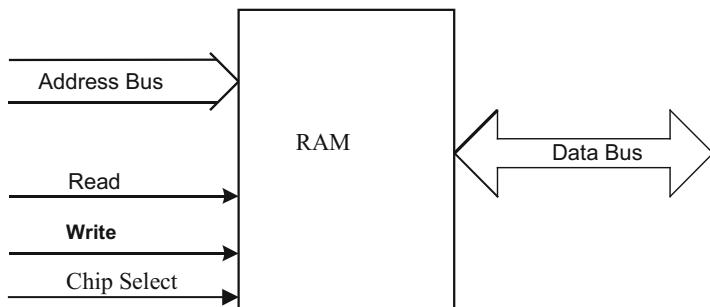


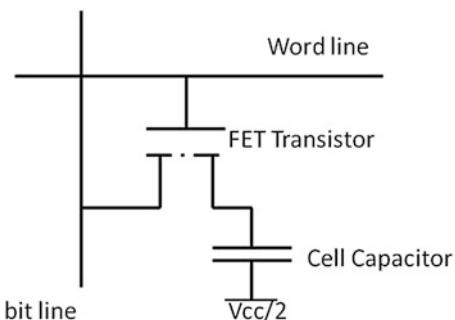
Fig. 7.1 RAM block diagram

Fig. 7.2 16 bytes of RAM

Address	
0000	10101011
0001	11001100
0010	10000001
0011	10000000
0100	11111111
0101	11111000
0110	10000000
0111	00000000
1000	00111111
1001	00000001
1010	01010101
1011	10000000
1100	00000011
1101	10000011
1110	11100000
1111	11000000

Table 7.1 Number of address and Memory locations

Number of addresses	Number of memory locations	Representation
10	$2^{10} = 1024$	1 K
11	$2^{11} = 2048$	2 K
12	$2^{12} = 4096$	4 K
13	$2^{13} = 8192$	8 K
14	$2^{14} = 16,384$	16 K
16	$2^{16} = 65,536$	64 K
20	$2^{20} = 1,048,576$	1 M
24	$2^{24} = 16,777,261$	16 M
32	$2^{32} = 4,294,967,296$	4 G

Fig. 7.3 1-bit DRAM

In Fig. 7.2, the address is 4 bits; therefore, there are $2^4 = 16$ memory locations, and if each location holds 1 B, then there is 16 B of memory, a memory with m address lines, then there is 2^m memory locations. Table 7.1 shows the number of address lines and equivalent decimal number of memory locations.

There are many types of RAM, such as *dynamic RAM (DRAM)*, *synchronous DRAM (SDRAM)*, *EDO RAM*, *DDR SDRAM*, *RDRAM*, and *static RAM (SRAM)*.

- *Dynamic RAM (DRAM)* is used in main memory. DRAM uses fewer components to make one bit; therefore, it can design DRAM integrated circuit (IC) with large capacity as 4 GB per IC; Fig. 7.3 shows one bit DRAM.

The cell capacitor can be charged with logic one or zero, but it requires to be refreshed (recharged) about every 1 ms. The CPU cannot read from or write to memory while the DRAM is being refreshed; this makes DRAM the slowest running memory.

- *Synchronous DRAM (SDRAM)*: SDRAM technology uses DRAM and adds a special interface for synchronization. It can run at much higher clock speeds than DRAM. SDRAM uses two independent memory banks. While one bank is recharging, the CPU can read and write to the other bank. Figure 7.4 shows a block diagram of SDRAM.

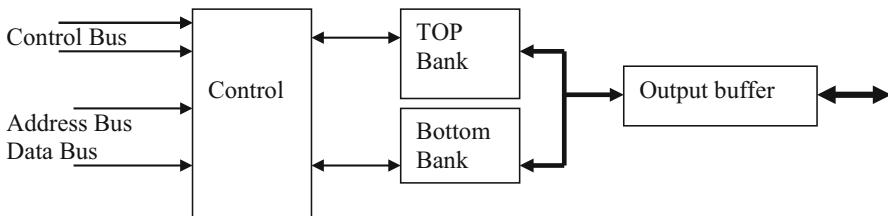


Fig. 7.4 Block diagram of SDRAM



Fig. 7.5 Rambus memory module (Courtesy Samsung Corp.)

- *Extended Data Out RAM (EDORAM)* transfers blocks of data to or from memory.
- *Double Data Rate SDRAM (DDR SDRAM)* is a type of SDRAM that transfers data at both the rising edge and the falling edge of the clock. It can move data twice faster than SDRAM; therefore, memory can run at the $\frac{1}{2}$ clock rate. DDR2 and DDR3 are an advancement on the DDR technology and further increase the number of data transfers per clock cycle. DDR2 RAM provides 4 data transfers per cycle, and DDR3 transfers 8 data per clock cycle. For 100 MHz clock rate and 64 bits data bus, the transfer rates for DDR are

$$\text{DDR} = 100 * 2 * 8 = 1600 \text{ MB/s (MB/s)}$$

$$\text{DDR2} = 100 * 4 * 8 = 3200 \text{ MB/s}$$

$$\text{DDR3} = 100 * 8 * 8 = 6400 \text{ MB/s}$$

- *Rambus DRAM (RDRAM)* was developed by Rambus Corporation. It uses multiple DRAM banks with a new interface that enables DRAM banks to transfer multiple words and also transfer data at the rising edge and the falling edge of clock. The RDRAM refreshing is done by the interface. The second generation of RDAM is called DRDRAM (Direct RDRAM), and it can transfer data at a rate of 1.6 Gbps. Figure 7.5 shows a RDRAM module.

DRAM Packaging

DRAM comes in different types of packaging such as SIMMs (single in-line memory module) and DIMM (dual in-line memory module).

Figure 7.6 shows SIMM, which is a small circuit board that one side of the board holds several chips. It has a 32 bit data bus.

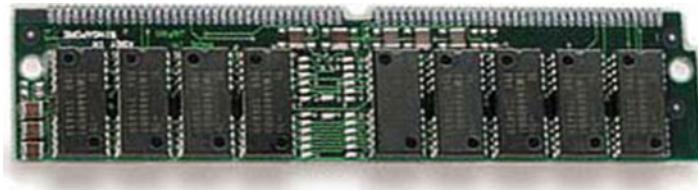


Fig. 7.6 DRAM SIMM

Table 7.2 Memory access time

Memory technology	Access time
SRAM	0.5–2.5 ns
DRAM	50–70 ns
Flash	$5 * 10^3$ – $5 * 10^5$

DIMM is a circuit board that both sides of the board hold several memory chips but has a 64 bit data bus.

- *Static RAM (SRAM)* is used in cache memory. SRAM is almost 20 times faster than DRAM and is also much more expensive. D Flip Flop is one bit static RAM.

ROM (Read-Only Memory)

Like its name suggests, information can be ready only from *read-only memory (ROM)*. ROM holds information permanently, even while there is no power to the ROM; this type of memory is called *nonvolatile memory*. Two types of ROM are listed below:

- *Erasable Programmable Read-Only Memory (EPROM)*: EPROM can be erased with ultraviolet light and reprogrammed with a device called an EPROM programmer. Flash ROM is a type of EEPROM.
- *Electrically Erasable PROM (EEPROM)*: EEPROM can be erased by applying specific voltage to one of its pin and can be reprogrammed with an EPROM programmer.
- *Flash Memory*: flash memory is a nonvolatile memory that has wide range applications such as flash drive, solid-state drive, memory card, and embedded system. Flash memory is a type of EEPROM that allows multiple memory location to be written or erased on one operation. There are two types of technology use for flash memory, and they are NAND and NOR flash memories; NAND flash memory has smaller access time than NOR flash memory; most flash memory uses NAND technology.

Memory Access Time The time the CPU places address on address bus and data appears on data bus or write the data into memory. Table 7.2 shows access time for different types of memory.

7.3 Hard Disk

Figure 7.7 shows the internal architecture of hard disk made of several platters, and platters hold the information; the functions of the heads are to read or write information from disk surface. The surface of platter is made of several tracks, and each track is divided into sectors as shown in Fig. 7.8.

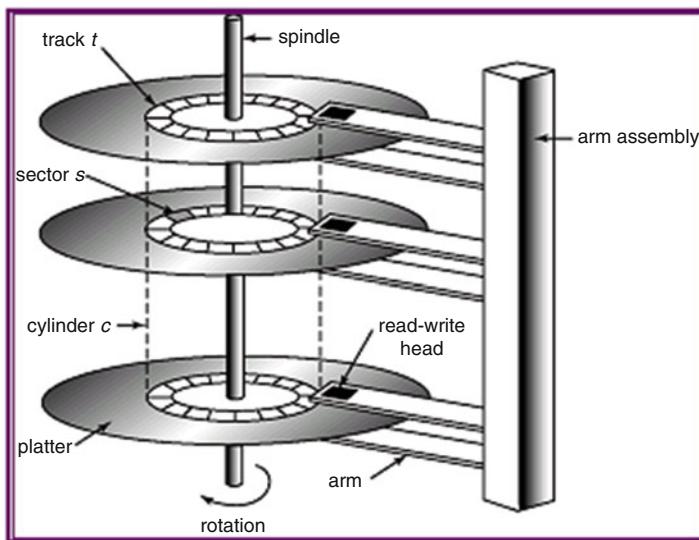


Fig. 7.7 Internal architecture of hard disk

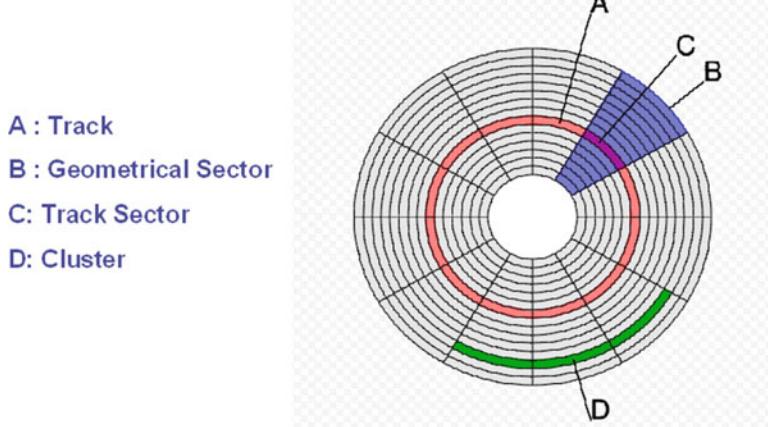


Fig. 7.8 Surface of a platter

Disk Characteristics

Access Time: the time that takes to start transfer data, and it is the sum of seek time and rotational delay.

Seek Time: the time that takes the head move to the proper track.

Rotational Delay: the time that it takes a sector to be positioned under read/write head and depend on rotation speed. The rotation speed represented by revolutions per minute (RPM) assumes the sector is away from head half of the track; therefore the rotation delay is calculated by

$$\text{Rotational Delay} = \text{Time for half revolution} = 60\text{s}/\text{RPM}*2$$

Disk Capacity: capacity of a disk calculated by

$$\begin{aligned}\text{Disk Capacity} = & \text{Number of surfaces}^*\text{Number of track/Surface}^* \\ & \text{Number of sectors/Track}^*\text{Number of bytes/Sector}\end{aligned}$$

Cluster

Each sector of a disk is 512 bytes (B), and cluster is made of one or more sectors, if a cluster is 1 kB, then it is made of two sectors. The 2 kB cluster is made of 4 sectors. Table 7.3 shows default values of cluster size.

Example 7.1 A disk drive has 8 surfaces, each surface has 1024 tracks, each track has 64 sectors, and each sector can hold 512 B and rotation speed of 6000RPM.

- (a) What is the capacity of disk?
- (b) What is the rotational delay?

$$\text{Disk capacity} = 8 * 1024 * 64 * 512 = 268,435,456 \text{ B}$$

$$\text{Rotation delay} = 60/6000 * 2 = 0.005 \text{ s}$$

Disk File System

A file system defines organization of information stored in hard disk; the windows OS (operating system) offers FAT16 (file allocation table) and FAT32 which are used for early windows OS; currently most windows OS uses NTFS (New Technology File System). NTFS offers better security such as permission to restrict access and encryption.

Table 7.3 Default cluster size

DISK size	NTFS cluster size
512–1024 MB	1 kB
1024 MB–2 GB	2 kB
2 GB–2 TB	4 kB

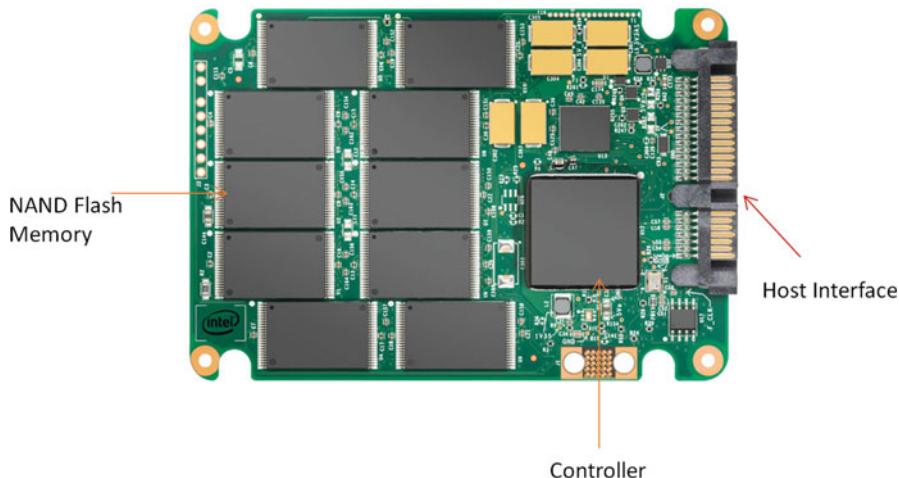


Fig. 7.9 Architecture of SSD

Table 7.4 Comparing the SSD with HDD

Characteristics	SSD	HDD
Access time	100 times faster than HDD	5000–10,000 μ s
Price	Expensive	Less expensive
Reliability	More reliable because it does not have any mechanical part	Less reliable
Capacity	Gigabytes	Terabytes
Power	Less power than HDD	More power than SSD

7.4 Solid-State Drive (SSD)

Hard drive is a slow device, and it can be replaced by SSD. SSD is made of nonvolatile NAND flash memory. Figure 7.9 shows architecture of SSD, and Table 7.4 compares SSD with HDD.

7.5 Memory Hierarchy

Computers come with three types of memory, which are arranged in a hierarchical fashion, as shown in Fig. 7.10:

Fig. 7.10 Memory hierarchy of a microcomputer

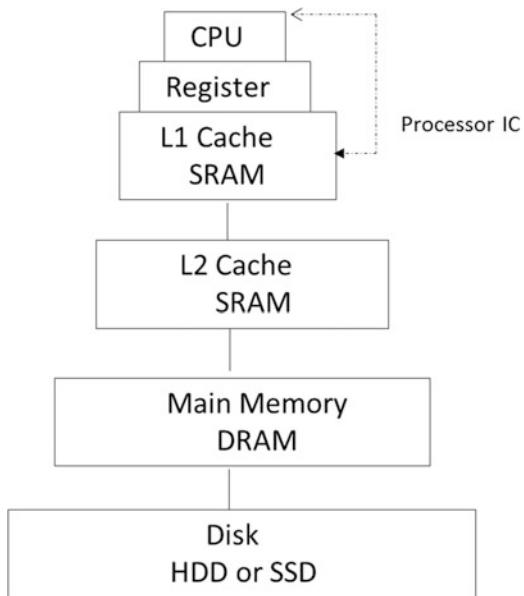


Table 7.5 Show price of different type of memory

Memory type	SRAM	DRAM	SSD	HDD
Cost	\$8.00/MB	\$0.16/MB	\$0.20/GB	0.05/GB
Access time	0.5–2.5 ns	50–70 ns	70–150 ns	5–20 ms

1. *Cache memory*: Cache memory is the fastest type of memory and is most often used inside CPU called L1 cache, and it is faster than main memory and, therefore, more expensive than main memory.
2. *Main memory*: Main memory uses DRAM and SDRAM. The program to be executed moves from secondary memory (disk or tape) into main memory.
3. *Secondary memory*: Second memory refers to memory such as hard disk, SSD, and CD-ROM (Table 7.5).

Cache Memory

Each cache memory location is called cache line which can hold a block of data from main memory. For the most processors, the cache memory is located inside CPU and called L1 cache; there are two types of cache in a CPU:

1. Data cache (D-cache): Data cache holds the data and it can be read or write by CPU.
2. Instruction cache (I-Cache): Instruction cache holds instruction and CPU only read from I-cache.

Cache Terminology

Miss: when CPU accesses the cache and data is not in cache, it is called cache miss

Hit: when CPU accesses the cache and data is in the cache, then it is called cache hit

Hit ratio: number of hits/number of miss + number of hits (total number of reads)

Block: multiple of main memory locations is called block

Physical address: address generated by CPU to access main memory

Virtual address: address generated by CPU to access virtual memory or secondary memory

Cache line or cache block: each cache line or block holds multiple bytes or words; the size of cache line is the same block in main memory

Temporal locality: once a memory location is referenced, then there is a high probability to be referenced again in near future

Spatial locality: when a memory location is accessed, then it is very likely the nearby locations will be accessed soon.

Cache Memory Mapping Methods

Figure 7.11 shows a cache with 4 locations and main memory with 8 memory locations, and the cache can hold only 4 memory locations of main memory; CPU first accesses the cache if data is not in cache and then accesses main memory and moves a block data into the cache; the question is where the data will store in the cache; this brings subject of mapping methods.

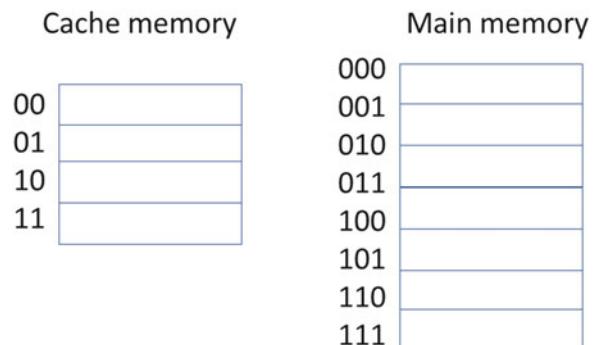
The mapping methods are used to map a block of main memory into the cache line (cache block), and following are types of methods used for mapping:

1. Direct mapping
2. Associative mapping
3. Set associative

Direct Mapping

Figure 7.12 shows a cache memory with four cache lines, and each line holds 4 B; the physical address seen by cache is divided into three fields and they are:

Fig. 7.11 Cache and main memory



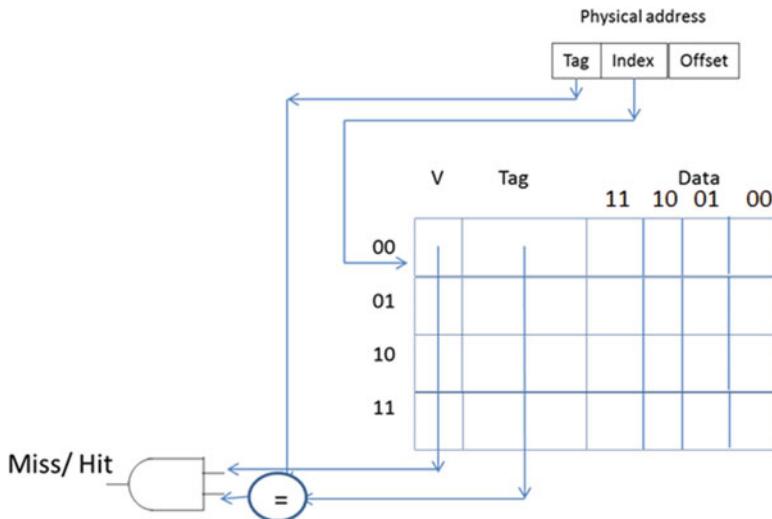


Fig. 7.12 Cache memory with 4 cache lines

Offset: determines the size of cache line (number of bytes or words) since each cache line can hold 4 memory locations and then the offset is 2 bits, and each block is 4 memory locations; also offset determines which of the four data to be transferred to CPU.

Index: index is the address to the cache; in this figure there are 4 cache lines and then index is 2 bits.

V-bit (valid bit): V-bit set to one to represent that data in cache line is valid.

Tag: Size of Tag = Size of Physical Address – (Size of Index + Size of Offset).

If physical address is 7 bits, then tag = $7 - (2 + 2) = 3$ bits.

If valid bit is one and tag in address field matches with the tag stored in cache, then results are hit; otherwise is miss.

When CPU receives miss from cache, then access the main memory and transfer a block of data from main memory to cache line using following equation for direct mapping:

$$\text{Cache line Address} = (\text{Main Memory Block Number}) \bmod N$$

where N is the number of cache lines.

Consider Fig. 7.13 cache and assume CPU generates address 010 10 11, the Fig. 7.13 shows format of physical address seen by cache.

The CPU uses the index value to access cache line 10 and if the valid bit is zero results in a miss, the CPU accesses the main memory and transfers block 01010 to cache line 10 according to following equation:

Fig. 7.13 Format of physical address for 0101011

Tag	Index	Offset
010	10	11

Fig. 7.14 Cache memory with four lines (four blocks)

V	Tag	Data			
		11	10	01	00
00	0				
01	0				
10	1	010	M(2B)	M(2A) M(29)	M(28)
11	0				

$$(01010)_2 = (10)_{10}$$

$$\text{Cache line number} = 10 \text{ modulo } 4 = 2 \text{ or } (10)_2$$

In this case each block is made up of 4 memory locations. Since the offset is two bits, it can refer any of 4 (2^2) chunks of data within a block of memory. The block at address 01010 in main memory with a 2 bit offset consists of memory locations 0101000 (M28), 0101001 (M29), 0101010 (M2A), and 0101011 (M2B).

In this case, M28, M29, M2A, and M2B are transferred to cache line 10, and the V-bit is set to one. The tag is stored in the tag field of cache as shown in Fig. 7.14.

Now, if the CPU generates address 0101010, where tag = 010, index = 10, and offset = 10, the CPU uses the index to access cache line 10. If on cache line 10 the V-bit equals 1 and the tag of the address matches with the tag in the cache line, then the result is a *hit*, and the CPU uses offset 10 to move data (M2A) in to the CPU. (Where offset 00 = M28, 01 = M29, 10 = M2A, 11 = M2B.)

Example 7.2 Figure 7.15 shows the main memory and cache memory of a computer. CPU generates (in hex) addresses 0 × 0, 0 × 2, 0 × 5, and 0 × 2. Assuming the cache is empty at the beginning, show the contents of the cache.

In this example each block and cache line is 2 B and main memory consists of 8 blocks. Figure 7.16 shows the physical address as seen by the cache.

- The byte offset is one bit. (2 B per block)
- The index is two bits. (cache consist of 4 lines = 2^2)
- The tag is one bit. (Bits in block – bits in index = 3 – 2 = 1)
- The CPU generates address 0 × 0 or 0000. Therefore, the tag is 0, the index is 00, and the offset is 0. The CPU accesses cache line 00 and the V-bit is zero which results in a *miss*. The CPU accesses main memory address 0000, transfers block 000 to the cache line 00, and sets the tag bit to zero and the V-bit to one.

Block	Address	Contents
000	0000	1
	0001	5
001	0010	6
	0011	7
010	0100	8
	0101	7
011	0110	5
	0111	2
100	1000	2
	1001	9
101	1010	6
	1011	7
110	1100	8
	1101	7
111	1110	5
	1111	2

V	Tag	Byte1	Byte0
00	01	0	5
01	01	0	7
10	01	0	7
11	01	1	5

Fig. 7.15 Cache memory and main memory of Example 7.2**Fig. 7.16** Physical address format for Example 7.1

Therefore, cache line 00 contains: V = 1, Tag = 0, Byte1 = 0 × 5, Byte0 = 0 × 1.

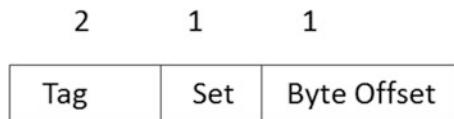
- Next the CPU generates address 0 × 2 or 0010. The index is 01 so the CPU accesses cache line 01, where the valid bit is zero which results in a *miss*. Then the CPU accesses main memory location 0010 and transfers block 001 into cache line 01, changes the valid bit to one, and stores the tag part of the address into the cache line's tag. Therefore, cache line 01 is now: V = 1, Tag = 0, Byte1 = 0 × 7, Byte0 = 0 × 6.
- The CPU generates address 0 × 5 or 0101. The index is 10, so the CPU accesses cache line 10 and the result is a *miss*. The CPU accesses main memory location 0101 and transfers block 010 to the cache, sets V to one, and stores the tag of the address into the cache's tag. Cache line 10 is now: V = 1, Tag = 0, Byte1 = 0 × 7, Byte0 = 0 × 8.
- The CPU generates address 0 × 2 or 0010, so it accesses cache line 01. The valid bit is 1 and the cache line tag matches the address tag, which results in a *hit*. The offset is 0, so the CPU reads byte 0 from cache line 01. This process will continue for other addresses.

	V	Tag	Byte1	Byte0
0	0			
1	0			

V	Tag	Byte1	Byte0
0	0		
0	0		

Fig. 7.17 Two-way set associate cache

Fig. 7.18 Physical address seen by cache for set associative mapping



Using the same size cache and main memory as above, blocks *000* and *100* will both be mapped onto cache line *00*. If the CPU generates addresses *0000*, *1000*, *0001*, and *1001* consecutively, then results will be misses for all four addresses. In order to reduce misses, then the cache can be divided into sets, and mapping method is called set associative mapping.

Set Associative Mapping

In set associative mapping, the cache memory is divided into sets. The size of the set can vary: examples include two-way set associative, four-way set associative, and so on. Figure 7.17 shows a two-way set associative cache, and Fig. 7.18 shows the physical address format seen by the cache. Using the previous examples as a base, the byte offset will remain one bit since it refers to one of two bytes stored on the cache line. The *set* identifier will be one bit that defines the set address; the tag size is calculated as follows:

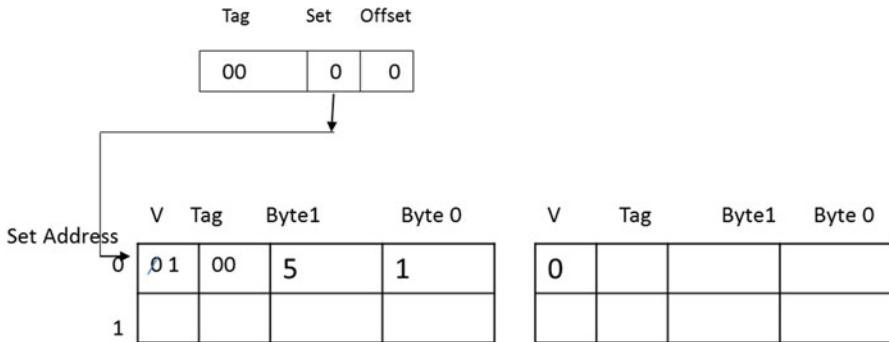
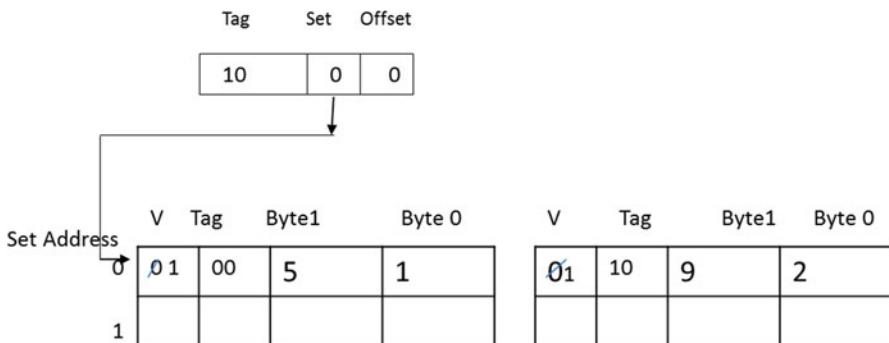
$$\text{Tag Size} = \text{Physical address size} - \text{Set address} - \text{Offset}$$

Assume the physical address is 4 bits, then Fig. 7.18 shows the physical address seen by cache.

Example 7.3 Consider the main memory from Fig. 7.15, where the cache is empty and it is divided into two sets as shown in Fig. 7.19. Show the contents of the cache if the CPU generates addresses 0×0 , 0×8 , 0×0 , and 0×8 .

- The CPU generates address 0×0 or *0000* and accesses cache set 0. Both cache lines in the set 0 have valid bits of 0, so the result is a *miss*. The CPU then accesses main memory, transfers contents of memory locations *0000* and *0001* into the cache, then changes the valid bit to one, and stores the tag part of the address into the cache's tag.

Next, the CPU generates address 0×8 or *1000* and accesses cache set 0. First line of the cache has a valid bit of 1 but the tag does not match (*10* vs. *00*). The CPU then accesses main memory, transfers contents of memory locations *1000* and *1001* into second line of the cache in the set 0, and changes the valid bit to one and stores the tag part of the address into the cache's tag. Now, when the CPU generates the addresses 0×0 and 0×8 again result *hits*.

**Fig. 7.19** Content of cache for address 0000**Fig. 7.20** Contents of cache for addresses 0000 and 1000

Replacement Method

In set associative, when CPU brings a new block into cache, then one of the cache lines must be replaced with new block; consider Fig. 7.20. If CPU generates address 0100 (tag = 01, set address = 0, and offset is 0), it accesses set 0, and both cache lines have valid bit one, but tags in cache lines do not match with address tag results miss, and then CPU accesses main memory and must move the contents of memory locations 0100 and 0101 into cache. CPU uses *least recently used (LRU)* method which moves new block from main memory and replaces it with block that has been longer in the cache. This method accomplishes by adding LRU bit to each cache line of the cache as shown in Fig. 7.21.

In Fig. 7.21, assume both cache lines in set 0 are empty, a new block moves into the first cache line in set 0, and LRU changed from 0 to 1; the second block moves to second cache line of set 0, and LRU changed from 0 to 1, but at the same time, LRU of first cache line will change from 1 to 0; therefore, the cache line with LRU = 0 contains block that has been longer in cache line.

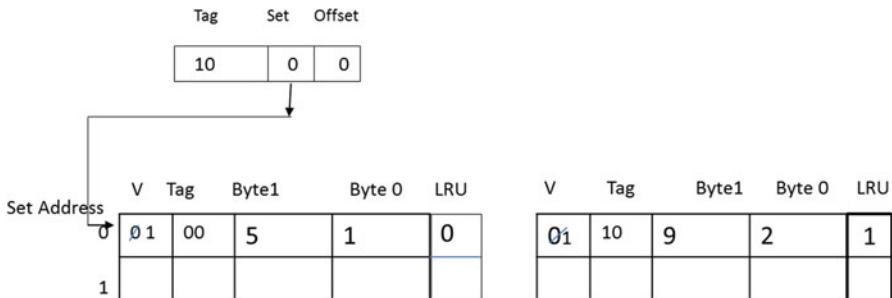


Fig. 7.21 Two set associative with LUR

Fig. 7.22 Associative mapping

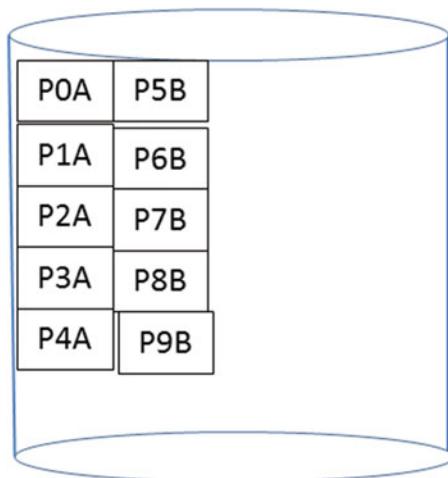
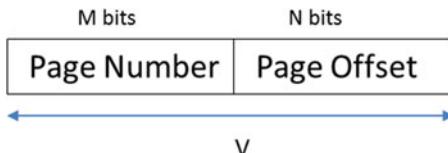
Valid	Address	Byte1	Byte0
1	0 00	5	1
1	1 00	9	2
0			
0			

Fully Associative Mapping

In fully associative mapping, the entire address is stored in the cache with its data. Figure 7.22 shows a fully associative cache with four lines after the CPU has accessed main memory locations 0×0 and 0×8 . If the CPU next generates address 0×0 or 0000 , then it will compare the address with each address in the cache, and if it matches, then it will read the data from the cache.

Cache Update Methods

1. *Write Through*: When new information is written to the cache, main memory is also updated.
2. *Buffered Write Through*: There is a buffer between cache and main memory, when new information is written to the cache, this information is written into buffer, and the CPU can access this memory before the new information can be written into main memory.
3. *Write Back (Copy Back)*: In this method, only the cache is updated, and main memory will be updated when the corresponding cache line is overwritten. In this method each cache line has a *dirty bit* to indicate if cache line has been modified or not.

Fig. 7.23 Virtual memory**Fig. 7.24** Virtual address format

7.5.1 Virtual Memory

Virtual memory is a HDD or SSD; it is used to store application data and instruction that is currently not needed to be process by the CPU. Virtual memory enables a system to run application larger than main memory. Disk is seen by CPU as virtual memory, if CPU has 16 address lines, then the size of virtual memory will be 2^{16} B. Application resides in disk and it is called process. When user runs a program, the operating system moves the pages of process into main memory. Virtual memory is divided into the pages as shown in Fig. 7.23; the process A occupied pages P0 through P4, and process B occupied pages P5–P9.

The CPU generates a virtual address (to access an address in the disk) of V -bits. These bits are divided into two identifiers: a virtual page number of M bits and a page offset of N bits as shown in Fig. 7.24. The total number of pages in the system is equal to 2^M , and the number of bytes (in a byte-addressable system) in a page is equal to 2^N . The total number of addresses in a system is equal to $2^{(N+M)}$ or 2^V .

Example 7.4 The capacity of a virtual disk is 2 MB (megabytes), and each page is 2 kB (kilobytes) in a byte-addressable system.

- (a) What are values of N and M ?
- (b) How many pages are in the disk?

Since each page is 2 kB, $2^N = 2048$ B, meaning N equals 11.

The capacity of the disk is 2 MB. $2^V = 2^M$ equals 2^{21} so $V = 21$ bits.

The number of pages, then, is equal to $2^{(21-11)}$. The disk contains 2^{10} or 1024 pages, and the size of each page is 2 kB.

Page Table With main memory divided into blocks, the size of each block (or frame) is equal to the page size. When the CPU transfers a page into main memory, it records the page number and corresponding block in the *page table*. The address line of the page table is the page number. Each line contains the frame or block number of the matching location in main memory and a valid bit that indicates whether the line is valid or not. Figure 7.25 shows a page table wherein pages P0, P1, P3, and P4 are transferred to the blocks 2, 3, 0, and 1, respectively.

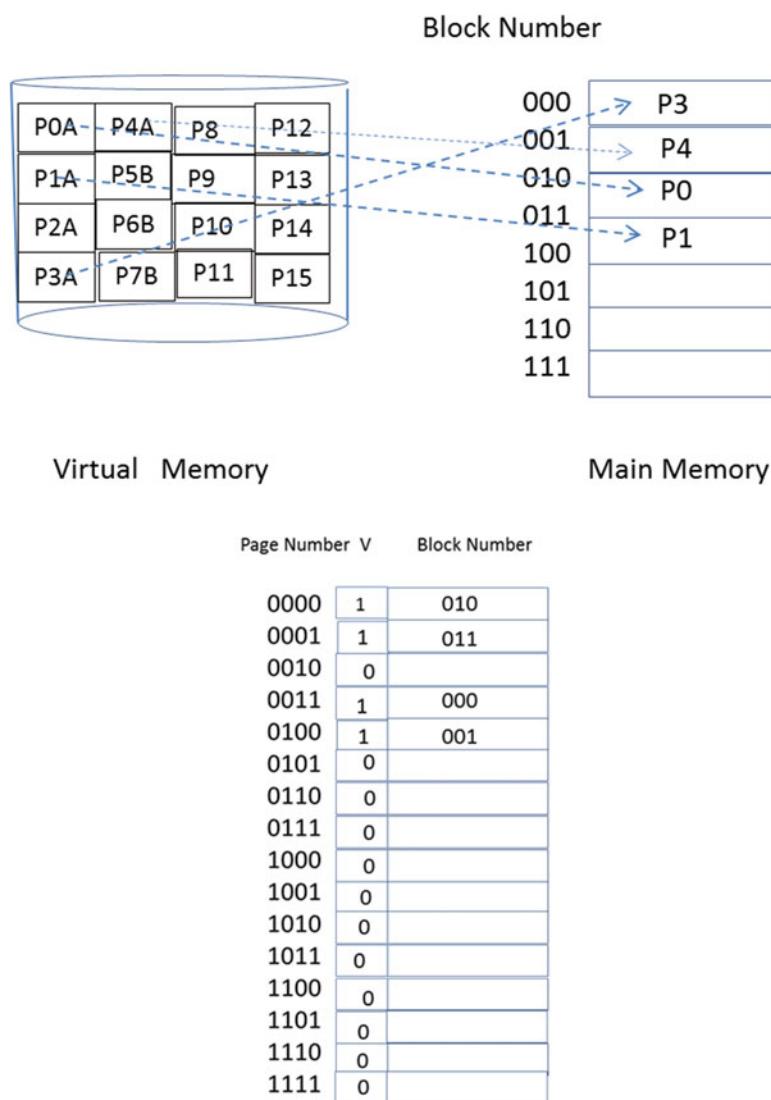


Fig. 7.25 Virtual memory, memory, and page table

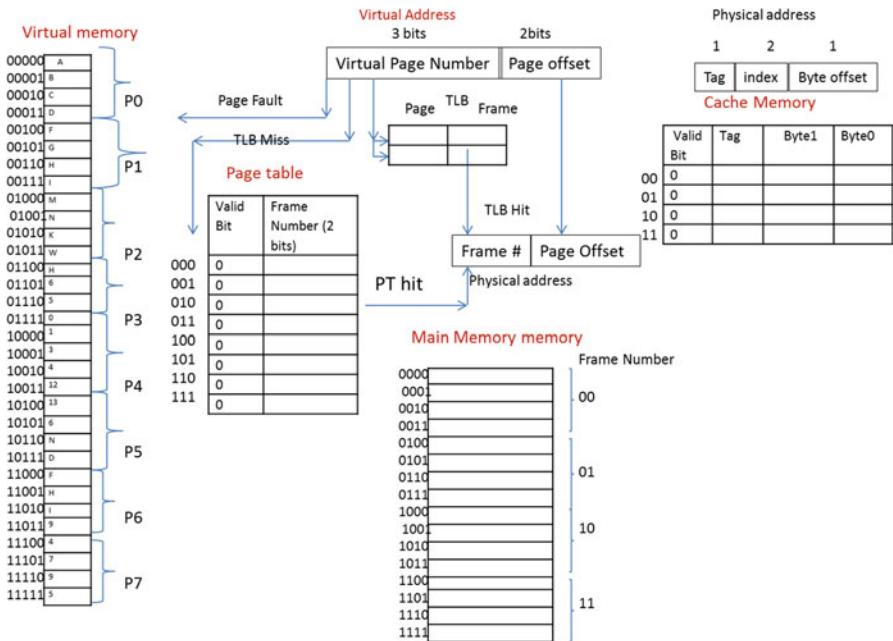


Fig. 7.26 Memory organization of a computer

Each process has its own page table stored in main memory. Since cache memory is faster, part of the page table referred to as the *translation lookaside buffer* (TLB) is stored in the cache. The TLB uses associative mapping.

7.5.2 Memory Organization of a Computer

Figure 7.26 shows memory organization of a computer which in this example consists of:

- Virtual memory (hard disk or solid-state drive)
- Main memory (A type of DRAM)
- Cache memory (SRAM)
- A page table which keeps track of pages in main memory
- The TLB which holds a part of the page table

Memory Operation

The following steps describe the operation of memory of a computer. First, the CPU generates a virtual address and checks the TLB to see if the corresponding page is in main memory already or not.

- A. If the TLB indicates that the corresponding page is in memory, then generate a physical address and check if the data is in the cache.
 - (a) If it is in the cache, then this called a *hit* and it reads the data from the cache
 - (b) If it is not in the cache, then it is called a *miss*, and the CPU accesses memory and moves a block of data into the cache then reads it.
- B. If the corresponding page is not in the TLB, then the CPU checks the page table.
 1. If the corresponding page is in main memory, then update the TLB and repeat from step 1.
 2. If corresponding page is *not* in main memory, then move the page from virtual memory into main memory, update the page table, update the TLB, and repeat from step 1.
- C. If the corresponding page is not in the page table, then the CPU moves the page from virtual memory into main memory, updates the page table, updates the TLB, and repeats from step 1.

Questions and Problems

1. Distinguish between volatile and none-volatile memory.
2. What does RAM stand for?
3. List three different types of RAM.
4. Which of the following memory types are used for main memory?
 - (a) ROM and SDRAM
 - (b) SRAM and DRAM
 - (c) SDRAM and DRAM
 - (d) DRAM and EPROM
5. _____ holds information permanently, even when there is no power.
 - (a) ROM
 - (b) DRAM
 - (c) RAM
 - (d) SRAM
6. What does ROM stand for?
7. Is flash memory a type of RAM or ROM?
8. What is the difference between EEPROM and EPROM?
9. What is capacity of a memory with 10 address lines and holds one byte per memory location?
10. What is the primary application of SRAM?
11. What is the primary application of DRAM?
12. Define the following terms:
 - (a) Track
 - (b) Sector
 - (c) Cluster

13. A hard disk consists of 4 surfaces, each surface consists of 80 tracks, and each track consists 32 sectors. Each sector holds 512 B. What is the capacity of this disk?
14. What is the function of file allocation table (FAT)?
15. List types of memory in a computer from fastest to slowest.
16. What are the types of cache?
17. What type of memory is used for cache memory?
18. What is virtual memory?
19. Distinguish between a virtual address and physical address.
20. Physical address determines size of
 - (a) Virtual memory
 - (b) Physical memory
 - (c) Cache memory
21. Show the format of a virtual address.
22. What is hit ratio?
23. Explain temporal locality.
24. Explain spatial locality.
25. List cache mapping methods.
26. Show format of address seen by the cache for direct mapping.
27. List cache mapping methods.
28. Show format of address seen by the cache for set associative mapping.
29. What is the function of a page number in a virtual address?
30. How many bits is the page offset if each page holds 8 kB?
31. What is the function of the page table?
32. What information is stored in TLB? Where is the TLB stored?
33. List cache mapping methods.
34. What is the advantage of set associative versus direct mapping of caches?
35. What are the three write policies used for memory?
36. _____ is the fastest type of memory.
 - (a) Cache memory
 - (b) Main memory
 - (c) Secondary memory
 - (d) Hard disk

Problems

1. The following main and cache memory are given. The CPU generates addresses $0 \times 0, 0 \times 2, 0 \times 3, 0 \times 4, 0 \times 5, 0 \times 3, 0 \times 6, 0 \times 6, 0 \times 7, 0 \times B, 0 \times D$, and $0 \times F$. Show the contents of the cache and find the hit ratio.

ADDRESS	Contents
0000	5
0001	0
0010	1
0011	11
0100	15
0101	09
0110	16
0111	23
1000	65
1001	01
1010	8
1011	9
1100	15
1101	0
1110	2
1111	5

2. The following memory and cache memory is given. CPU generates addresses $0 \times 1, 0 \times 2, 0 \times 1, 0 \times 8, 0 \times 9, 0 \times 1C, 0 \times 1D, 0 \times 3$, and 0×4 .

 - (a) Show the contents of the cache using two-way set associative mapping; assume a LRU replacement policy.
 - (b) What is the hit rate?

Set Address	V	Tag	B1	B0	LRU	V	Tag	B1	B0	LRU
00	0				0	0				0
01	0				0	0				0
10	0				0	0				0
11	0				0	0				0

Address	Content	Address	Content
00000	5	10000	5
00001	3	10001	0
00010	11	10010	1
00011	6	10011	11
00100	7	10100	15
00101	8	10101	09
00110	9	10110	12
00111	12	10111	23
01000	0	11000	65
01001	0	11001	21
01010	8	11010	8
01011	7	11011	7
01100	9	11100	9
01101	0	11101	0
01110	2	11110	2
01111	5	11111	5

3. A computer has 24 bit physical addresses and each memory location holds one byte. This computer has 64 cache lines and each line holds 16 B. Show the format of the address (tag, index, and byte offset) using
- (a) Direct mapping
 - (b) 4-way set associative
 - (c) 8-way set associative
4. A computer has 32 kB of virtual memory and 8 kB of main memory with a page size of 512 B.
- (a) How many bits are in the virtual address?
 - (b) How many pages are in virtual memory?
 - (c) How many bits are required for the physical address?
 - (d) How many frames or blocks are in main memory?
5. A computer with 256 MB of virtual memory, 4 MB of main memory, and 8 kB of cache memory. Assume a page size of 2 kB.
- (a) What is the size of a virtual address?
 - (b) What is the size of a physical address?
 - (c) How many pages are in virtual memory?
 - (d) How many blocks are in main memory?

- (e) What is the size of the page table? (Include the number of locations and the total size of each location including all information.)
6. A computer has 20 bits of virtual memory and each page is 2 kB.
 - (a) What is the size of virtual memory?
 - (b) How many pages are in virtual memory?
7. A computer with 4 words per block has 4 K blocks of cache and 1 M blocks of main memory.
 - (a) What is the size of a physical address?
 - (b) Determine the size of the tag, index, and word offset of physical address using direct mapping.
 - (c) Determine the size of the tag, set, and word offset of physical address using Two-way set associative mapping.
8. CPU of Fig. 7.26 generates addresses 0×00 and $0 \times 0b$; assume page 0 map into block 1 and page 2 map in block 0, show the contents of page table.

Chapter 8

Assembly Language and ARM Instructions

Part I

Objectives: After completing this chapter, you should be able to:

- Explain the function of compiler and the assembler.
- Convert HLL to the machine language.
- Show ARM processor architecture.
- Describe the function of processor state register (PSR).
- List instruction classification based on number of the operands.
- Learn different types of the ARM instructions.
- Describe the operation of conditional instructions.
- Convert HLL to the assembly language.
- Explain the shift and the rotate instructions.
- Explain the operation of stack instructions.
- Explain application of the Branch instructions.

8.1 Introduction

Programmers use high-level language to develop application program; in order for the program to become an executable form, it must be converted in machine code (binary).

Figure 8.1 shows a high-level language (HLL) converted to machine code, the compiler converts HLL into assembly language, and then assembler converts assembly language to machine language (bits) by assembler.

Each CPU has a set of instructions which represents the type of operations the CPU can perform, and these instructions are represented in *mnemonic* forms or abbreviation, for example, the addition instruction is represented by “ADD,” and subtraction instruction is represented by “SUB.”

ADD R1, R2, R3 means add contents of R2 with R3 register and store results in R1 register. R1, R2, and R3 are called operands.

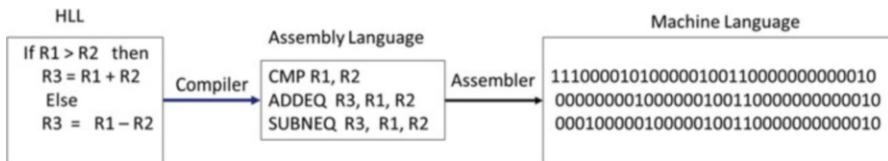


Fig. 8.1 Converting HLL to machine language

The following HLL are converted to assembly language:

HLL Assembly Language

R3=R1+R2 ADD R3, R1, R2

R3=R1-R2 SUB R3, R1, R2

The programmer uses instructions to write assembly language. The applications of assembly language are:

- Assembly language is used for writing fastest code.
- It helps to better understand HLL.
- Writing compiler for HLL requires knowledge of assembly language.
- It is used in embedded system and driver.
- HLL may not provide access to hardware then assembly language can be used.

8.2 Instruction Set Architecture (ISA)

Manufacturers of CPUs publish a document that contains information about the processor such as list of registers, function of each register, size of data bus, size of address bus, and list of instructions that can be executed by the CPU. Each CPU has a known instruction set that a programmer can use to write assembly language program. Instruction sets are specific to each type of processor. Pentium processors use a different instruction set than ARM processor. The instructions classified are based on number of operands or type of operation.

8.2.1 *Classification of Instruction Based on Number of Operands*

No Operand Instructions. The following are some of the instructions that do not require any operands:

HLT	Halt the CPU
NOP	No operation

- PUSH operand:** Push operand into top of the stack
POP operand Remove the operand from top of the stack

One-Operand Instructions The following are some of the instructions that require one operand.

INC	<i>operand</i>	Example: INC R1 – Increment register R1 by 1
DEC	<i>operand</i>	Example: DEC R1 – Decrement register R1 by 1
J	<i>target</i>	Jump to memory location labeled by target
ADD	<i>operand</i>	Add operand to the accumulator (ACC) ACC → ACC + <i>operand</i>

Two-Operand Instructions The following are some of the instructions that require two operands.

ADD Rd, Rn Example: ADD R1, R2 – R1←R1+R2

Intel Instruction Set Architecture uses two operands.

MOV EAX, EBX ; EAX ← EBX

Three-Operand Instructions Most modern processors use instructions with three operands, such ARM, MIPS, and Itanium

ADD R1, R2, R3 ; R1← R2 +R3

8.3 ARM Processor Architecture

Advanced RISC Machine (ARM) was developed by the Acorn Company. ARM is a leader supplier of microprocessors in the world, ARM develops the core CPU, and thousands of suppliers add more functional units to the core. ARM uses two types instruction called Thumb and Thumb-2. Thumb instructions are 16 bits and thumb-2 instructions are 32 bits; currently most ARM processors use 32-bit instructions.

ARM contains 15 registers called R0 through R15, R0 through R12 called general propose registers. ARM is able to execute Thumb instructions (16-bit instructions) and Thumb-2 32 bits instruction. Thumb instructions use registers R0 through R7.

ARM is intended for applications that require power efficient processors, such as telecommunications, data communication (protocol converter), portable instrument, portable computer, and smart card. ARM is basically a 32-bit RISC processor

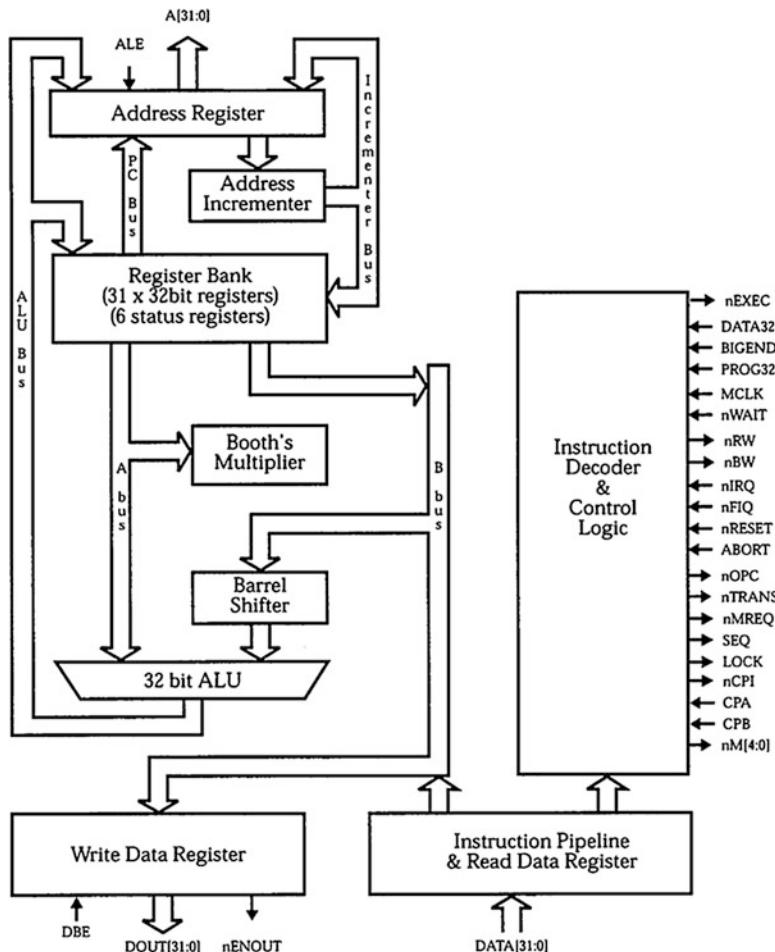


Fig. 8.2 Block diagram of ARM7 architecture

(32-bit data bus and address bus) with fast interrupt response for the use in real-time applications. A block diagram of ARM7 processor is shown in Fig. 8.2.

Instruction Decoder and Logic Control The function of instruction decoder and logic control is to decode instructions and generate control signals to other parts of processor for execution of instructions.

Address Register To hold a 32-bit address for address bus

Address Increment It is used to increment an address by four and place it in address register.

Register Bank Register bank contains thirty-one 32-bit registers and 6 status registers.

Barrel Shifter It is used for fast shift operation.

ALU 32-bit ALU is used for arithmetic and logic operation.

Write Data Register The processor put the data in Write Data Register for write operation.

Read Data Register When processor reads from memory it places the result in this register.

ARM Operation Mode

ARM can operate in one of the following modes:

1. *User mode*: Use for normal operation.
2. *IRQ mode*: This interrupt mode is designed for handling interrupt operations.
3. *Supervisory mode*: Used by operating system.
4. *FIQ mode*: Fast interrupt mode.
5. *Undefined mode*: When an undefined instruction executed.
6. *Abort mode*: This mode indicates that current memory access cannot be completed, such as when data is not in memory and the processor requires more time to access disk and transfer block of data to memory.

8.4 ARM Registers

ARM7 has 31 general registers and 6 status registers. At user mode, only 16 registers and 1 Program Status Register (PSR) are available to programmers. The registers are labeled R0 through R15. R15 is used for program counter (PC), R14 is used for link register, and R13 is used for stack pointer (SP). Figure 8.3 shows user mode registers.

Current Program Status Register (CPSR). Figure 8.4 shows the format of PSR. This register is used to store control bits and flag bits. The flag bits are N, Z, C, and V, and the control bits are I, F, and M0 through M4. The flag bits may be changed during a logical, arithmetic, and compare operation.

Flag Bits

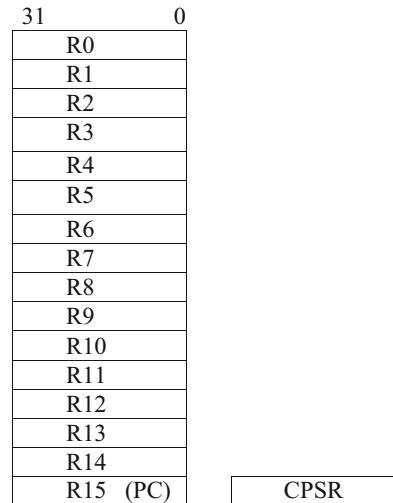
N (negative): N = 1 means result of an operation is negative, and N = 0 means result of an operation is positive.

Z (zero): Z = 1 means result of an operation is zero, and Z = 0 result of an operation is not zero.

C (carry): C = 1 means result of an operation generated a carry, and C = 0 means result of an operation did not produce a carry.

V (overflow): V = 1 means result of an operation generated an overflow, and V = 0 means result of an operation did not generate an overflow.

Fig. 8.3 User mode registers



31	30	29	28	27	7	6	5	4	3	2	1	0
N	Z	C	V	Unused	I	F	T	M4	M3	M2	M1	M0

Fig. 8.4 Storage format for CPSR

Control Bits

I (interrupt bit): When this bit sets to one, it will disable the interrupt, and this means the processor does not accept any software interrupt.

F-bit is used to disable and enable *fast interrupt request mode* (FIQ) mode.

M4, M3, M2, M1, and M0 are mode bits, and they are equal to 10000 for user mode.

T (State bit): T = 1 Processor executing Thumb instructions, T = 0 processor executing ARM instructions.

8.5 ARM Instructions

ARM architecture supports Thumb 16-bit and Thumb-2 32-bit instruction set. Most of the ARM instructions use three operands. These instructions are classified based on their instructions format and operations that are listed as follows:

- (A) Data processing instructions
- (B) Single data swap
- (C) Shift and rotate instructions
- (D) Unconditional instructions and conditional instructions
- (E) Stack operations

- (F) Branch
- (G) Multiply instructions
- (H) Data transfer

8.5.1 Data Processing Instructions

The data processing instructions are as follows: AND, EOR, SUB, RSB, ADD, ADC, SBC, RSB TST, TEQ, CMP, CMN, ORR, MOV, BIC, and MNW. Data processing instructions use register operands and immediate operand. The general format of data processing instructions is:

Mnemonic {S}{Condition} Rd, Rn, operand2

Mnemonic: Mnemonic is abbreviation of an operation such as ADD for addition

{ }: Commands inside the { } is optional such as S and condition

S: When an instruction contains S mean update the Processor Status Register (PSR) flag bits

Condition: Condition define the instruction will executed if meet the condition

Rd: Rd is destination register

Rn: Rn is operand1

Operand2: Operand2 can be register or immediate value

A. Registers Operands The operands are in registers. First register is destination register, second register is operand1 and third register is operand2.

Following are arithmetic and logic operations instructions with register operands.

ADD R0, R1, R2 ; R0=R1+R2 Add contents of register R1 with register R2 and place the result in register R0.

ADC R0, R1, R2; ; R0 = R1+R2 +C Add with carry C is carry bit.

SUB R0, R2, R3 ; R0=R2-R3 where R2 is first operand and R3 is second operand

SBC R0, R2, R3; ;R0=R2-R3+C-1 SUB with carry.

RSB R0, R2, R5 ;R0= R5-R2 Reverse SUB.

RSC R0, R2, R5 ;R0=R5-R2+C-1 Reverse sub with carry.

AND R0, R3, R5 ;R0= R3 AND R5.

ORR R7, R3, R5; ;R7=R3 OR R5.

EOR R0, R1, R2 ;R0 = R1 Exclusive OR with R2.

BIC R0, R1, R2 ;Bit clear. The one in second operand clears corresponding bit in first operand and stores the results in destination register.

Example 8.1 Assume contents of R1 is 111111111011111, and R2 is 1000 0100 1110 0011 after execution of *BIC R0,R1,R2* the R0 contains 0111 101100011100.

A. Immediate Operand In immediate operand, operand2 is an immediate value and maximum can be 12 bits

ADD R1, R2, #&25 ;R1=R2+&#amp;amp;amp;amp;amp;amp;amp;amp;25, # means immediate and &#amp;amp;amp;amp;amp;amp;amp;amp; means the immediate value is in hexadecimal.

AND R2, R3, #&45 ;R2 = R3 AND &45.

EOR R2, R3, #&45 ;R2= R3 Exclusive OR &45.

Example 8.2 What are the contents of R1 after executing the following instruction? Assume R2 contains 0x12345678

ADD R1, R2, #0x345

The ADD instruction will add contains of R2 with 0x2345 and store the result in R1, then R1 = 0x123459BD.

Setting Flag Bits of PSR The above instructions do not affect the flag bit of PSR because the instructions do not have option S. By adding suffix S to the instruction, the instruction would affect the flag bit.

ADDS R1, R2, R3 ;The suffix S means set appropriate flag bit.

SUBS R1, R2, R2; ;This will set zero flag to 1.

8.5.2 Compare and Test Instructions

ARM processor uses the compare and test instructions to set flag bits of PSR and following are compare and test instructions.

CMP, CMN, TST, and TEQ, these instruction uses two operands for compare and test, the result of their operations do not write to any register

CMP Instruction (Compare Instruction) The CMP instruction has following format

CMP Operand1, Operand2

The CMP instruction compares Operand1 with Operand2; this instruction subtracts Operand2 from Operand1 and sets the appropriate flag. The flag bit set based on the result of the operation as follows

Z flag set if Operand2 equal operand1

N flag is set if operand1 less than operand2

C flag is set if result of operation generate carry

Example 8.4 Assume R1 contains 0x00000024, and R2 contains 0x00000078; the operation CMP R1, R2 will set N flag to 1.

CMP Rd, immediate value, the immediate value can be 8 bits such as

CMP R1, #0xFF

CMN Compare Negate The CMN has following format

CMN Operand1, Operand2

The instruction will add operand1 with operand 2 and set appropriate flag bit.

Example 8.5 Assume R1 contains 0x00000024 and R2 contains 0x13458978: the operation CMN R1, R2 with result carry and set C flag to 1.

TST (Test Instruction) The test instruction has following format

TST Operand1, Operand2

The test instruction performs AND operation between operand1 and Operand2 and sets appropriate flag bit. The operand can be immediate value or register such as

TST R1, R2; This instruction performs R1 AND R2 operation and sets the appropriate flag.

OR

```
TST R1, immediate, the immediate value can be 8 bits such as
TST R1, 0xFF
TEQ R1, R2 ;This instruction performs R1 Exclusive OR R2.
```

If R1 is equal to R2, then Z-flag is set to 1.

8.5.3 Register Swap Instructions (**MOV** and **MVN**)

The register swap instructions have the following general formats.

A. **MOV{S}{condition} Rd, Rm**

Move the contents of Rm to Rd

Example 8.6 What is the content of R1 after execution of the following instructions?

Assume R2 contains 0X0000FFFF.

a. **MOV R1, R2 ;R1 ← R2**
 R2=0x0000FFFF

b. **MVN R1, R2 ; R1 ← NOT R2**
 R2= 0xFFFF0000

A. **MOV{S}{condition} Rd, immediate value**

Immediate value is 16 bits, the range of immediate value if from 0x00000000 to 0x0000FFFF.

Example 8.7

MOV R2, # 0x45 , the contents of R2 will be 0x00000045

B. MOV Rn, Rm, lsl # n ; shift Rm n times to the left and store the result Rn

C. Conditional MOV

MOVEQ R2, 0x56 ; if zero bit is set then executes MOVEQ

8.5.4 Shift and Rotate Instructions

ARM combined the rotate and shift operation with other instructions; the ARM processor performs following shift operations.

LSL	Logical Shift Left
LSR	Logical Shift Right
ASR	Arithmetic Shift Right
ROR	Rotate Right

Logical Shift Left (LSL). In logical shift left operations, each bit of register shifted to the left as shown in Fig. 8.5 and a zero will be placed in the least significant bit, the logical shift left multiplies the contents of register by two.

LSL R1, R1, n , shift to left R1 n times and store result in R1

Example 8.8 What is the content of R1 after executing the following instruction? Assume R1 contain 0x00000500.

LSL R1, R1, 8
R1= 0x00050000

Logical Shift Right (LSR). In logical shift right operation, each bit of register shifted to the right as shown in Fig. 8.6, and a zero will be placed in the most significant bit; the logical right divides the contents of register by two.

LSR R1, R1, n ,shift to right R1 n times and store result in R1

Fig. 8.5 Logical shift left

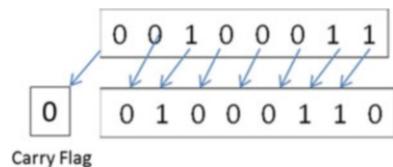
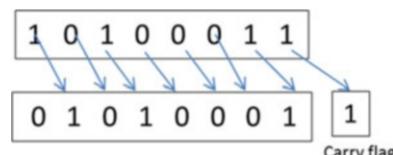


Fig. 8.6 Logical shift right



Example 8.9 What are the contents of R1 after executing the following instruction: assume R1 contains 0x00000050.

```
LSR R1, R1, 4
R1= 0x00000050
```

Arithmetic Shift Right (ASR). In arithmetic shift right, the most significant bit does not change and each bit shifted to the right as shown in Fig. 8.7.

Rotate Right Figure 8.8 shows an 8-bit register and Fig. 8.9 shows the register after rotating one time.

Example 8.10 What is the content of R1 after rotating 16 times? Assume R1 contains 0X0000FFFF

```
ROR R1, R1 , #16
R1= 0xFFFF0000
```

ARM combines data processing instructions and shift operation; shift operation is applied to the second operand of the instruction.

Example 8.11 Register R2 contains 0XEEEEFFFF, by executing.

```
MOV R1, R2, ROR # 16 ;the R2 rotate 16 times and store results in R1
```

by rotating 16 times the contains of R1 will be xFFFFEEE

Fig. 8.7 Arithmetic shift right

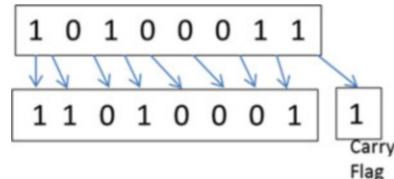
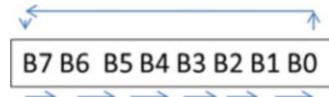


Fig. 8.8 Rotate right operation



B0 B7 B6 B5 B4 B3 B2 B1 B0

Fig. 8.9 One bit rotate right operation

ADD R1, R2, R3, LSL #4 ;R1= R2 + R3 x 2^4 , R3 is shifted 4 times to the left and result is added to R3 and placed in R1.

Also a register can hold number of times the operand2 must be shifted.

ADD R1, R2, R3, LSL R4	:R1= R2 + R3 X 2^{R4} , Number of times R3 to be shifted is in R4.
MOV R0, R1, LSL #3	:Shift R1 to the left three times and move the result to R0.

8.5.5 ARM Unconditional Instructions and Conditional Instructions

Figure 8.10 shows the general format of an ARM instruction. ARM instruction defines two types of instructions, namely:

1. Unconditional instruction
2. Conditional instruction

Condition code defines the type of instruction. If this field is set to 1110, then the instruction is an unconditional instruction, otherwise the instruction is a conditional instruction. To use an instruction as a conditional instruction, the condition will suffix to the instruction. The suffixes are:

<u>Condition Code Condition</u>
0000 EQ equal
0001 NE not equal
0010 CS carry set
0111 CC carry is clear
0100 MI negative (N flag is set)
0101 PL positive (N flag is zero)
0110 VS overflow set
0111 VC overflow is clear
1000 HI higher for unsigned number
1001 LS less than for unsigned number
1010 GT greater for signed number
1011 LT signed less than

Condition Code	Instruction		
31 28 27			1

Fig. 8.10 General format of an ARM instruction

```

1100 GT Greater Than
1101 LE less than or equal
1110 AL unconditional instructions
1111 Unused code

```

The processor checks the condition flag before executing the conditional instruction. If it matches with the condition instruction, then the processor executes the instruction, otherwise skips the instruction.

ADDEQ R1, R2, R3 ;If zero flag is set and it will execute this instruction.

Example 8.10 Convert the following HLL to ARM assembly language.

```

If R1=R2 then
ADD R3, R4, R5
Endif

```

ARM assembly language for the above program would be:

```

CMP R1, R2
ADDEQ R3, R4, R5

```

Example 8.11 Convert the following HLL to ARM assembly language.

```

If R1 = R2 Then R3= R4-R5
Else
If R1 > R2 Then R3=R4+R5

```

ARM assembly language for the above program would be:

```

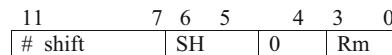
CMP R1, R2
SUBEQ R3, R4, R5
ADDGT R3, R4, R5

```

8.6 ARM Data Processing Instruction Format

The instruction format is used by assembler to convert instruction to machine code; Fig. 8.11 shows data processing instruction format.

31	28	27	26	25	24	21	20	19	16	15	12	11	0
Cond	0 0	I		Op code		S		Rn		RD		Operand 2	

Fig. 8.11 Data processing instruction format**Fig. 8.12** Operand2's format when bit 4 is equal to 0

Condition Code To determine if the instruction is a conditional or a unconditional instruction,

I bit I=0 means the operand2 is a register, I=1 means the operand 2 is an immediate value.

Op Code The OP Code determines types of instruction and followiong are the op codes for data processing instructions

Instruction	Op Code	
AND	0000	
EOR	0001	
SUB	0010	
RSB	0011	
ADD	0100	
ADC	0101	
SBC	0110	
RSC	0111	
TST	1000	
TEQ	1001	
CMP	1010	set condition by Op1-Op2
CMN	1011	set condition for Op1+ Op2
ORR	1100	
MOV	1101	Rd=operand2
BIC	1110	
MVN	1111	Rd= NOT operand2

S bit S = 0 do not change flag bits of PSR register, S = 1 set condition flags of PSR register.

Rn Rn is first operand, and it can be any of the 16 registers, R0 through R15.

Rd Rd is destination register, and it can be any of the 16 registers, R0 through R15.

Operand2 When I = 0 the operand2 is a register and Fig. 8.12 shows operand2's format.

Shift To determine immediate value for number of times Rm must be shifted

SH To determine types of shift operation

Rm second operand

Operation SH value

- LSL 00 Logical Shift Left
- LSR 01 Logical Shift Right
- ASR 10 Arithmetic Shift Right
- ROR 11 Rotate Right

Example 8.12 Convert the following instructions to machine code.

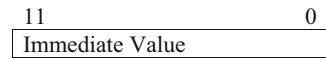
ADD R1, R2, R3, LSL #3

31	28	27 26	25 24	21 20	19	16 15	12 11	7 6 5	4	3	0
Cond 1110	0 0	I 0	Op code 0100	S 0	Rn 0010	RD 0001	#Shift 0011	SH 00	0	RM 0011	

When bit 4 of operand2 is set to 1, the number of times Rm must be shifted is in a register.

Figure 8.13 shows format of operand2 of Fig. 8.11.

I=1: The operand 2 would have following format.



11	8	7	6	5	4	3	0
RS	0	SH	1	Rm			

Fig. 8.13 Format of Operand2 when bit 4 is equal to 1

8.7 Stack Operation and Instructions

Part of the memory is used for temporary storage is called stack; the stack pointer holds the address of top of the stack as shown in Fig. 8.14.

The register R13 is assigned as stack pointer (SP), and the stack uses the following instruction.

- a. **Push {condition} Rn** : transfer the contains of Rn into stack and add 4 to the stack pointer

Example 8.12 Assume the content of R3 is 0x01234567; Fig. 8.15 shows the contents of Stack after executing push R3.

Example 8.14 Show contents of stack and SP in Fig. 8.16 after execution of Push R4; assume R4 contains 0X5645321F.

Fig. 8.14 Stack architecture

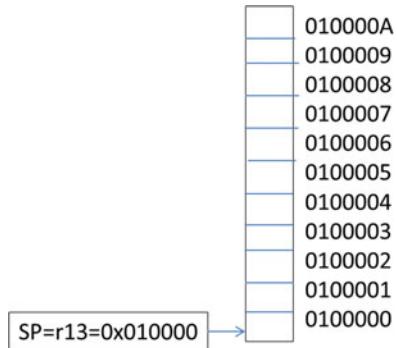


Fig. 8.15 Shows contains of stack after execution of push R3

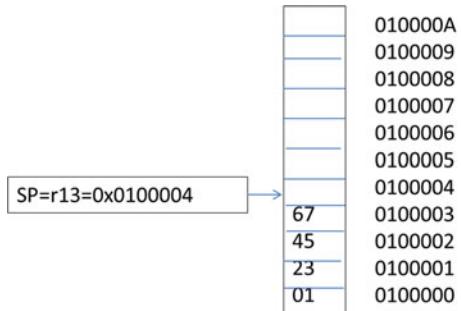


Fig. 8.16 Show stack after push operation

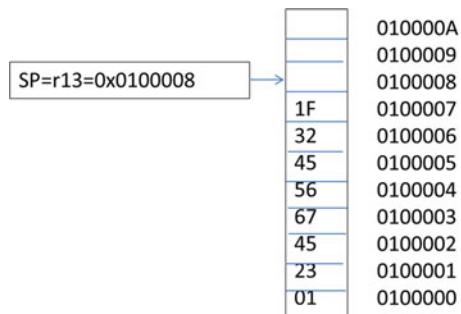
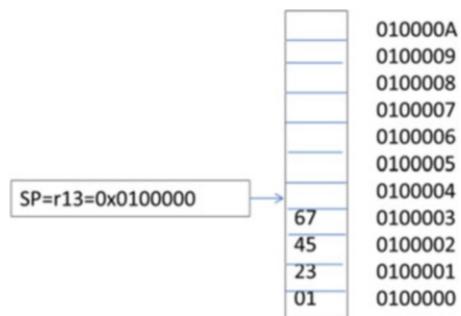


Fig. 8.17 Contents of stack after POP operation



POP Instruction: the POP instruction has following format

POP{condition} Rn

POP Rn: the pop instruction remove the word from top the stack and store it into register rn and automatically decrement stack pointer by 4

Example 8.15 Show the contents of stack and SP of Fig. 8.16 after execution POP R0; the contents of R0 will be 0x1FAD7856 and stack will look like as in Fig. 8.17.

8.8 Branch (B) and Branch with Link Instruction (BL)

The Branch instruction has following general format.

B{condition} label

B label ; branch to location label.

BEQ label ; if flag bit Z=1 then execute this instruction

BL Subroutine ;it will branch to subroutine and save contents of PC (R15) to R14 (link register) for return from subroutine.

Example 8.16 Write a subroutine to find the value of $Y = 16X + 4$; assume R1 holds the Y and R2 holds X.

```
BL Funct
Funct SUB R1, R1, R1
ADD R1, R1, R2, LSL4
ADD R1, R!, #04
MOV R15, R14 ; Move return address to PC
```

8.8.1 B and BL Instruction Format

31	28 27	25 24	23	0
Cond	101	L	offset	

L=0 means Branch and condition for branch can be set by Cond field.
L=1 Mean Branch and Link

Instruction

- B Branch always
- BAL Branch Always
- BEQ Branch if Equal
- BNE Branch if Not equal
- BPL Branch on positive
- BMI Branch on negative
- BCC Branch if carry flag is clear
- BLO Branch below for unsigned number
- BCS Branch carry flag is set
- BHS Branch if higher for unsigned number
- BVC Branch if Over flow flag is clear
- BVS Branch if Over flow flag is clear
- BGT Branch greater for signed number
- BGE Branch greater or equal for signed number
- BLT Branch Less than for signed number
- BLE Branch Less than or equal for signed number
- BLS Branch less than or equal for unsigned number

Example 8.17 Rewrite following assembly language using conditional instructions.

```
CMP R1,R2
BEQ Exit
ADD R1, R2, R3
Exit:
SUB R1, R5, R6
```

By using conditional instructions, the above assembly language can be represented by

```
CMP R1,R2
SUBEQ R1,R5,R6
ADDNE R1,R2,R3
```

8.9 Multiply (MUL) and Multiply-Accumulate (MLA) Instructions

MUL instruction
 MUL Rd, Rm, Rs ; Rd= Rm*Rs

MLA Multiply and Accumulate
 MLA Rd, Rm, Rs, Rn ; Rd= Rm*Rs +Rn

8.9.1 *Multiply Instruction Format*

31	28 27	22 21	20	19	16 15	12 11	8	7	4	3
0	Cond	00000	A	S	Rd	Rn	RS	1001	Rm	

A=0 MUL instruction
 A=1 MLA instruction
 S=0 Do not change flag bit
 S=1 Set the flag bits
 Rd is destination register
 Rs, Rm and Rn are the operands

8.10 Summary

- The function of compiler is to convert the HLL to the assembly language.
- The function of assembler is to convert the assembly language to the machine code (binary).
- The computer instruction is represented by mnemonic form such as “ADD.”
- Each instruction may have one or two or three operands, ADD R1, R2, and R3 where R1, R2, and R3 are called operands.
- ARM stand for Advanced RISC Machine and ARMv7 uses 32-bit and 16-bit instruction.
- ARMv7 contain 31 registers and only 16 registers R0 through R15 used by programmer.
- The Register R15 is used for the program counter (PC), R14 is used for the link register (LR), and R13 is used for the stack pointer (SP).
- The PSR register is used to store control bits (I, F, M, and T) and flag bits (N, Z, C, and V).
- The ARM processor offers two types of instructions, and they are unconditional and conditional instruction.
- The instructions CMP, CMN, TST, and TEQ will set processor status register.
- Part of the memory is used for the stack, and the stack pointer holds the address of the top of the stack.
- Chapter 9 covers more ARM instructions such as load, store, pseudo instructions, bits field instructions, ARM addressing mode, and data representation in the memory.

8.11 Problems and Questions

1. Explain how HLL converted to Machine code.
2. List types of instructions based on number of operands.
3. Which register of ARM processor is used for the program counter (PC)?
4. Which register of ARM processor is used for stack pointer (SP)?
5. Which register of ARM processor is used for link register?
6. What is contents of R5 after execution of following instruction, assume R2 contains 0X34560701 and R3 contains 0X56745670
 - (a) ADD R5, R2, R3
 - (b) AND R5, R3, R2
 - (c) XOR R5, R2, R3
 - (d) ADD R5, R3, #0x45
7. What are the contents of R1? Assume R2 = 0x00001234.
 - (a) MOV R1, R2, LSL #4
 - (b) MOV R1, R2, LSR #4

8. What is the difference between these two instructions?

- (a) SUBS R1, R2, R2
- (b) SUB R1,R2, R2

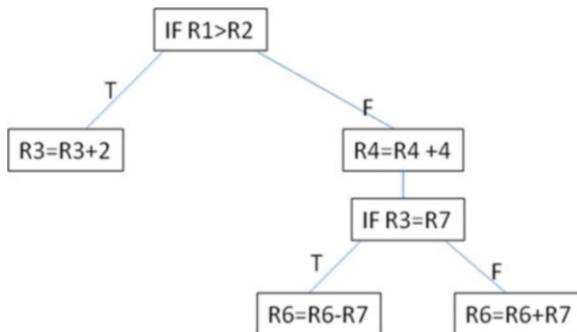
9. Convert the following HLL language to ARM instructions.

```
IF R1>R2 AND R3>R4 then
R1= R1 +1
Else
R3=R3 +R3*8
Endif
```

10. Convert the following HLL language to ARM instructions.

```
IF R1>R2 OR R3>R4 then
R1= R1 +1
Else
R3=R3 +R5*8
Endif
```

11. Convert the following flowchart to ARM assembly language.



12. Write a program to add ten numbers from 0 to 10 or convert the following C language to ARM assembly language.

```
int sum;
int i;
sum = 0;
```

```
for (i = 10 ; i > 0 ; i -- ) {
sum = sum +1
}
```

13. Write a program to convert the following HLL to ARM assembly.

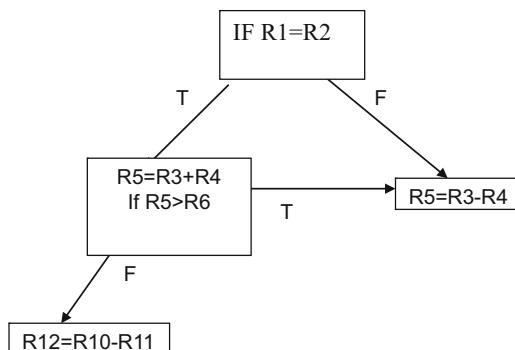
```
a= 10;
b=45;
while ( a!= b ) {
if (a < b)
a = a +5;
else
b= b+5;
}
```

SOLUTION:

14. Convert the following HLL to ARM assembly.

```
IF R1>R2 AND R3>R4 then
R1= R1 +1
Else
R3=R3 +R5*8
Endif
```

15. Convert the following flowchart to ARM assembly.



Chapter 9

ARM Instructions Part II

Objectives: After completing this chapter, you should be able to:

- Explain the different types of load instructions.
- List the different types of store instructions.
- Distinguish the different types of ARM addressing mode.
- List the ARMv7 pseudo instructions.
- Learn the application of ADR and LDR instructions.
- Explain the bit field instruction operation.
- Learn how the data are represented in memory.

9.1 Introduction

The data transfer instructions are used to transfer data from memory to registers and from registers to memory. ARM processor used LDR and STR instructions to access memory. LDR and STR able to use register indirect, pre-index addressing, and post-index addressing to access memory. ARM offers several pseudo instructions which used by programmer and assembler to convert them to ARM instructions.

9.2 ARM Data Transfer Instructions

Load Instructions (LDR). The LDR instruction is used to read data from memory and store it into a register, and it has the following general format.

LDR[type]{condition} Rd, Address

Where “type” defines the following load instructions

LDR	Load 32 bits (word)
LDRB	Load 1 byte
LDRH	Load 16 bits (half word)
LDRS	Load signed byte
LDRSB	Load sign extension
LDRSH	Load signed half word
LDM	Load multiple words

Condition is an optional such as LDREQ load data if Z flag =1 and Rd is destination register.

Example 9.1 Assume R0 holds address 0000 and the following memory is given, show the contents of R1 and R3 after executing following instructions.

Address	Contents
0	0X85
1	0XF2
2	0X86
3	0XB6

LDRH R1, [R0] R1 = 0x0000F285
 LDRSH R3, [R0] R3 = 0xFFFFF285

9.2.1 ARM Pseudo Instructions

ARM supports multiple pseudo instructions; the pseudo instruction is used by the programmer, and assembler converts the pseudo instruction to ARM instruction.

ADR Pseudo Instruction ADR is used to load the address of memory location into a register and has the following format.

ADR Rd, Address

Example 9.2 The following instructions will read the address of data and then load the data into register R3:

ADR R0, table	Move address represented by table
LDR R3, [R0]	R3 = 0x23456780
Address	Data
Table	0x23456780

LDR Pseudo Instruction LDR pseudo instruction is used for loading a constant into a register. In order to move a 32 bits constant into a register, the instruction MOV Rd, #value only can move 12 bits to the register Rd because the operand2 in

instruction format for MOV is 12 bits. The LDR pseudo instruction has following format.

LDR Rd, = Value

Example 9.3 The following instruction will load the R1 with 0x23456789:

LDR R1, = 0x23456789

9.2.2 *Store Instructions (STR)*

The STR instruction is used to transfer contents of a register into memory and has following general format.

STR[type]{condition} Rd, [address]

Where “type” defines the following instruction types

STR	Store 32 bits (word)
STRB	Store 1 byte
STRH	Store 16 bits (half word)
STM	Store multiple words

Example 9.4

STR R5, [R3] Store contents of R5 into the memory location that R3 holds the address; R3 is the base register.

9.3 ARM Addressing Mode

- The ARM processor support ARM offers several addressing modes and they are pre-indexed, pre-indexed with immediate offset, pre-indexed with register offset, pre-index with scaled register, pre-index with register offset and write back, post-index with immediate offset, post-index with register offset, and post-index with scaled register offset; the following table shows a summary of ARM addressing modes.

Addressing mode	Assembler syntax	Effective address (EA)
Immediate	MOV R1, #0X25	Data is part of instruction
Pre-indexed	[Rn]	EA = Rn
Pre-indexed with immediate offset	[Rn, # offset]	EA = Rn + offset
Pre-indexed with register offset	[Rn, ± Rm]	EA = Rn ± Rm
Per-index with scaled register	[Rn, Rm, Shifted]	EA = RN + Rm shifted
Pre-indexed with an immediate offset and write back	[Rn, offset]!	EA = Rn + offset Rn = Rn + offset

(continued)

Addressing mode	Assembler syntax	Effective address (EA)
Pre-index with register offset and write back	[Rn, ± Rm,]!	EA = Rn ± Rm Rn = Rn ± Rm
Pre-index with scaled register offset and write back	[Rn, Rm, Shifted]!	EA = Rn ± Rm shifted Rn = Rn ± Rm shifted
Post-index with immediate offset	[Rn], offset	EA = Rn Rn = Rn + offset
Post-index with register offset	[Rn], ± Rm	EA = Rn Rn = Rn ± Rm
Post-index with scaled register offset	[Rn], ± Rm. SHL #n	EA = Rn Rn = Rn ± Rm shifted

9.3.1 Immediate Addressing

In immediate addressing, the operand is part of instruction such as

MOV R0, #0x34

or

ADD R1, R2, 0x12

9.3.2 Pre-indexed

In pre-index addressing mode represented by [Rn], the effective address (EA) is contents of Rn such as

LDR R2, [R3]

Pre-indexed with Immediate Offset

Pre-indexed with immediate offset is represented by [Rn, #offset] such as

LDR R0, [Rn, #Offset]

The offset is an immediate value such as

LDR R1, [Rn, #0x25]

EA = R2 + 0x25

Pre-indexed with Register Offset

The offset can be register or register with shift operation:

LDR R0, [R1, R2]

EA = R1 + R2

Example 9.5 What is the effective address of following address? Assume R5 contains 0X00002345

[R5, #0x25]

$$EA = 0x000002345 + 0X25 = 0x0000236A$$

Example 9.6 What is effective address of following pre-index addressing, assume R5 = 0x00001542 and R2 = 0X00001000

[R5, R2]

$$EA = R5 + R2 = 0X00001542 + 0X00001000 = 0X00002542$$

Pre-indexed with Scaled Register

The offset contains register with shift operation:

LDR R0, [Rn , R2 , LSL#2]

Example 9.7 What is EA of following instruction?

LDR R0, [Rn , R2 , LSL#2]

$$EA = Rn + R2 * 4$$

R2 shifted to the left twice (multiply by 4) and added to Rn.

9.3.3 Pre-indexed with Write Back

The general format for pre-index addressing with write back is

[Rn, Offset]!

The exclamation (!) character is used for write back; the offset can be immediate value or register or shifted register:

$$EA = Rn + \text{offset} \quad \text{and} \quad Rn = Rn + \text{offset}$$

Pre-index with Immediate Offset and Write Back

LDR R0, [R1,# 4]!

$$EA = R1 + 4 \quad \text{and} \quad R1 \text{ updated by } R1 = R1 + 4.$$

Example 9.8 What is the effective address and final value of R5 for following instruction? Assume the contents of R5 = 0x 00002456:

LDR R0, [R5, #0X4]!

$$EA = R5 + 0x4 = 0x000245A$$

$$R5 = R5 + 0x4 == 0x000245A$$

Pre-index with Register Offset and Write Back

LDR R0, [R1, R2]!
 $EA = R1 + R2$ $R1 = R1 + R2$

Example 9.9 What is the effective address and final value of R5 of following instruction? Assume the contents of R5 = 0x 00002456 and R2 0X00002222:

LDR R0, [R5, R2]!
 $EA = R5 + R2 = 0x00004678$
 $R5 = R5 + R2 = 0x00004678$

Pre-index with Scaled Register Offset and Write Back

LDR R1, [Rn, R2, LSL#2]!
 $EA = Rn + R2 * 4$
 $Rn = Rn + +R2 * 4$

9.3.4 Post-index Addressing

The general format of post-index addressing is

LDR R0, [Rn], offset
Offset can be immediate value or register or shifted register.

Post-index with an Immediate Value

LDR R0, [Rn], #4
Effective address = Rn and $Rn = Rn + 4$

Post-index with Register Offset

LDR R0, [Rn], Rm
Effective address = Rn and $Rn = Rn + Rm$

Post-index with Scaled Register Offset

LDR R0, [Rn], Rm, SHL#4
Effective address = Rn and $Rn = Rn + Rm * 16$

9.4 Swap Memory and Register (SWAP)

The swap instruction combines the load and stores instructions into one instruction, and it has following format.

SWP Rd, Rm, [Rn]

The register Rd is destination register, Rm Swap memory and register (SWAP) is the source register, and Rn is base register.

The swap instruction performs following functions.

Rd \leftarrow memory [Rn] Load Rd from memory location [Rn]

[Rn] \leftarrow Rm store the contents of Rm in memory location [Rd]

SWPB Rd, Rm, [Rn] Swap one byte

9.5 Bits Field Instructions

ARM offers two bit field instructions and they are bit field clear (BFC) and bit field insertion (BFI).

9.5.1 BFC (Bit Field Clear Instruction)

BFC has following general format.

BFC {cond} Rd, # lsb, #width

Rd is destination register.

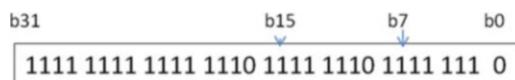
lsb determines start of bit position in the source register (Rd) to be clear.

Width determines number of bits to be clear from lsb to msb of the Rd register.

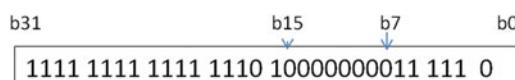
Example 9.10 Write an instruction to clear bits 7 through 15 of register R4; assume R4 contains 0xFFFFFEFE.

BFC R4, #7, #8 clear bit 7 through bit 15 (8 bits) of register R4.

The initial value in R4 is.



After clearing bit 7 through 15 of R4 results.



9.5.2 BFI (Bit Insertion Instruction)

Bit insertion is used to copy a set of bit from one register Rn into register Rd starting from lsb of Rd; BFI has following format.

BFI{cond} Rd, Rn, #lsb, #width

Rd is destination Reg.

Rn is source register.

#lsb starting bit from Rn.

#width number of bit starting from lsb of Rn.

Example 9.11 Copy 8 bits of R3 starting from bit 4 to R4; assume R3 contains 0xFFFFEBBCD and R4 contains 0xEE035007.

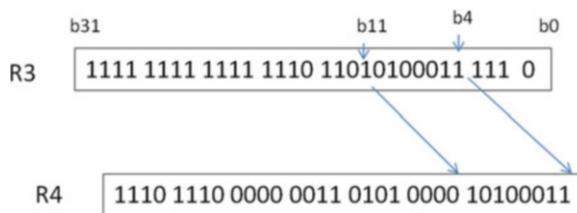
BFI R4, R3, #4, #8, and this instruction will copy 8 bits from B4 to B11 of R3 into B0 through B7 of R4, the initial value of R3 in binary.

11101110000000 11010100000000111

The initial value of R4 in binary is

1110 1110 0000 0011 0101 0000 0000 0111

The instruction will copy 8 bits from bit 4 of R3 into R4 starting from bit 0 of R4.



9.6 Data Representation and Memory

ARM processors define a word as 4 bytes and a half word as 2 bytes. Data can be represented in the form of hexadecimal, decimal, and binary.

- (a) Decimal numbers, such as 345
- (b) Hexadecimal numbers, such as 0x2345, where “x” represents hexadecimal

(c) Binary or base 2, such as 2_10111100

Memory holds data and code. Figure 9.1 shows a block diagram of memory. The address of memory defines the location of the data, where each location of ARM processor memory holds one byte. In assembly language, a label, as shown in Fig. 9.2, represents the address of memory.

Figure 9.2 shows how each memory location holds one byte. Storing two bytes (half word) of data, such as 0x4563, can be stored two different ways called Big Endian and Little Endian.

Big Endian. In Big Endian the most significant byte (MSB) of data is stored first in memory. In Fig. 9.3, 45 is the most significant byte, and 63 is the least significant for the number 0x4563.

The ARM 7 operates in Big and Little Endian; each memory location of ARM7 holds one byte and a word (4 bytes) can be stored in memory in two different ways: Big Endian and Little Endian.

Big Endian. In Big Endian the most significant byte of a word is stored at the lowest address.

Example 9.12 The 0x34569312 may be stored in Big Endian form as shown in Fig. 9.3.

Fig. 9.1 Memory with the binary address

00	23
01	4A
10	56
11	F5

Fig. 9.2 Memory with the labeling address

List	23
List+1	4A
List+2	56
List+3	F5

Fig. 9.3 Big Endian representation of hex number 34569312

Memory	
000	34
001	56
010	93
011	12

Fig. 9.4 Little Endian representation of hex number 34569312

Memory	
000	12
001	93
010	56
011	34

Little Endian. In LittleEndian the least significant byte of a word is stored at the lowest address.

Example 9.13 Hex number 34569312 may be stored in Little Endian form as shown in Fig. 9.4.

9.7 Summary

- ARM instruction uses LDR and STR to read and write to memory.
- The load instruction can be used to load one byte (LDRB), load 2 bytes (LDHB), and load 4 bytes (LDR).
- LDRSB (load signed extension) is used to load one byte and extended the sign of the data.
- LDRSH (load signed extension) is used to load two bytes and extended the sign of the data.
- The ARM pseudo instructions are ADR (load address of memory location) and LDR (load a 32 bit value into a register).
- ARM processor store instructions are STR (store one word), STRB (store one byte), and STRH (store half word).
- ARM offers several addressing modes and they are pre-indexed, pre-indexed with immediate offset, pre-indexed with register offset, pre-index with scaled register, pre-index with register offset and write back, post-index with immediate offset, post-index with register offset, and post-index with scaled register offset.
- Data can be represented in memory in the form of Big Endian and Little Endian.
- In Big Endian the most significant byte of a word is stored at the lowest address.
- In Little Endian the least significant byte of a word is stored at the lowest address.
- Chapter 10 covers how to use Keil development tools and run and debug a program, programming rules, directives, and a sample program.

Problem

1. Trace following instructions; assume list starts at memory location 0x00000018 and using ARM Big Endian:

ADR R0, LIST ; Load R0 with address of memory location list
 MOV R10, #0x2

- (a) LDR R1, [R0]
- (b) LDR R2, [R0, #4]!

- (c) LDRB R3, [R0], #1
- (d) LDRSB R5, [R0], #1
- (e) LDRSH R6, [R0]

LIST DCB 0x34, 0xF5, 0x32, 0xE5, 0x01, 0x02, 0x8, 0xFE

2. Work problem #1 part A and B using Little Endian.

- (a) R1 = 0xE532F534
- (b) R2 = 0xFE080201

3. What is contents of register R7 after execution following program?

```
ADR R0, LIST
LDRSB R7, [R0]
LIST DC 0xF5
```

4. What are the contents of register Ri for the following load Instructions? Assume R0 holds the address of list using Little Endian.

- (a) LDR R1, [R0]
- (b) LDRH R2, [R0]
- (c) LDRB R3, [R0], #1
- (d) LDRB R4, [R0]
- (e) LDRSB R5, [R0], #1
- (f) LDRSH R6, [R0]

List DCB 0x34, 0xF5, 0x32, 0xE5, 0x01, 0x02

5. The following memory is given, show the contents of each register, and assume R1 = 0x0001000 and R2 = 0x00000004 (use Little Endian).

- (a) LDR R0, [R1]
- (b) LDR R0, [R1, #4]
- (c) LDR R0, [R1, R2]
- (d) LDR R0, [R1, #4]!

1000	23
	13
	56
	00
1004	45
	11
	21
	88
1008	03
	08
	35
	89
100C	44
	93

6. What are the effective address and contents of R5 after executing following instructions? Assume R5 contains 0x 18 and r6 contains 0X00000020.

- (a) STR R4, [R5]
- (b) STR R4, [R5, #4]
- (c) STR R4, [R5, #8]
- (d) STR R4, [R5, R6]
- (e) STR R4, [R5], #4

Chapter 10

ARM Assembly Language Programming Using Keil Development Tools

Objectives: After completing this chapter, you should be able to:

- Explain the function development tool.
- Explain the function of cross-assembler.
- List several development tools for running assembly language program.
- Install the Keil development tools.
- Run and debug a program.
- Use program template to write your own program.
- Learn programming rules.
- Represent data in memory for an assembly language program.
- Learn the application of directives.
- Distinguish the different types of data directives.
- Run a step-by-step program and observe the contents of each register.

10.1 Introduction

Processor manufacturers publish documentation that contains information about their processors, such as lists of registers, the function of each register, size of the data bus, size of the address bus, and a list of the instructions that can be executed. Each CPU has a known instruction set that a programmer can use to write assembly language programs. Instruction sets are specific to each type of processor. For example, Pentium processors implement a different instruction set than ARM processors. Programs written using the instruction set of a processor are said to be written in assembly language. The function of an **assembler** is to convert assembly language to machine code (binary) that the CPU can execute.

When an assembler runs on one processor but can assemble instructions for a different processor with a different instruction set it is called a **cross-assembler**. Processor simulators are a key development tool, since they allow for a controllable

test environment in a setting such as a Windows or Linux workstation. They may also facilitate the transfer or download of the program to the target processor. The following development tools are some which support ARM processors:

1. ARM Keil Microcontroller Tools (www.keil.com)
2. IAR Embedded Workbench (www.iar.com)
3. GNU ARM Assembler (www.gnu.org)

10.2 Keil Development Tools for ARM Assembly

For the examples in this book, **Keil µVision® IDE** (integrated development environment) from Keil's **Microcontroller Development Kit (MDK) version 5** is used. A free version of this software can assemble and simulate the execution of ARMv7 instructions provided the size is under 32 K. The download is available from Keil's website: <http://www.keil.com>.

When first installed, a dialog titled **Pack Installer** may open after the installer has finished. This utility assists the user in downloading and installing environments for µVision to enable the simulation of different boards and devices. By default, however, several device templates come pre-installed with µVision (Fig. 10.1).

- To get started, open µVision and select *Project* → *New µVision Project* . . .
- Name your project and choose a location to save it in.
After saving, a dialog will open and prompt you to *Select Device for Target “Target 1”* Depending on whether or not you have installed any additional packs from the *Pack Installer*, this screen may look different. Several **ARM** processors are included with the default installation. For the examples in this book, the **ARM Cortex M3 (ARMCM3)** was selected.
- Select **ARM Cortex M3** → **ARMCM3** and press OK. (Fig. 10.2)

For each processor, µVision has several libraries available. Some are essential, such as start-up configuration, while others are optional extensions to enable

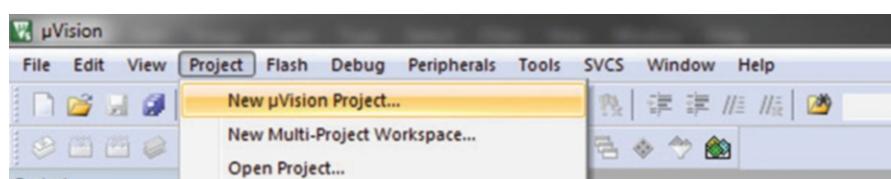


Fig. 10.1 Creating a new project in Keil µVision® IDE v5.22

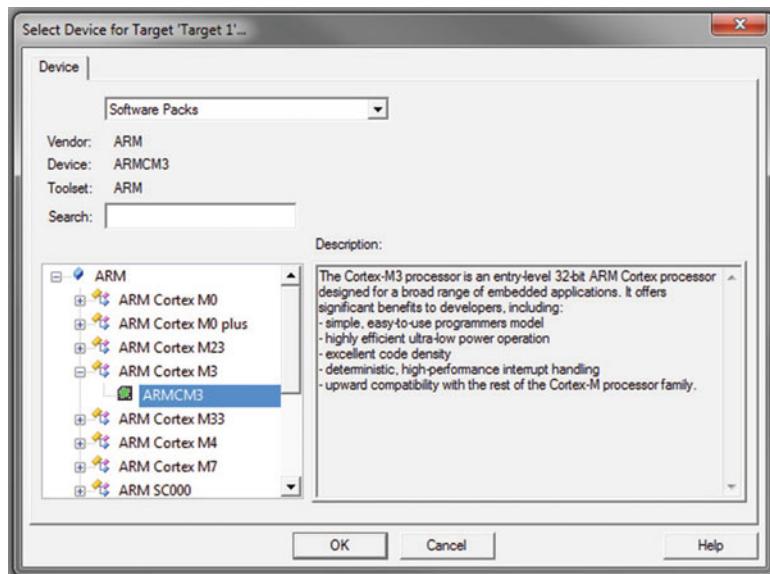


Fig. 10.2 Selecting the ARM Cortex M3 processor

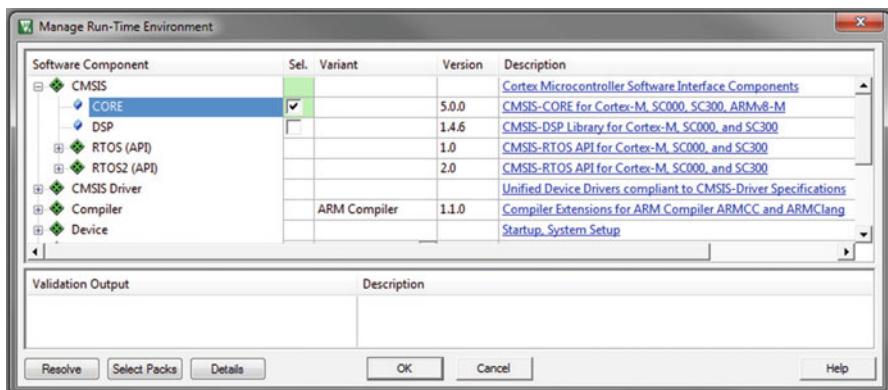


Fig. 10.3 The CORE library to run the ARMCM3 processor

broader functionality, such as Ethernet drivers and Graphics interfaces. To run simple ARMv7 assembly programs, only the start-up component is needed.

- Select CMSIS → CORE and hit OK. (Fig. 10.3)

Now, you should have a blank project open in the *Project* pane, which by default is on the left side of the window, under the *Menu* bar. Next, the project needs to be configured to use the simulator to run the programs.

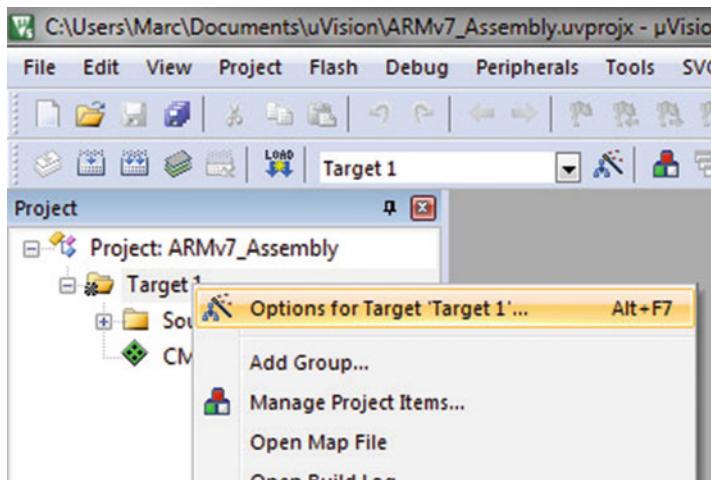


Fig. 10.4 Changing the project configuration

- Right click on the *Target 1* folder and select *Options for Target "Target 1"...* (Fig. 10.4)
- Click on the *Debug* tab and select *Use Simulator*. (Fig. 10.5)
- Click on *Target* and select *Use MicroLIB* as shown in Fig. 10.6
- Add a new item to the project by right click the *Source Group 1* folder in the project pane as Fig. 10.7
- Create a new assembler source file (*Asm* file or *.s*), name it, and then save it as shown in Fig. 10.8

Assembly programs follow a certain structure and have what are called **directives**. These will be explained later on in the chapter, but they instruct the assembler on how to structure much of the final program. Much like many high-level language programs run inside of a main “function” or “method,” the following example uses the routines *_Vectors* and *Reset_Handler* (which are called by default by the processor we selected).

Example 10.1 This program reads two numbers and stores the sum in R3 as shown Fig. 10.9.

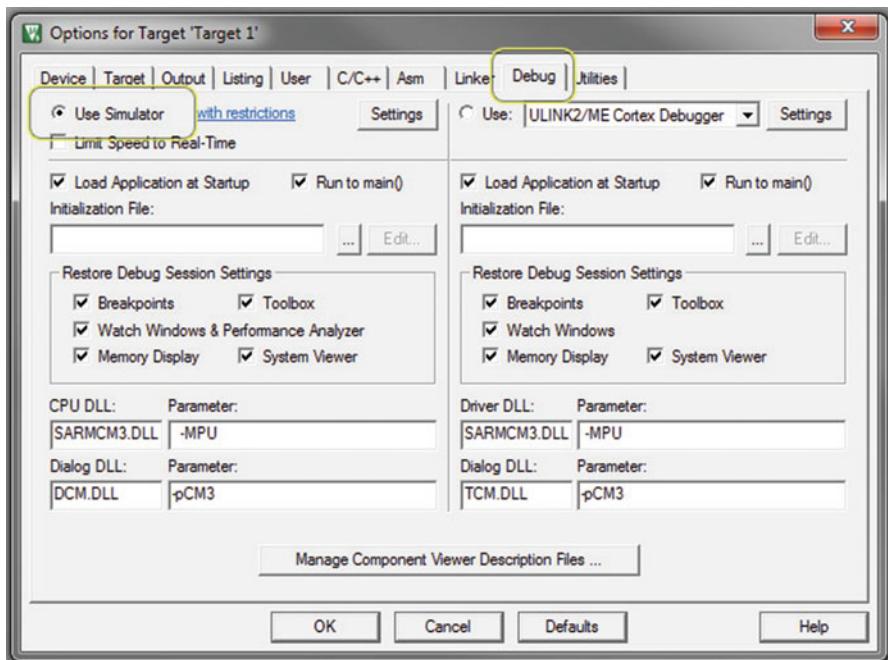


Fig. 10.5 Setting the project to use the simulator

10.2.1 Assembling a Program

Once source code is ready to be assembled, you may have the assembler attempt to translate and execute the program in the simulator. The first step is to create the assembly program by having the assembler translate your source code. There are both keyboard shortcuts and menu buttons to do so. Both of the options listed below are available on the menu bar as shown in Fig. 10.10.

- **F7** will build all target files (*e.g., All source files in Target 1*).
- **Ctrl + F7** will build the currently active file (*e.g., The file being modified*).

The **Build Output** panel on the bottom of the window will show any errors, warnings, or if the project was built successfully. A successful build should look like Fig. 10.11, whereas a failure will give error descriptions to help the programmer find where the code is incorrect.

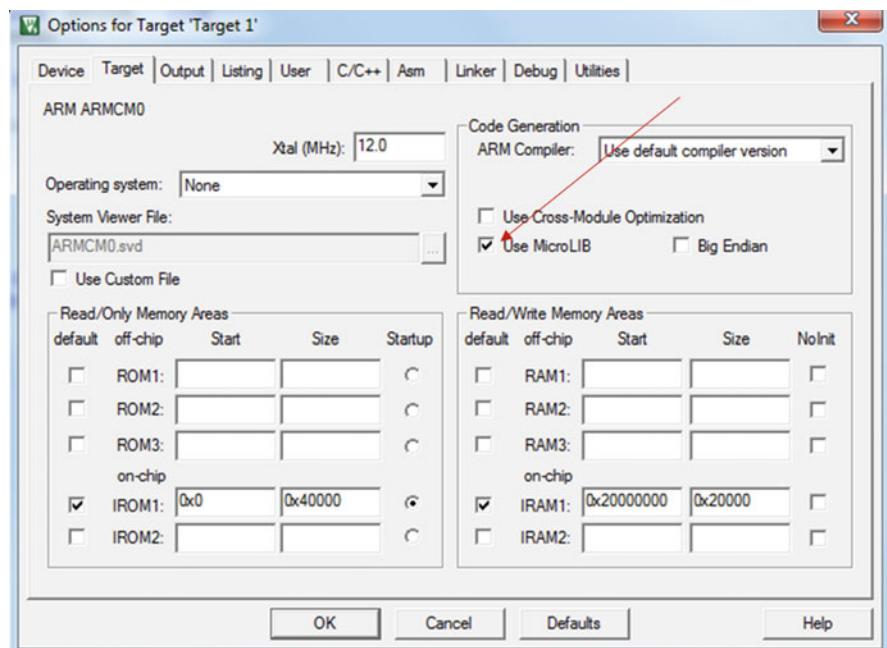


Fig. 10.6 Options for Target1 (Use Micro LIB)

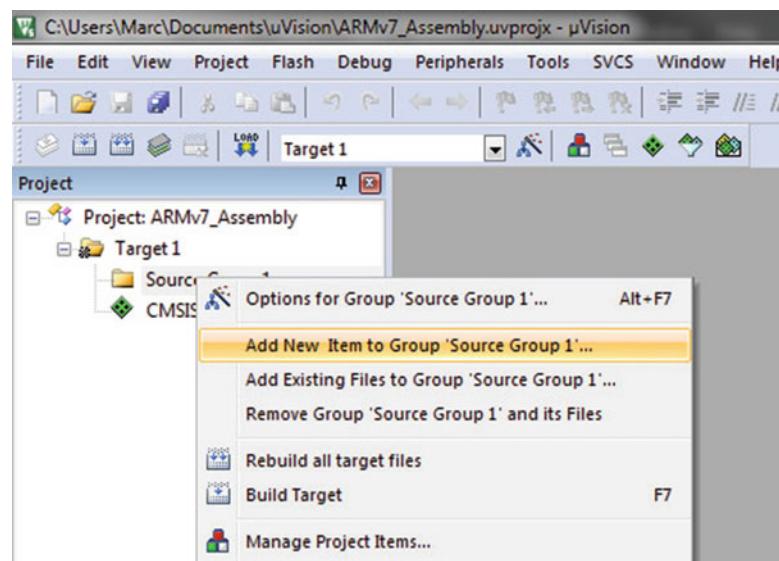


Fig. 10.7 Adding an item to the project

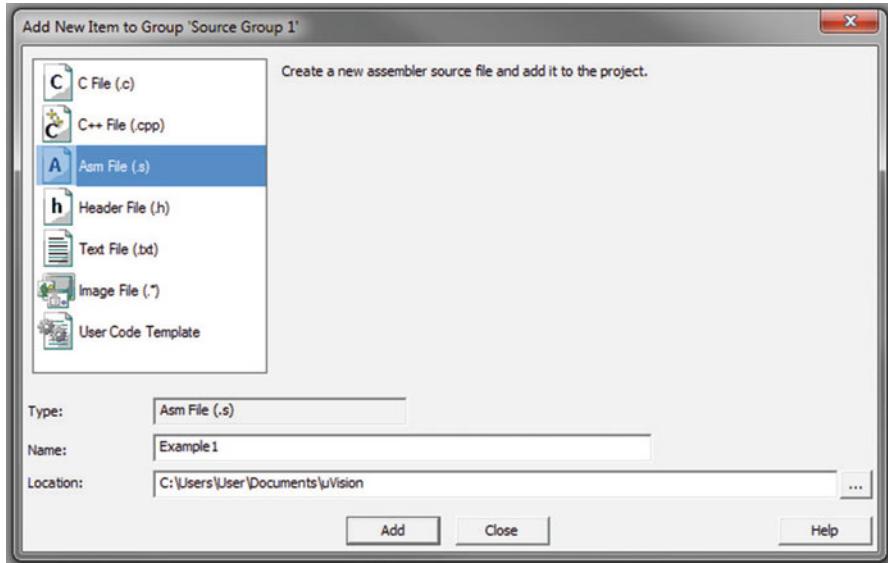


Fig. 10.8 Create the assembly source file

```
1      AREA RESET,DATA,READONLY
2      EXPORT __Vectors
3
4      __Vectors
5      DCD 0x20001000 ;stack pointer value when stack is empty
6      DCD Reset_Handler ;reset vector
7      ALIGN
8
9      AREA MYCODE, CODE, READONLY
10
11
12      ENTRY
13      EXPORT Reset_Handler
14      Reset_Handler
15
16      MOV R1, #Q
17      MOV R2, #P
18      ADD R3, R1, R2
19      P EQU 5
20      Q EQU 6
21      STOP B STOP
22
23      END; end of the program
```

Fig. 10.9 Source code for Example 10.1

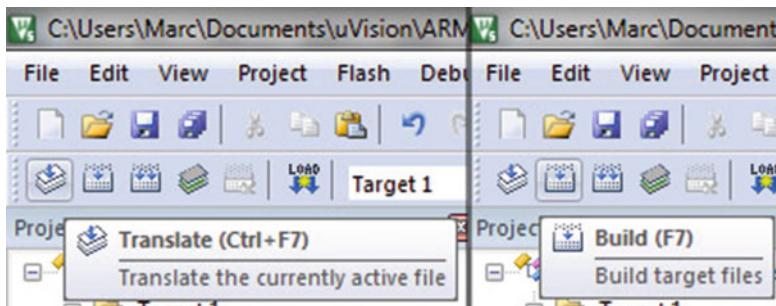


Fig. 10.10 Buttons used to assemble program

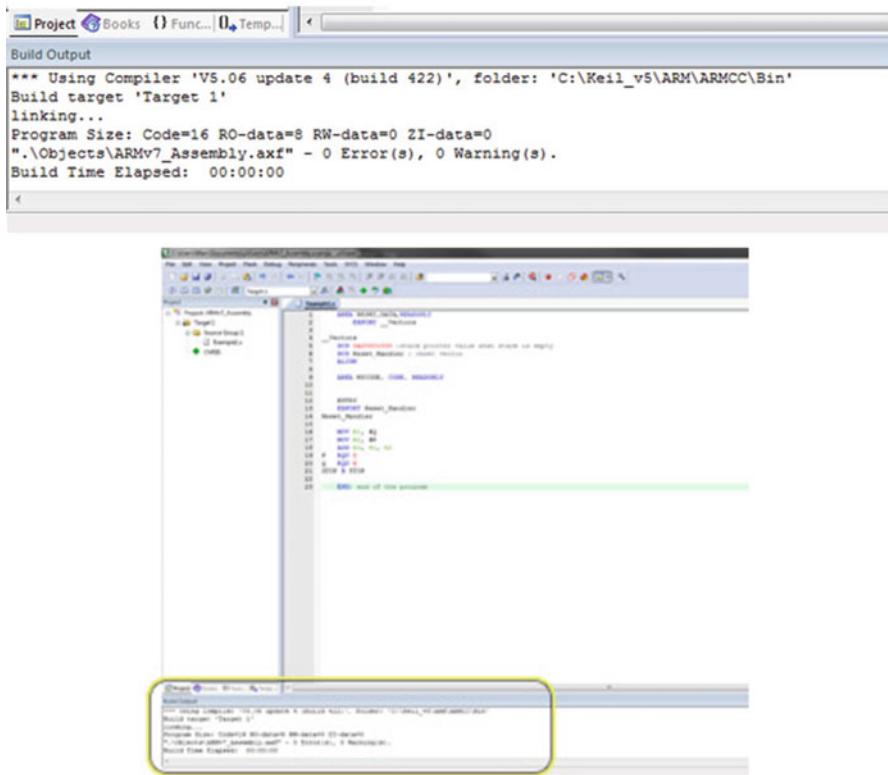


Fig. 10.11 Build Output for a successful assembly

10.2.2 Running the Debugger/Simulator

Now that you have compiled a piece of code, you will want to debug the code for testing. To start the debugger, click on **Debug → Start/Stop Debug Session** from the menu bar as shown in Fig. 10.12. (*μVision may prompt a warning that it is running in evaluation mode – if so, simply press OK.*)

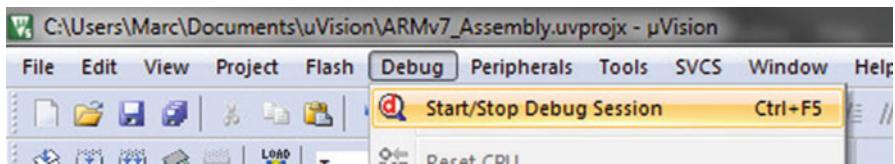


Fig. 10.12 Starting/stopping the debugger

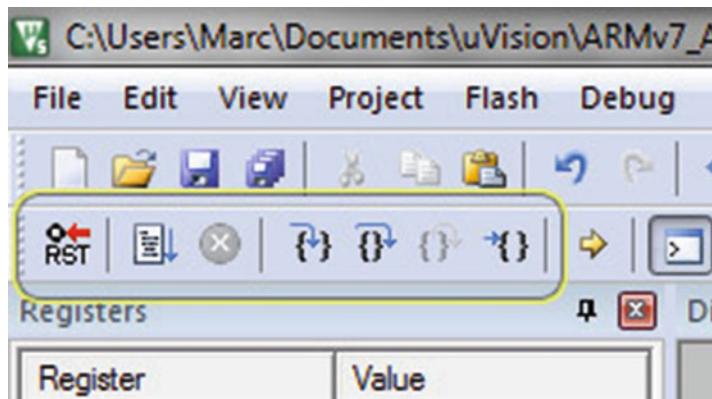


Fig. 10.13 Location of Debug Menu buttons

By default, the registers will be displayed in the *Registers* pane on the left side. If you click the “+” next to the *xPSR* line, you can view the current *flag bits* – this is the **Program Status Register (PSR)**.

The *Disassembly* pane will display some of the current data, such as the machine code instructions and notes of what line in the source code is being executed, and at what memory address.

To run the program, you may use the following buttons/keypresses (Fig. 10.13):

- **Reset** – Reset the CPU and restart the program.
- **Run (F5)** – Run the entire program until the next breakpoint (if set).
- **Stop** – Stop the currently executing code.
- **Step (F11)** – Execute the current instruction line.
- **Step Over (F10)** – Execute a single step *over* a function.
- **Step Out (Ctrl + F11)** – Finish the current function and stop.
- **Run to Cursor Line (Ctrl + F10)** – Execute the program until it reaches the current cursor line.

Example 10.2 Running the code from Fig. 10.8.

- First, retype the code exactly as shown in Fig. 10.8.
- Assemble the code by saving the file (or **Ctrl + S**) then pressing **F7 (or)** to translate the assembly language file into machine code. The *Build Output* panel should look like Fig. 10.11.
- Run the simulator/debugger by pressing **Ctrl + F5** or  under the *Debug* menu. Press OK if the *EVALUATION MODE* prompt appears.
- Press **F11** or  to “step” one line and execute an instruction, and watch the changes in each panel. While debugging, the simulator will highlight the currently running or modified data. See Fig. 10.14 for an example which should resemble your screen after the first “step.” This will execute our first bit of code, **MOV R1, #Q**, and store the value of Q (6) into register R1.
- μVision’s debugger will highlight the next instruction in the source code (**MOV R2, #P**), the modified registers (R1, R15), and show in the

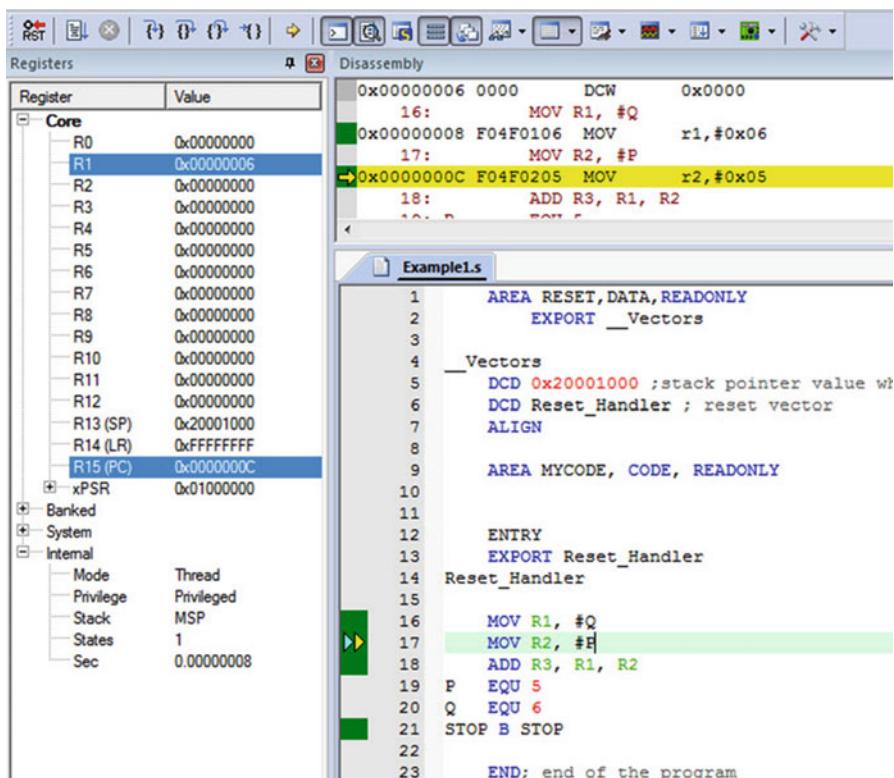


Fig. 10.14 The debugger automatically highlights the most relevant information

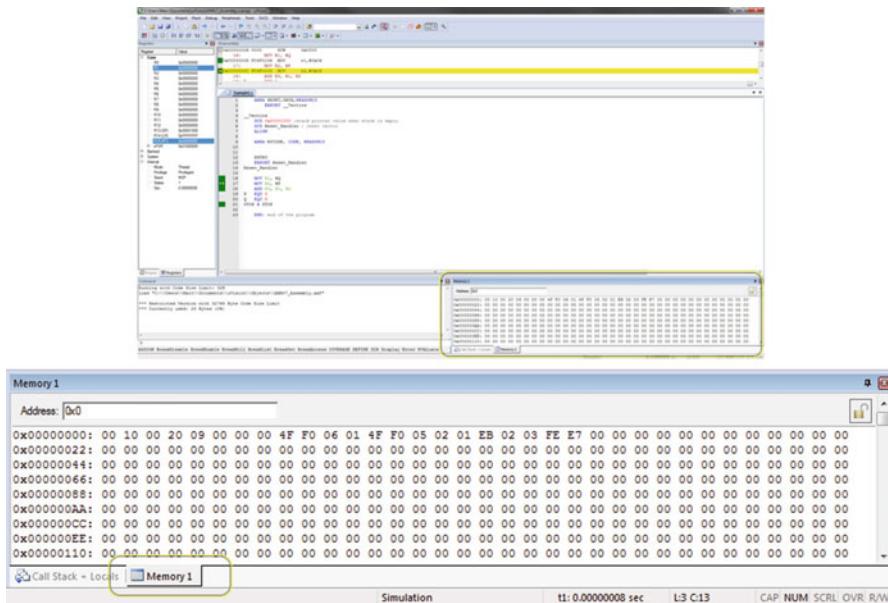


Fig. 10.15 Location of the Memory window and panel tab

Disassembly pane the machine code and memory address of the instruction with a label of the original assembly code.

- Continue to “step” through the code, pressing F11 or the step button each time until the program has executed. Watch the changes in each register at each step.

Another way to observe the functionality of your program is to view the current memory. All of the instructions translated from source code and predefined data are stored in memory. The *Disassembly* pane will display an instruction 32-bit hexadecimal address in memory next to each instruction, for example.

To view the current values in memory while debugging, open the Memory 1 panel in the bottom right corner (Fig. 10.15). Up to four windows are available, and by default *Memory 1* should be enabled. If it is not, it may be enabled under the *Menu* bar by clicking **View** → **Memory Windows** → **Memory 1**. (An enabled window will have this icon next to it: ).

To search memory, enter the hexadecimal address of the portion of memory you would like to view. Since it is a byte-addressable processor, each address holds one byte of information, and is displayed as two hexadecimal digits.

```

AREA RESET,DATA,READONLY
EXPORT __Vectors

_Vectors
    DCD 0x20001000 ;stack pointer value when stack is empty
    DCD Reset_Handler ; reset vector
    ALIGN

AREA MYCODE, CODE, READONLY

ENTRY
EXPORT Reset_Handler
Reset_Handler

YOUR PROGRAM CODE HERE

; comments like this are ignored by the assembler
; mark them with a semicolon and use them to make
; notes throughout your programs

STOP B STOP

END; end of the program

```

Fig. 10.16 Program template for ARCMC3 processor in Keil µVision v5

10.2.3 Program Template

Figure 10.16 contains a sample template of code to write a program for the ARM Cortex M3. The source code located between the *Reset_Handler* and *STOP* label is executed when the program is run. (*All labels must have no whitespace like spaces or tabs on the left – they must be the first text in the column, and the first characters on the line.*)

10.3 Programming Rules

CASE Rules Instructions, symbols, and labels can be written in uppercase or lowercase but cannot be combined (e.g., MOV or mov is correct, but MoV or moV is not).

Comments The programmer can write comments after a semicolon (;)

```
MOV R1, R2; Moving contents of R2 to R1
```

Base	Prefix	Example
Decimal (10)	-	17
Hexadecimal (16)	0x	0x11
Binary (2)	2__	2_00010001

Fig. 10.17 Numerical representation formats

Label	Data	Memory Address	Data
List	0x23	0x400	0x23
List+1	0x4A	0x401	0x4A
List+2	0x56	0x402	0x56
List+3	0xF5	0x403	0xF5

Fig. 10.18 Block diagram of memory if *List* is stored at address 0x400**Fig. 10.19** Big vs. Little Endian

	Big Endian	Little Endian
0x400	0x20	0x0F
0x401	0x00	0x00
0x402	0x00	0x00
0x403	0x0F	0x20

10.4 Data Representation and Memory

ARM processors define a word as 4 bytes and a half word as 2 bytes. Data can be represented in the form of hexadecimal, decimal, and binary numbers (Fig. 10.17).

Data and code are held in memory. Figure 10.18 shows a block diagram of memory. The *address* defines the location of the data in memory. Each location of an ARM processor's memory holds one byte. In assembly language, a label – as shown in Fig. 10.14 – represents the address in memory for the data. When the code is translated, the assembler automatically decides what address to use in place of the label and substitutes it where appropriate in the program.

Since each memory location holds one byte, the programmer must be careful when working with *words* and *half words*. Processors can function with either **Big Endian** or **Little Endian** ordering. Figure 10.19 shows the number 0x2000000F stored at 0x400 in both systems.

- The ARM Cortex M3 used for these examples is a **Little Endian processor**.

10.5 Directives

A directive is an assembler command that is executed by the assembler. Directives never produce any machine code. Directives are used to indicate the start of code or data and the end of the program. A simple directive is END, which marks the end of

a program. Some of the most useful directives used by the ARM Assembler are as follows:

- **AREA** – defines a segment of memory
- **ENTRY** – defines the start of the program
- **EQU** – used to assign a constant to a label
 - X EQU 6
 - MOV R1, #X ; R1 = #6

10.5.1 Data Directive

Data directives define the types and size of data.

- **DCB** (Define Constant Byte)
- **DCW** (Define Constant Half Word)
- **DCD** (Define Constant Word)
- **SPACE** (Reserve a zeroed block of memory)

DCB (Define Constant Byte). This directive is used for allocating one or more bytes in memory.

- list1 DCB 0xF,10,2_00010001
 - list1 : 0x0F
 - list1 + 1: 0x0A
 - list1 + 2: 0x11

DCW (Define Constant Half Word). This directive defines constant half words (16 bits, 2 bytes) and requires two memory locations per half word.

- list1 DCW 0xFF00, 0x13
 - list1 : 0x00
 - list1 + 1: 0xFF
 - list1 + 2: 0x13
 - list1 + 3: 0x00

DCD (Define Constant Word) DCD is used to define a word (32 bits, 4 bytes) and requires four memory locations per word.

- list1 DCD 0x12345678, 0xFF
 - list1 : 0x78
 - list1 + 1: 0x56
 - list1 + 2: 0x34
 - list1 + 3: 0x12
 - list1 + 4: 0xFF
 - list1 + 5: 0x00
 - list1 + 6: 0x00
 - list1 + 7: 0x00

Character Strings. A sequence of characters is called a character string. In ARM assembly, strings must be *null-terminated* in that they must end with a 0 value when they are defined.

- List1 DCB "Assembly", 0
- List2 DCB "I have \$250", 0

The assembler breaks the string into bytes and stores them each in Little Endian order.

Single Character. When storing a single character in a register or memory location, the character must be inside single quotation marks. The assembler converts the ASCII to hexadecimal.

- List DCB 'A'

SPACE. Reserves memory locations for later use.

- List SPACE 20
 - Reserves 20 bytes of memory starting at *List*.

10.6 Memory in µVision v5

Memory in µVision is simulated, and the program tries to replicate real-world conditions. Many microprocessors use a combination of ROM (read-only memory) and RAM and will have a program stored in ROM to respond to a power-up, reboot, or other situation where RAM will not be propagated or reliable.

To do this, memory is marked as none, some, or all of the following permission flags:

- *Exec* – Memory holds instructions and can be executed.
- *Read* – Memory can be read.
- *Write* – Memory can be written to.

By default, the area in memory that most directives will store their data in is marked as both *exec* and *read*, but not *write*. This mimics ROM since the instructions stored there can be read and run, but attempts to write to those locations (with STR or similar) will not work. The assembler is also unlikely to notify you of this result.

Example 10.3 What are the contents of *list1* after execution, if stored in *ROM*?

```
ADR R0, list1 ;store the address of list1 in R0
MOV R1, #2 ;store 2 in R1
LDRB R2, [R0] ;load the byte at list1 into R2
```

```

ADD R3, R1, R2 ; R3←R1+R2 (0+2 = 2)
STRB R3, [R0] ;store R3 (#2) at list1
List1 = 0x00

```

While µVision and ARM source libraries allow for programs to more easily utilize data stored in RAM rather than ROM, it goes beyond the scope of this chapter. However, knowing what addresses are marked as *read* and *write*, you can still use RAM to store data into memory.

By default, for the **ARMCM3** processor, memory locations 0x20000000 – 0x20020000 are marked as *read* and *write* RAM in µVision.

Example 10.4 What are the contents of memory at 0x200000000 after the execution of these instructions?

```

list1 DCB 0x0

ADR R0, list1 ; store the address of list1 in R0
MOV R1, #2 ;store 2 in R1

LDRB R2, [R0] ;load the byte at list1 into R2

ADD R3, R1, R2 ; R3←R1+R2 (0+2 = 2)

MOV R4, #0x20000000 ; store our initial RAM address in R4
STRB R3, [R4] ;store R3 (#2) at 0x20000000
List1 = 0x00
0x20000000 0x02

```

10.7 Summary

- The simulation of a processor which run on different processor is called cross-assembler.
- There are several development tools for the ARM processor such Keil, IAR, and GNU.
- The ARM instructions and labels can be written in uppercase or lower case but cannot combined.
- The ARM processor defines word as 4 bytes, half word as two bytes, and they can be represented in binary (2_1000011), hex (0x24), or decimal 45.
- The data directives are DCB (Define Constant Byte), DCW (Define Constant Half Word), DCD (Define Constant Word), and SPACE (reserved a zeroed block of memory).

- The DCB is used to represent one byte in memory location such as
LIST DCB 0x32
- The DCW is used to represent half word in memory location such as
LIST DCW 0x3245
- The DCD is used to represent a word in memory location such as
LIST DCD 0x87673245
- The SPACE directive is used to reserve memory location with zero values in all of the locations such as
LIST SPACE 20
- The character string must be terminated by null (0) such as
List DCB “WELCOME”, 0
- The single catheter in a memory location must be inside of single quotations such as
List DB ‘A’

Problems

1. Write a program to add elements of List1 and store in the List2.

```
List1      DCB  0x23, 0x45, 0X23, 0x11
List2      DCB  0x0
```

2. Write a program to find the largest number and store it in memory location List3.

```
List1      DCD      0x23456754
List2      DCD      0X34555555
List3      DCD      0x0
```

3. Write a program, find the sum of data in memory location LIST, and store the SUM in memory location sum using loop.

```
List      DCB    0x23, 0x24, 0x67, 0x22, 0x99
SUM      DCD    0x0
```

4. Show the content of registers R1 through R5 after execution of the following program:

```
AREA  NAME, CODE, READONLY
      EXPORT SystemInit
      EXPORT __main
```

```

    ENTRY
SystemInit

__main

    AREA Directives, CODE, READONLY
        ENTRY

        ADR R0, LIST1
        LDRB R1, [R0]
        LDRB R2, [R0, #1]!
        LDRB R3, [R0,#1]!
        LDRB R4, [R0,#1]!
        LDRB R5, [R0,#1]
List      DCB 0x23, 0x24, 0x67, 0x22, 0x99
        align
        END

```

5. Write assembly language to clear bit position 0, 3, 5, and 6 of R12; the other bits must be unchanged (using ARM instruction).

Solution:

```

LDR R1, #0x00000069
BIC R12, R12, R1

```

6. Write assembly language program for the following HLL:

```

IF R1 = R0
Then
ADD R3, R0, #5
Else
SUB R3, R0, #5

```

7. Write a program to read memory location LIST1 and LIST2 and store the sum in LIST3.

```

LIST1 DCD 0x00002345
LIST2 DCD 0X00011111
LIST3 DCD 0x0

```

8. Write a program to multiplying two numbers using subroutine.

9. Write a program to add eight numbers using Indirect addressing.

```
LIST DCB 0x5, 0x2,0x6,0x7 ,0x9,0x1,0x2,0x08
```

10. Write a program to add eight numbers using Post-index addressing.

```
LIST DCB 0x5, 0x2,0x6,0x7 ,0x9,0x1,0x2,0x08
```

11. Write a program to convert the following HLL language to ARM instructions.

```
IF R1=R2 AND R3>R4 then
```

```
R1= R1 +1  
Else  
R3=R3 +R3*8  
Endif
```

12. What are the contents of R4 after execution of the following program.

```
__main  
  
LDR R1, =0xFF00FF  
ADR R0, LIST1  
LDR R2, [R0]  
AND R4, R2, R1  
  
LIST1 DCD 0X45073487
```

13. Write a program to convert the following HLL to assembly language.

```
If R1=R2 then  
R3= R3+1  
If R1<R2 Then  
R3=R3-1  
If R1>R2 Then  
R3=R3-5
```

14. Write a subroutine to calculate value of Y where $Y = X^2 + x + 5$, assume x is represented by

```
LIST DCB 0x5
```

```
LIST1 DCB 0x5
```

15. Write a program to rotate R1 16 times; assume R1 contains 0x12345678.

16. Write a program to compare two numbers and store largest number in a memory location LIST.

```
M1      EQU    5
N1      EQU    6
LIST2  DCB    0x0
```

17. Write a program to read a word memory location LIST and clear bit position B4 through B7 of register R5; assume R5 contains 0xFFFFFFFF.

```
LDR R0, =0x000000F0
LDR R5, =0xFFFFFFFF
```

18. Write program to load Register R1, R2, R3, and R4 from memory location LIST

```
LIST DCD 0x12345AAA, 0x0000BBBB, 0x0000CCCC, 0X00000DDD
```

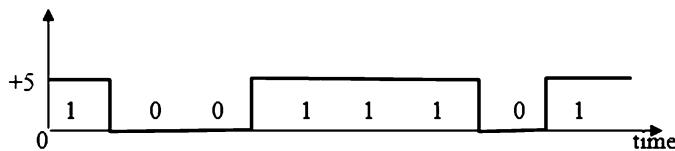
Appendix: Digital Design Laboratory Experiments Using LOGISIM

Chapter 1: Problems and Questions

2. List three computer output devices.

Monitor, speaker, printer

4. Show a digital signal.



- (a) Byte = 8 bits
(b) Half word = 16 bits
(c) Word = 32 bits
6. Convert the following decimal numbers to binary:
- (a) $35 = 1000011$
(b) $85 = 1010101$
(c) 23.25

$$\begin{aligned}
 23 &= 10111 \\
 0.25 * 2 &= 0.5 \quad a_{-1} = 0 \\
 0.5 * 2 &= 1.0 \quad a_{-2} = 1 \\
 23.25 &= 10111.01
 \end{aligned}$$

8. Convert the following binary numbers to hexadecimal:

- (a) $1110011010 = 39\ A$
- (b) $1000100111 = 227$
- (c) $101111.101 = 101111.1010 = 2F.A$

10. The following frequencies of digital signals are given; find the clock cycle of digital signal:

- (a) 10 Hz $T = 1/F = 1/10 = 0.1$ second
- (b) 200Hz $T = 1/F = 1/200 = 0.005$ second
- (c) 10000 Hz $T=1/10000 = 0.1$ milliseconds
- (d) 4 MHz $T = 1/ 4 *10^6 = 0.25 *10^{-6} = 0.25$ microseconds

12. Convert the following decimal number to base 16:

- (a) $(234)_{10} =$

Quotient	Remainder
----------	-----------

 $234/16 = \quad 14 \quad 10 = A \text{ in hex} = a0$
 $14/16 = \quad 0 \quad 14 = E \text{ in hex} = a1$
 $(a_1 \ a_0)_{16} = (EA)_{16}$
- (b) $(75)_{10} =$

Quotient	Remainder
----------	-----------

 $75/16 \quad 4 \quad 11 = (B)_{16}$
 $4/16 \quad 0 \quad 4 = (4)_{16}$
 $(c) \ (75)_{10} = (4B)_{16}$

14. Find two's complements of the following numbers:

- (a) 11111111
 Two's complement of a number = complement of the number +1
 $11111111 = 00000000 +1 = 00000001$
- (b) 10110000 = 01001111 +1 = 01010000
- (c) 10000000 = 01111111 +1 = 10000000
- (d) 00000000 = 11111111 +1 = 00000000

16. Represent $(465)_{10}$ in BCD.

$$(0100 \ 0110 \ 0101)_{BCD}$$

18. Represent $(110010000100)_{BCD}$ in decimal.

Invalid number

20. Subtract the following unsigned numbers using two's complement:

(a) $11110011 - 11000011$

Add minuend to the two's complement of subtrahend.

1. Two's complement of $11000011 = 00111100 + 1 = 00111101$

2. Add the result of step 1 to the minuend.

$$\begin{array}{r} 11110011 \\ + 00111101 \\ \hline 100110000 \end{array}$$

Adding the two 8 bits results in 9 bits, the most significant called carry; discard the carry, and the result is positive + 00110000.

(b) $10001101 - 11111000$

Two's complement of $11111000 = 00000111 + 1 = 00001000$

$$\begin{array}{r} 10001101 \\ + 00001000 \\ \hline 10010101 \end{array}$$

10010101 – adding two 8 bits results in 8 bits; take two's complement of sum, and the result is negative.

Two's complement of $10010101 = 01101010 + 1 = 01101011$

Result – 01101011

22. What is the largest 16-bit binary value that can be represented by

- (a) Unsigned number
- (b) Signed magnitude

(A) $2^{16} - 1$

(B) $+2^{15} - 1$ or $-2^{15} - 1$

24. Convert the following IEEE 745 single precision to decimal number:

(a) 1 10000100 01110000000000000000000000000000

(b) 0 01111100 11100000000000000000000000000000

(A) S = 1 mean number is negative

Exponent = $10000100 - 01111111 = 132 - 127 = 5$

Mantissa = 1.0111

Number = $-1.0111 * 2^5 = -1011100 = -92$

(B)

S=0 mean number is positive

Exponent = $01111100 - 01111111 = 124 - 127 = -3 = -11$

Mantissa = 1.111

$+ 1.111 * 2^{-3} = 0.001111 = 0.234375$

26. Convert each of the following signed magnitude number to decimal:

- (a) 11000011
- (b) 10001111

(A)

The most significant bit represents the sign

$$-1000011 = -35$$

(B)

$$-00001111 = -15$$

28. Perform the following addition:

$$(0F4A)_{16} + (420B)_{16} = (5155)_{16}$$

Chapter 2: Answers

2. If A = 11001011 and B = 10101110, what are the results of following operations value? of following operations?

- (a) A AND B
- (b) A OR B

(a) Performing bit by bit and operation

$$A = 11001011$$

$$B = 10101110$$

$$A \text{ AND } B = 10001010$$

(b) Performing bit by bit or operation

$$A = 11001011$$

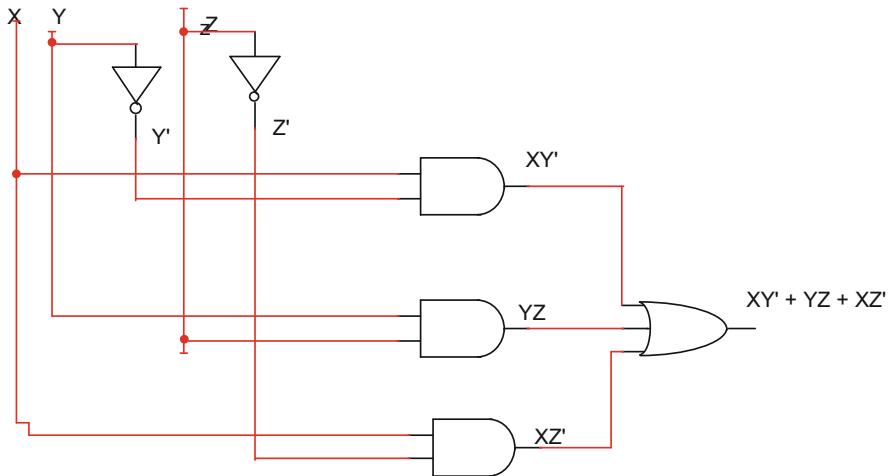
$$B = 10101110$$

$$A \text{ OR } B = 11101111$$

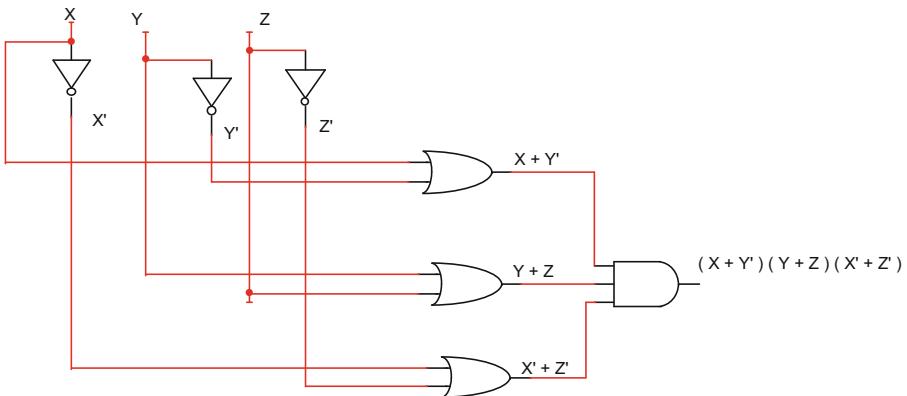
4. Draw logic circuits for the following functions:

- (a) $F(X,Y,Z) = XY' + YZ + XZ'$
- (b) $F(X,Y,Z) = (X + Y')(Y + Z)(X' + Z')$

(a)



(b)



6. Simplify following functions

$$(a) F(X, Y, Z) = XY + X'Y + XZ$$

Solution

$$F(X, Y, Z) = Y(X + X') + XZ = Y + XZ$$

$$(b) F(X, Y, Z) = (X + Y)(X' + Y + Z)$$

Solution

$$F(X, Y, Z) = (XX' + XY + XZ + X'Y + YY + YZ) \text{ where } XX' = 0 \text{ and } YY = Y$$

$$F(X, Y, Z) = (XY + XZ + X'Y + Y + YZ)$$

$$F(X, Y, Z) = Y(X + X' + 1 + Z) + XZ$$

$$F(X, Y, Z) = Y + XZ$$

$$F(X, Y, Z) = XY'Z + XYZ + Y'ZF(X, Y, Z) = XZ(Y' + Y) + Y'Z$$

$$F(X, Y, Z) = XZ + Y'Z$$

(c) $F(X, Y, Z) = XY + YX'Z$

$$F(X, Y, Z) = Y(X + X'Z) \text{ where } X + X'Z = X + Z$$

$$F(X, Y, Z) = Y(X + Z)$$

(d) $F(X, Y, Z) = X'Y + YXZ'$

$$F(X, Y, Z) = Y(X' + XZ') = Y(X' + Z')$$

(e) $F(X, Y, Z) = XY + (X + Y + Z)'X + YZ$

$$F(X, Y, Z) = XY + (X'Y'Z')X + YZ$$

$$F(X, Y, Z) = XY + YZ$$

(f) $F(X, Y, Z) = (XY)' + (X' + Y + Z')'$

(g) $F(X, Y, Z) = X' + Y' + XY'Z$

$$F(X, Y, Z) = Y'(1 + XZ) + X' = X' + Y'$$

8. If $A = 10110110$ and $B = 10110011$, then find

(a) A NAND B

(b) A NOR B

(c) A XOR B

(a) NAND each bit of A with corresponding bit of B

$$A = 10110110$$

$$B = 10110011$$

$$A \text{ NAND } B = 01001101$$

(b)

$$A = 10110110$$

$$B = 10110011$$

$$A \text{ NOR } B = 01001000$$

(c)

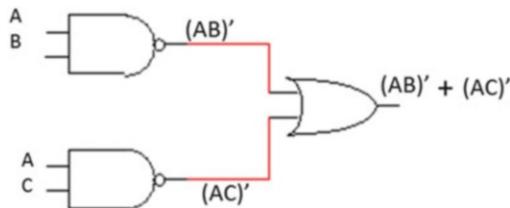
$$A = 10110110$$

$$B = 10110011$$

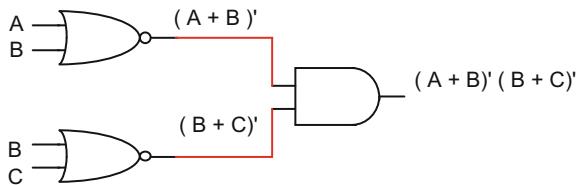
$$A \text{ XOR } B = 00000101$$

10. Show the output of the following logic circuits:

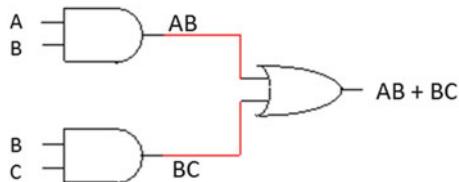
(a)



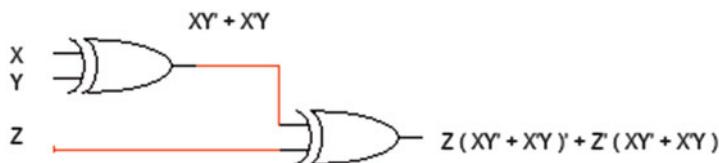
(b)



(c)



12. Find the output function of the following logic circuit:



14. Show the truth table for each of the following functions:

$$(a) F(X,Y,Z) = XY' + XZ' + YZ$$

$$(b) F(X,Y,Z) = (X + Y)(X + Z')$$

$$(c) F(X,Y,Z) = XY(Y + Z')$$

(a)

X	Y	Z	Y'	(XY)	(XY)'	(X+Y')	X (X+Y')	(XY)' + X (X+Y')
0	0	0	1	0	1	1	0	1
0	0	1	1	0	1	1	0	1
0	1	0	0	0	1	0	0	0
0	1	1	0	0	1	0	0	0
1	0	0	1	0	1	1	1	1
1	0	1	1	0	1	1	1	1
1	1	0	0	1	0	1	1	1
1	1	1	0	1	0	1	1	1

$$(b) F(X,Y,Z) = (X + Y + Z')'(X' + Y')$$

X	Y	Z	X'	Y'	Z'	(X'+Y')	(X+Y+Z')	(X+Y+Z')'	(X+Y+Z')'(X'+Y')
0	0	0	1	1	1	1	1	0	0
0	0	1	1	1	0	1	0	1	1
0	1	0	1	0	1	1	1	0	0
0	1	1	1	0	0	1	1	0	0
1	0	0	0	1	1	1	1	0	0
1	0	1	0	1	0	1	1	0	0
1	1	0	0	0	1	0	1	0	0
1	1	1	0	0	0	0	1	0	0

(c)

X	Y	Z	Y'	(X XOR Y)	(X NOR Y')	(X XOR Y)(X NOR Y')
0	0	0	1	0	0	0
0	0	1	1	0	0	0
0	1	0	0	1	1	1
0	1	1	0	1	1	1
1	0	0	1	1	0	0
1	0	1	1	1	0	0
1	1	0	0	0	0	0
1	1	1	0	0	0	0

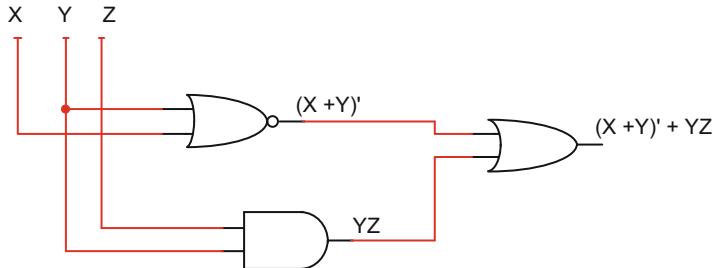
(d)

X	Y	Z	X'	Y'	$(X' + Y' + Z)$	$(X + Y)$	$(X' + Y' + Z)(X + Y)$
0	0	0	1	1	1	0	0
0	0	1	1	1	1	0	0
0	1	0	1	0	1	1	1
0	1	1	1	0	1	1	1
1	0	0	0	1	1	1	1
1	0	1	0	1	1	1	1
1	1	0	0	0	0	1	0
1	1	1	0	0	1	1	1

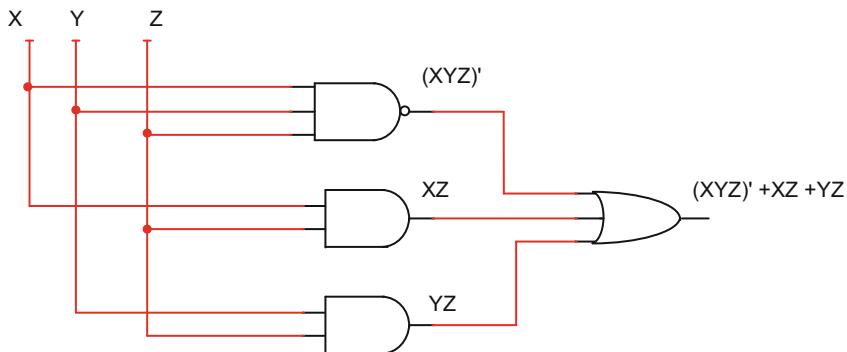
16. Draw logic circuits for the following functions.

- (a) $F(X,Y,Z) = (X + Y)' + YZ$
 (b) $F(X,Y,Z) = (XYZ)' + XZ + YZ$

(a)



(b)



Chapter 3: Solution

Problems

2. Generate truth tables for the following functions:

(A) $F(X,Y,Z) = \sum(1,3,6,7)$

X	Y	Z	F
0	0	0	0
0	0	1	1
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	0
1	1	1	1

(B) $F(X,Y,Z) = \pi(1,3,4)$

Maxterms represent zeros in the truth table.

X	Y	Z	F
0	0	0	1
0	0	1	0
0	1	0	1
0	1	1	0
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	1

(C) $F(W,X,Y,Z) = \sum(1,4,7,10,12,15)$

Minterms represent ones in the truth table.

(D) $F(W,X,Y,Z) = \pi(2,3,4,7,10,11,12,13)$

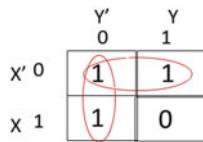
Maxterms represent zeros in the truth table.

$$F(X,Y,Z) = Y'Z' + YZ$$

4. Simplify following functions using K-map

(a)

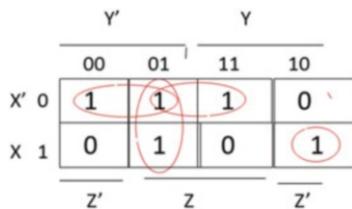
X	Y	F
0	0	1
0	1	1
1	0	1
1	1	0



$$F(X,Y) = X' + Y'$$

(b)

X	Y	Z	F
0	0	0	1
0	0	1	1
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	0



$$F(X,Y,Z) = X'Y' + X'Z + Y'Z + XYZ'$$

(C)

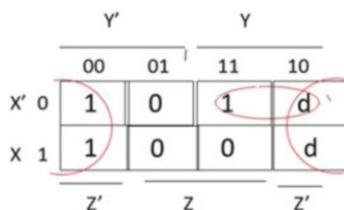
A	B	C	D	F
0	0	0	0	1
0	0	0	1	0
0	0	1	0	1
0	0	1	1	1
0	1	0	0	0
0	1	0	1	1
0	1	1	0	1
0	1	1	1	1
1	0	0	0	1
1	0	0	1	1
1	0	1	0	0
1	0	1	1	0
1	1	0	0	0
1	1	0	1	1
1	1	1	0	1
1	1	1	1	1

$$F(W, X, Y, Z) = WZ + W'X'Y' + W'XZ' \quad \text{SOP}$$

6. Simplify the following functions where D is a *don't care* function:

$$(A) F(X, Y, Z) = \sum(0, 3, 4)$$

$$D(X, Y, Z) = \sum(2, 6)$$



$$F(X, Y, Z) = Z' + X'Y$$

$$(A) F(W, X, Y, Z) = \sum(0, 1, 3, 5, 9, 11)$$

$$D(W, X, Y, Z) = \sum(2, 4, 8, 10)$$

		Y'		Y			
		00	01	11	10		
WX		m0	m1	m3	m2	D'	
W'	00	1	1	1	d	X'	
	01	d	1	0	0	X	
	11	0	0	0	0	X'	
	10	d	1	1	d	D'	
W		D		D'		D'	

$$F(W,X,Y,Z) = X' + W'Y'$$

8. Simplify the following function and draw logic circuit using

- (A) NAND gates
- (B) NOR gates

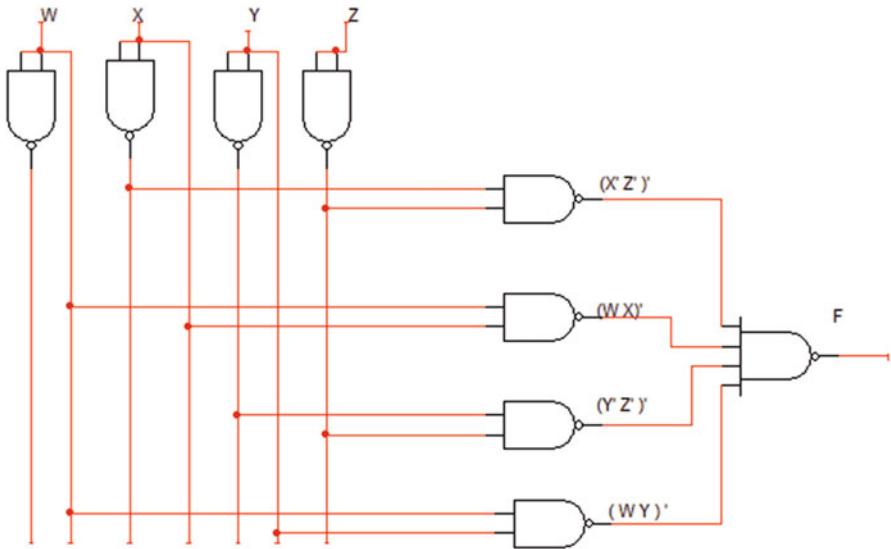
$$F(W,X,Y,Z) = W'X'Z' + XY'Z' + WX + WY + WY'X'Z'$$

		Y'		Y			
		00	01	11	10		
WX		m0	m1	m3	m2	Z'	
W'	00	1	0	0	1	X'	
	01	1	0	0	0	X	
	11	1	1	1	1	X'	
	10	1	0	1	1	Z'	
W		Z		Z'		Z'	

$$F(W,X,Y,Z) = X'Z' + WX + Y'Z' + WY$$

$$F(W,X,Y,Z) = [(X'Z' + WX + Y'Z' + WY)']'$$

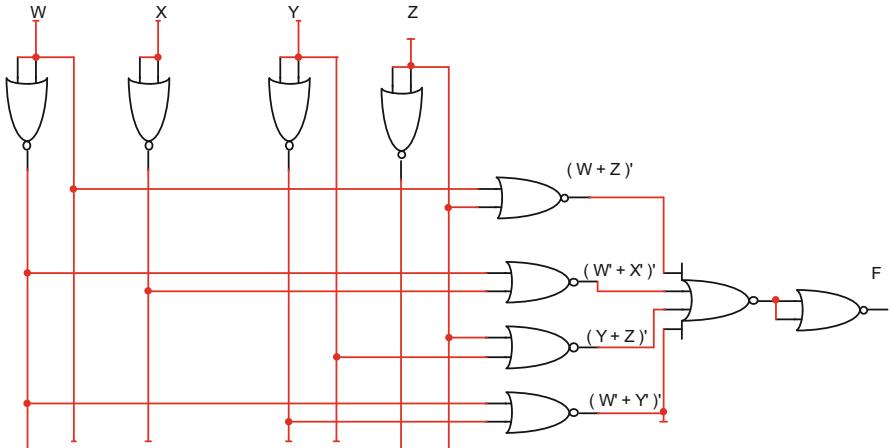
$$F(W,X,Y,Z) = [(X'Z')' (WX)' (Y'Z')' (WY)']' \quad \text{NAND form}$$



$$F(W,X,Y,Z) = [(X'Z')' (WX)' (Y'Z')' (WY')]'$$

$$F(W,X,Y,Z) = [(X + Z)(W' + X')(Y + Z)(W' + Y')]'$$

$F(W,X,Y,Z) = (X + Z)' + (W' + X')' + (Y + Z)' + (W' + Y)'$ NOR form



Chapter 4

2. Find the output of the following gates:



4. Design a logic circuit with three inputs and one output; the output generates even parity bit of the inputs; assume zero is even.

- (a) Show the truth table.
- (b) Find output function.
- (c) Draw logic circuit.

X	Y	Z	F
0	0	0	1
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	0

$$F(X,Y,Z) = m_0 + m_3 + m_5 + m_6$$

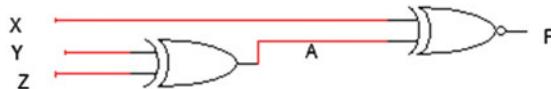
		Y'		Y			
		00	01	11	10		
X' 0	0	1	0	1	0		
	1	0	1	0	1		
		Z'		Z		Z'	

$$F(X,Y,Z) = X'Y'Z' + X'YZ + XY'Z + XYZ' = X'(Y'Z' + YZ) + X(Y'Z + YZ')$$

If $Y'Z + YZ' = A$ then $Y'Z' + YZ = A'$

Therefor function F can be written as

$$F(X,Y,Z) = X'A' + XA = X \text{ XNOR } A$$

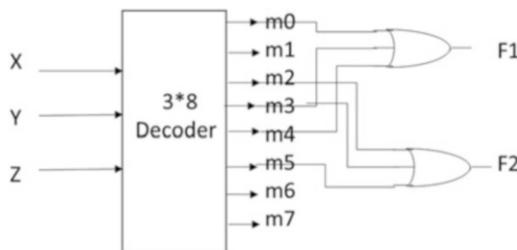


6. Implement the following functions using only one decoder and external gates:

$$F_1(X, Y, Z) = \sum(0, 3, 4)$$

$$F_2(X, Y, Z) = \sum(2, 3, 5)$$

The function requires a 3*8 decoder.



8. The following multiplexer is given; complete its table.

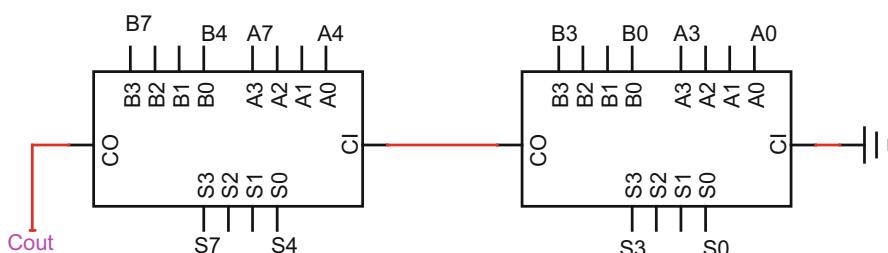
A	B	C		F
0	0	0		0
0	1	1		1
0	1	0		0
1	1	1		1
1	0	0		1
1	0	1		0
1	1	0		1
0	0	1		0

3*8*1 MUX

Inputs: 0, 1, 2, 3, 4, 5, 6, 7

Control: A, B, C

10. Design an 8-bit binary adder using 4-bit binary adders.

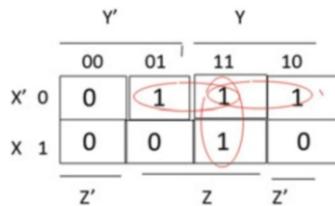


12. Design a combination logic with three inputs and three outputs, if input 0, 1, 2, or 3 then output 3 more than input, if input 4, 5, 6, or 7 then output 3 less than input.

X	Y	Z	A	B	C
0	0	0	0	1	1
0	0	1	1	0	0
0	1	0	1	0	1
0	1	1	1	1	0
1	0	0	0	0	1
1	0	1	0	1	0
1	1	0	0	1	1
1	1	1	1	0	0

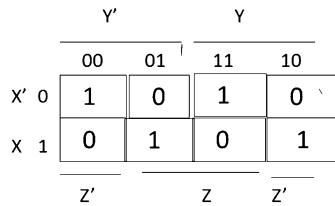
Making K-map for A, B, and C

K-map for A



$$A(X, Y, Z) = X'Z + X'Y + YZ$$

K-map for B



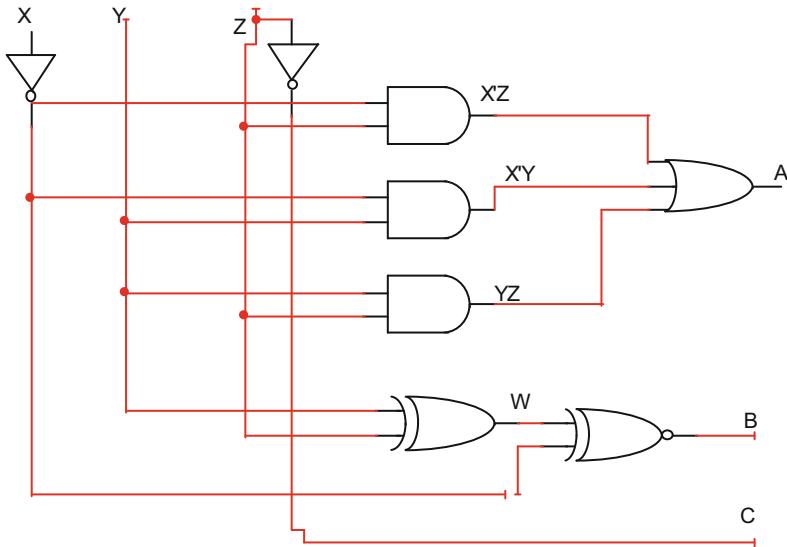
$$B(X, Y, Z) = X'Y'Z' + X'YZ + XY'Z + XYZ' = X'(Y'Z' + YZ) + X(Y'Z + YZ')$$

If $Y'Z + YZ' = W$ then

$$B(X, Y, Z) = X'W' + XW = X \text{ XNOR } W \text{ and } W = Y \text{ XOR } Z$$

Function for C – by looking at the truth table, the column for C is complement of Z, then

$$C = Z'$$



14. Design a combinational circuit with four inputs and one output; the input to the combination circuit is BCD, and the output generates even parity for the input.

W	X	Y	Z	F
0	0	0	0	0
0	0	0	1	1
0	0	1	0	1
0	0	1	1	0
0	1	0	0	1
0	1	0	1	0
0	1	1	0	0
0	1	1	1	1
1	0	0	0	1
1	0	0	1	0
1	0	1	0	d
1	0	1	1	d
1	1	0	0	d
1	1	1	0	d
1	1	1	1	d

		Y'				Y	
		00	01	11	10		
WX		m ₀ 0	m ₁ 1	m ₃ 0	m ₂ 1		
W'	00						x'
	01	m ₄ 1	m ₅ 0	m ₇ 1	m ₆ 0		x
W	11	m ₁₂ d	m ₁₃ d	m ₁₅ d	m ₁₄ d		x'
	10	m ₈ 1	m ₉ 0	m ₁₁ d	m ₁₀ d		
		Z'	Z		Z'		

$$F(W,X,Y,Z) = W'X'Y'Z + XY'Z' + WY'Z' + XYZ + X'YZ'$$

16. Design a 4-bit ALU to perform the following functions:

$$A+B, A-B, A+1, A', B', A \text{ OR } B, A \text{ XOR } B, A \text{ AND } B$$

Solution

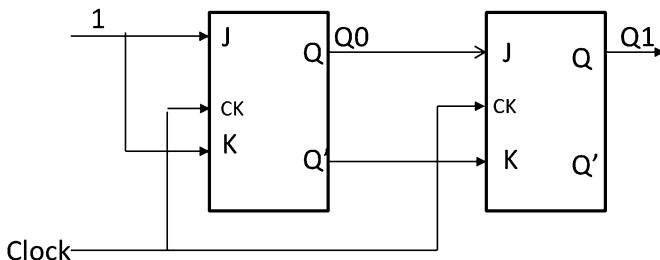
This is 4-bit ALU; therefore, it requires four multiplexers. This ALU has eight functions; therefore, each multiplexer is 8*1.

Chapter 5: Problems

2. Complete the following table for JK flip-flop:

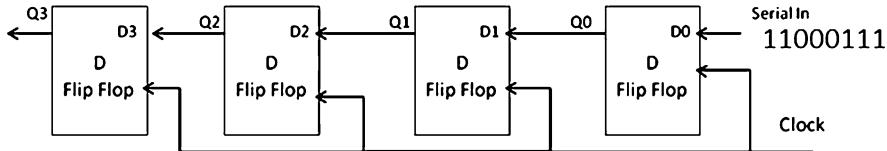
J	K	Q(t) present output	Q(t+1) next output
0	0	0	0
0	0	1	1
0	1	0	0
0	1	1	0
1	0	0	1
1	0	1	1
1	1	0	1
1	1	1	0

4. The following figure shows a sequential logic; complete the following table; assume initial value of Q1 = 0 and Q2 = 0. Use logicism to verify your answer.



Clock	Q0	Q1
Initial value	0	0
Clock #1	1	0
Clock #2	0	1
Clock #3	1	1

6. The following shift register is given; find the output after five clock pulses.

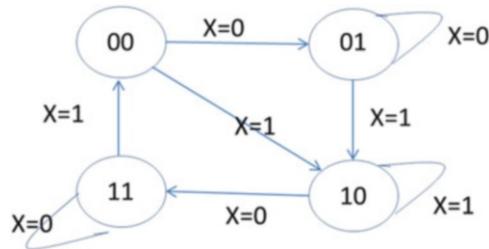


Q3	Q2	Q1	Q0	Clock
0	0	0	0	
0	0	0	1	#1
0	0	1	1	#2
0	1	1	0	#3
1	1	0	0	#4
1	0	0	0	#5

8. Complete the following excitation table for JK flip-flop:

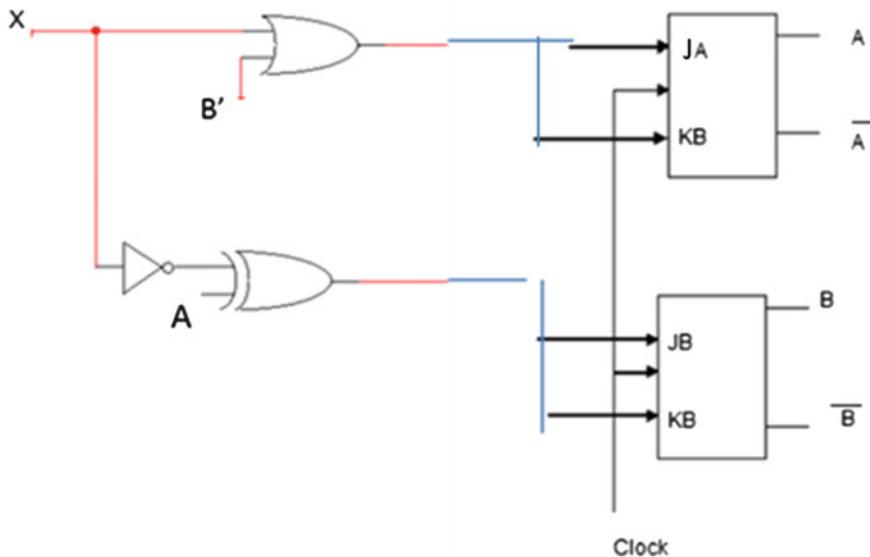
Q(t)	Q(t+1)	J	K
0	0	0	d
0	1	1	d
1	0	d	1
1	1	d	0

10. Find the state table for the following state diagram:



Present state		Next state		
		X=0	X=1	AB
A	B	A	B	AB
0	0	0	1	10
0	1	0	1	10
1	0	1	1	10
1	1	1	1	00

12. Show state table and state diagram for the following circuit:



Present state		Next state			
		X=0		X=1	
A	B	A	B	A	B
0	0	1	1	1	0
0	1	0	1	1	1
1	0	0	0	0	1
1	1	1	1	0	0

Chapter 6

Review Questions

- **Multiple choice questions**

The function of the _____ is to perform arithmetic operations.

- (a) Bus
- (b) Serial port
- (c) ALU
- (d) Control unit

Answer: C

2. When you compare the functions of a CPU and a microprocessor, _____

- (a) They are the same.
- (b) They are not the same.
- (c) The CPU is faster than microprocessor.
- (d) The microprocessor is faster than CPU.

Answer: A

4. The CISC processor control unit is _____.

- (a) Hardware
- (b) Microcode
- (c) a and b
- (d) None of the above

Answer: A

6. Which of the following buses are 32-bit?

- (a) ISA
- (b) PCI and EISA
- (c) EISA and ISA
- (d) MCA and ISA

Answer: A

Short-Answer Questions

2. Explain the functions of a CPU.

Answer: The CPU is the “brain” of the computer and is responsible for accepting data from input devices, processing the data into information, and transferring the information to memory and output devices.

4. What is the function of a control unit?

Answer: The function of the control unit is to control input/output devices, generate control signals to other components of the computer such as read and write signals, and perform instruction execution.

6. How many bits in a half word? 16

8. Distinguish between a CPU and a microprocessor.

Answer: If the control unit registers and ALU are packaged into one integrated circuit, it is a microprocessor; if they are not packaged in the same unit, it is a CPU.

10. Explain the function of DMA.

Answer: DMA (direct memory access) allows the transfer of blocks of data from memory to an I/O device or vice versa. This is done directly without using the CPU.

12. What is the application of a serial port?

Answer: USB which has many applications is a type of serial port.

14. What is the maximum memory for a CPU with 16 address lines and 8 data lines?

Answer: A CPU with 16 address lines and 8 data lines can have a maximum memory of 524,288 bits ($2^{16} * 8$).

16. List characteristics of RISC processor.

Answer: The characteristics of a RISC processor are the following: it requires a new instructions, all instructions are of the same length, most instructions are executed in one machine clock cycle, control unit is hardwired, and it has few address modes and a large number of registers.

18. What is the advantage of multicore processor versus single core?

Answer: A multicore processor can execute multiple instructions simultaneously which increases performance over a single core processor.

20. Explain fetch instruction.

Answer: The fetch instruction moves an instruction from the memory into the CPU.

22. Calculate the execution time for problem 21 using non-pipeline processor.

Answer: 100 ms

24. List types of disk controller.

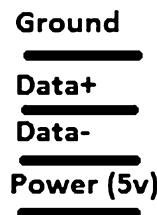
Answer: There are two types of disk controllers being integrated disk electronics (IDE) and small computer system interface (SCSI).

26. List two serial buses.

Answer: USB and FireWire.

28. Show pin connection of a USB port.

Answer:



30. What is the application of FireWire?

Answer:

FireWire is a high-speed serial bus used for digital devices such as digital video or camcorders.

Chapter 7: Questions and Problems

2. What does RAM stand for?

Answer: RAM stands for random-access memory.

4. Which of the following memory types are used for main memory?

- (a) ROM and SDRAM
- (b) SRAM and DRAM
- (c) SDRAM and DRAM
- (d) DRAM and EPROM

Answer: C

6. What does ROM stand for?

Answer: Read-only memory

8. What is the difference between EEPROM and EPROM?

Answer: EPROM requires the use of an ultraviolet light to be erased, while EEPROM can be erased by applying a specific voltage to one of its pins.

10. What is the primary application of SRAM?

Answer: The primary application of SRAM is used as cache for the CPU.

12. Define the following terms:

- (a) Track
- (b) Sector
- (c) Cluster

Answer:

- (A) Tracks are the division of platters into circular paths.
- (B) Sectors are each of the tracks further broken down into smaller pieces.
- (C) A cluster is a grouping of sectors.

14. What is the function of File Allocation Table (FAT)?

Answer:

FAT defines organization of information stored on a hard disk, FAT16 and FAT32 were used on earlier Windows applications.

16. What are the types of cache?

Answer: Data cache (D-cache) and Instruction cache (I-cache).

18. What is virtual memory?

Answer: Virtual memory is either a hard disk drive (HDD) or solid state drive (SSD) that is used to store application data and instructions from the main memory that are not currently needed by the CPU.

20. Physical address determines the size of

- (a) Virtual memory
- (b) Physical memory
- (c) Cache memory

Answer: B

22. What is hit ratio?

Answer:

Hit ratio is the number of hits/number of misses number of hits.

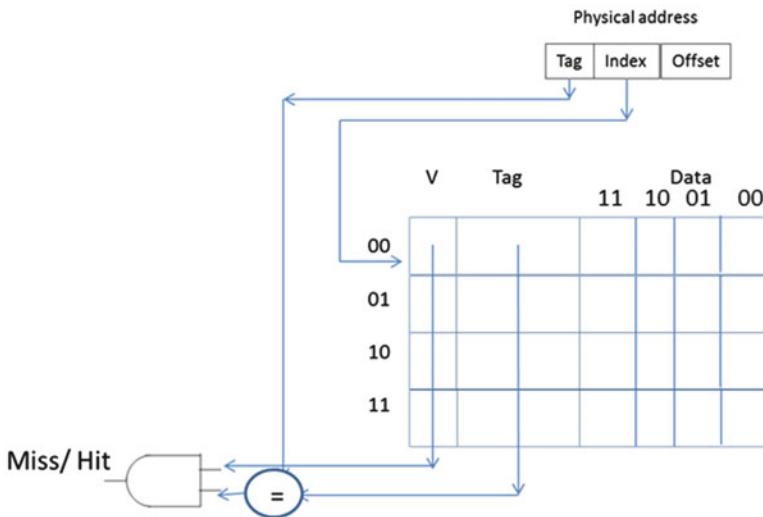
24. Explain spatial locality.

Answer:

The idea that when a memory location is accessed, it is very likely that nearby memory locations will also need to be accessed.

26. Show a format of address seen by the cache for direct mapping.

Answer:



28. What is the function of a page number in a virtual address?

Answer: The page number is used as part of a virtual address to identify pages.

30. What is the function of the page table?

Answer:

The page table is used to keep track of the page number of each page and the corresponding block of data. The page table also keeps track of whether each page is in the main memory or virtual memory.

32. What is the advantage of set associative versus direct mapping of caches?

Answer: Set associative mapping will have less misses than direct mapping.

34. _____ is the fastest type of memory.

- (a) Cache memory
- (b) Main memory
- (c) Secondary memory
- (d) Hard disk

Answer: A

Problems

2. The following memory and cache memory are given. CPU generates addresses 0x1, 0x2, 0x1, 0x8, 0x9, 0x1C, 0x1D, 0x3, and 0x4.

- (a) A. Show the contents of the cache using two-way set associative mapping; assume a LRU replacement policy.
- (b) What is the hit rate?

Address	Content	Address	Content
00000	5	10000	5
00001	3	10001	0
00010	11	10010	1
00011	6	10011	11
00100	7	10100	15
00101	8	10101	09
00110	9	10110	12
00111	12	10111	23
01000	0	11000	65
01001	0	11001	21
01010	8	11010	8
01011	7	11011	7
01100	9	11100	9
01101	0	11101	0
01110	2	11110	2
01111	5	11111	5

Initial value for V-bit and LUR

Set address	V	Tag	B1	B0	LRU	v	Tag	B1	B0	LRU
00	0				0	0				0
01	0				0	0				0
10	0				0	0				0
11	0				0	0				0

Format of address seen by cache

2 bits				2 bits				1 bit			
Tag				Set address				Byte offset			
Set address	V	Tag	B1	B0	LRU	V	Tag	B1	B0	LRU	
00	0->1	00	0	5	0->-1>-0	0->1	01	0	5	0->1	
01	0->1	00	11	3	0->1	0->1				0	
10	0->1	11	0	9	0->-1>-0	0->1	00	7	6	0->1	
11	0			0		0				0	

4. A computer has 32 Kbytes of virtual memory and 8 Kbytes of main memory with a page size of 512 bytes.

- (a) How many bits are in the virtual address?
- (b) How many pages are in the virtual memory?
- (c) How many bits are required for the physical address?
- (d) How many frames or blocks are in the main memory?
 - (a) 15 virtual address
 - (b) $2^{15} / 2^9 = 2^6 = 64$ pages
 - (c) $2^{13} = 8k$ physical address is 13 bits

6. A computer has 20 bits of virtual memory and each page is 2KB.

- (a) What is the size of virtual memory?
- (b) How many pages are in virtual memory?

Answer:

- (a) $2^{20} = 1\text{MB}$
- (b) $2^{20} / 2^{11} = 2^9$ pages

8. CPU of Fig. 7.24 generates addresses 0x00 and 0x0b; assume Page0 map into block1 and page 2 map in block 0; show the contents of page table

Address 0X00

Page#	Offset
000	00

Page number is the address to the page table

Address 0X0b

Page table		
	Valid bit	Frame number (2 bits)
000	0 1	01
001	0	
010	0 1	00
011	0	
100	0	
101	0	
110	0	
111	0	
	0	

Page #	offset
010	11

010 is the address to page table.

Chapter 8

2. List types of instructions based on number of operands:

Instructions with no operand such as HLT

Instruction with two operands such as MOV R1, R2

Instruction with three operands such as ADD R1, R2, R3

4. Which register of ARM processor is used for Stack Pointer (SP)?

R13

Problems

6. What are the contents of R1? Assume R2 = 0x00001234.

(a) MOV R1, R2, LSL #4

R1 = 0x00012340

(b) MOV R1, R2, LSR #4

R1 = 0x00000123

8. Convert the following HLL language to ARM instructions.

```
IF R1>R2 AND R3>R4 then
```

```
R1= R1 +1
```

```
Else
```

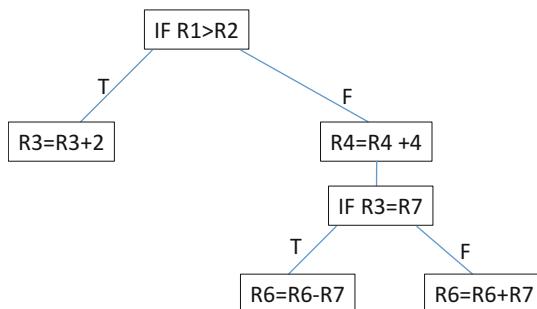
```
R3=R3 +R3*8
```

```
Endif
```

Solution

```
CMP R1, R2
CMPGT R3, R4
ADDGT R1,R1, #& 1
ADDLE R3, R3, R5 LSL #3
```

6. Convert the following flowchart to ARM assembly language.



Solution

```
CMP R1, R2
ADDGT F3, R3, #&2
ADDLE R4, R4, #&5
CMPLE R3, R7
SUBEQ R6,R6, R7
ADDNE R6,R6, R7
```

8. Write a program to convert the following HLL to ARM assembly:

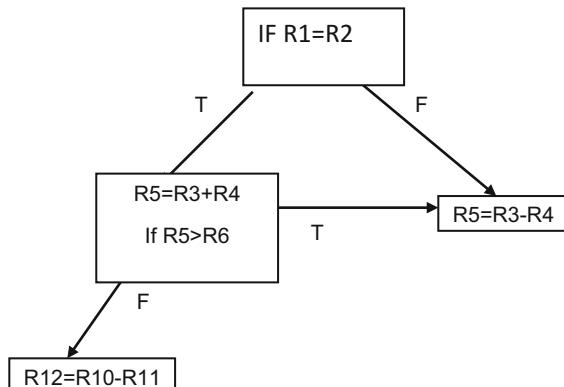
```
a= 10;
b=45;
while (a! =b) {
if (a < b)
a = a +5;
else
b= b+5;
}
```

SOLUTION:

Solution

```
MOV R1, #10
MOV R2,45
Loop:
CMP R1, R2
BEQ Halt
ADDLT R1, R1,#5
ADDGT R2, R2, #5
B loop
Halt
```

10. Convert the following flow chart to ARM assembly:



```

CMP R1, R2
SUBNE R5, R3, R4
BNE Halt
ADDEQ R5, R3 R4
CMPEQ R5, R6
SUBLTE R12, R10, R11
SUBGT R5, R3, R4
Halt

```

Chapter 9

Problem

Trace the following instructions; assume list start at memory location 0x0000018, and using ARM Big Endian.

ADR R0, LIST ; Load R0 with address of memory location List
MOV R10, #0x2

- (a) LDR R1, [R0]
- (b) LDR R2, [R0, #4]!
- (c) LDRB R3, [R0], #1
- (d) LDRB R4, [R0 , R10]!
- (e) LDRSB R5, [R0], #1
- (f) LDRSH R6, [R0]

LIST DCB 0x34, 0xF5, 0x32, 0xE5, 0x01, 0x02, 0x8, 0xFE

Solution

ADR R0, LIST ; Load R0 with address of memory location List
MOV R10, #0x2

a. LDR R1, [R0]	;R0=0x18	R1=0x34F532E5
b. LDR R2, [R0, #4]!	;R0= 0x1C	R2 =0x010208FE
c. LDRB R3, [R0] , #1	;R0= 0x19	R3=0x34
d. LDRB R4, [R0 , R10]!	;R0= 0x1A	R4=0X32
e. LDRSB R5, [R0], #1	;R0= 0x19	R5=0x34
f. LDRSH R6, [R0]	;R0= 0x18	R6=0x34F5

LIST DCB 0x34, 0xF5, 0x32, 0xE5, 0x01, 0x02, 0x8, 0xFE

2. Work problem #1 part A and B using Little Endian

- (a) R1 = 0xE532F534
- (b) R2 = 0xFE080201

4. What are the contents of register Ri for the following load instructions; assume R0 holds the address of list using Little Endian.

- (a) LDR R1, [R0]
- (b) LDRH R2, [R0]
- (c) LDRB R3, [R0] , #1
- (d) LDRB R4, [R0]
- (e) LDRSB R5, [R0], #1
- (f) LDRSH R6, [R0]

List DCB 0x34, 0xF5, 0x32, 0xE5, 0x01, 0x02

Solution

- (a) LDR R1, [R0] ;R1=0xE532F534
- (b) LDRH R2, [R0] ; R2=0x0000F534
- (c) LDRB R3, [R0], #1 ;R3=0x00000034
- (d) LDRB R4, [R0] ;R4= 0x000000F5
- (e) LDRSB R5, [R0], #1 ; R5=0xFFFFFFFF
- (f) LDRSH R6, [R0] ;R6=0xFFFFE532

List DCB 0x34, 0xF5, 0x32, 0xE5, 0x01, 0x02

6. What is the effective address and contains of R5 after executing the following instructions? Assume R5 contains 0x 18 and r6 contains 0X00000020.

- (A) STR R4, [R5]
- (B) STR R4, [R5, #4]
- (C) STR R4, [R5, #8]
- (D) STR R4, [R5, R6]
- (E) STR R4, [R5], #4

Solutions

- (A) STR R4, [R5] EA= 0x18
- (B) STR R4, [R5, #4] EA= 0x18 + 4= 0x1C
- (C) STR R4, [R5, #8] EA=0x18 +8=0x20
- (D) STR R4, [R5, R6] EA= 0x18 +0x20 = 0x38
- (E) STR R4, [R5], #4 EA= 0x18, R5=0x18 +4=0x1C

Chapter 10

Solutions

For all program, the following templet were used:

```

AREA RESET, DATA, READONLY
EXPORT __Vectors

__Vectors
    DCD 0x20001000 ; stack pointer value when stack is empty
    DCD Reset_Handler ; reset vector

    ALIGN

AREA MYCODE, CODE, READONLY

ENTRY
EXPORT Reset_Handler
Reset_Handler

```

Location of Your Code

```

STOP B STOP

END ;End of the program

```

2. Write a program to find the largest number and store it in memory location LIST3. Assume numbers are in location LIST1 and LIST2.

```

__main
    ADR R0, LIST1
    LDR R1, [R0]
    ADR R0, LIST2
    LDR R2, [R0]
    CMP R1, R2
    BHI RESULT ; IF R1>R2
    MOV R1, R2

RESULT
    ADR R0, LIST3
    STR R1, [R0]
LIST1    DCD 0x23456754
LIST2    DCD 0X34555555
LIST3    DCD 0x0

```

4. Write a program to add two numbers, the number represented by

```
N1      EQU    5
M1      EQU    7
```

Solution

```
MOV r6, #M1    ; Load r6 with 7
MOV r8, #N1
__main
    ADD R7, R6, R8    ; ADD R6 with R8 and store in R7

N1      EQU    5
M1      EQU    7
```

6. Write a program, add LIST1 to LIST2, and store the sum in LIST3.

```
__main
    ADR R1, LIST1    ; ADR is Pseudo Instruction
    LDR R2, [R1]
    ADR R3, LIST2
    LDR R4, [R3]
    ADD R5, R2,R4
    ADR R8, LIST3
    STR R5 , [R8]
LIST1  DCD 0x00002345
LIST2  DCD 0X00011111
LIST3  DCD 0x00000000
```

8. Write a program for multiplying two numbers.

```
__main
    LDR R1, =0x22222222
    LDR R2, =0x3
    MUL R3, R1,R2
```

10. Write a program to add eight numbers using Post-index addressing

LIST DCB 0x5, 0x2,0x6,0x7 ,0x9,0x1,0x2,0x08

Solution

```

    ADR R0, LIST
__main
    SUB R5,R5,R5
    MOV R1,#0x8
LOOP
    LDRB R2, [R0], #1
    ADD R5, R5, R2
    SUB R1, R1, #01
    CMP R1, #0x0
    BNE     LOOP
    ALIGN
LIST DCB 0x5, 0x2,0x6,0x7 ,0x9,0x1,0x2,0x08

```

10. Write a program to convert the following HLL language to ARM instructions:

IF R1=R2 AND R3>R4 then

```

R1= R1 +1
Else
R3=R3 +R3*8
Endif

```

```

    ADR R6, LIST1
    ADR R7, LIST2
    ADR R8, LIST3
    ADR R9, LIST4
        LDR R1, [R6]
        LDR R2, [R7]
        LDR R3, [R6]
        LDR R4, [R7]

        CMP R1, R2
        CMPEQ R3, R4
        ADDGT R1,R1, # 1
        ADDLE R3, R3, R3, LSL #3

    ALIGN
LIST1 DCD 0x58
LIST2 DCD 0x95

```

```
LIST3 DCD 0x24
LIST4 DCD 0x234
STOP B STOP
```

12. Write a program to convert the following HLL to assembly language:

```
If R1=R2 then
R3= R3+1
IF R1<R2 Then
R3=R3 -1
If R1>R2 Then
R3=R3 -5
```

Solution

```
MOV R1, #0x9
MOV R2, #0x6
MOV R3, #0x5
_main
CMP R1, R2
ADDEQ R3, R3, #0x1
SUBLE R3, R3, #0x1
ADDGT R3, R3, #0x3
```

14. Write a program to rotate R1 16 times; assume R1 contains 0x12345678.

```
_main
ADR R0, LIST
LDR R1, [R0]
ROR R1, R1, #16
LIST      DCD 0x12345678
```

16. Write a program to read a word memory location LIST and clear bit position B4 through B7 of register R5; assume R5 contains 0xFFFFFFFF.

```
LDR R0, =0x000000F0
LDR R5, =0xFFFFFFFF
```

Solution

```
LDR R0, =0x000000F0  
LDR R5, =0xFFFFFFFF  
_main  
BIC R4, R5, R0
```

18. Write program to load Register R1, R2, R3, and R4 from memory location LIST.

LIST DCD 0x12345AAA, 0x0000BBBB, 0x0000CCCC , 0X0000DDD

```
_main  
ADR R0, LIST  
LDM R0, {R1,R2,R3,R4}
```

LIST DCD 0x12345AAA, 0x0000BBBB, 0x0000CCCC , 0X00000DDD

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