Chapter 1: Digital Systems and Binary Numbers

- Digital age and information age
- Digital computers
  - general purposes
  - many scientific, industrial and commercial applications
- Digital systems
  - telephone switching exchanges
  - digital camera
  - electronic calculators, PDA's
  - digital TV
- Discrete information-processing systems
  - manipulate discrete elements of information

Reference : Digital Design: With an Introduction to the Verilog HDL, VHDL, and SystemVerilog, 6th Edition
M. Morris R. Mano, Michael D. Ciletti

Signal

- An information variable represented by physical quantity
- For digital systems, the variable takes on discrete values
  - Two level, or binary values are the most prevalent values
- Binary values are represented abstractly by:
  - digits 0 and 1
  - words (symbols) False (F) and True (T)
  - words (symbols) Low (L) and High (H)
  - and words On and Off.
- Binary values are represented by values or ranges of values of physical quantities

Digital System

- A digital system is an interconnection of digital modules. **To understand the operation of each digital module, it is necessary to have a basic knowledge of digital circuits and their logical function.**
- A major trend in digital design methodology is the use of a HDL to describe and simulate the functionality of a digital circuit, **it is important that students become familiar with an HDL-based design methodology.**

Binary Numbers

- Decimal number

$$\cdots a_5 a_4 a_3 a_2 a_1 . a_{-1} a_{-2} a_{-3} \cdots$$

Decimal point

a_j

Base or radix

Power

$$\cdots + 10^5 a_5 + 10^4 a_4 + 10^3 a_3 + 10^2 a_2 + 10^1 a_1 + 10^0 a_0 + 10^{-1} a_{-1} + 10^{-2} a_{-2} + 10^{-3} a_{-3} + \cdots$$

Example:

$$7,329 = 7 \times 10^3 + 3 \times 10^2 + 2 \times 10^1 + 9 \times 10^0$$

- General form of base-r system

$$a_n \cdot r^n + a_{n-1} \cdot r^{n-1} + \cdots + a_2 \cdot r^2 + a_1 \cdot r^1 + a_0 + a_{-1} \cdot r^{-1} + a_{-2} \cdot r^{-2} + \cdots + a_{-m} \cdot r^{-m}$$

Coefficient: $a_j = 0$ to $r - 1$

Binary Numbers

Example: Base-2 number

$$(11010.11)_2 = (26.75)_{10}$$

$$= 1\times 2^4 + 1\times 2^3 + 0\times 2^2 + 1\times 2^1 + 0\times 2^0 + 1\times 2^{-1} + 1\times 2^{-2}$$

Example: Base-5 number

$$(4021.2)_5$$

$$= 4\times 5^3 + 0\times 5^2 + 2\times 5^1 + 1\times 5^0 + 2\times 5^{-1} = (511.5)_{10}$$

Example: Base-8 number

$$(127.4)_8$$

$$= 1\times 8^3 + 2\times 8^2 + 1\times 8^1 + 7\times 8^0 + 4\times 8^{-1} = (87.5)_{10}$$

Example: Base-16 number

$$(\mathrm{B65F})_{16} = 11\times 16^3 + 6\times 16^2 + 5\times 16^1 + 15\times 16^0 = (46,687)_{10}$$

Binary Numbers

Example: Base-2 number

$$(110101)_2 = 32 + 16 + 4 + 1 = (53)_{10}$$

Special Powers of 2

- 2^{10} (1024) is Kilo, denoted "K"
- 2^{20} (1,048,576) is Mega, denoted "M"
- 2^{30} (1,073, 741,824)is Giga, denoted "G"

Powers of two

Table 1.1

Table 1.1
Powers of Two

n	2^n	n	2^n	n	2^n
0	1	8	256	16	65,536
1	2	9	512	17	131,072
2	4	10	1,024 (1K)	18	262,144
3	8	11	2,048	19	524,288
4	16	12	4,096 (4K)	20	1,048,576 (1M)
5	32	13	8,192	21	2,097,152
6	64	14	16,384	22	4,194,304
7	128	15	32,768	23	8,388,608

Arithmetic operation

Arithmetic operations with numbers in base *r* follow the same rules as decimal numbers.

Binary Arithmetic

- Single Bit Addition with Carry
- Multiple Bit Addition
- Single Bit Subtraction with Borrow
- Multiple Bit Subtraction
- Multiplication
- BCD Addition

Binary Arithmetic

- **Addition**

Augend:	101101
Addend:	+100111
Sum:	1010100

- **Subtraction**

Minuend:	101101
Subtrahend:	–100111
Difference:	000110

- **Multiplication**

Multiplicand	1011
Multiplier	× 101
Partial Products	1011
	0000 -
	1011 - -
Product	110111

Number-Base Conversions

Name	Radix	Digits
Binary	2	0,1
Octal	8	0,1,2,3,4,5,6,7
Decimal	10	0,1,2,3,4,5,6,7,8,9
Hexadecimal	16	0,1,2,3,4,5,6,7,8,9,A,B,C,D,E,F

- The six letters (in addition to the 10 integers) in hexadecimal represent: 10, 11, 12, 13, 14, and 15, respectively.

Number-Base Conversions

Example1.1

Convert decimal 41 to binary. The process is continued until the integer quotient becomes 0.

	Integer Quotient		Remainder	Coefficient
$41/2 =$	20	+	1/2	$a_0 = 1$
$20/2 =$	10	+	0	$a_1 = 0$
$41/2 =$	20	+	0	$a_2 = 0$
$41/2 =$	20	+	1/2	$a_3 = 1$
$41/2 =$	20	+	0	$a_4 = 0$
$41/2 =$	20	+	1/2	$a_5 = 1$

$$(41)_{10} = (a_5a_4a_3a_2a_1a_0)_2 = (101001)_2$$

Number-Base Conversions

- The arithmetic process can be manipulated more conveniently as follows:

Integer	Remainder
41	
20	1
10	0
5	0
2	1
1	0
0	1

101001 = answer

Number-Base Conversions

Example 1.2

Convert decimal 153 to octal. The required base *r* is 8.

Integer	Remainder
153	
19	1
2	3
0	2

$= (231)_8$

Example1.3

Convert $(0.6875)_{10}$ to binary.

The process is continued until the fraction becomes 0 or until the number of digits has sufficient accuracy.

Number-Base Conversions

Example1.3

	Integer		Fraction	Coefficient
$0.6875 \times 2 =$	1	+	0.3750	$a_{-1} = 1$
$0.3750 \times 2 =$	0	+	0.7500	$a_{-2} = 0$
$0.7500 \times 2 =$	1	+	0.5000	$a_{-3} = 1$
$0.5000 \times 2 =$	1	+	0.0000	$a_{-4} = 1$

$$(0.6875)_{10} = (0.a_{-1}a_{-2}a_{-3}a_{-4})_2 = (0.1011)_2$$

- To convert a decimal fraction to a number expressed in base *r*, a similar procedure is used. However, multiplication is by *r* instead of 2, and the coefficients found from the integers may range in value from 0 to *r* – 1 instead of 0 and 1.

Number-Base Conversions

Example1.4

Convert $(0.513)_{10}$ to octal.

$$0.513 \times 8 = 4.104$$
$$0.104 \times 8 = 0.832$$
$$0.832 \times 8 = 6.656$$
$$0.656 \times 8 = 5.248$$
$$0.248 \times 8 = 1.984$$
$$0.984 \times 8 = 7.872$$

$$(0.513)_{10} = (0.406517\ldots)_8$$

- **From Examples 1.1 and 1.3:** $(41.6875)_{10} = (101001.1011)_2$
- **From Examples 1.2 and 1.4:** $(153.513)_{10} = (231.406517)_8$

Octal and Hexadecimal Numbers

♣ **Numbers with different bases: Table 1.2.**

Table 1.2
Numbers with Different Bases

Decimal (base 10)	Binary (base 2)	Octal (base 8)	Hexadecimal (base 16)
00	0000	00	0
01	0001	01	1
02	0010	02	2
03	0011	03	3
04	0100	04	4
05	0101	05	5
06	0110	06	6
07	0111	07	7
08	1000	10	8
09	1001	11	9
10	1010	12	A
11	1011	13	B
12	1100	14	C
13	1101	15	D
14	1110	16	E
15	1111	17	F

Octal and Hexadecimal Numbers

- Conversion from binary to octal can be done by positioning the binary number into groups of three digits each, starting from the binary point and proceeding to the left and to the right.

$$(10\ 110\ 001\ 101\ 011 \cdot 111\ 100\ 000\ 110)_2 = (26153.7406)_8$$
$$2\quad 6\quad 1\quad 5\quad 3\qquad 7\quad 4\quad 0\quad 6$$

- Conversion from binary to hexadecimal is similar, except that the binary number is divided into groups of four digits:

$$(10\ 1100\ 0110\ 1011 \cdot 1111\ 0010)_2 = (2C6B.F2)_{16}$$
$$2\quad C\quad 6\quad B\qquad F\quad 2$$

- Conversion from octal or hexadecimal to binary is done by reversing the preceding procedure.

$$(673.124)_8 = (110\ 111\ 011 \cdot 001\ 010\ 100)_2$$
$$6\quad 7\quad 3\qquad 1\quad 2\quad 4$$

$$(306.D)_{16} = (0011\ 0000\ 0110 \cdot 1101)_2$$
$$3\quad 0\quad 6\qquad D$$

Complements of Numbers

- There are two types of complements for each base-*r* system: the radix complement and diminished radix complement.

⟹ the *r*'s complement and the second as the (*r* – 1)'s complement.

Diminished Radix Complement

Given a number N in case r having n digits, the $(r-1)$'s complement of N is defined as $(r^n - 1) - N$. For decimal numbers, $r = 10$ and $r - 1 = 9$, so the 9's complement of N is $(10^n - 1) - N$.

Example:

The 9's complement of 546700 is $999999 - 546700 = 453299$.

The 9's complement of 012398 is $999999 - 012398 = 987601$.

- For binary numbers, $r = 2$ and $r - 1 = 1$, so the 1's complement of N is $(2^n - 1) - N$.

Example:

The 1's complement of 1011000 is 0100111

The 1's complement of 0101101 is 1010010

Complements of Numbers

Radix Complement

The *r*'s complement of an *n*-digit number *N* in base r is defined as $r^n - N$ for $N \neq 0$ and as 0 for $N = 0$. Comparing with the $(r - 1)$'s complement, we note that the *r*'s complement is obtained by adding 1 to the $(r - 1)$'s complement, since $r^n - N = [(r^n - 1) - N] + 1$.

Example: Base-10

The 10's complement of 012398 is 987602
The 10's complement of 246700 is 753300

Example: Base-10

The 2's complement of 1101100 is 0010100
The 2's complement of 0110111 is 1001001

Complements of Numbers

Subtraction with Complements

The subtraction of two *n*-digit unsigned numbers $M - N$ in base r can be done as follows:

1. Add the minuend M to the r's complement of the subtrahend N. Mathematically, $M + (r^n - N) = M - N + r^n$.
2. If $M \geqq N$, the sum will produce and end carry r^n, which can be discarded; what is left is the result $M - N$.
3. If $M < N$, the sum does not produce an end carry and is equal to $r^n - (N - M)$, which is the r's complement of $(N - M)$. To obtain the answer in a familiar form, take the r's complement of the sum and place a negative sign in front.

Complements of Numbers

Example 1.5

Using 10's complement, subtract 72532 – 3250.

	$M =$	72532
10's complement of	$N =$	$+96750$
	Sum =	169282
	Discard end carry 10^5 =	-100000
	Answer =	69282

Example 1.6

Using 10's complement, subtract 3250 – 72532

	M =	03250
10's complement of	N =	$+27468$
	Sum =	30718

⇒ There is no end carry.

⇒ Therefore, the answer is – (10's complement of 30718) = – 69282.

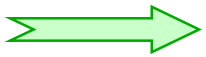
Complements of Numbers

Example 1.7

Given the two binary numbers *X* = 1010100 and *Y* = 1000011, perform the subtraction (a) X – Y and (b) *Y* – *X* by using 2's complement.

(a)		
	X =	1010100
	2's complement of Y =	+0111101
	Sum =	10010001
	Discard end carry 2^7 =	–10000000
	Answer. X – Y =	0010001

(b)		
	Y =	1000011
	2's complement of X =	+ 0101100
	Sum =	1101111



There is no end carry. Therefore, the answer is *Y* – *X* = – (2's complement of 1101111) = – 0010001.

Complements of Numbers

- Subtraction of unsigned numbers can also be done by means of the (r – 1)'s complement. Remember that the (r – 1) 's complement is one less then the r's complement.

Example 1.8

Repeat Example 1.7, but this time using 1's complement.

(a) $X - Y = 1010100 - 1000011$

$X =$	1010100
1's complement of $Y =$	± 0111100
Sum =	10010000
End-around carry =	+ 1
Answer. $X - Y =$	0010001

(b) $Y - X = 1000011 - 1010100$

$Y =$	1000011
1's complement of $X =$	+ 0101011
Sum =	1101110

There is no end carry, Therefore, the answer is $Y - X$ = – (1's complement of 1101110) = – 0010001.

Signed Binary Numbers

- To represent negative integers, we need a notation for negative values.
- It is customary to represent the sign with a bit placed in the leftmost position of the number.
- The convention is to make the sign bit 0 for positive and 1 for negative.

Example:

Signed-magnitude representation:	10001001
Signed-1's-complement representation:	11110110
Signed-2's-complement representation:	11110111

- **Table 3** lists all possible four-bit signed binary numbers in the three representations.

Signed Binary Numbers

Table 1.3
Signed Binary Numbers

Decimal	Signed-2's Complement	Signed-1's Complement	Signed Magnitude
+7	0111	0111	0111
+6	0110	0110	0110
+5	0101	0101	0101
+4	0100	0100	0100
+3	0011	0011	0011
+2	0010	0010	0010
+1	0001	0001	0001
+0	0000	0000	0000
−0	—	1111	1000
−1	1111	1110	1001
−2	1110	1101	1010
−3	1101	1100	1011
−4	1100	1011	1100
−5	1011	1010	1101
−6	1010	1001	1110
−7	1001	1000	1111
−8	1000	—	—

Signed Binary Numbers

Arithmetic Addition

The addition of two numbers in the signed-magnitude system follows the rules of ordinary arithmetic. If the signs are the same, we add the two magnitudes and give the sum the common sign. If the signs are different, we subtract the smaller magnitude from the larger and give the difference the sign if the larger magnitude.

- The addition of two signed binary numbers with negative numbers represented in signed-2's-complement form is obtained from the addition of the two numbers, including their sign bits.
- A carry out of the sign-bit position is discarded.

Example:

+ 6	00000110	− 6	11111010
+13	00001101	+13	00001101
+ 19	00010011	+ 7	00000111
+ 6	00000110	− 6	11111010
−13	11110011	−13	11110011
− 7	11111001	− 19	11101101

Binary Codes

BCD Code

Table 1.4
Binary-Coded Decimal (BCD)

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

A number with *k* decimal digits will require 4*k* bits in BCD. Decimal 396 is represented in BCD with 12bits as 0011 1001 0110, **with each group of 4 bits representing one decimal digit.** A decimal number in BCD is the same as its equivalent binary number only when the number is between 0 and 9. A BCD number greater than 10 looks different from its equivalent binary number, even though both contain 1's and 0's. Moreover, **the binary combinations 1010 through 1111 are not used and have no meaning in BCD.**

Signed Binary Numbers

Arithmetic Subtraction

♣ **In 2's-complement form:**

1. Take the 2's complement of the subtrahend (including the sign bit) and add it to the minuend (including sign bit).
2. A carry out of sign-bit position is discarded.

$$(\pm A) - (+B) = (\pm A) + (-B)$$
$$(\pm A) - (-B) = (\pm A) + (+B)$$

Example:

(– 6) – (– 13) ⟹ (11111010 – 11110011)

⟹ (11111010 + 00001101)

⟹ 00000111 (+ 7)

Binary Codes

Example:

Consider decimal 185 and its corresponding value in BCD and binary:

$$(185)_{10} = (0001\ 1000\ 0101)_{BCD} = (10111001)_2$$

BCD Addition

4	0100	4	0100	8	1000
+5	+0101	+8	+1000	+9	+1001
9	1001	12	1100	17	10001
			+0110		+0110
			10010		10111

Binary Codes

Example:

Consider the addition of 184 + 576 = 760 in BCD:

BCD	1	1		
	0001	1000	0100	184
	+0101	0111	0110	+576
Binary sum	0111	10000	1010	
Add 6		0110	0110	
BCD sum	0111	0110	0000	760

Decimal Arithmetic

0	375
+9	760
0	135

Binary Codes

Other Decimal Codes

Table 1.5
Four Different Binary Codes for the Decimal Digits

Decimal Digit	BCD 8421	2421	Excess-3	8, 4, −2, −1
0	0000	0000	0011	0000
1	0001	0001	0100	0111
2	0010	0010	0101	0110
3	0011	0011	0110	0101
4	0100	0100	0111	0100
5	0101	1011	1000	1011
6	0110	1100	1001	1010
7	0111	1101	1010	1001
8	1000	1110	1011	1000
9	1001	1111	1100	1111
	1010	0101	0000	0001
Unused	1011	0110	0001	0010
bit	1100	0111	0010	0011
combi-	1101	1000	1101	1100
nations	1110	1001	1110	1101
	1111	1010	1111	1110

Binary Codes

- Gray Code

Table 1.6
Gray Code

Gray Code	Decimal Equivalent
0000	0
0001	1
0011	2
0010	3
0110	4
0111	5
0101	6
0100	7
1100	8
1101	9
1111	10
1110	11
1010	12
1011	13
1001	14
1000	15

Binary Codes

ASCII Character Code

Table 1.7
American Standard Code for Information Interchange (ASCII)

	$b_7b_6b_5$							
$b_4b_3b_2b_1$	000	001	010	011	100	101	110	111
0000	NUL	DLE	SP	0	@	P	`	p
0001	SOH	DC1	!	1	A	Q	a	q
0010	STX	DC2	“	2	B	R	b	r
0011	ETX	DC3	#	3	C	S	c	s
0100	EOT	DC4	$	4	D	T	d	t
0101	ENQ	NAK	%	5	E	U	e	u
0110	ACK	SYN	&	6	F	V	f	v
0111	BEL	ETB	‘	7	G	W	g	w
1000	BS	CAN	(	8	H	X	h	x
1001	HT	EM	)	9	I	Y	i	y
1010	LF	SUB	*	:	J	Z	j	z
1011	VT	ESC	+	;	K	[	k	{
1100	FF	FS	,	<	L	\	l	|
1101	CR	GS	–	=	M	]	m	}
1110	SO	RS	.	>	N	∧	n	~
1111	SI	US	/	?	O	–	o	DEL

Binary Codes

ASCII Character Code

Control Characters

NUL	Null	DLE	Data-link escape
SOH	Start of heading	DC1	Device control 1
STX	Start of text	DC2	Device control 2
ETX	End of text	DC3	Device control 3
EOT	End of transmission	DC4	Device control 4
ENQ	Enquiry	NAK	Negative acknowledge
ACK	Acknowledge	SYN	Synchronous idle
BEL	Bell	ETB	End-of-transmission block
BS	Backspace	CAN	Cancel
HT	Horizontal tab	EM	End of medium
LF	Line feed	SUB	Substitute
VT	Vertical tab	ESC	Escape
FF	Form feed	FS	File separator
CR	Carriage return	GS	Group separator
SO	Shift out	RS	Record separator
SI	Shift in	US	Unit separator
SP	Space	DEL	Delete

Binary Codes

ASCII Character Code

Control characters

NUL	Null	DLE	Data-link escape
SOH	Start of heading	DC1	Device control 1
STX	Start of text	DC2	Device control 2
ETX	End of text	DC3	Device control 3
EOT	End of transmission	DC4	Device control 4
ENQ	Enquiry	NAK	Negative acknowledge
ACK	Acknowledge	SYN	Synchronous idle
BEL	Bell	ETB	End-of-transmission block
BS	Backspace	CAN	Cancel
HT	Horizontal tab	EM	End of medium
LF	Line feed	SUB	Substitute
VT	Vertical tab	ESC	Escape
FF	Form feed	FS	File separator
CR	Carriage return	GS	Group separator
SO	Shift out	RS	Record separator
SI	Shift in	US	Unit separator
SP	Space	DEL	Delete

ASCII Character Codes

- American Standard Code for Information Interchange **(Refer to Table 1.7)**
- A popular code used to represent information sent as character-based data.
- It uses 7-bits to represent:
  - 94 Graphic printing characters.
  - 34 Non-printing characters
- Some non-printing characters are used for text format (e.g. BS = Backspace, CR = carriage return)
- Other non-printing characters are used for record marking and flow control (e.g. STX and ETX start and end text areas).

ASCII Properties

ASCII has some interesting properties:

- **Digits 0 to 9 span Hexadecimal values 30_{16} to 39_{16} .**
- **Upper case A - Z span 41_{16} to $5A_{16}$.**
- **Lower case a - z span 61_{16} to $7A_{16}$.**
  - **Lower to upper case translation (and vice versa) occurs by flipping bit 6.**
- **Delete (DEL) is all bits set, a carryover from when punched paper tape was used to store messages.**
- **Punching all holes in a row erased a mistake!**

Binary Codes

Error-Detecting Code

- To detect errors in data communication and processing, an eighth bit is sometimes added to the ASCII character to indicate its parity.
- A ***parity*** bit is an extra bit included with a message to make the total number of 1's either even or odd.

Example:

Consider the following two characters and their even and odd parity:

	With even parity	With odd parity
ASCII A = 1000001	01000001	11000001
ASCII T = 1010100	11010100	01010100

Binary Codes

Error-Detecting Code

- **Redundancy (e.g. extra information), in the form of extra bits, can be incorporated into binary code words to detect and correct errors.**
- **A simple form of redundancy is parity, an extra bit appended onto the code word to make the number of 1's odd or even. Parity can detect all single-bit errors and some multiple-bit errors.**
- **A code word has even parity if the number of 1's in the code word is even.**
- **A code word has odd parity if the number of 1's in the code word is odd.**

Binary Storage and Registers

Registers

- A *binary cell* is a device that possesses two stable states and is capable of storing one of the two states.
- A *register* is a group of binary cells. A register with *n* cells can store any discrete quantity of information that contains *n* bits.

n cells ⇒ **2^n possible states**

  - A binary cell
    - two stable state
    - store one bit of information
    - examples: flip-flop circuits, ferrite cores, capacitor
  - A register
    - a group of binary cells
    - AX in x86 CPU

Register Transfer

- a transfer of the information stored in one register to another
- one of the major operations in digital system
- an example

Transfer of information

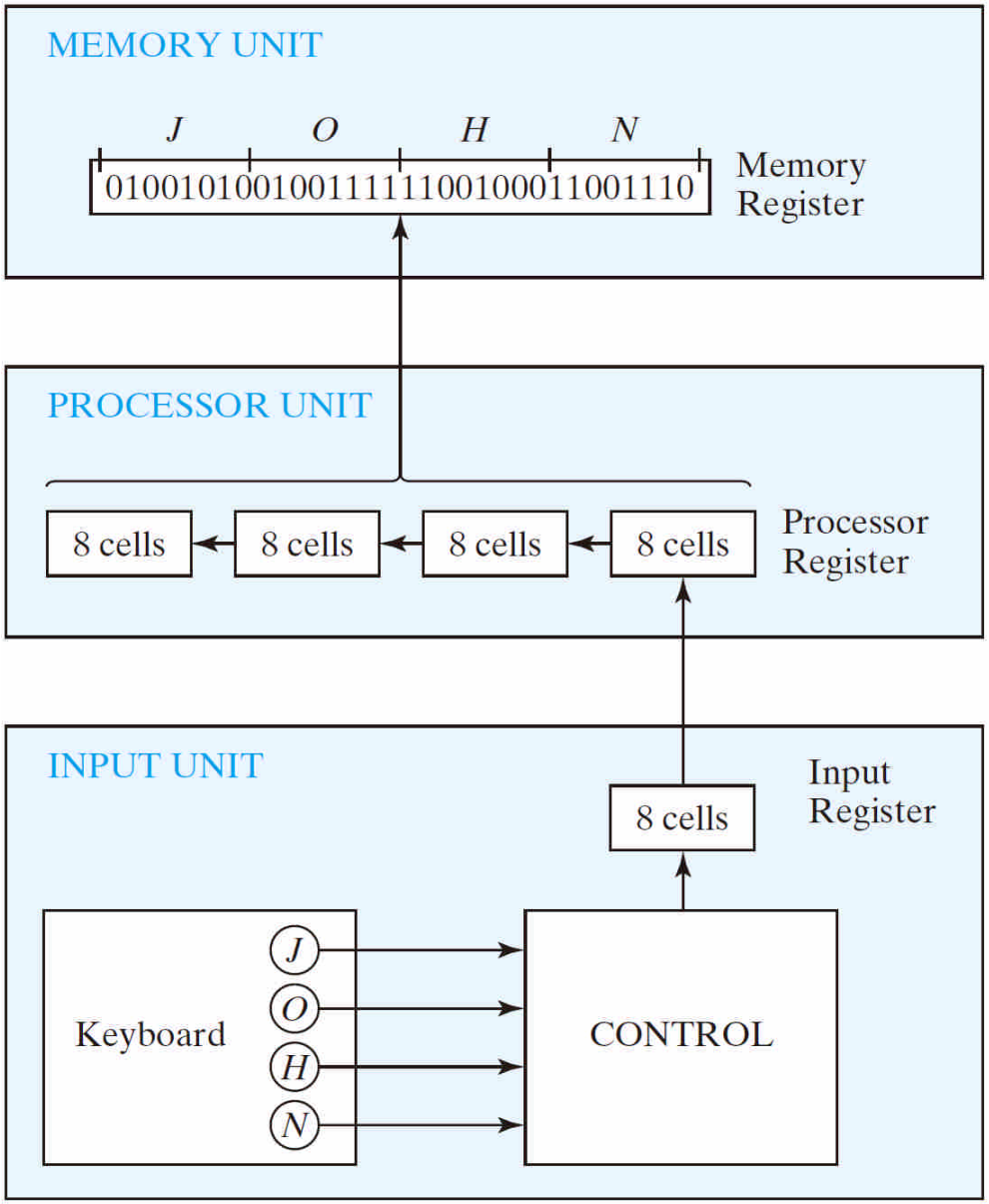


FIGURE 1.1
Transfer of information among registers

- **The other major component of a digital system**
  - **circuit elements to manipulate individual bits of information**

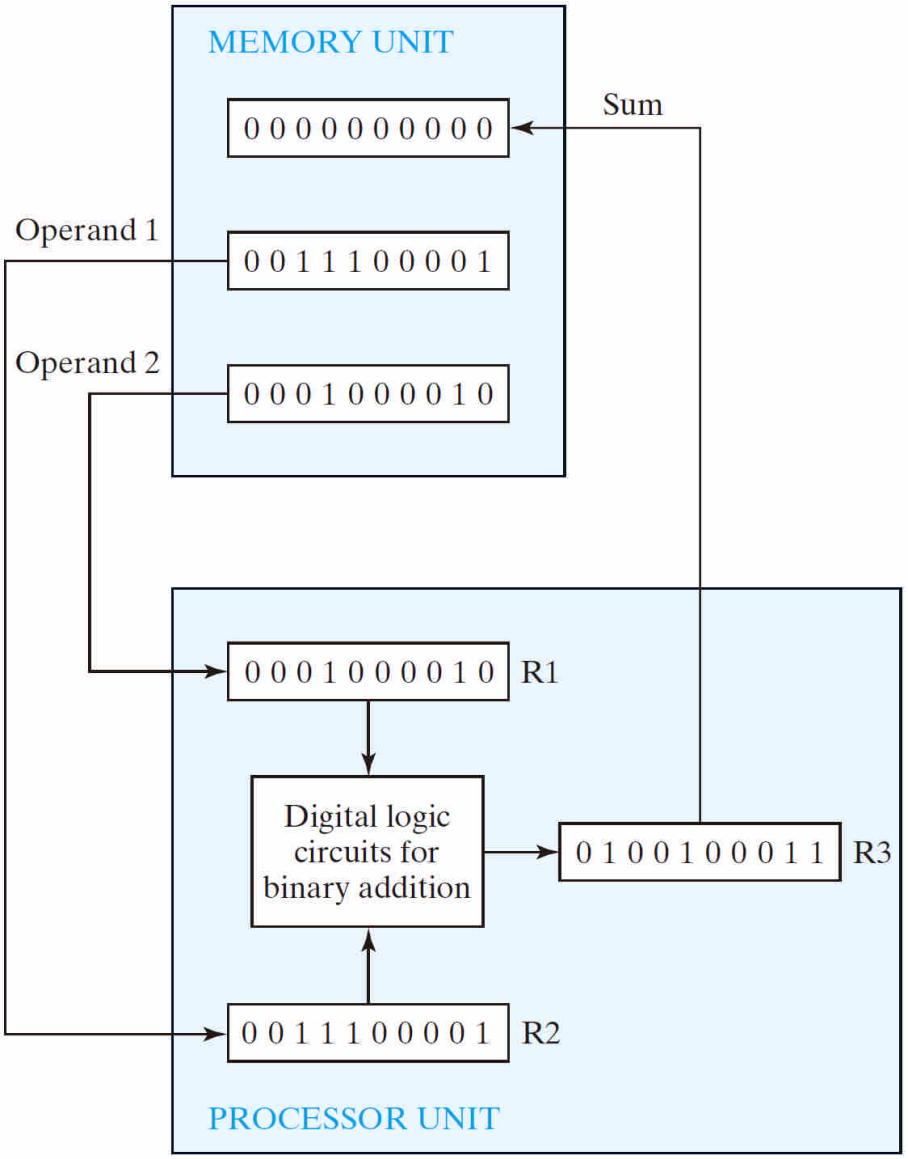


FIGURE 1.2
Example of binary information processing

Binary Logic

Definition of Binary Logic

- Binary logic consists of binary variables and a set of logical operations. The variables are designated by letters of the alphabet, such as A, B, C, x, y, z, etc, with each variable having two and only two distinct possible values: 1 and 0, There are three basic logical operations: AND, OR, and NOT.

1. AND: This operation is represented by a dot or by the absence of an operator. For example, $x \cdot y = z$ or $xy = z$ is read "x AND y is equal to z," The logical operation AND is interpreted to mean that $z = 1$ if only $x = 1$ and $y = 1$; otherwise $z = 0$. (Remember that x, y, and z are binary variables and can be equal either to 1 or 0, and nothing else.)
2. OR: This operation is represented by a plus sign. For example, $x + y = z$ is read "x OR y is equal to z," meaning that $z = 1$ if $x = 1$ or $y = 1$ or if both $x = 1$ and $y = 1$. If both $x = 0$ and $y = 0$, then $z = 0$.
3. NOT: This operation is represented by a prime (sometimes by an overbar). For example, $x' = z$ (or $\overline{x} = z$) is read "not x is equal to z," meaning that z is what z is not. In other words, if $x = 1$, then $z = 0$, but if $x = 0$, then $z = 1$, The NOT operation is also referred to as the complement operation, since it changes a 1 to 0 and a 0 to 1.

Binary Logic

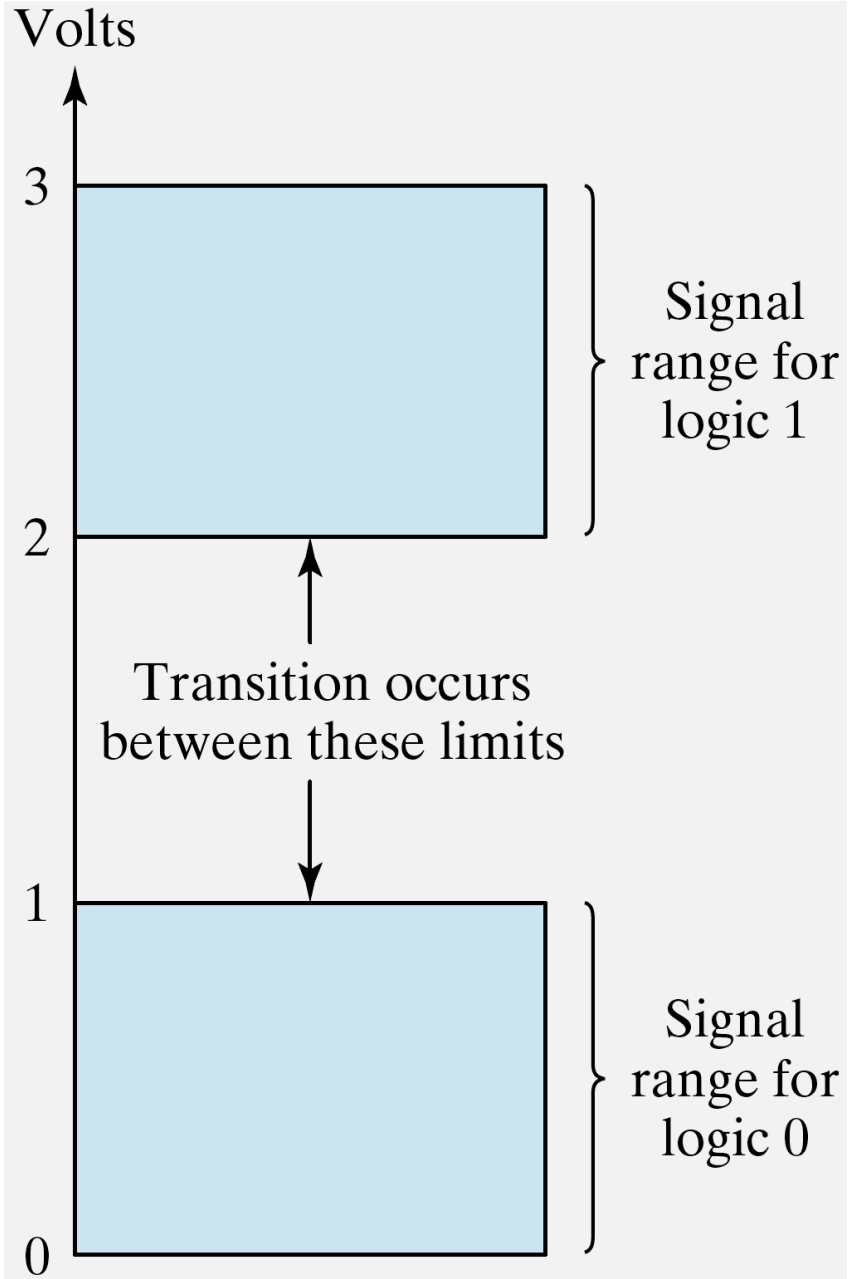
- **The truth tables for AND, OR, and NOT are given in Table 1.8.**

Table 1.8
Truth Tables of Logical Operations

AND			OR			NOT	
x	y	$x \cdot y$	x	y	$x + y$	x	x'
0	0	0	0	0	0	0	1
0	1	0	0	1	1	1	0
1	0	0	1	0	1		
1	1	1	1	1	1		

Binary Logic

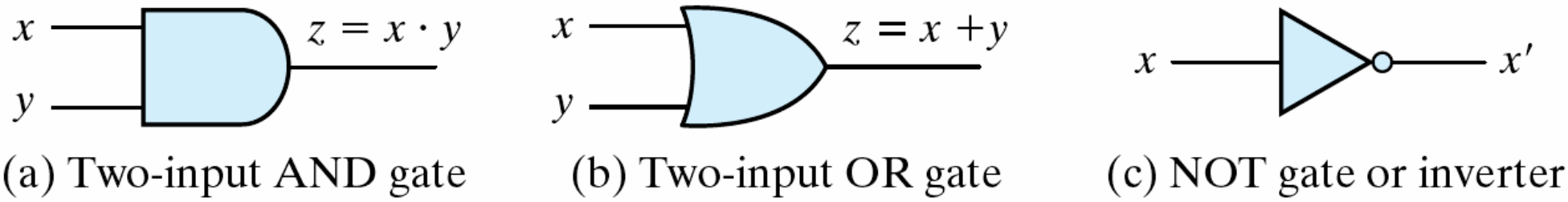
- **Logic gates**
  - **Example of binary signals**



Binary Logic

Logic gates

♣ **Graphic Symbols and Input-Output Signals for Logic gates:**



(a) Two-input AND gate (b) Two-input OR gate (c) NOT gate or inverter

Fig. 1.4 Symbols for digital logic circuits

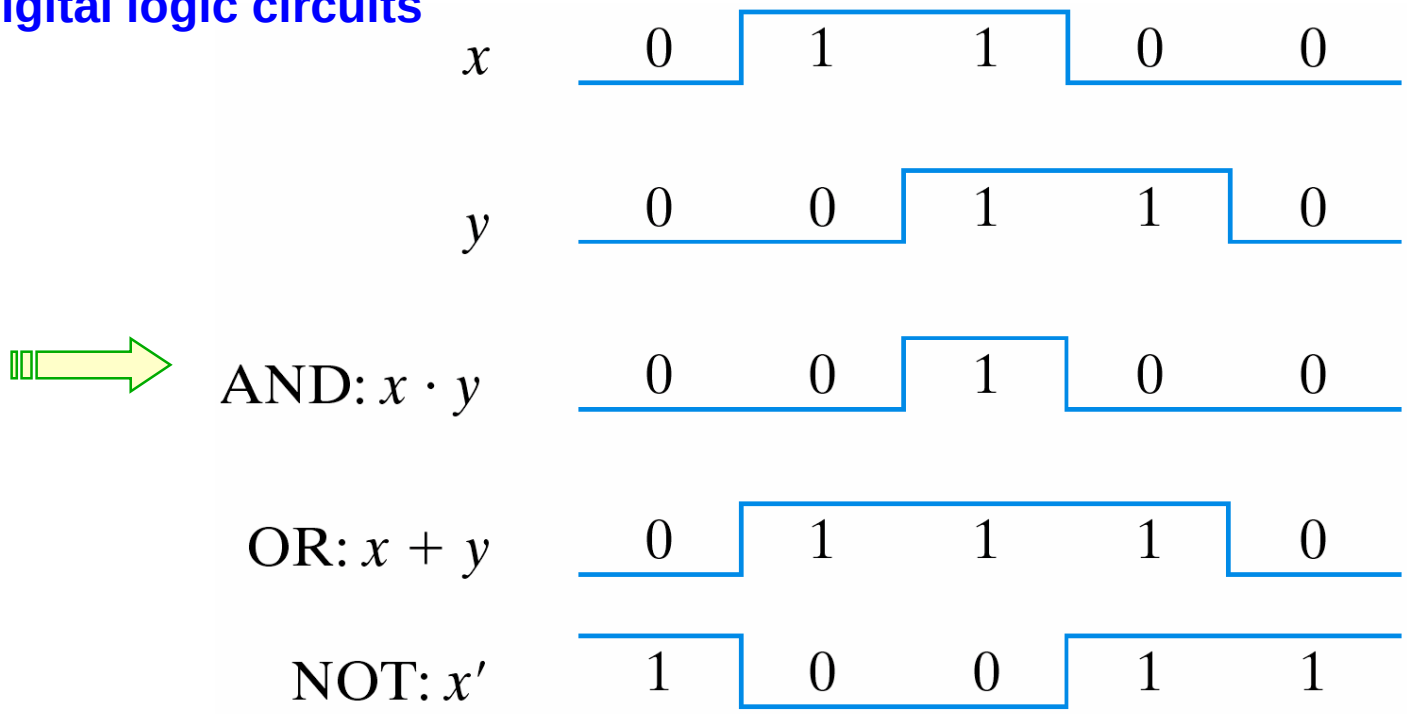
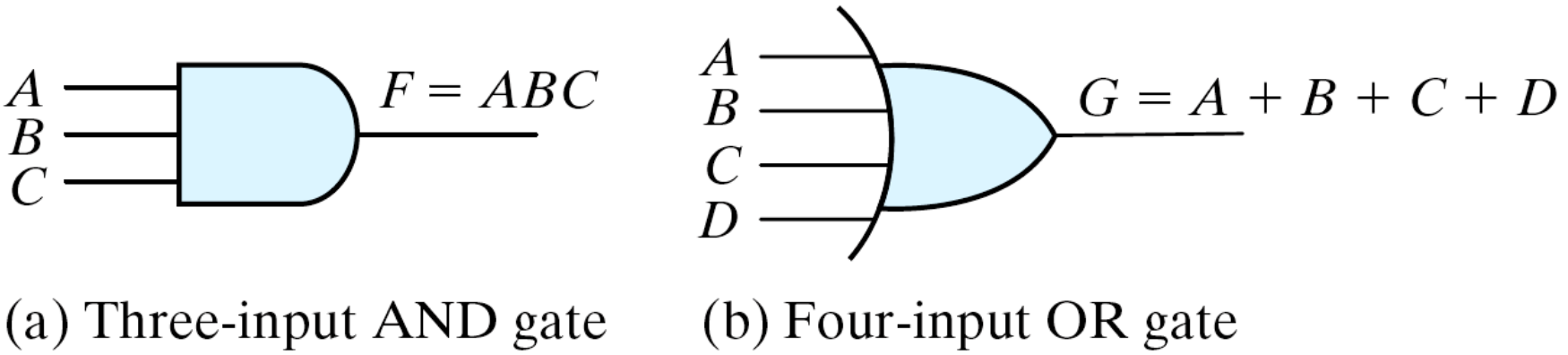


Fig. 1.5
Input-Output signals for gates

Binary Logic

Logic gates

♣ **Graphic Symbols and Input-Output Signals for Logic gates:**



(a) Three-input AND gate (b) Four-input OR gate

Fig. 1.6 Gates with multiple inputs

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